International Space Station Research Results Accomplishments: 2000-2011

The dawning of a new age of research...

International Space Station

Research Results Accomplishments: An Analysis of Results from 2000-2011

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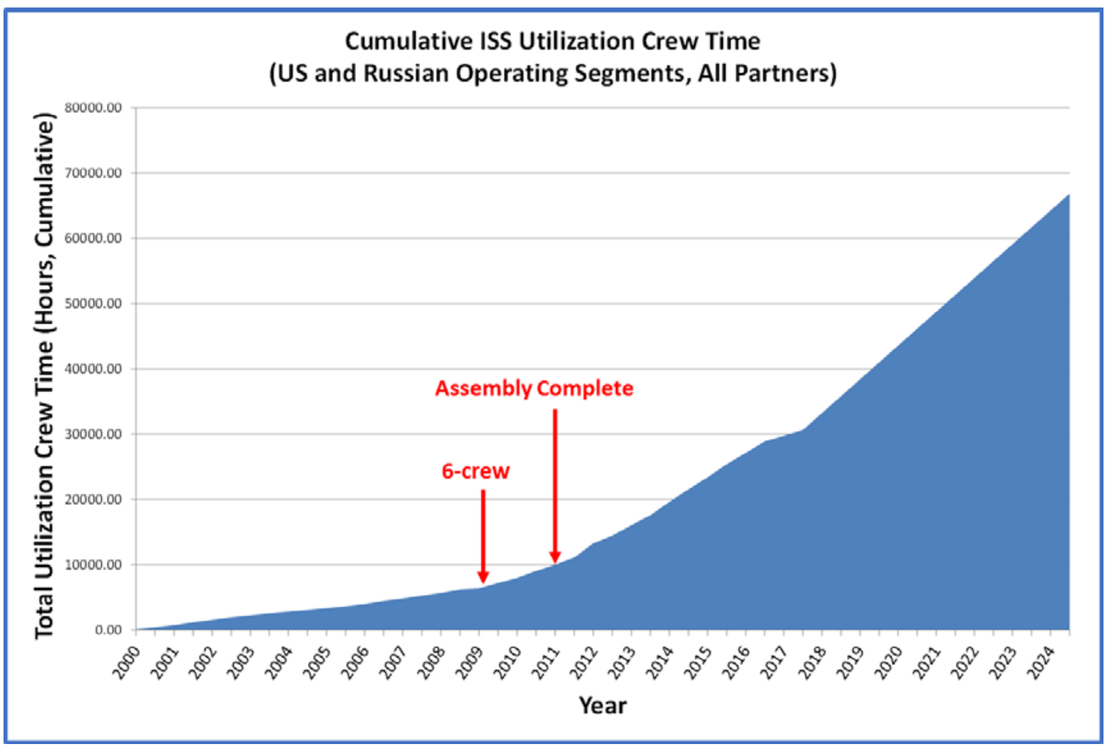
INTRODUCTION

NASA's International Space Station (ISS) celebrated 15 years of operations in November 2013 and is living up to expectations as a leading space laboratory, hosting state-of-the-art science facilities, and providing researchers with a continuous microgravity environment to conduct investigations across many disciplines.

From the first ISS element, launched in November 1998, the ISS has supported investigations and technology demonstrations that will advance NASA's human exploration capabilities beyond low-Earth Orbit (LEO), and improve the daily lives of people on Earth well beyond its operational lifetime. The first 15 years of utilization on ISS has helped answer scientific questions ranging from "How do fluids flow in space?" to "What are the origins of the universe?" The science and technology returns have grown at a steady pace. Even before the assembly of ISS was completed in 2011, the on-orbit crew were busy performing experiments, and with the full complement of a 6-person crew, more than 1 600 investigations have been conducted to date across the international partnership.

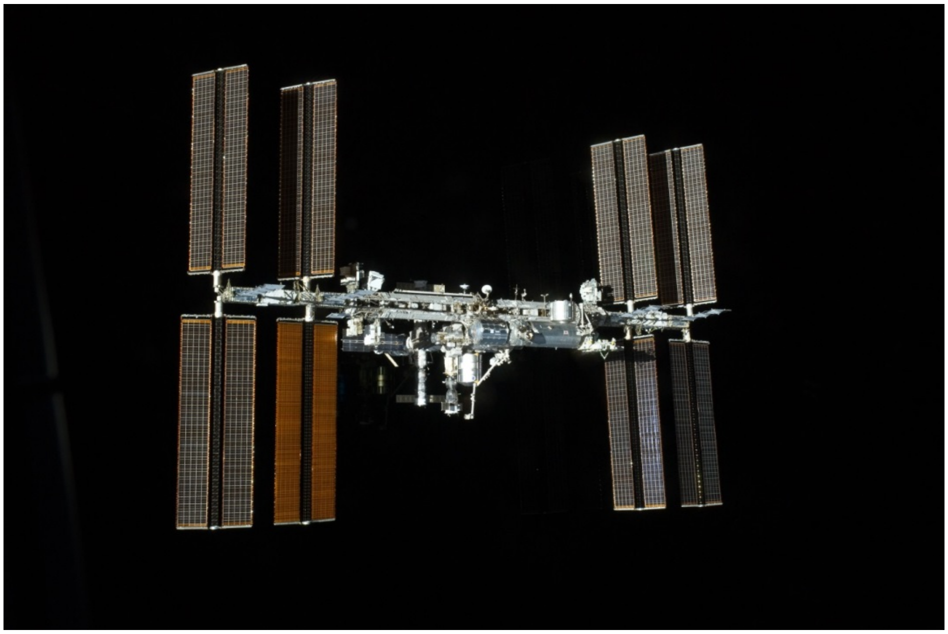


Cumulative Amount of Crew Time dedicated ISS Utilization

This report is intended to provide an archival record of the internationally-sponsored ISS research results collected for investigations performed from 2000-2011 on ISS (Expedition 0 through 30), including scientific publications from studies based on operational data. These investigations represent the research of thousands of scientists around the globe, and have impacts beyond the field of space research into traditional areas of science in multidisciplinary ways that no Earth-based laboratory has done. Yet much like a typical laboratory on Earth, the logistics of the ISS allows for many investigations to be carried forward over several ISS crew expeditions, enabling repeated experimentation and data collection that traditional science calls for. One example of this is the Seedling Growth-1 (SG-1) joint NASA-ESA experiment that was implemented as an extension of the earlier Tropi-1 and Tropi-2 plant growth experiments that first confirmed the existence red-light based phototropism in roots and hypocotyls of seedlings. Researchers were able to capitalize on Tropi results in the SG-1 design by improving different lighting conditions, decreasing seed storage time, and adding real-time seedling observation through improved image downlink [4].

The results from ISS have so far yielded updated new insights into how to better live and work in space, such as addressing radiation effects on crew health [4], combating bone and muscle loss [1, 7], improving designs of systems that handle fluids in microgravity [12], and how to most efficiently maintain environmental control [15]. Latest examples of the ISS utilization applications relevant to our life on Earth is published in the second edition of the *ISS Benefits for Humanity,* which documents several tangible benefits that have resulted from ISS utilization in areas of Earth Observation and Disaster Response, Human Health, Global Education, Innovative Technology, and Economic Development of Space [2]. These benefits include such examples of how space-based research leads to improvements in therapies for balance disorders [2, 16] and contributions to improvements in smart fluids for advanced braking systems and earthquake dampening devices [2, 6]. ISS results also show promise in diverse applications such as medicine [2, 10] and global maritime tracking [11] and have advanced our knowledge of our planet's health while also contributing to disaster response efforts [2, 13, 9, 8]. With all its diversity, the ISS continues to inspire millions of students in ways that only space can [14, 5, 3].

The ISS offers a unique platform for science with critical capabilities not available anywhere else. It provides long-duration microgravity exposure, thermosphere exposure, and external environment exposure for material observations at high inclination, altitude, and velocity. The microgravity environment of the ISS allows scientists to observe unique behaviors that are otherwise masked by gravity on Earth, such as thermocapillary and fluid flows, protein crystal growth, flame structures, and the structure of living cells. The ISS platform also provides access to extreme heat and cold cycles, ultra vacuum, atomic oxygen, and high-energy radiation.



STS135-E011788 – The International Space Station is seen from Space Shuttle *Atlantis* after undocking on STS-135 Flight Day 12, the final shuttle undocking, July 2011.

It is a fully-integrated laboratory, and the US assets have been designated as a National Laboratory, opening up world-class research opportunities to users from other US government agencies, universities, and the private sector. The laboratory features 4 key modules for ISS research; the Russian "Zarya," U.S. "Destiny," the European "Columbus," and the Japanese "Kibo." These laboratories provide equipment essential to space-based research such as: plant growth chambers; sample processing tools; multipurpose storage racks; combustion racks; fluid racks; materials science lab; protein crystallization facilities; Earth observation facilities; refrigerator/freezers; centrifuges; furnaces; vacuum chambers; materials processing facilities; gloveboxes; microscopes; incubators; spectrometer/spectrophotometers; a rodent habitat; an aquarium; a variety of cosmic ray detectors and probes; equipment to support small satellite deployments; a full array of human research equipment; and, facilities for externally mounted experiments.

This technical publication provides an archival record of the ISS research accomplished through Expedition 30, both as part of formal investigations and from early scientific analysis of data collected as part of operating the station. By scientific discipline, the investigations are collected as follows:

- **Biology and Biotechnology** – studies of biology using microgravity conditions to gain insight into the effect of the space environment on living organisms. Areas of emphasis include cellular biology, biotechnology, and plant biology.
- **Earth and Space Science** – studies of the Earth system as it relates to space. Areas of emphasis include astrobiology, astrophysics, heliophysics, Earth remote sensing, and near-Earth space environment.
- **Educational Activities and Outreach** – activities and investigations allowing students and the public to connect with the ISS mission. These activities inspire students to excel in science, technology, engineering, and math and share the astronauts' unique view of the Earth and space with scientists and the public.
- **Human Research** – human medical research to develop the knowledge that is needed to send humans on exploration missions beyond low-Earth orbit. These

studies focus on the effect of living in space on human health, and countermeasures to reduce health risks that will be incurred by living in space in the future. Areas of emphasis include physiological studies related to the effects of microgravity on bone and muscle, other physiological effects of space flight, psycho-social studies, and radiation studies.

- **Physical Science** – studies of physics and chemistry in microgravity. Areas of emphasis include materials sciences experiments, physical properties and phase transitions in polymers and colloids, fluid physics, and crystal growth experiments.
- **Technology Development and Demonstration** – studies and tests of new technologies for use in future exploration missions. Areas of emphasis include spacecraft materials and systems, and characterization and control of the microgravity environment on ISS.
- **Results from ISS Operations** – in addition to the formal, peer-reviewed scientific research and experiments, the ISS supports a large body of research using data from ISS operations, including routine medical monitoring of the crew and data that is collected in the ISS environment, both inside and outside of the ISS.

This report includes a summary of the research results across the entire international partnership that were conducted through the first 30 ISS Expeditions. The investigations are presented topically by the research disciplines, and alphabetically within each topical section. Of the investigations that are summarized here, some are completed with results released, some are completed with preliminary results, and some remain ongoing. For each case we provide an overview of the research objectives and the results that have been returned to date. We also indicate whether additional activities are planned for future ISS missions at the time of writing. Please note there are additional investigations/projects not included in this publication that are continuously updated at http://www.nasa.gov/stationresults.

For interested readers, the appendices provide a full listing of research publications sorted by discipline and investigation acronyms.

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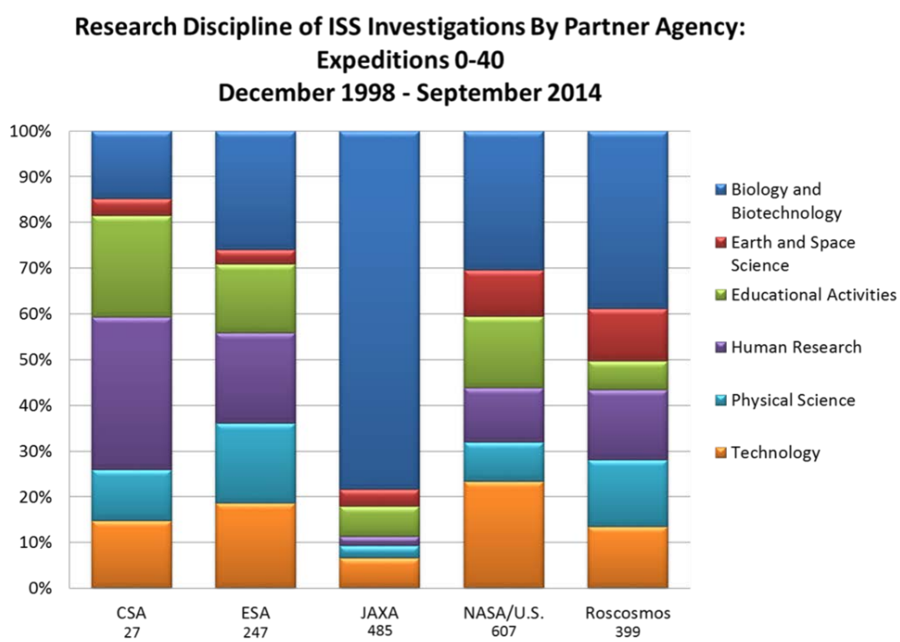
EXECUTIVE SUMMARY

INTERNATIONAL SPACE STATION RESEARCH RESULTS DURING THE ASSEMBLY AND UTILIZATION YEARS: 2000-2011

Several years before the first module of the International Space Station (ISS) was launched in 1998, an international collaboration between the Canadian Space Agency (CSA), European Space Agency (ESA), Japanese Aerospace Exploration Agency (JAXA), State Space Corporation of Russia (Roscosmos), and the National Aeronautics and Space Administration (NASA) was developed. This partnership has worked together for nearly 2 decades to complete one of the most ambitious engineering projects ever conceived, and has initiated a research program that has grown since "Assembly Complete" in 2011.

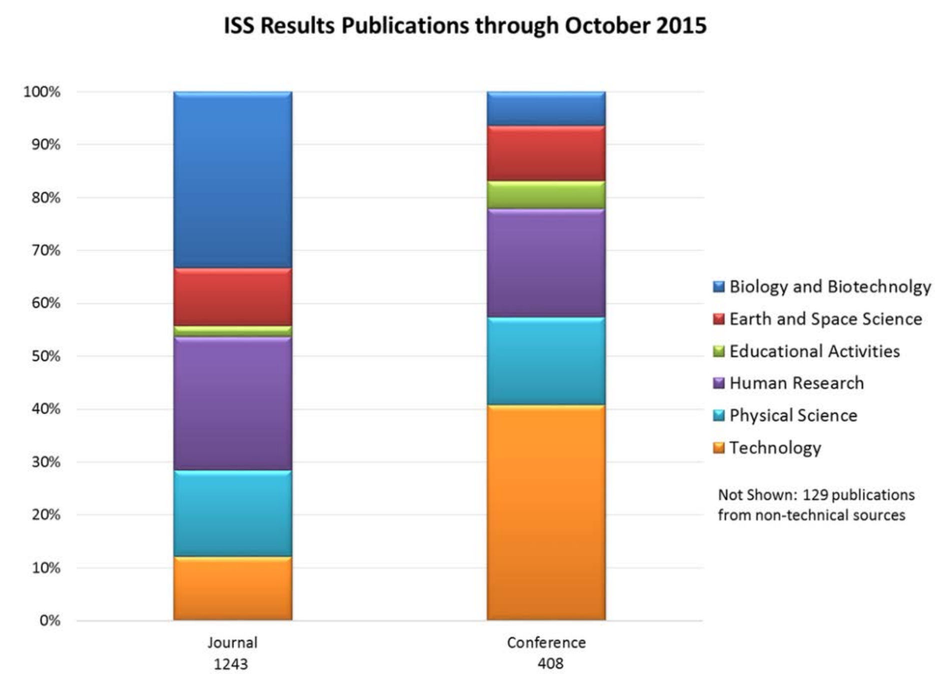
Even as the vehicle was being built during the ISS assembly phase, the potential benefits of space-based research and development were demonstrated, including the advancement of scientific knowledge based on experiments conducted in space, development and testing of new technologies, and derivation of Earth applications from new understanding. The international utilization strategy is based on research spanning several disciplines. The ability to complete follow-up investigations in a period of months allows researchers to make rapid advances based on new knowledge gained from ISS activities. Now, during the utilization phase, and with extension of the ISS through at least 2024, the ISS partners work together to track the objectives, accomplishments, and applications of the new knowledge gained in a way that will impact humanity like no laboratory on Earth.



Distribution by discipline of NASA's ISS experiments for Expeditions 0 through 40. Graph courtesy of JSC/NASA.

NASA's ISS Program Science office maintains an online experiment database (www.nasa.gov/iss-science) that tracks and communicates ISS research activities across the entire ISS partnership, and it is continuously updated. It captures ISS experiment summaries and results, and includes citations to the result publications and patents as they become available. After any one research activity is completed on ISS, it often takes 3-5 years for completed data analysis and publication of results in a scientific journal [7]. The culmination of these results for experiments performed through Expedition 30 are now published in this report, with approval by the ISS partnership. As of December 2015, over 1 200 journal publications describe ISS research. Non-journal publications resulting from ISS utilization include 59 patents and over 400 conference proceedings.

Journal articles of ISS science results range across the international partnership and across the disciplines. For example, in PLoS One, ESA-sponsored scientists published molecular evidence of plant seedling stress response to the microgravity environment by documenting the depletion in proteins associated with normal plant metabolism and the increase in proteins associated with stress responses [2]. Scientists from Roscosmos-sponsored programs have leveraged data gathered from long-duration spaceflight to develop new tools for biological and immunological testing in space, impacting space-related immune deficiency research while advancing health care in remote and resource-restricted areas [3]. CSA scientists from the CCISS investigation published in *the Journal of Applied Physiology* that while the current countermeasures on ISS maintain cardiovascular stability in resting conditions in space; key aspects of cardiovascular health with potential long-term consequences are not yet protected [4]. Advancing our knowledge of our universe, JAXA investigators have published MAXI investigation observations in *Nature* of a “first-ever”: the instant that a massive black hole swallowed a star, along with data that revealed the existence of a hypernova remnant estimated to be 3 million years old, perhaps the first in our galaxy [5]. The collaboration of global scientists involved in the NASA-sponsored Alpha Magnetic Spectrometer-02 investigation have published intriguing evidence of “new phenomena” in *Physical Review Letters,* as the instrument was the first to sift through galactic cosmic rays in energy ranges beyond 200Gev, challenging theoretical models of cosmic predictions when searching for evidence of elusive dark matter [1]. One of the earliest ISS investigations was also the most collaborative- the *ICE-First* investigation included investigators from France, Canada,



A compilation of the number of publications resulting from research aboard the ISS. Each discipline has produced a steady stream of published results.

Japan, and the United States to study the effects of the spaceflight environment on living systems, using the *Caenorhabditis elegans* as the model organism of study. This report shares the publications of this initial collaboration across the different aspects that were studied, including radiobiology, muscle protein changes, ageing, radiation effects on living organisms, apoptosis, and DNA damage and repair [6].

A Look to the Future — Supporting Exploration and benefits to humanity

As the ISS continues to be a test bed for new technology and scientific discovery, scientists and engineers around the world build on ISS results, leading to greater research impacts and scientific collaboration across both space-related and non-space-related fields of science. The ISS partnership eagerly awaits results of the collaborative research performed on the first-ever one-year ISS human expedition, 3D printing/manufacturing in space, protein crystal growth, advanced telerobotics and materials testing, new rodent research and other model organism capabilities, additional instruments to study our climate, and unique contributions to fundamental physics, all while inspiring the next generation of innovators and artists. As ISS research activities and operations continue, scientific data derived from earlier experiments will continuously be re-examined, refined, and assembled with new data and findings, including data from other fields never considered. We anticipate successful ISS research will continue to be used to sow the seeds of new ideas and formulate new conclusions and hypotheses to be tested on future missions both in LEO and on Earth.

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BIOLOGY AND BIOTECHNOLOGY

The ISS laboratories enable scientific experiments in the biological sciences that explore the complex responses of living organisms to the microgravity environment. The lab facilities support the exploration of biological systems ranging from microorganisms and cellular biology to integrated functions of multicellular plants and animals. Several of the biological sciences experiments have facilitated new technology developments that allow growth and maintenance of living cells, tissues, and organisms.

Drosophila Motility, Behaviour and Ageing (Ageing)

Research Area: Animal Biology – Invertebrates

Expedition(s): 7 and 8

Principal Investigator(s):

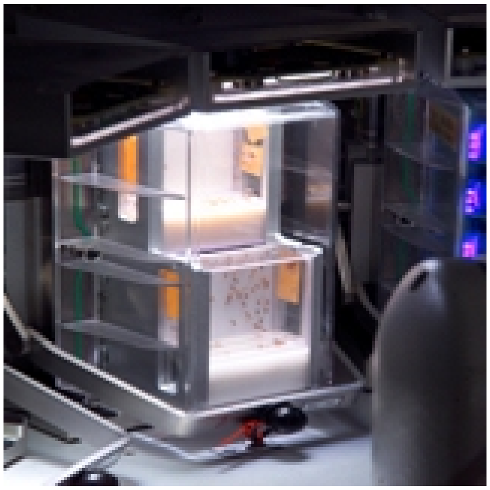
- Roberto Marco, PhD*, Universidad Autonoma de Madrid, Madrid, Spain
- Raúl Herranz, PhD, Centro de Investigaciones Bioligicas, Madrid, Spain

**Deceased*

Research Objectives

The Drosophila Motility, Behaviour and Ageing (Ageing) experiment studies the mechanisms of the abnormal motility response encountered in space by young Drosophila flies with consequences on the posterior aging response of the flies. For this purpose, a long-lived strain, a short-lived strain, and a strain showing an abnormal gravitropic response on the ground are studied.

Results



Drosophila chambers. ESA image.

Ageing was sent into space to gain a better understanding of the biological responses in living organisms after prolonged exposure to microgravity. On October 18, 2003, a total of 450 *Drosophila melanogaster* flies were sent to the ISS for an 11 day flight to study their motility behavior. Motility behaviors were studied in 4 different fly strains- short lived mature flies, short lived young flies, gravity altered flies, and long lived young flies. In this experiment, the mature fly strain had the highest motility levels. Previous tests led scientists to believe the young flies would have the highest motility levels; however these young flies were exposed to lower temperatures during transport. Temperature plays a huge role in motility levels, and unfortunately skewed this study because only the young flies were exposed and not the mature flies. Although activity levels were increased in all strains, because of the cold transport, they did not reach their full potential and a reflight of this investigation will need to be run for more conclusive results (de Juan 2007).

Once samples were returned to Earth, it was determined that the structural components for the sensory and nervous system are rather insensitive to microgravity. No observable changes were found in any of the fly strains. Dendritic and axonal activities remained the same and the somata size was only slightly altered (Horn 2007).

Although this research line was closed due to the premature death of the PI (Roberto Marco) in 2008, additional work using those and additional altered gravitaxis drosophila strains was performed later in simulated microgravity ground based facilities. Both simulated microgravity and hypergravity environments led to alterations in the behavior of the flies, as well as with accelerated ageing, especially since the processes are related, strains selected for a different gravitaxis sensibility show different ageing responses (Herranz 2008; Serrano 2010, 2012). It has been particularly interesting to use diamagnetism as a new tool for behavioral studies in flies exposed to altered gravity conditions (Hill 2012).

PUBLICATION(S)

Herranz R, Hill RJ, Dijkstra CE, Eaves L, van Loon JJ, Medina F. The behavioral-driven response of the Drosophila imago transcriptome to different types of modified gravity. *Genomics Discovery*. 2013;1(1):1. doi: 10.7243/2052-7993-1-1.

Hill RJ, Larkin O, Dijkstra CE, et al. Effect of magnetically simulated zero-gravity and enhanced gravity on the walk of the common fruitfly. *Journal of the Royal Society Interface*. 2012;9(72):1438-1449. doi: 10.1098/rsif.2011.0715.

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Horn ER, Dournon C, Frippiat J, Marco R, Boser S, Kirschnick U. Development of neuronal and sensorimotor systems in the absence of gravity: Neurobiological research on four soyuz taxi flights to the International Space Station. *Microgravity Science and Technology*. 2007;19(5-6):164-169. doi: 10.1007/BF02919474.

This investigation is complete and all results are published.

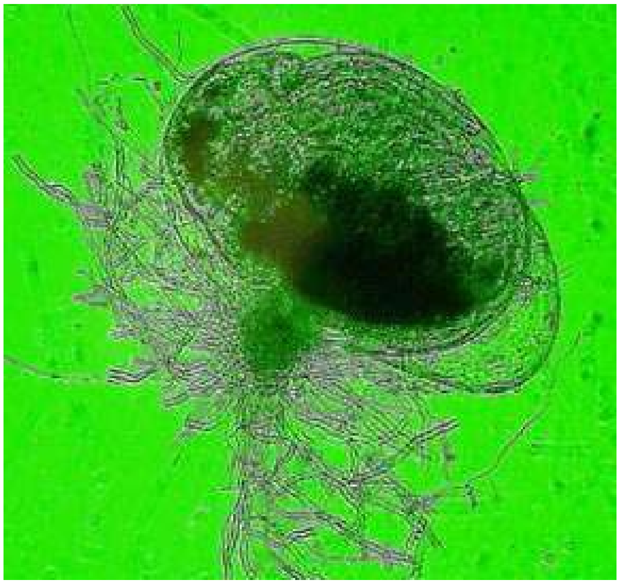
ROSCOSMOS

STUDY OF THE RESISTANCE OF A MODELED CLOSED ECOSYSTEM AND CHAINS OF ITS COMPONENTS IN MICROGRAVITY (AKVARIUM)

Research Area: Animal Biology – Invertebrates
Expedition(s): 11-17
Principal Investigator(s):
- Vladimir N. Sychev, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

The Study of the Resistance of a Modeled Closed Ecosystem and Chains of its Components in Microgravity (Akvarium) examines the impact of spaceflight factors on dormant embryos of lower aquatic crustaceous organisms (*Daphnia magna, Streptocephalus torvicornis, Eucypris species,* etc.) in the diapause and the larval stages and capable of remaining in cryptobiosis (an ametabolic state of life entered by an organism in response to adverse environmental conditions) for an extended period of time.



Eggs of freshwater crustaceans (species *Daphnia magna*) after exposure on board the International Space Station. Roscosmos image.

EARTH BENEFITS

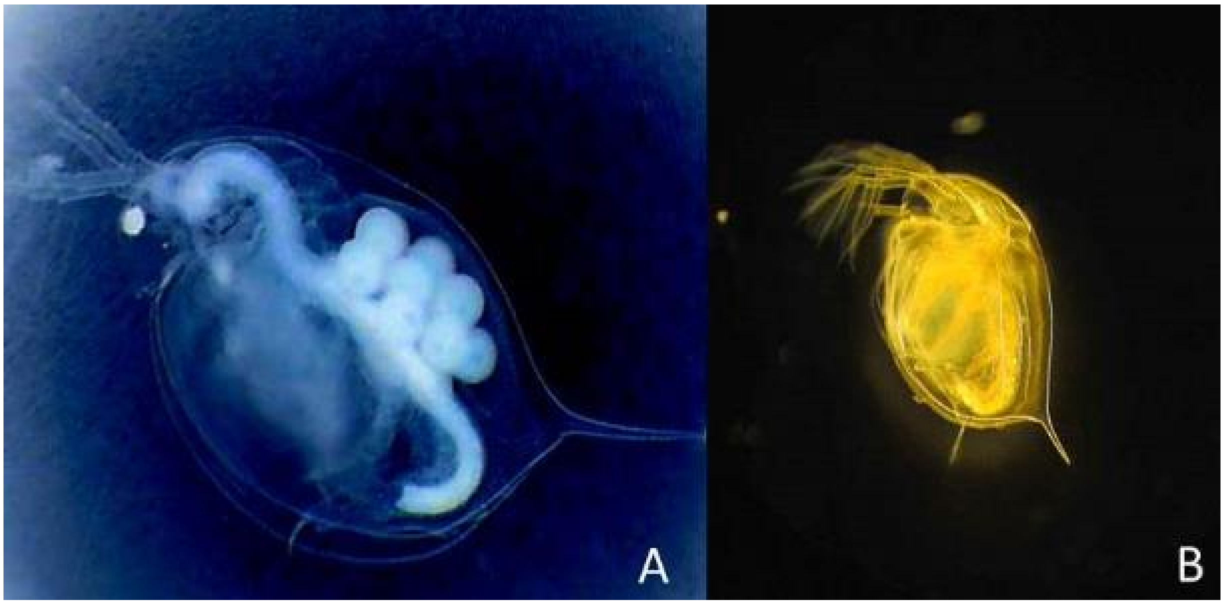
The results obtained may also be important for the ecology of terrestrial communities. The existence of such a capability significantly changes the understanding of the role of the maternal effect in microevolutionary processes in bodies of water. If such a phenomenon is observed with respect to other stress factors typical on the Earth’s surface, such as ultraviolet radiation, then the properties of diapause embryos on dry land and at the bottom of bodies of water will be different, as will their capability to fight against something specific after reactivation.

SPACE BENEFITS

The experiment results enable data to be obtained on the impact of spaceflight conditions on the resilience of the functioning of a closed ecosystem and on the growth and development of individual organisms that are components of the autotrophic and heterotrophic links of the closed ecosystem.

RESULTS

The results obtained made it possible to hypothesize that exposure on the International Space Station (ISS) acted on the dry *D. magna* embryos as a stress factor, weakening their vital activity. This manifested as both a decrease in reactivation effectiveness and a change in the dynamic of the average sizes of specimens capable of hatching, which took the form of the slower emergence of young fish from smaller, and thus weaker, embryos. The effect of spaceflight factors is also manifested in the second generation of *Daphnia,* causing a transition to gamogenesis and the production of males in the population. The *D. magna* embryos after exposure on the ISS manifested a high sensitivity to the effect of the fungal parasite *Pitium daphniarum* as compared to the control, which among other factors raises the question of biological safety measures from spacecraft flora regarding biological material intended for long-term space transportation.



Daphnia magna female (A) and male (B). Roscosmos image.

In *S. torvicornis,* a decrease in growth and reproduction parameters was observed, however, unlike the control, this was not confirmed statistically due to extremely high variability and relating to its parameter assessment error. The only statistically significant factor for this species was the effect of day length on the growth of females.

The studies of *Artemia salina* showed that the temperature threshold of expression activation of the gene encoded in the Hsp90 molecular chaperone was substantially lower in response to thermal stress in *Artemia nauplius* from the flight samples than in the ground control group. This manifested as a sharp increase detected in the level of Hsp90 gene expression in both flight groups with thermal stress of 32-33°C, while in the control groups the minimum thermal stress required to initiate Hsp90 synthesis was 37-38°C.

Investigations on the ground did not identify an impact of spaceflight factors on the rate of reactivation and subsequent vital activity on the chironomid *Polypedilum vanderplanki* larva exposed on the ISS in a state of cryptobiosis. The fertility in the experiment animals did not differ from that of the control animals.

These results showed that a cell in a dormant stage and containing just 5% water is capable of acquiring and transferring information on the effects of negative factors after transitioning from the dormant stage to an active state, thus also confirming data from molecular/genetic research. These results provide the rationale for continuing in-depth studies of the impact of spaceflight factors on dormant stage living organisms belonging to various taxonomic groups.

PUBLICATION(S)

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Gusev OA, Okuda T, Sychev VN, Levinskikh MA, Sugimoto M. Perspectives of RNA/DNA studies using latent stages of invertebrates and plants exposed to spaceflight and outer space environments. *Space Utilization Research*. 2007;344-346.

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This investigation is complete and all results are published.

CAENORHABDITIS ELEGANS RNAI SPACE EXPERIMENT (CERISE)

Research Area: Animal Biology-Invertebrates
Expedition(s): 20 and 21
Principle Investigator(s):
- Atsushi Higashitani, PhD, Tohoku University, Sendai, Japan

RESEARCH OBJECTIVES

Caenorhabditis Elegans RNAi Space Experiment (CERISE) evaluates the effect of microgravity on RNA interference and studies how the space environment effects protein phosphorylation and signal transduction in the muscle fibers of *Caenorhabditis elegans*.

ISS021E031956 – Astronaut Jeffrey Williams works on the *C. Elegans* RNAi Space Experiment at the Clean Bench Operation Chamber in the Japanese Experiment Module - Pressurized Module. JAXA image.

EARTH BENEFITS

In addition to the RNAi experiment, investigators studied the molecular effect of microgravity on the *C. elegans* muscular cells using transcriptome and proteome analyses. The current results indicate alterations in muscular, cytoskeletal, and mitochondrial proteins of spaceflown *C. elegans*. This data could potentially clarify the molecular mechanism of human muscle atrophy caused by aging and unloading.

SPACE BENEFITS

The efficiency of RNAi and Green Fluorescent Protein (GFP) technologies used in space illustrate the relative ease with which these important tools can be incorporated into future experiments to study the molecular mechanisms underpinning the biological alterations induced by spaceflight. In addition, researchers would like to understand the molecular mechanisms of spaceflight-induced muscle atrophy in order to eliminate the significant risk on astronaut health and mission performance from CERISE data.

RESULTS

Comparison of the in-orbit samples to its Ground Control (GC) equivalent showed no differences. The Gene expression of 228 microRNAs of the 232 analyzed were also unaffected during the micro-g duration. RNAi applied to a GFP reduced chromosomal *gfp* expression in gonad tissue, which was not different from the GC samples. RNAi applied to an *rbx-1* also induced abnormal chromosome segregation in the gonad for the in-orbit samples. Finally, RNAi applied to lysosomal cathepsins prevented degradation of the muscle-specific α-actin protein in both micro-g and GC conditions (Etheridge [a] 2011).

Treatment with RNAi works as effectively in microgravity as on Earth within multiple tissues, suggesting RNAi may provide an effective tool for combating spaceflight-induced pathologies aboard future long-duration space missions. Furthermore, this is the first demonstration that RNAi can be utilized to block muscle protein degradation, both on Earth and in space. Scientists are now attempting to analyze the effect of microgravity on the *C. elegans* muscular cells using transcriptome and proteome analyses (Etheridge [b] 2011).

PUBLICATION(S)

Etheridge T, Nemoto K, Hashizume T, et al. The effectiveness of RNAi in *Caenorhabditis elegans* is maintained during spaceflight**.** *PLOS ONE*. 2011;6(6): e20459.

Etheridge T, Nemoto K, Hashizume T, et al. The next phase of life-sciences spaceflight research: harnessing the power of functional genomics. *Communicative & Integrative Biology.* 2011;4:6, 1-2.

This investigation is complete; however additional results are pending publication.

Commercial Generic Bioprocessing Apparatus (CGBA), Three Investigations

Research Areas: Animal Biology – Invertebrates (Synaptogenesis in Microgravity)
Cellular Biology (Kidney Cell Gene Expression)
Microbiology (Antibiotic Production in Space)

Expedition(s): 0, 2, and 4

Principal Investigator(s):
- Haig Keshishian, PhD, Yale University, New Haven, Connecticut
- Timothy G. Hammond, MD, Durham Veterans Affairs Medical Center, Durham, North Carolina
- David M. Klaus, PhD, University of Colorado, Boulder, Colorado

Research Objectives

Synaptogenesis in Microgravity (Keshishian)

CGBA-Synaptogenesis in Microgravity (SM) uses the Commercial Genetic Bioprocessing Apparatus (CGBA) hardware to examine how microgravity affects nervous system development of fruit flies, *Drosophila melanogaster*. This investigation uses *D. melanogaster* embryos and larvae to observe how nerves that control movement navigate through an embryonic central nervous system (CNS) and attach to muscle fibers. Investigators observe how the synapses, which are the junction between 2 nerve cells where signals are transferred from one nerve to another, develop both during and after the embryonic stage.

ISS004E11048 – The Commercial Generic Bioprocessing Apparatus isothermal containment module v.3, installed in Expedite the Processing of Experiments for Space Station rack just above astronaut Dan Bursch's extended left arm; photograph taken during Expedition 4.

Kidney Cell Gene Expression (Hammond)

The primary objective of CGBA - Kidney Cell Gene Expression (KCGE) is to assess how microgravity alters the genes controlling protein production in kidney cells. The investigator hopes to be able to manipulate the kidney cells to produce specific tissues that can be used in models when developing medicines or in humans. The kidney cell samples are drawn into the test tubes containing a preservative approximately 2 hours after reaching orbit. Once the samples are drawn, a messenger RNA (mRNA) preservative is added to the cell cultures for postflight analysis.

Antibiotic Production in Space (Klaus)

The objective of this experiment is to determine whether secondary metabolite production in microbes is impacted by long-duration spaceflight. Previous research, which was conducted during short-duration space shuttle flights, identified significant potential for antibiotic production by microorganisms in orbit. The CGBA Antibiotic Production in Space (APS) experiment is the first International Space Station (ISS) investigation to test whether long-duration exposure to microgravity stimulated antibiotic production in microorganisms. The experiment uses *Streptomyces plicatus* to produce the antibiotic compound actinomycin D. Actinomycin D is an anti-tumor antibiotic used to treat tumors of the bone, urogential tract, skeletal muscle, kidney, and testis.

Earth Benefits

Researchers believe microgravity presents a pure environment to study different human physiological systems. Scientists hope to gain a better understanding of how nerves develop and attach to muscle fibers during the CGBA-SM experiment. Newly acquired information may be used to produce treatments for various nervous system diseases. CGBA-KCGE aims to manipulate cell samples to create tissues similar in structure to those found in the human body. These tissues can be applied to many different types of research and can be used for developing new medications to treat various diseases. Insight gained through observations made during CGBA-APS target further improvements in antibiotics production and efficiency in facilities on Earth. The microgravity environment is vital in determining the critical factors observed in increasing antibiotic production and may lead to economic gain through an increase in fermentation efficiency.

Space Benefits

Postflight images show tray with waste bag and samples visible (dark substance indicates actinomycin D), close up of remaining viable culture from opened tray, and sample bags. NASA Marshall Space Flight Center image.

As the drive for long-duration space exploration increases, it is imperative to understand how microgravity affects the human body. CGBA-SM focuses on the developing nervous system. The information derived from this investigation can aid in generating countermeasures to offset the negative effects of spaceflight. CGBA-KCGE observes the effects that microgravity has on cellular structures and gives insight to how the human body reacts at the cellular level. These changes may lead to the development of countermeasures that would lower the human risk of long-duration spaceflight. CGBA-APS concentrates on the accelerated rate of antibiotic production in microgravity in comparison to those produced on Earth. Researches think the ability to grow large quantities of antibiotics in microgravity will further pharmaceutical research.

Results

Synaptogenesis in Microgravity

Preliminary results based on the 30-day postflight report, provided by Dr David Klaus of BioServe Space Technology, indicated that although the CGBA hardware operated successfully, there were unexpected temperature drifts above the planned temperature in 2 of the 7 containers. While ground tests were completed for comparison to the inflight samples, final data analysis has not been released.

Kidney Cell Gene Expression

Preliminary results indicated that an average of 60% of the kidney cell samples from CGBA-KCGE were drawn into the Vacutainers. Although the sample size was smaller, the samples were sufficient for postflight analysis. For the synaptogenesis experiment with fruit flies, preliminary results indicated that although the CGBA hardware operated successfully, there were unexpected temperature drifts above the planned temperature in 2 of the 2 containers. While ground tests were completed for comparison to the in-flight samples, final data analysis has not been released.

Antibiotic Production in Space

This experiment originally flew on Expedition 2 but was unable to function due to technical issues. Its reflight took place during Expedition 4 where the hardware performed as planned. Samples of antibiotic were taken at 4-day intervals. A total of 48 samples of *Streptomyces plicatus* were used to produce the antibiotic compound actinomycin D for a span of 72 days on orbit. The initial production of actinomycin D from in-orbit samples was higher than those produced during the ground tests. This was true for samples that were taken on day 8 (15.6 % increase) and day 12 (28.5% increase) of the investigation. Beginning at day 16, the ground experiment produced more antibiotics than the in-orbit experiment. This trend continued for the remainder of the experiment. The causes for the higher yield during the first 12 days of the experiment are still unknown. One theory is that there is a shorter lag phase, which allowed ISS samples to reach the growth and production phases sooner than the ground samples (Benoit 2005). Identifying the mechanism that caused increased production of antibiotics while in microgravity and applying them to production on Earth could be advantageous to the pharmaceutical industry. A method for transferring the microgravity research results to Earth-based production has not yet been identified.

Publication(s)

Benoit MR, Li W, Stodieck LS, et al. Microbial antibiotic production aboard the International Space Station. *Applied Microbiology Biotechnology*. 2006;70(4):403–411.

Klaus DM, Howard HN. Antibiotic efficacy and microbial virulence during spaceflight. *Trends in Biotechnology*. March 24, 2006. doi: 10.1016/j.tibtech.2006.01.008.

Klaus D, Benoit M, Bonomo J, et al. Antibiotic production in space using an automated fed-bioreactor system. *AIAA International Space Station Utilization – 2001*, Cape Canaveral, FL; October 15–18, 2001.

These investigations are complete and all results are published.

CRICKETS IN SPACE-2 (CRISP-2)

Research Area: Animal Biology-Invertebrates
Expedition(s): 10 and 11
Principal Investigator(s): ● Eberhard R. Horn, University of Ulm, Ulm, Germany

RESEARCH OBJECTIVES

The Crickets in Space-2 (CRISP-2) experiment follows on from a previous experiment, Development of an Insect Gravity Sensory System in Space, performed on the Neurolab STS-90 mission in 1998. Results revealed that the development of gravity-related behavior in crickets was not affected by weightlessness while the physiology of a specific neuron linked to posture sensitivity was modified.

RESULTS

Successful in-flight fertilization was obtained; high-quality neuroanatomical stainings from embryonal nervous systems were obtained; and after landing, embryos could be reared until hatching to test consequences of in-flight fertilization even on the behavioral level. A total number of 112 embryos and 1st larvae from in-flight fertilization were available for the studies. The number of ground controls was 103. Interestingly, the µg-exposed larvae hatched earlier than larvae from the 1-g ground controls.

Top: 1 of the 2 Cricket Containers (CC), showing the adult compartment (CC-AC), the egg collectors (CC-EC), and hatching larvae compartments (CC-LC). Bottom: Egg collectors in open and closed configuration. ESA image.

The results coming from the Eneide (Soyuz 10S/Soyuz 9S exchange) flight revealed that after in-microgravity fertilization, the AST-ir-, PSK-ir-, and CCAP-ir-neurones developed as after on-ground fertilization. This holds not only for neurons with only short neurites located either only within the cerebrum, the thoracic, or the abdominal ganglia chain, but also for those neurons such as PSK-ir neurons that project throughout the whole nervous system, with cell somata lying in the protocerebrum and dendritic arborizations within the cerebral, thoracic, and abdominal ganglia.

Lack of significant differences between 1 g- and altered gravity-larvae does not exclude an altered-gravity sensitivity during early development. Compensatory mechanisms might be activated during ongoing altered gravity conditions to overcome transient deviations from normal neuronal development. The earlier hatching of the 1st instar larvae after in-flight fertilization as demonstrated for the spaceflight experiment CRISP-2 makes this hypothesis very likely.

PUBLICATION(S)

Horn ER, Dournon C, Frippiat J, Marco R, Boser S, Kirschnick U. Development of neuronal and sensorimotor systems in the absence of gravity: Neurobiological research on four Soyuz taxi flights to the international space station. *Microgravity Science and Technology*. 2007;19(5-6):164-169. doi: 10.1007/BF02919474.

Kirschnick U, Agricola H, Horn ER. Effects of altered gravity on identified peptidergic neurons of the cricket *Acheta Domesticus*. *Gravitational and Space Biology*. August 2006;19(2):135-136.

This investigation is complete and all results are published.

FUNGAL PATHOGENESIS, TUMORIGENESIS, AND EFFECTS OF HOSE IMMUNITY IN SPACE (FIT)

Research Area: Animal Biology – Invertebrates

Expedition(s): 13

Principal Investigator(s):
- Sharmila Bhattacharya, PhD, NASA's Ames Research Center, Moffett Field, California

RESEARCH OBJECTIVES

The Fungal Pathogenesis, Tumorigenesis, and Effects of Host Immunity in Space (FIT) experiment primarily studies the effects of spaceflight on the immune system responses of the fruit fly, *Drosophila melanogaster*. Since there is evidence that suggests the immune system of organisms is affected by spaceflight, this proposal seeks to assess the extent and the detailed molecular biological changes that are associated with spaceflight. In addition, this work also investigates the progression of cancerous and benign tumors in sensitized mutant lines (cells that turn into tumors) that show an increase in tumor formation, and is coupled with the effect of radiation exposure.

Dr Sharmila Bhattacharya, checks the health of the fly culture in readiness for the shuttle flight experiment. NASA Ames Research Center image.

EARTH BENEFITS

Microbial effects of pathogens on wild type and immune-compromised hosts are of great relevance to human immune diseases.

SPACE BENEFITS

It is a known fact that space travel affects the genetic activity of crew members, but researchers cannot yet predict which genes are affected or precisely determine how gravity signals a gene to change. FIT is the first step in answering these questions.

RESULTS

FIT studied the effects of spaceflight on the immune system responses of the common fruit fly. Even short-term spaceflight affects the fundamental process of cellular and humoral (secretion of antimicrobial peptides into the blood and accessory processes) immunity and phagocytosis (the cell engulfing microorganisms) functions and the maturation of immune cells in *Drosophila melanogaster* (fruit fly) innate immune system (the first line of defense against invading microorganisms). Many of these changes mirror alterations seen in human innate immune systems postflight. The large number of fruit flies returned from FIT allowed a significant number of assays to be conducted postflight. Physiological changes observed in the innate immune system could be explained by gene expression changes, allowing a fundamental understanding of the underlying molecular pathways affected by spaceflight (Marcu 2011).

PUBLICATION(S)

Taylor K, Kleinhesselink K, George MD, et al. Toll mediated infection response is altered by gravity and spaceflight in *Drosophila*. *PLOS ONE*. January 24, 2014;9:e86485. doi: 10.1371/journal.pone.0086485.

Marcu O, Lera MP, Sanchez ME, et al. Innate immune responses of *Drosophila melanogaster* are altered by spaceflight. *PLOS ONE*. 2011;6(1):1-10. doi: 10.1371/journal.pone.0015361.

Fahlen TF, Sanchez ME, Lera MP, Blazevic E, Chang J, Bhattacharya S. A study of the effects of spaceflight on the immune response in *Drosophila melanogaster*. *Gravitational and Space Biology.* 2006;19(2):133-134.

This investigation is complete and all results are published.

International *Caenorhabditis Elegans* Experiment First Flight (ICE-First), Eight Investigations

Research Area: Animal Biology-Invertebrates

Expedition(s): 8

Principal Investigator(s):

- Noriaki Ishioka, Japan Aerospace Exploration Agency, Tsukuba, Japan
- Shuji Honda, Tokyo Metropolitan Institute of Gerontology, Tokyo, Japan
- Atsushi Higashitani, Tohoku University, Sendai, Japan
- Hiroaki Kagawa, Okayama University, Okayama, Japan
- Catharine A. Conley, PhD, NASA's Headquarters, Washington, DC, United States Development
- Akira Higashibata, Japan Aerospace Exploration Agency, Tsukuba, Japan
- Stuart Kim, PhD, Stanford University, Stanford, California
- Laurent Segalat, Université Lyon 1, Villeurbanne, France
- Ann Rose, PhD, University of British Columbia, Vancouver, British Columbia, Canada

Research Objectives

The International *Caenorhabditis elegans* Experiment First Flight (ICE-First) investigation is a collaborative effort conducted by scientists from several countries, which have the opportunity to work as a team to design related experiments that would produce valuable results for scientists across multiple disciplines. Researchers use *C. elegans* (nematode worms) because they are relatively simple organisms that are used as a model for a wide variety of biological processes.

ICE-First-Aging (Honda)

International *Caenorhabditis elegans* Experiment - First - Aging (ICE-First-Aging) performs an analysis of the aging related protein aggregation and the effects of aging in muscle cells.

This image shows a magnified image of 2 adult worms and 1 juvenile worm crawling in the liquid media that was used for the ICE-First mission.

ICE-First-Apoptosis (Higashitani)

International *Caenorhabditis elegans* Experiment First Flight-Apoptosis (ICE-First-Apoptosis) studies the germ line development including meiotic (process of cell division that produces reproductive cells) chromosomal dynamics and germ cell apoptosis (programmed cell death) under microgravity conditions.

ICE-First-Cells (Kagawa)

International *Caenorhabditis elegans* Experiment First Flight-Cells (ICE-First-Cells) studies the effect of spaceflight on cell migration and muscle cells in *C. elegans* development.

ICE-First-Development (Conley)

International *Caenorhabditis elegans* Experiment First Flight-Development (ICE-First-Development) studies the morphometry (measurements) of larval (immature) *C. elegans* development during spaceflight.

ICE-First-Gene Expression (Higashibata)

International *Caenorhabditis elegans* Experiment First Flight-Gene Expression (ICE-First-Gene Expression) studies the effect of spaceflight on gene expression and protein alteration in *C. elegans*.

ICE-First-Genomics (Kim)

International *Caenorhabditis elegans* Experiment First Flight-Genomics (ICE-First-Genomics) investigates the whole-genome microarray analysis of responses to spaceflight in *C. elegans*.

ICE-First-Muscle Proteins (Segalat)

International *Caenorhabditis elegans* Experiment First Flight-Muscle Proteins (ICE-First-Muscle Proteins) studies the correlation between proteins, muscle growth, and endurance in relation to a microgravity environment.

ICE-First-Radiobiology (Rose)

International *Caenorhabditis elegans* Experiment First Flight-Radiobiology (ICE-First-Radiobiology) studies the effects of radiation on living organisms by comparing space-flown normal and genetically modified strains of worms with comparable worms grown on Earth for differences in the presence and expression of glutamine rich proteins.

Earth Benefits

By understanding fundamental processes in *C. elegans*, scientists can achieve a better understanding of such processes in humans. The breakdown of these essential functions often results in disease and medical pathologies, thus allowing scientists to use *C. elegans* to study development, nerve function, behavior, and aging. With certain genetic techniques used in this experiment, highlighting the genes where differences occur in comparison to Earth data can further provide scientists with a direction of where to develop research in the future, either on similar organisms or humans. These investigations can also lead to a further understanding of how radiation may affect the human function on Earth as well as in space.

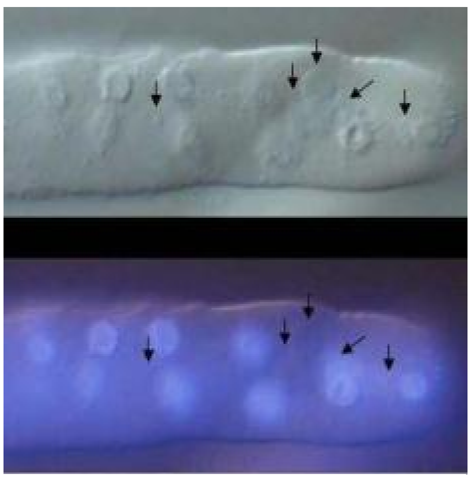
Space Benefits

As the possibilities for longer-term spaceflight are increasing, it is crucial to understand the effects that microgravity will have on organisms at the genetic level. It is important for human life in space to study the effects of environmental factors during spaceflight on a number of physiological phenomena. Results from the ICE-First experiments can help scientists better understand the adverse effects that could be experienced, such as cell and muscle atrophy. ICE-First also hopes to gain a better insight on how different organisms are affected by radiation exposure over a long period of time in microgravity. These investigations present several opportunities for further studies including the possibly of automated experiment in flight, which is critical for experiments on deep spaceflight to other planetary bodies.

RESULTS

ICE-FIRST-AGING

ICE-First-Aging performs an analysis of the aging related protein aggregation and the effects of aging in muscle cells of *C. elegans* worms during ISS Expedition 8. To examine the effect of spaceflight on muscle protein aggregation, space-exposed and ground control nematodes were compared during the larval and young adult stages from the ICE-First investigation. The polyglutamine (portion of protein) aggregation in the space-flown organisms was less than that in the ground control organisms. These findings suggest that the protein aggregation rate of the space-flown nematodes was slower than that of the ground controls (Honda 2012). Szewczyk 2008, indicated that the total stowage space required for the eight type I cassettes to house the ICE-First investigation was minimal. Despite this limited size, mass experiments for investigators from 4 space agencies were returned, a total of 53 independent samples, each of which contained more than 100 individual animals. The concept of accommodating a number of experiments within a limited available volume and upmass appears to have merit. By setting flight constraints first and bringing together established *C. elegans* researchers second, it was possible to design and successfully execute the flight portion of these experiments within 1 year. In the past, the time from flight grant solicitation to completion of a flight experiment has been longer than 3 years (Szewczyk 2008).



Typical morphology of apoptotic cells in the pachytene region of dissected gonads of *C. elegans*. Gonads were dissected from ced-1 mutants of spaceflight sample and DNA were stained with DAPI (blue fluorescent). Apoptotic cells without the fluorescent are indicated as arrows.

ICE-FIRST-APOPTOSIS

Checkpoint-induced apoptosis is involved in maintaining genomic stability through the elimination of cells that have failed to repair DNA damage. However, the occurrence of checkpoint-induced and other types of physiological apoptosis in animals during or as a result of spaceflight has not been documented. Approximately 300 germ cells of *C. elegans* undergo apoptosis (programmed cell death) during normal development. DNA damage-induced checkpoint apoptosis also occurs in germ cells, at the meiotic pachytene nucleus stage (stage of chromosomal crossover). Results indicate that pachytene checkpoint apoptosis and physiological apoptosis in germ cells occurred normally in the space exposed nematodes. Thus, the normal occurrence of several kinds of apoptosis, including checkpoint apoptosis, during spaceflight supports the hypothesis that humans would retain the ability to eliminate cells that have failed to repair DNA lesions introduced by cosmic radiation during spaceflight (Higashitani 2005).

ICE-FIRST-CELLS

As with wild-type animals, histologic study of unc-15 (e73) animals was conducted using phalloidin and anti-paramyosin staining. In both ground control and space-flown unc-15 animals, deformed thin filaments and the aggregated paracrystalline forms of paramyosin (component of smooth muscles) were noted. However, in space-flown worms, partially formed normal paramyosin filaments were also observed. Additionally, the space-flown animals displayed a normal muscle filament to body-width ratio that was not observed in the ground control animals. Thus, spaceflight appears to have partially rescued the histologic defects of the paramyosin mutant. Again as with wild-type animals, Western Blots were used to assess the levels of paramyosin, myosin heavy chains B and C, actin, and tropomyosin III (a type of protein). Space-flown unc-15 mutant animals displayed increased levels of paramyosin and myosin heavy chains relative to both ground controls and space-flown wild-type animals. In contrast, actin remained the same and tropomyosin III was slightly depressed, although the depression was not statistically significant. Thus, as with wild-type animals, the thick and thin filament proteins showed different effects in response to spaceflight. However, unlike wild-type animals, which showed decreased thick filament proteins in response to spaceflight, unc-15 animals showed increased thick filament proteins. These observations suggest 2 things. First, spaceflight has a differential effect on thick and thin filaments regardless of mutations in a thick filament gene. Second, spaceflight allows animals to better compensate for a mutation in the thick filaments by increasing thick filament gene expression. Together the histologic and Western Blot data from unc-15 animals suggest that altered muscle development, induced by spaceflight, allows partial rescue of the defects induced by the mutation. A direct elucidation of the functional consequences and the mechanism underlying the rescue remains to be demonstrated. If spaceflight does indeed rescue the functional consequences of mutations in muscle proteins, this suggests that muscles damaged in flight may be better able to repair than muscle damaged on Earth, a view that runs counter to the current conventional wisdom. However, while scientists have presented the unc-15 data as spaceflight having “rescued” the effects of the mutation, the investigators have correctly pointed out that there may be concerns with this apparent rescue. Specifically, their data can also be interpreted to show that increased muscle protein degradation, a required component of muscle atrophy, is found in the mutants vs wild-type. If the investigators are correct, this reinforces the currently widely held view that muscles damaged during spaceflight may not be properly able to repair. Future studies are clearly needed (Adachi 2007).

ICE-FIRST-GENE EXPRESSION

DNA microarray is a powerful technique to analyze the microgravity effect on gene expression. The gene expression levels between the ground control worms and the space-flown worms showed and the number of genes transcriptionally altered was listed up by gene ontology (GO) terms. In the space-flown worms, the up-regulated genes were dominant in the GOs related to embryonic and larval development, gametogenesis, and reproduction, and the down-regulated genes were dominant in the GOs related to locomotory behavior, G-protein coupled receptor protein, and ion transport. Myo-3, unc-54, and hlh-1 genes described in a previous section are categorized as the down-regulated genes in “locomotory behavior.” These results indicate that microgravity especially plays an important role of locomotory regulation, early embryo-genesis, and the regeneration process in *C. elegans*. The alterations of entire protein expression of the space-flown worms were analyzed by a combination of two-dimensional gel electrophoresis. Over 1000 protein spots were detected with SYPRO Ruby stain, and approximately 200 phosphoprotein spots were detected with Pro-Q Diamond stain. Approximately 10%-15% spots significantly increased or decreased in the flight samples compared with the ground control (Higashibata 2006, 2007).

ICE-First-Development

ICE-First-Development shows that the growth and development of space-flown *C. elegans*, using liquid CeMM, was essentially the same as *C. elegans* grown under similar conditions in the laboratory. These results are as anticipated based upon previous demonstrations of normal growth and development in flight for animals grown on the traditional NGM (Nematode Growth Medium), and from the extrapolation of normal growth and development in flight for animals grown on both NGM and liquid CeMM; the later data was generated by extrapolation due to the delayed recovery of samples following the tragic breakup of the Space Shuttle *Columbia*. The demonstration of grossly normal growth and development suggests that CeMM presents opportunities for further studies including the possibility of automated experiments in flight, which is absolutely critical for experiments on deep spaceflights to other planetary bodies.

ICE-First-Genomics

There are 3 themes that emerged from the ICE-First-Genomics microarray data. First, there are few genes that show reproducible changes in response to spaceflight when assayed in multiple replicates of a population. This may mean that gene responses to spaceflight are small and/or that the number of genes altered in response to spaceflight is relatively small. Second, there are some genes that show reproducible changes in response to spaceflight both within replicates of a population and across populations. Notably, the genes that have these highly reproducible changes are largely metabolic (decreased) and stress response genes (increased). Additionally, the bulk of these genes are thought to be regulated by 2 signaling pathways that the worm uses to sense and respond to the external environment, Insulin and TGF-beta. Third, within the class of genes that gave reproducible changes in expression, it is possible to identify genes that change in only 2 of 3 populations during spaceflight; for example, decreased expression of neuromuscular genes. This may suggest differential sensitivity of populations to spaceflight, or population differences in exposure to multiple vs individual stressors associated with spaceflight. This may also explain why one population of space-flown worms had a postflight movement defect while one did not, and also why there is wide variability in muscle loss in astronauts and cosmonauts. Together, these results paint a semi-convincing picture of how *C. elegans* modulate gene expression in response to spaceflight.

ICE-First-Muscle Proteins

Unfortunately, due to loss of funding, the ICE-First-Muscle Proteins investigation was unable to produce any results.

PUBLICATION(S)

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Higashibata A, Higashitani N, Imamizo-Sato M, et al. Spaceflight induces reduction of paramyosin and troponin T: Proteomic analysis on two dimensional electrophoresis of space-flown *Caenorhabditis elegans*. *Current Biotechnology.* 2013;2(3):262-271. doi: 10.2174/22115501113029990015.

Honda Y, Higashibata A, Matsunaga Y, et al. Genes down-regulated in spaceflight are involved in the control of longevity in *Caenorhabditis elegans*. *Scientific Reports.* 2012;2:487. doi: 10.1038/srep00487.

Adenle AA, Johnsen R, Szewczyk NJ. Review of the results from the International *C. Elegans* first experiment (ICE-FIRST). *Advances in Space Research.* 2009;44(2):210-216. doi: 10.1016/j.asr.2009.04.008.

Adachi R, Takaya T, Kuriyama K, Higashibata A, Ishioka N, Kagawa H. Spaceflight results in increase of thick filament but not thin filament proteins in the paramyosin mutant of *Caenorhabditis Elegans*. *Advances in Space Research.* 2008;41(5):816-823. doi: 10.1016/j.asr.2007.10.016.

Selch F, Higashibata A, Imamizo-Sato M, et al. Genomic response of the nematode *Caenorhabditis elegans* to spaceflight. *Advances in Space Research.* 2008;41(5):807-815. doi: 10.1016/j.asr.2007.11.015.

Szewczyk NJ, Tillman J, Conley CA, et al. Description of International *Caenorhabditis Elegans* experiment first flight (ICE-FIRST). *Advances in Space Research.* 2008;42(6):1072-1079. doi: 10.1016/j.asr.2008.03.017.

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Zhao Y, Jones M, Baillie D, Rose A. Developing an integrating biological dosimeter for spaceflight. *Microgravity Science and Technology.* 2007;19(5-6):201-204. doi: 10.1007/BF02919482.

Higashibata A, Szewczyk NJ, Conley CA, Imamizo-Sato M, Higashitani A, Ishioka N. Decreased expression of myogenic transcription factors and myosin heavy chains in *Caenorhabditis elegans* muscles developed during spaceflight. *Journal of Experimental Biology.* 2006;209(pt 16):3209-3218. doi: 10.1242/jeb.02365.

Zhao Y, Lai K, Cheung I, et al. A mutational analysis of *Caenorhabditis elegans* in space. *Mutation Research - Fundamental and Molecular Mechanisms of Mutagenesis.* 2006;61(1-2):19-29. doi: 10.1016/j.mrfmmm.2006.05.001.

Higashitani A, Sasagawa Y, Sugimoto T, et al. Checkpoint and physiological apoptosis in germ cells proceeds normally in spaceflown *Caenorhabditis elegans*. *Apoptosis.* 2005;10(5):949-954.

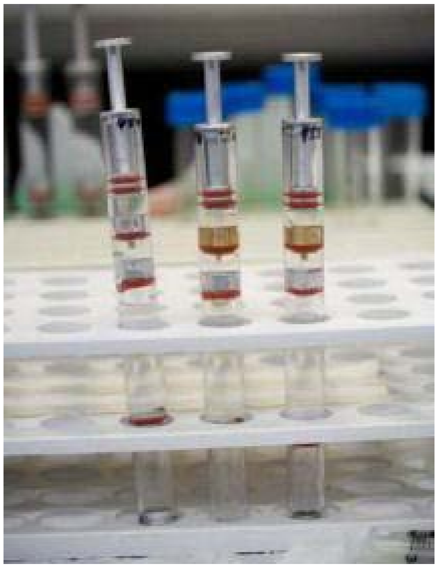
These investigations are complete and all results are published.

NANORACKS-UNIVERSITY OF FLORIDA-1 (NANORACKS-UF-SQUIDS-1)

Research Area: Animal Biology – Invertebrates
Expedition(s): 27 and 28
Principal Investigator(s):
- Jamie S. Foster, PhD, University of Florida, Gainesville, Florida

RESEARCH OBJECTIVES

NanoRacks-University of Florida-Squids-1 (NanoRacks-UF-Squids-1) examines the effect of the space environment on the normal developmental timeline of the cooperative relationship between the Hawaiian Bobtail *Squid Euprymna* scolopes and the luminescent bacterium Vibrio fischeri. The goal of this project is to determine whether beneficial microbes that typically associate with animal tissues are negatively impacted by microgravity.



Squid loaded into flight hardware waiting for packing into trays. University of Florida image.

EARTH BENEFITS

For the approximately 3.8 billion years that life has existed on Earth, gravity has been one of the few constants throughout the evolution process. By experimenting in microgravity conditions we can potentially assess the impact gravity has had on life's evolution as well as delineate developmental triggers or cues that may otherwise be obscured by gravity. This may expand our basic understanding of how gravity has influenced the evolution of life on Earth.

Juvenile squid after returning from space. University of Florida image.

SPACE BENEFITS

The research complements those studies underway in pathogenic organisms, as several gene pathways (e.g. hfq) are common to both mutualistic and pathogenic organisms. By understanding what commensal/mutualistic bacteria are experiencing in microgravity, we can deepen our understanding of human health in the space environment.

RESULTS

Results indicated that the bacteria were able to colonize the host squid tissue in situ under microgravity conditions. Only 3 animals were tested, therefore there were not enough specimens for a rigorous study; however, the data provided proof of concept of the feasibility of using these animals in microgravity conditions.

This investigation is complete and all results are published.

INTEGRATED ASSESSMENT OF LONG-TERM COSMIC RADIATION THROUGH BIOLOGICAL RESPONSES OF THE SILKWORM, *BOMBYX MORI*, IN SPACE (RAD SILK)

Research Area: Animal Biology-Invertebrates
Expedition(s): 21 and 22
Principle Investigator(s):
- Toshiharu Furusawa, PhD, Kyoto Institute of Technology University, Kyoto, Japan

RESEARCH OBJECTIVES

Integrated Assessment of Long-term Cosmic Radiation Through Biological Responses of the Silkworm, *Bombyx mori*, in Space (Rad Silk) examines the effects of radiation exposure in microgravity on silkworms. The data collected during this investigation may lead to a greater understanding of how the radiation defense system is affected by different factors from space radiation and a microgravity environment to develop new treatments and preventative measures for radiation effects.

ISS021E028099 – Expedition 21 Commander Frank De Winne works on the Integrated Assessment of Long-term Cosmic Radiation Through Biological Responses of the Silkworm, *Bombyx mori*, in Space (Rad Silk) experiment in the Japanese Experiment Module. JAXA image.

EARTH BENEFITS

Radiation effects are critical for biological creatures. The data collected during this investigation may lead to a greater understanding of how the radiation defense system is affected by different factors from space radiation and microgravity environment. This data could potentially be used to help develop new treatments and preventative measures for radiation effects.

SPACE BENEFITS

This may help develop Space Radiation Biodosimeter using silkworm eggs, and thus can provide fundamental information on the effects of cosmic rays on biological systems that can then be applied to better protect humans against cosmic radiation.

RESULTS

The environmental conditions aboard the International Space Station (ISS) include microgravity and radiation from cosmic rays and heavy ion beams. Crew members aboard the ISS are always exposed to cosmic radiation, therefore a biodosimetric assessment of health risks associated with radiation exposure is requested. Silkworm eggs possess excellent potential to be developed into a biodosimeter.

Effect of microgravity on embryonic development

Silkworm eggs that are in a dormant state (called diapause) are optimal for use on the ISS. To ensure a stable diapause state, eggs were kept at 25°C for the first 30 days after oviposition and then at 5°C for 30 days. These eggs were then transported to the ISS where they were kept continuously at 2°C for about 3 months in the incubator in the ISS until recovery. Portions of these eggs were transferred to either microgravity or 1G compartments in the Cell Biology Experimental Facility (CBEF) of the ISS, and then incubated at 20°C for 6 days to resume embryonic development. The embryos underwent development normally after exposure to microgravity and 2°C and about 50% of embryos exposed to 1G and 20°C also performed embryonic reversal. In contrast, embryos did not carry out embryonic development after exposure to microgravity and 20°C, suggesting that microgravity affects embryonic development in silkworm eggs.

Chromosome aberration by cosmic rays

Heterozygous eggs exposed to heavy ion particles resulted in somatic mutations appearing as white spots on the black integument during larval stage. The white spots were caused by the loss of a chromosomal fragment carrying the P^S gene from epidermal cells during growth and development. Based on the above result, the following experiments were undertaken: The Passive Dosimeter for Life Science Experiments in Space (PADLES), estimated that total cosmic radiation was 15-20mGy in the ISS over about 3 months. No mutations were seen in the integument of the larvae (first filial generation) from these eggs. However, in the second generation, the larvae exhibited white spots on the black integument of their dorsal surface, and many white spots appeared on the gray dorsal integument of $p/p/P^S$ larvae in the third generation. This indicated that cosmic rays damage genes in the primordial germ cells during embryonic development of the first generation.

Effects of cosmic rays on gene expression

The cosmic radiation appeared to suppress the expression of the gene encoding a small heat shock protein among several genes known to respond to environmental stress. The extent of gene suppression in each egg was different, suggesting that the dose and type of cosmic ray that hit each egg might have varied. These results alter the focus from studying the biological effect of cosmic rays at a mass level into a more specific focus, looking at each individual level using the silkworm egg.

Future research will aim to determine what type of cosmic rays and how great a dose is needed to cause chromosome aberration and suppression of gene expression.

PUBLICATION(S)

Furusawa T, Fukamoto K, Sakashita T, et al. Targeted heavy-ion microbeam irradiation of the embryo but not yolk in the diapause-terminated egg of the silkworm, *Bombyx mori*, induces the somatic mutation. *Journal of Radiation Research.* 2009;50(4):371-375. doi: 10.1269/jrr.09021.

Furusawa T, Nojima K, Ichida M, et al. Introduction to the proposed space experiments aboard the ISS using the silkworm, *Bombyx mori*. *Biological Sciences in Space*. 2009;23(2):61-69. doi: 10.2187/bss.23.61.

This investigation is complete; however additional results are pending publication.

STUDY OF THE GROWTH POTENTIAL OF STATOCONIA IN THE ORGAN OF BALANCE OF GASTROPODS IN WEIGHTLESSNESS (STATOKONIA)

Research Area: Space Biology and Biotechnology (zoology of invertebrates)
Expedition(s): 10-15
Principal Investigator(s):
- Givi I. Gorgiladze, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

The Study of the Growth Potential of Statoconia in the Organ of Balance of Gastropods in Weightlessness (Statokonia) investigation evaluates the nature and dynamic of new formation and the growth of statoconia when exposed to weightlessness.

Ulitka container with the cover removed and the automatic temperature recorder on Panel #406 in the ISS RS SM. Roscosmos image

SPACE BENEFITS

This knowledge both adds to our understanding of and underscores the importance of the gravitational field in the structural organization of the organ of balance. The fact established that the test mass increased in the organ of balance in orbital flight must be taken into consideration when developing a medical support strategy for long-term manned spaceflight.

RESULTS

The most significant results of the experiment: the discovery that the test mass in the organ of balance depended on the extent of the gravitational field; mass increased under conditions of weightlessness and decreased under conditions of increased gravity. Furthermore, this phenomenon is of an adaptive nature, appearing in the restoration of the normal picture during the readaptation period to the Earth's gravitational force. New information was obtained on the morphology, elemental composition, and test mass ultrastructure in the organ of balance in the 2 types of gastropods. The hypothesis was put forward that statoconia nuclei occur in the sensitive cells of the statocyst, and then are imported into its cavity. The topography of the sensitive cells of the statocyst was established. The information obtained on the structural organization of the organ of balance/statocyst of *H. lucorum* and *P. rivulare* enable these objects to be used as models in studies in the field of gravitational (space) biology.

PUBLICATION(S)

Bukiya RD, Gorgiladze GI, Taktakishvili AD, Kalandarishvili EL. Light and electron microscopy of cellular components in statocysts of the land snail *Helix lucorum*. *Bulletin of the Russian Academy of Sciences: Biological series;* 2010.

Gorgiladze GI, Bukiya RD, Davitashvili MT, et al. Morphological Peculiarities Statoconia in Statocysts of Terrestrial Pulmonary Snail Helix Lucorum. *Bulletin of Experimental Biology and Medicine.* July 17, 2010;149(2):269-272. doi: 10.1007/s10517-010-0924-1.

Gorgiladze GI. Morphological features of the inertial mass in statocysts of the terrestrial gastropods Helix lucorum and Pomatias rivulare exposed to microgravity. *Doklady Biological Sciences.* August 17, 2010;433(1):271-274. doi: 10.1134/S0012496610040101. [*Original Russian Text © G.I. Gorgiladze, 2010, published in Doklady Akademii Nauk, 2010, Vol. 433, No. 4, pp. 566–569.*]

Gorgiladze GI. Regenerative capacity of the planarian Girardia tigrina and the snail Helix lucorum exposed to microgravity during an orbital flight on board the international space station. *Doklady Biological Sciences.* August 20, 2008;421(1):244-247. doi: 10.1134/S0012496608040078. *[Original Russian Text © G.I. Gorgiladze, 2008, published in Doklady Akademii Nauk, 2008, Vol. 421, No. 1, pp. 131–134.]*

Gorgiladze GI, Bukiya RD, Davitashvili MT, et al. The destructive impact of increased gravitational force on the inertial mass in statocysts of *Helix lucorum*. *Proceedings of the Academy of Sciences.* 2006;406(3):416-418.

Gorgiladze GI, Bukiya RD, Kozyrev SA, Kalandarishvili EL. Structural/functional organization of the statocyst in *Helix lucorum* in normal conditions and conditions of a changing gravitational field*. XIII Conference Space Biology and Aerospace Medicine,* Moscow, Russia; June 13-16, 2006.

Bukiya RD, Taktakishvili AD, Kalandarishvili EL, Gorgiladze GI. Morphological features of the cellular components of the statocyst in the land snail *Helix lucorum*. *Bulletin of the Academy of Sciences of Georgia: Biological series A.* 2005;31(6):815-822.

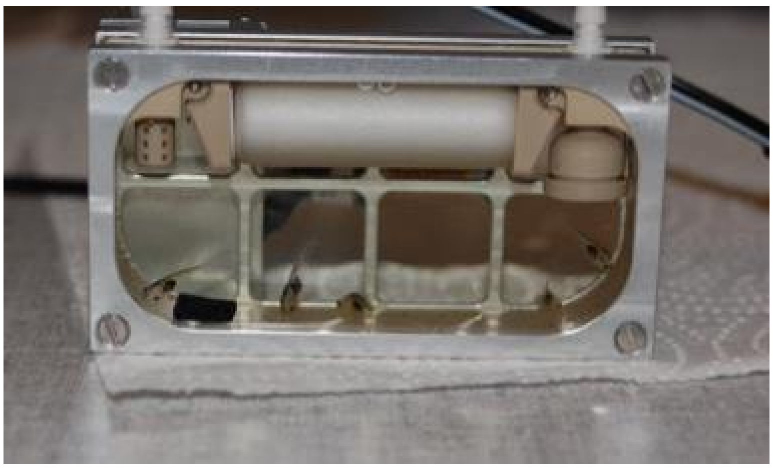
This investigation is complete and all results are published.

CELLULAR MODIFICATIONS WITHIN THE VESTIBULO-OCULAR SYSTEM DURING ADAPTATION TO MICROGRAVITY IN A DEVELOPING AMPHIBIAN, XENOPUS LAEVIS (XENOPUS)

Research Area: Animal Biology-Invertebrates
Expedition(s): 18
Principal Investigator(s):
- Eberhard Horn, University of Ulm, Ulm, Germany

RESEARCH OBJECTIVES

The Cellular Modifications within the Vestibulo-ocular System during Adaptation to Microgravity in a Developing Amphibian, Xenopus laevis (Xenopus) experiment characterizes the effect of microgravity on development of the vestibular ocular systems in *Xenopus laevis* tadpoles at late development stages.



Cellular Modifications within the Vestibulo-ocular System during Adaptation to Microgravity in a Developing Amphibian, Xenopus laevis tadpoles in Experiment Container. ESA image.

RESULTS

Stage 20-21 embryos (4 dpf) were exposed to microgravity during a 10-day spaceflight, or to 3-g hypergravity following the same time schedule. After termination of altered gravity, the rVOR was recorded twice in most animals. The main observations were as follows: (1) after the first rVOR appearance at stage 37 (16 dpf), both rVOR gain, and amplitude increased steadily up to saturation levels of 0.22 and 20◦, respectively. (2) Three days after termination of microgravity, flight and ground larvae showed no rVOR; 1 day later, the rVOR could be induced only in ground larvae. Differences disappeared after 3 weeks. (3) For 10 days after 3-g exposure, rVOR development was similar to that of 1-g controls but 3 weeks later, 3-g larvae showed a larger rVOR than 1-g controls. These observations indicated that the immature vestibular system is transiently sensitive to microgravity exposure and that exposure of the immature vestibular system to hypergravity led to a slowly growing vestibular sensitization.

PUBLICATION(S)

Horn ER, Gabriel M. Gender-related sensitivity of development and growth to real microgravity in Xenopus laevis. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*. September 30, 2013. doi: 10.1002/jez.1831.

Gabriel M, Frippiat J, Frey H, Horn ER. The sensitivity of an immature vestibular system to altered gravity. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*. 2012;317(6):333-346. doi: 10.1002/jez.1727.

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Horn ER, Gabriel M. Gravity-related critical periods in vestibular and tail development of Xenopus laevis. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*. November 1, 2011;315(9):505-511. doi: 10.1002/jez.698.

Horn ER, Dournon C. Experiences from a French-German project - on the integration of pupils in an actual space experiment. *Microgravity Science and Technology*. 2007;19(5-6):230-234. doi: 10.1007/BF02919488.

Horn ER, Boser S, Membre H, Dournon C, Husson D, Gualandris-Parisot L. Morphometric investigations of sensory vestibular structures in tadpoles (Xenopus laevis) after a spaceflight: Implications for microgravity-induced alterations of the vestibulocular reflex. *Protoplasma*. 2006;229(2-4):193-203. doi: 10.1007/s00709-006-0213-z.

Horn ER. Microgravity-induced modifications of the vestibulocular reflex in Xenopus laevis tadpoles are related to development and the occurrence of tail lordosis. *Journal of Experimental Botany*. 2006;209(15):2847-2858. doi: 10.1242/jeb.02298.

Horn ER. “Critical Periods” in vestibular development or adaptation of gravity sensory systems to altered gravitational conditions. *Archives Italiennes De Biologie*. 2004;142:155-174.

This investigation is complete and all results are published.

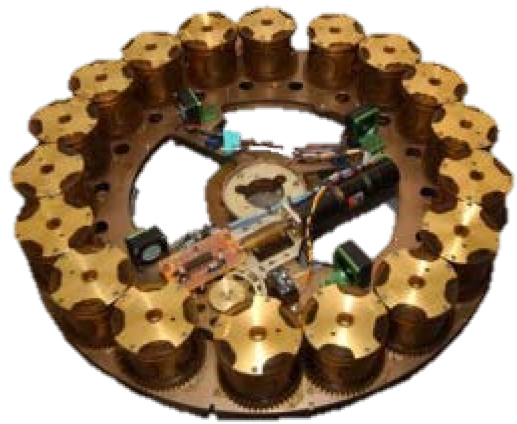
Avian Development Facility (ADF), Two Investigations

Research Area: Animal Biology – Vertebrates
Expedition(s): 4
Principal Investigator(s):
- J. David Dickman, PhD, Baylor College of Medicine, Houston, Texas
- Stephen B. Doty, PhD, Hospital for Special Surgery, New York, New York

Research Objectives

ADF-Otolith (Dickman)

The avian (bird) experimental model offers opportunities to observe microgravity induced changes in many systems, including the otolith, cardiovascular, musculoskeletal, immunological and neurological. The ADF-Otolith investigation studies the formation of inner ear bones and neurons (involved in the otolith system) under the influence of microgravity.


One of 2 Avian Development Facility (ADF) carousels, each featuring 18 sample containers. During space missions, one carousel rotates at 77.3 RPMs to simulate a 1g gravity field. The other carousel remains motionless to provide a microgravity environment for the specimens inside. Besides eggs, the ADF can carry fish, plants, insects or cells in its sample containers. NASA's Ames Research Center image.

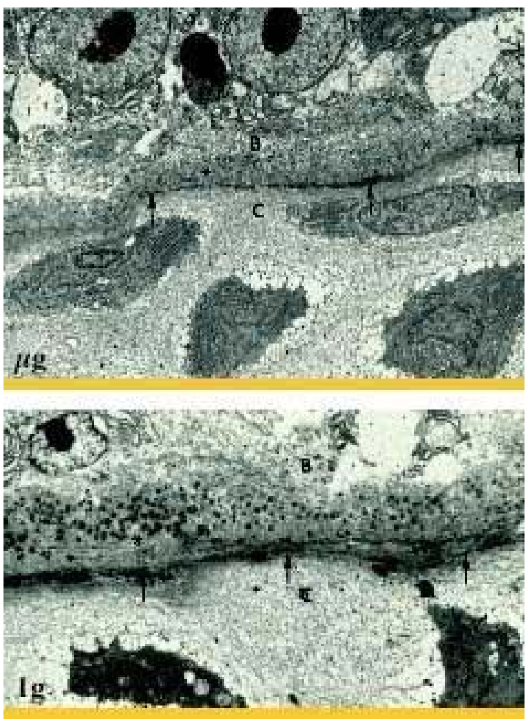
ADF-Skeletal (Doty)

Under microgravity conditions, bones demineralize, resulting in osteoporosis like (brittle bones) conditions. The study of embryos that develop in microgravity is an important piece of the bone loss puzzle. ADF-Skeletal investigates how the mechanism of bone formation during development of the limbs in quail embryos could provide basic information to help prevent bone loss in crew members during long-duration missions.

Earth Benefits

During embryonic development on Earth, the visual system, if deprived of light during the early critical period, can be impaired or eliminated during maturation. In the vestibular system, which controls normal postural, eye, and head movement responses during motion, no efforts to study the effects of gravity upon development have been extensively performed. Thus, it is currently unknown whether altered gravity environments affect vestibular system development and subsequent reflex motor behavior. The research should provide basic answers to questions related to vestibular receptor pathology that is known to occur with aging humans and in some disease cases.

On Earth, fracture healing consists of cartilage formation, conversion of cartilage to a temporary bony structure, and new bone formation involving osteoblast and collagen synthesis. Furthermore, the healing of a bone fracture in the elderly is very slow and may not result in a fully healed bone. In addition, significant populations of elderly adults suffer from loss of bone material due to the onset of osteoporosis. Since the microgravity environment is known to stimulate the loss of bone material in adults in a very short period of time, the spaceflight microgravity environment is the ideal location to conduct experiments aimed at understanding bone loss. By using the ADF, specimens can be incubated in the exact same environment with the only difference being 1 g versus microgravity. This experimental condition is not available on Earth and is critical to specifically isolating the cause of bone material loss. It is anticipated that the data from this ADF study can provide scientists with key information to identify the specific biological processes that contribute to bone loss and the mechanism of this disease process. Overall, the identification of the specific biological processes can provide scientists and pharmaceutical companies candidate targets for the development of therapeutic agents.



Electron micrographs of quail limb bones that formed under the influence of microgravity show decreased mineralization compared to bones formed in normal gravity. The letters "B" and "C" indicate bone and cartilage sides of the sample, respectively, with the arrows marking the junction between bone and cartilage cells. The asterisks indicate where mineralization begins. The bone that developed during spaceflight (top) shows less mineral compared to the control sample (bottom); the control sample clearly shows mineral deposits (dark spots) that are absent in the flight sample. NASA’s Johnson Space Center image.

Space Benefits

The ADF is the first step to creating new technologies that can support critical biological research in direct support of human space travel. The subsystems used to support the biological specimens can be applied to technologies directed to supporting other animals or the crew.

It is a known fact that crew members lose bone material soon after they enter the weightless environment of space. The loss of bone material poses a significant health risk because the crew members’ bones weaken and become more susceptible to breakage. Also, since they are adults, their body's ability to regenerate the lost bone material once they return to Earth is very limited. Currently, no therapies exist that can stimulate the production of new bone material. The spaceflight microgravity environment is ideal for studying bone formation and material loss because its effects on the skeleton are rapid and occur within days of entry into space. This ADF-Skeletal experiment is designed to investigate the biological processes that are key to stimulating new bone formation. By using the ADF, this experiment can control the embryogenesis environment so that components affected by the spaceflight environment, especially microgravity, can be identified. By comparing the data to the simulated 1 g in flight controls and ground controls, the ADF experiment can identify specific changes to bone formation that are due to the microgravity environment, which in turn, points out the specific biological systems (molecular, cellular, and systemic) that are sensitive to changes in gravity.

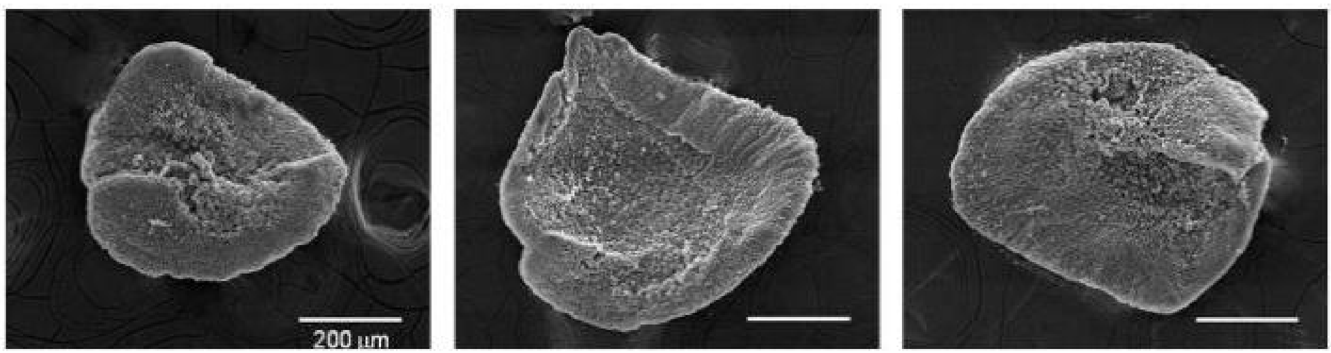
These therapeutics could be used to both stop bone loss or stimulate the generation of bone material while the crew member is in flight.

ADF-Otolith studies how the absence of gravity during the body's formative stage affects basic neural function in an effort to isolate the major influences on the neurovestibular system, the system that allows us to control our eye movement, balance, and coordination.

RESULTS

ADF-OTOLITH

The inner ear bones of the embryos developed in microgravity appear to be larger than those found in the controls that remained on Earth. There are some indications that the fan-shaped arrangement of receptor cells may also be altered under the influence of microgravity. Conclusive data from this investigation is pending further analysis (Increment 4 One Year Postflight Report).



Scanning electron micrographs of fused otoconial stones from embryonic day 12 quail embryos. Three saccule stones are shown, one each from an embryo raised from fertilization in 0g (left), 1g flight (middle), and 2g laboratory centrifugation (right). J. David Dickman image.

ADF-SKELETAL

No spaceflight effects were observed for osteocalcin levels in the day 12 embryos, based on bone matrix stating. Since osteocalcin reflects the degree of bone mineralization, this would suggest that mineralization is not affected in an older embryo. However, direct mineralization quantitative studies have not been reported for day 7 and day 12 embryos, which should provide definitive evidence for whether osteocalcin-associated processes are affected.

The second finding was that the spaceflight embryos on the spinning carousel or stationary carousel had a reduced level of collagen-synthesizing activity as compared to the ground control specimens, although the sample size was small. If this trend is validated, it would suggest that spaceflight has a component that can affect collagen synthesis that is not correctable by an applied 1 g force. These insights might be important for the development of appropriate countermeasures for space travel. (Increment 4 One Year Postflight Report). Due to the limited number of samples, statistical analysis was never completed and therefore the work was not publishable.

These investigations are complete and all results are published.

EMBRYONIC DEVELOPMENT OF AMPHIBIANS IN WEIGHTLESSNESS (AQUARIUS)

Research Area: Animal Biology - Vertebrates

Expedition(s): 3

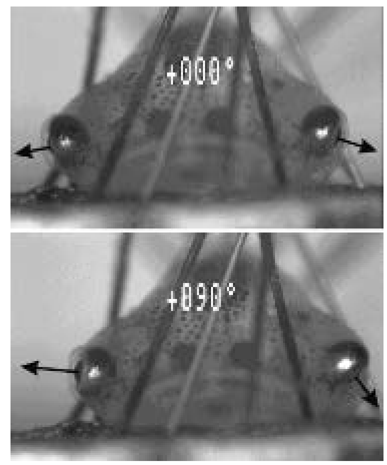
Principal Investigator(s):
- Eberhard R. Horn, University of Ulm, Ulm, Germany
- Christian Dournon, Universite Henri Poincare, Nancy, France

RESEARCH OBJECTIVES

The Embryonic Development of Amphibians in Weightlessness (Aquarius) investigation studies whether altered gravity affects vestibulocular and spinal motor systems in a correlated manner on *xenopus laevis* embryos.

RESULTS

After exposure to altered gravity, each tadpole was tested for its roll-induced vestibulocular reflex (rVOR) and 3 hours later it was tested for the neuronal activity recorded from the ventral roots during fictive swimming. It was observed that weightlessness affected ventral root activity during fictive swimming and rVOR. In particular, ventral root activity changes included a significant decrease of the rostrocaudal delay and a significant increase of episode duration. The rVOR-amplitude was transiently depressed. All modifications of the rVOR and ventral root-activity recovered to normal levels within 4 to 7 days after termination of altered gravity. Significant correlations between the rVOR amplitude and ventral root activity during the recording period have been observed in both tadpoles with or without altered gravity experience. The data are consistent with the assumptions that during this period of life, which is characterized by a progressive development of vestibulocular and vestibulospinal projections (i), weightlessness retards the development of ventral root activity while hypergravity accelerates it; (ii) that weightlessness retards the rVOR development while hypergravity caused a sensitization, and that (iii) altered gravity induced changes of ventral root activity during fictive swimming have a vestibular origin.



Vestibuloocular reflex in *Xenopus laevis*. The numbers inside the frames indicate that the tadpole shown with its frontal view is lying either horizontally (000°) or on its right side (090°) inducing the asymmetric posture of the eyes. E.R. Horn image.

PUBLICATION(S)

Boser S, Dournon C, Gualandris-Parisot L, Horn ER. Altered gravity affects ventral root activity during fictive swimming and the static vestibuloocular reflex in young tadpoles (Xenopus laevis). *Archives Italiennes De Biologie*. March 2008; 146(1):1-20.

Horn ER, Dournon C. Experiences from a French-German project - on the integration of pupils in an actual space experiment. *Microgravity Science and Technology*. 2007;19(5-6):230-234. doi: 10.1007/BF02919488.

Horn ER, Boser S, Membre H, Dournon C, Husson D, Gualandris-Parisot L. Morphometric investigations of sensory vestibular structures in tadpoles (Xenopus laevis) after a spaceflight: Implications for microgravity-induced alterations of the vestibuloocular reflex. *Protoplasma*. 2006;229(2-4):193-203. doi: 10.1007/s00709-006-0213-z.

Horn ER. Microgravity-induced modifications of the vestibuloocular reflex in Xenopus laevis tadpoles are related to development and the occurrence of tail lordosis. *Journal of Experimental Botany*. 2006;209(15):2847-2858. doi: 10.1242/jeb.02298.

This investigation is complete and all results are published.

Commercial Biomedical Testing Module: Effects of Osteoprotegerin on Bone Maintenance in microgravity (CBTM)

Research Area: Animal Biology – Vertebrates

Expedition(s): 4

Principal Investigator(s):

- Ted A. Bateman, PhD, University of North Carolina, Chapel Hill, North Carolina

Research Objectives

Commercial Biomedical Testing Module: Effects of Osteoprotegerin on Bone Maintenance in Microgravity (CBTM) provides the capability to use the microgravity environment for evaluation of new pharmaceutical candidates in small mammals. Results may expedite the review of new pharmaceuticals for allowing immediate access to new disease treatments.

Earth Benefits

In microgravity, the messages received by the osteoblasts and osteoclasts are altered. Specifically, without the stresses caused by the Earth's gravitational pull, osteoclasts remove more bone and osteoblasts deposit less new bone. Understanding how these signals change and how OPG mitigates these changes gives scientists insight in how to fight bone loss in crew members during long-duration spaceflight and in osteoporosis patients on Earth as osteoporosis is a major public health threat for an estimated 44 million people worldwide.

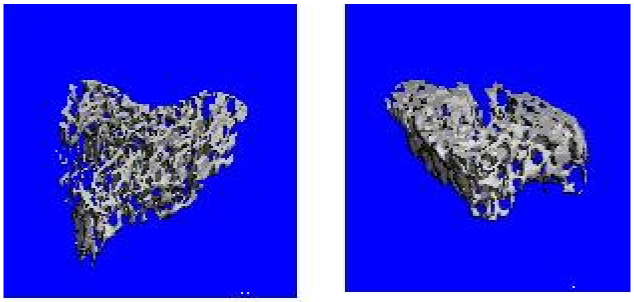


Image on the left shows a microCT image of trabecular bone from proximal tibia from spaceflight mouse compared to ground control mouse on right. NASA's Marshall Space Center image.

Space Benefits

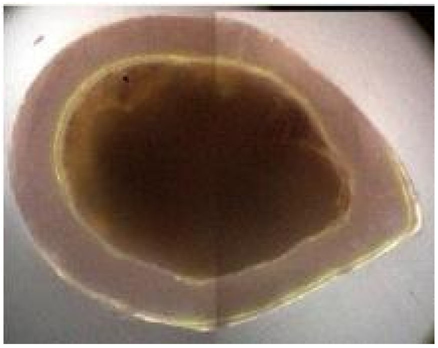
Crew members suffer from a significant loss of bone mass during spaceflight, the International Space Station (ISS) Medical Project office has developed some countermeasures to hinder the rapid loss of bone mass. Despite these countermeasures, bone mass loss continues to be a problem for crew members. Finding additional countermeasures increases the overall health of crew members on long-duration missions.

Results

During ISS Expedition 4, 24 female mice were flown to ISS on shuttle flight STS-108 in 3AEMs. The AEMs remained on STS-108 throughout the 12-day mission.

Mice exposed to microgravity exhibited a 15%-20% decline in femur elastic strength and a 40%-60% decrease in bone formation when compared to the controls. The femur elastic strength decline was caused by 3 mechanisms: reduced bone formation, increased bone resorption, and inhibition of mineralization. OPG treatment in mice exposed to microgravity nearly reversed the decline in strength and the increase in bone resorption found in untreated mice (Bateman 2004).

Mechanical testing data were complimented by serum, messenger ribonucleic acid (mRNA), and histological analyses that indicated a decline in bone formation and an increase in bone resorption in addition to an inhibition of mineralization. OPG mitigated the decline in mechanical strength by preventing increase in resorption and maintaining mineralization. In addition to this detailed analysis of skeletal properties, a secondary analysis of calf muscles from placebo-treated specimens was performed to collect baseline data to validate space-flown mice as an appropriate model for sarcopenia (age-related muscle loss). Spaceflight caused a 15%-30% decline in muscle fiber diameter size compared to appropriate ground controls (Harrison 2003).



Fluorescent image of femur diaphysis from ground control placebo treated mouse, indicating greatly decreased bone formation (calcein label indicates where bone was forming at the time of launch, allowing quantification of bone formation rates during flight. NASA's Marshall Space Center image.

Data obtained from the mice following return to Earth indicated some alternations in immune functions. Analysis of the spleenocytes (immune cells produced by the spleen) indicated an increase in B-cell (white blood cell that matures in the bone marrow and, when stimulated by an antigen, differentiates into plasma cells) production compared to T-cells (white blood cells that complete maturation in the thymus and have various roles in the immune system). A slightly lower white blood-cell count in the flight animals compared to the controls was not statistically significant. The spleen mass was 18%-28% lower in flight mice compared to controls. Results also indicated that flight mice weighed 10%-12% less than ground controls (Pecaut 2003).

The ability to survive a major physical trauma in microgravity may be compromised due to an altered immune system. Platelets (constituent of blood that promotes clotting at the site of injury) are the primary cells involved in the wound healing process. The animals studied had significantly higher platelet levels but low volume compared to the controls. This indicates that the lack of platelets in the wound-healing process is not a problem but that platelets formed in microgravity have a decreased functionality in the wound healing process. Data indicated that a short stay in microgravity can induce significant changes in immune defense mechanisms, hematopoiesis (blood cell formation), and other aspects of health (Gridley 2003).

Analysis of microarray data revealed that 272 mRNAs were significantly altered by spaceflight, the majority of which displayed similar responses to hindlimb suspension, while reloading tended to counteract these responses. Several mRNAs altered by spaceflight were associated with muscle growth, including the PI3 kinase regulatory subunit p85 alpha, insulin response substrate-1, the forkhead box O1 transcription factor, and MAFbx/atrogin1. Moreover, myostatin mRNA expression tended to increase while mRNA levels of the myostatin inhibitor FSTL3 tended to decrease in response to spaceflight. In addition, mRNA levels of the slow-oxidative fiber associated transcriptional co-activator peroxisome proliferator associated receptor-(PPAR) gamma coactivator-1alpha and the transcription factor PPAR-alpha were significantly decreased in spaceflight gastrocnemius. Finally, spaceflight resulted in a significant decrease in levels of the microRNA miR-206. Together these data demonstrate that spaceflight induces significant changes in mRNA expression of genes associated with muscle growth and fiber type (Allen 2008).

PUBLICATION(S)

Lloyd SA, Morony SE, Ferguson VL, et al. Osteoprotegerin is an effective countermeasure for spaceflight-induced bone loss in mice. *Bone*. December 2015;81:562-572. doi: 10.1016/j.bone.2015.08.021.

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Bateman TA. Molecular therapies for disuse osteoporosis. *Gravitational and Space Biology*. 2004;17(2):83-89.

Milstead J, Simske SJ, Bateman TA. Spaceflight and hindlimb suspension disuse models in mice. *Biomedical Sciences Instrumentation*. 2004;40:105-110.

Gridley DS, Nelson GA, Peters LL, et al. Genetic models in applied physiology: selected contribution: effects of spaceflight on immunity in the C57BL/6 mouse. II. Activation, cytokines, erythrocytes, and platelets. *Journal of Applied Physiology*. 2003;94(5):2095-2103.

Harrison BC, Allen DL, Girten BE, et al. Skeletal muscle adaptations to microgravity exposure in the mouse. *Journal of Applied Physiology.* 2003;95(6):2462-2470. doi: 10.1152/japplphysiol.00603.2003.

Pecaut MJ, Nelson GA, Peters LL, et al. Genetic models in applied physiology: selected contribution: effects of spaceflight on immunity in the C57BL/6 mouse. I. Immune population distributions. *Journal of Applied Physiology*. May 2003; 94(5):2085-2094. doi: 10.1152/japplphysiol.01052.2002.

This investigation is complete and all results are published.

Commercial Biomedical Testing Module-2: (CBTM-2)

Research Area: Animal Biology – Vertebrates
Expedition(s): 15
Principal Investigator(s):
- H.Q. Han, MD, PhD, Amgen Research, Thousand Oaks, California

Research Objectives

S118E09308 – The Commercial Biomedical Test Module - 2 (CBTM-2) hardware seen in this image flew onboard STS-118/13A.1 in August 2007. CBTM-2 tests the effectiveness of an experimental therapeutic as a possible countermeasure for muscle atrophy.

Commercial Biomedical Test Module - 2 (CBTM-2) uses a validated mouse model to examine the effectiveness of an experimental therapeutic as a possible countermeasure for muscle atrophy.

Earth Benefits

Muscle atrophy resulting from disuse and reduced physical activity affects millions of Americans particularly in the aging population. This condition contributes to increased bone fractures, negative metabolic changes and decreased levels of physical activity. Results from this investigation could help inform the development of potential interventions for muscle wasting related to a range of diseases, including cancer, kidney failure and age-related frailty.

Space Benefits

Testing the effects of a potential countermeasure to the muscle loss that occurs during long-duration spaceflight can potentially provide NASA with a non-exercise, therapeutic countermeasure that helps ensure crew member health and well being.

Results

During International Space Station (ISS) Expedition 15, 24 mice were flown to the ISS on shuttle flight STS-118 in 3 Animal Enclosure Modules (AEMs). The AEMs remained on STS-118 throughout the mission. Utilizing a tissue sharing program CBTM-2 was able to support several additional investigations that have yielded the results below.

Expression and localization of vascular myocyte calcium release channels

Researchers found that exposure to microgravity during 8 days in the ISS decreases the expression of the ryanodine receptor 1 (RyR1), which is a calcium release channel inside cells in primary cultured myocytes (muscle cells) from rate hepatic portal vein. Identical results were found in portal vein from mice exposed to microgravity during an 8-day shuttle spaceflight. To evaluate the functional consequences of this physiological adaptation, evoked calcium signals obtained in myocytes from hindlimb unloaded rats, in which the shift of blood pressure mimics the effects of microgravity, were compared to those obtained in smooth muscle cells from rats injected with a chemical agent directed against the RyR1 protein. In both conditions, calcium release was significantly decreased. In contrast, in spontaneous hypertensive rats, an increase in RyR1 expression was observed as well as the calcium-induced calcium release mechanism. Taken together, these results show that myocytes were directly sensitive to gravity level and that they adapt their calcium signaling pathways to vascular pressure by the regulation of the RyR1 expression.

Effect of spaceflight on macrophase differentiation and activation

This study involved the analysis of bone marrow cells from the CB<T-2 payload following a 13-day flight on the space shuttle to determine how spaceflight affected differentiation of cells in the granulocytic lineage (important white blood cells produced in the bone marrow). The bone marrow cells were isolated from the humerii (long bones of the upper limb or forelimb) of mice. A cell counting method was utilized to assess the expression of several molecules (Ly6C,CD11b,CD31 (PECAM-1),Ly6G (Gr-1),F4/80,CD44 and c-Fos) that defines the maturation state of cells in the granulocytic lineage on 3 bone marrow cell subpopulations (R1, R2 and R3) defined by their size and light scattering properties. There were no observable characteristic differences between total bone marrow cells isolated from flight and ground-control mice. Nevertheless, there were subpopulation differences observed that suggests neutrophil activation in response to landing. Decreases were noticed in Ly6C, c-Fos, CD44high and Ly6G. An increase in F4/80 suggested that the cells in the bone marrow R3 subpopulation of the mice flown on the shuttle were more differentiated compared to the ground-controls. A loss in body weight was also noticed in the mice that flew in space that suggest that they were subjected to chronic stress beyond what was endured on landing. Therefore, it is not unreasonable to suggest that there are significant changes in bone marrow phenotype in response to the stress of the spaceflight experience (Ortega 2008).

The effects of spaceflight on stress and immunity

Understanding lymphocyte activity associated with spaceflight stressors is important in determining the impact on associated cancer risk. This study examined the T-lymphocytes in C57BL/6 mice (a traditional inbred strain of lab mice) after the return from a 13-day space shuttle mission. Flight mice (FLT) and ground controls similarly housed in Animal Enclosure Modules (AEMs) were evaluated within 3 to 5 hours after landing. Muscle strength testing and nuclear magnetic resonance body composition measurements were performed on the mice. After euthanasia (painlessly put to death), spleen and thymus samples were analyzed. DNA synthesis in splenocytes (any one of the different white blood cell types situated in the spleen) from FLT mice was low in response to phytohemagglutinin (PHA-plant chemical used to stimulate the multiplication of white blood cells, specifically T cells) compared to AEM controls. There was a lower percentage of T cells and higher percentage of natural killer (NK) cells (both of which are involved in attacking tumor cells), in the FLT mice, but the percentage of B cells (involved in producing antibodies) were similar to AEM controls. The secretion capacity of 4 cytokines (small secreted proteins that serve to regulate the immune system) in response to activation via signaling molecules, similarly to what occurs in the body, was significantly different in the FLT mice compared with the AEM controls. Cancer-related gene expression profiles in the thymus differed greatly between the FLT mice and the AEM groups. The data obtained from this study collectively exhibits that T cell distribution, function, and gene expression are significantly modified shortly after return from the spaceflight environment. However, it remains to be determined whether the quantified changes are brief and primarily due to the tremendous physiological stress of landing and readaptation or have an enduring effect on risk for infection and/or cancer (Gridley 2009).

Studies have shown that the spaceflight environment can impact several physiological systems potentially resulting in serious consequences for immunity. The primary aim of this study was to investigate changes in immune parameters concerning the spleen, liver, and thymus in response to flight. C57BL/6 mice (a common inbred strain of lab mice) were flown on a 13-day space shuttle mission. In response to flight, the mice exhibited reductions in liver, spleen, and thymus masses in comparison to ground controls. The changes in organ masses suggest that the mice were subject to psychological and/or physiological stress inflight or during landing. Splenic (pertaining to the spleen) white blood cells (WBCs) and numbers of leukocyte (cells in the blood that destroy disease-causing microorganisms) subpopulations were significantly reduced after flight. To determine the recovery and proliferative capacity of lymphocytes, this study characterized spontaneous blastogenesis (unstimulated DNA synthesis). The observed increase in [3H]-TdR incorporation into DNA (tritiated thymidine-method for estimating capacity for cell regeneration) by splenic lymphocytes demonstrated that ex vivo (outside the body) DNA synthesis was increased after flight and suggests that cells were capable of shifting into a proliferative (or recovery) state once removed from any stress-induced inhibition in vivo (inside the body). In contrast, LPS (lipopolysaccharides-large molecules found in the outer membrane of many common bacteria) induced proliferation was decreased in the flight mice, indicating that the ability to respond to a potent B cell mitogen (substance that indices cell division) may be compromised. The flight mice demonstrated an increased capacity to produce biological responses, interleukin-6 and interleukin 10 (IL-6 and IL-10- chemical messengers secreted by cells of the immune system), but not TNF-α (Tumor Necrosis Factor- alpha- protein that can cause tumor cell death when injected into tumor-bearing mice). The genes responsible for scavenging ROS (Reactive Oxygen Species play vital roles in normal cell functions, but are also sources of tissue and DNA damage) were shown to be up-regulated after flight. The data confirm that immune parameters are influenced by the spaceflight environment. Furthermore, these data also suggest that exposure to the spaceflight environment can increase anti-inflammatory mechanisms and change the ex vivo response to LPS, which is a bacterial component that typically indices a strong response from the immune system (Farnaz 2009).

Genetic analysis in young adult mice at 8 weeks of age after exposure to spaceflight aboard the space shuttle for a period of 13-days demonstrate that spaceflight induces significant changes in mRNA expression of genes in the thymus that regulate stress, hormone receptor metabolism, and T white blood cell signaling activity. These data explain, in part, the reported systemic compromise of the immune system after exposure to microgravity. The results of the study provide insight into how spaceflight affects stress-related gene expression in addition to influencing genes associated with specific immunological processes in the thymus itself. The results also show a connection between many of the altered genes via their relation to a wide range of physiologic processes, including stress and immune response (Lebsack 2010).

Space radiation and microgravity effects on regulation of lung tissue

NASA has reported pulmonary abnormalities in crew members on space missions, but changes in lung tissue have not been fully documented. CBTM-2 evaluated the health effects on the lungs resulting from increased levels of radiation, inhalation of possible pathogen, and low oxygen levels. Tissue examination showed profibrosis-like (excess growth of fibrous connective tissue) changes occurred in flown mice, more abundant collagen accumulation around blood vessels, and thicker walls compared with lung samples from ground mice. However, no marked abnormality was found in bronchiolar and alveolar lining. The findings suggest that the flight mice may have experienced some degree of lung remodeling. Taken together, the data demonstrate that significant changes can be readily detected shortly after return from spaceflight in the expression of factors that can adversely affect lung function. The study concludes that compromised lung function that is due to spaceflight may result from disturbance of the balance between deposition and breakdown of connective tissue within the lungs. In the future, investigations should be performed on samples taken during flight, after long-term missions, and at later time points after landing to fully document the take-off, residence in space, landing and oxygen availability effects on lung morphology (Tian 2009).

Ovarian follicular and luteal development in the spaceflight mouse

This study aimed to assess changes in the gross morphology of the ovarian tissue from mice flown on shuttle mission STS-118 and tissues from corresponding control animals. The experiment consisted of 3 groups of animals: 2 sets of control animals and 1 set of flight animals (each set contained 12 mice). The results showed that there was a presence of developing follicles (structures that contain immature eggs) at all stages as well as the presence of corpora lutea (structure formed after the release of the egg) in all 3 treatment groups indicating no significant gross morphological changes occur within ovarian tissue when exposed to spaceflight for 13 days or less. Flight tissue was morphologically indistinguishable from both ground control and baseline tissue.

Future studies of this nature should consider the stages of the estrous cycle for each mouse both pre and postflight. This should be confirmed with hormonal data as well as by vaginal smears. Mice should be housed in as small groups as possible. The scent of male excreta could be introduced to the environment to circumvent the Lee-Boot effect, where the estrous cycle of female mice is prolonged or halted in crowded environments or those that lack a male. Analysis of the ovarian tissue should go beyond gross morphology and should look at indicators such as capillary density and kit ligand, a signaling molecule important in the formation of eggs, and expression (Smith 2012).

Effects of spaceflight on the expression of liver proteins in the mouse

The aim was to investigate changes in the profile of major liver proteins of the mouse that are introduced by conditions associated with spaceflight. Raw data was derived from mass spectroscopic analyses of formalin-fixed paraffin-embedded tissue sections of liver from mice.

The raw data was analyzed by 2 different search engines, using shotgun proteomics, a process by which the proteins are digested and the smaller components separated and read. Statistically significant ($p<0.05$) changes of 8 proteins were achieved in the mouse liver. Of the 8 proteins, only carbamoyl-phosohate synthetase and 60kDa heat shock protein, a chaperonin, gave significant positive $\log_2$ fold change values, a statistical approach for detecting differential expression. Carbomoyl-phosphate synthetase was the protein present in the highest concentration, and up-regulation is consistent with increased amino acid breakdown resulting from gravitational changes and/or stress associated with missions in space. Glycine N-methyltransferase, a methyl group transferring enzyme which participates in detoxification chemistry in the liver cells was down-regulated. Fructose-bisphosphate aldolase B levels were also down-regulated.

Results reveal 8 of the 67 proteins showed statistical differences between flight and ground. Some of these are linked to detoxification pathways within the liver (carbamoyl-phosohate synthetase, glycine N-methyltransferase, S-adenosylmethionine synthetase) and some to carbohydrate metabolism (fructose-bisphosphate aldolase B, alpha-enolase). The 60kDa heat shock protein was up-regulated, probably because of its relation to stress. Regucalcin was highly down-regulated possibly limiting osteoporosis. Ribonuclease UK114, also known as heat responsive protein 12, was down regulated also possibly due to the stress of spaceflight (Gridley 2012).

Publication(s)

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This investigation is complete and all results are published.

COMMERCIAL BIOMEDICAL TESTING MODULE-3: ASSESSMENT OF SCLEROSTIN ANTIBODY AS A NOVEL BONE FORMING AGENT FOR PREVENTION OF SPACEFLIGHT-INDUCED SKELETAL FRGILITY IN MICE (CBTM-3-SCLEROSTIN ANTIBODY)

Research Area: Animal Biology – Vertebrates

Expedition(s): 27 and 28

Principal Investigator(s):

- Chris Paszty, PhD, Amgen Research, Thousand Oaks, California
- Hua Zhu (David) Ke, MD, Amgen Research, Thousand Oaks, California
- Louis S. Stodieck, PhD, University of Colorado, BioServe Space Technologies, Boulder, Colorado
- Martyn Robinson, PhD, Union Chimique Belge, Brussels, Belgium
- Mary L. Bouxsein, PhD, Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, Massachusets
- Ted A. Bateman, PhD, University of North Carolina, Chapel Hill, North Carolina
- Virginia L. Ferguson, PhD, University of Colorado, BioServe Space Technologies, Boulder, Colorado

RESEARCH OBJECTIVES

Commercial Biomedical Testing Module-3: Assessment of sclerostin antibody as a novel bone forming agent for prevention of spaceflight-induced skeletal fragility in mice (CBTM-3-Sclerostin Antibody) is one in a series of investigations designed to determine if administering an experimental agent preflight reduces the loss of bone associated with spaceflight. Humans and animals have been observed to lose bone mass during the reduced gravity of spaceflight. The sclerostin antibody is designed to inhibit the action of "sclerostin", a protein that is a key negative regulator of bone formation, bone mass, and bone strength.

S118E09327 -– STS-118 Mission Specialist Tracy Caldwell and Pilot Charles Hobaugh observe the Animal Enclosure Modules in the Middeck of the Space Shuttle *Endeavour*.

EARTH BENEFITS

If the sclerostin antibody proves successful in reducing spaceflight induced bone mass loss, the results may point towards possible prevention and treatment of the bone loss that can result from "skeletal disuse" in such conditions as immobilization, stroke, cerebral palsy, muscular dystrophy, spinal cord injury, and reduced physical activity.

Space Benefits

If the novel bone forming agent proves successful in mitigating bone mass loss in-flight, this would demonstrate the potential application of pharmacologic sclerostin inhibition as a countermeasure for use in long-duration human spaceflight missions.

Results

Data is currently under additional analysis.

Publication(s)

Gridley DS, Mao XW, Tian J, et al. Genetic and apoptotic changes in lungs of mice flown on the STS-135 mission in space. *In Vivo*. July 8, 2015;29:423-433.

Hwang S, Crucian BE, Sams CF, Actor JK. Post-spaceflight (STS-135) mouse splenocytes demonstrate altered activation properties and surface molecule expression. *PLOS ONE*. May 13, 2015; 10:e0124380. doi: 10.1371/journal.pone.0124380.

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This investigation is complete; however additional results are pending publication.

COMMERCIAL BIOMEDICAL TESTING MODULE-3: STS-135 SPACEFLIGHT'S AFFECTS ON VASCULAR ATROPHY IN THE HIND LIMBS OF MICE (CBTM-3-VASCULAR ATROPHY)

Research Area: Animal Biology – Vertebrates
Expedition(s): 27 and 28
Principal Investigator(s):
- Ron Midura, PhD, Cleveland Clinic Foundation, Cleveland, Ohio

RESEARCH OBJECTIVES

Commercial Biomedical Testing Module-3: STS-135 spaceflight's effects on vascular atrophy in the hind limbs of mice (CBTM-3-Vascular Atrophy) examines the effects of spaceflight on the skeletal bones of mice and the efficacy of a novel agent that may mitigate the loss of bone associated with spaceflight. Humans and animals have been observed to lose bone mass during the reduced gravity of spaceflight. CBTM-3-Vascular Atrophy specifically determines if there is a correlation between spaceflight induced altered blood supply to the bones and surrounding tissues with a resultant loss of bone mass.

EARTH BENEFITS

As noted in the preceding paragraph, if a correlation is found between blood supply to bone and bone mass regulation, new insights into the mechanisms governing how the body responds to skeletal unloading can likely result. These insights might lead not only to new therapies for maintaining a healthy musculoskeletal system during long-duration spaceflights but also new therapies for treating muscle and bone wasting diseases on the Earth.

SPACE BENEFITS

If a correlation is found between blood supply to bone and bone mass regulation, new insights into the mechanisms governing how the body responds to skeletal unloading can result. Such insights may lead to new therapies for maintaining a healthy musculoskeletal system during long-duration spaceflights.

RESULTS

Ground-based studies in rats subjected to chronic head-down tail suspension have been conducted to simulate the fluid shift towards the head and general cardiovascular deconditioning that occurs with spaceflight. The purpose of this study was to test the hypothesis, derived from the results of the aforementioned experiments, that 13 days of spaceflight aboard the STS-135 mission would enhance narrowing of the blood vessels, increase the thickness of the innermost layers of the arterial wall, and elicit no change in the mechanical properties of mouse cerebral arteries (Taylor 2013).

Contrary to the hypothesis, the results showed that myogenic vasoconstriction was less in cerebral arteries from spaceflight mice, passive pressure-diameter response indicated greater ability for vascular expansion and contraction and mechanical testing revealed that the arteries from spaceflight animals had lower effective elastic modulus (tendency to be deformed when force is applied) and stiffness. Gross structural measurements demonstrated that maximal diameter was greater in spaceflight mice, while medial wall thickness of cerebral arteries was not different between spaceflight and ground control mice. These results demonstrate that spaceflight alters vasoconstrictor, mechanical, and gross structural properties of cerebral resistance arteries. Collectively, these changes in the functional vasoconstrictor and mechanical properties of cerebral arteries suggest that blood flow to the brain may be elevated during spaceflight. Although elevated partial pressure of CO_2 in the closed microgravity environment may contribute to alterations in the properties of cerebral arteries, high CO_2 levels alone cannot fully account for such changes. Finally, if similar alterations in the properties of cerebral arteries occur in crew members, elevations in brain blood flow could serve to elevate intracranial pressure and possibly contribute to the visual impairment reported to occur in crew members (Taylor 2013).

Cardiovascular adaptations to microgravity undermine the physiologic capacity to respond to challenges related to an upright posture on return to terrestrial gravity. This study investigates the influence of spaceflight on the constriction of mouse muscle arteries either in response to a stimulus (vasoconstriction) or under their own power (myogenic contraction) and to determine the impacts on bone and muscle mass loss. Total body mass tended to be lower in spaceflight animals, and muscle mass was 7%-13% lower in spaceflight mice. Spaceflight was found to decrease vasoconstrictor responses but did not affect the myogenic responsiveness. The thickness of the vessel walls was not found to differ between the two groups. The lack of change in vessel wall thickness suggests that the blood volume redistribution is insignificant in mice during spaceflight and likely reflects that blood flow to the portion of muscle being tested was preserved. This is an important shortcoming and demonstrates that the mouse may not be an ideal animal model to study this phenomenon. If applicable to the human condition, these results suggest that microgravity-induced changes in the vasoconstrictor characteristics of skeletal muscle resistance arteries could compromise the ability to raise peripheral vascular resistance in order to regulate arterial blood pressure when standing (Stabley 2012).

PUBLICATION(S)

Gridley DS, Mao XW, Tian J, et al. Genetic and apoptotic changes in lungs of mice flown on the STS-135 mission in space. *In Vivo*. July 8, 2015;29:423-433.

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This investigation is complete; however additional results are pending publication.

C. ELEGANS TO ASSESS GENOMIC DAMAGE ON LONG-DURATION FLIGHTS (ELERAD)

Research Area Animal Biology - Vertebrates
Expedition(s) 14
Principal investigator(s)
- David L. Baillie PhD, Simon Fraser University, Burnaby, British Columbia, Canada

RESEARCH OBJECTIVES

C. Elegans to Assess Genomic Damage on Long-Duration Flights (Elerad) uses the nematode *Caenorhabditis elegans* as a biological dosimeter of space radiation. Using specific regions of the *C. elegans* genome, this study determines the types of damage induced by space radiation, studies accumulating doses of radiation, and assesses the rate, and type of mutations. The study also makes it possible to map the location of genetic rearrangements within worms.

EARTH BENEFITS

Space provides a unique laboratory to study how life and physiologic functions adapt from the cellular level to that of the entire organism. The results obtained in this set of experiments demonstrate that the model organism *C. elegans* can be used to study the effects of altered gravity and suggest that *C. elegans* respond to radiation experienced during spaceflight by altering the expression of genes of interest to development of human countermeasures.

SPACE BENEFITS

As space exploration opens new horizons, it is crucial to be able to provide countermeasures to the effects of the space environment on the human body. The fact that the biological results obtained with *C. elegans* appear to have strong similarities to those obtained in human beings, suggests that not only does *C. elegans* prove an invaluable model for understanding the fundamental biological changes seen during spaceflight, but that it may also be crucial for understanding those changes associated with human health concerns in space.

RESULTS

The exploration of space and colonization of other planets involves numerous physiological changes induced by known factors such as microgravity and radiation exposure. Genetic changes are yet unknown in humans but highly-likely to occur. To accelerate discovery of genetic changes in novel experimental conditions, *C. elegans*, a model organism was used. (Model organisms are non-human species with fully-sequenced genomes that have already been extensively studied and are able to provide insights that parallel human results.) Elerad evaluated reproductive organ radiation damage that can be passed on to offspring during a prolonged period aboard the International Space Station. The eventual goal is the development of an integrating biological dosimeter for spaceflight.

PUBLICATIONS

Oczypok EA, Etheridge T, Freeman J, et al. Remote automated multi-generational growth and observation of an animal in low-Earth orbit. *Journal of the Royal Society Interface*. 2012;9(68):596-9.

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This investigation is complete; however additional results are pending publication.

Mice Drawer System (MDS)

Research Area: Animal Biology – Vertebrates
Expedition(s): 19-22
Principal Investigator(s):
- Ranieri Cancedda, MD, University of Genoa (Unige) and IST National Cancer Research Institute, Genoa, Italy

Research Objectives

Mice Drawer System (MDS) is an Italian Space Agency experiment that uses a validated mouse model to investigate the genetic mechanisms underlying bone mass loss and other microgravity effect on different tissues such as muscles, glands, and brain. Research conducted with the MDS is an analog to the human research program, which has the objective to extend the human presence safely beyond low-Earth orbit.

S128E007107 – Astronauts Nicole Stott, Expedition 20 flight engineer; and Patrick Forrester, STS-128 mission specialist, work in the Kibo laboratory of the International Space Station while Space Shuttle *Discovery* remains docked to the station.

Earth Benefits

Microgravity is considered by the scientific community as an accelerated model for studying terrestrial osteoporosis. Results obtained in this space experiment facilitate the understanding of genetic elements that protect people from osteoporosis. The targeted users are crew members after a long-term space mission, elderly people (especially post-menopausal women), and patients after long-time immobilization.

Space Benefits

Crew members suffer from a significant loss of bone mass during spaceflight; the International Space Station (ISS) Medical Project office has developed some countermeasures to hinder the rapid loss of bone mass. Despite these countermeasures, bone mass loss continues to be a problem for crew members. Finding additional countermeasures increases the overall health of crew members on long-duration missions.

Results

Mice Drawer System (MDS) reached the ISS on board Shuttle *Discovery* Flight 17A/STS-128 on August 28, 2009. MDS returned to Earth on November 27, 2009, on Shuttle *Atlantis* Flight ILF3/STS-129 after a 91-day stay, performing the longest duration of mice in space. MDS flew 3 wild-type (Wt) and 3 pleiotrophic transgenic (PTN) mice to determine the microgravity effects levied on each mouse. Unfortunately, during the investigation, 1 PTN mouse and 2 Wt mice died due to either health related or payload-related reasons. MDS participated in a Tissue Sharing Program with 20 different research groups in order to determine if microgravity induced any tissue modifications, with a primary focus on bone loss (Cancedda 2012).

Bone turnover in wild type and pleiotrophin-transgenic mice housed for 3 months in the International Space Station

One of the major goals of the MDS experiment was to investigate bone alterations in 3 Wt and 3 PTN-Tg male mice (2 months old at the time of launch) after 3-month permanence aboard the ISS.

The study revealed bone loss during spaceflight in the weight-bearing bones of both strains. For both PTN-Tg and Wt mice a decrease of the trabecular number as well as an increase of the mean trabecular separation was observed after the flight, whereas trabecular thickness did not show any significant change.

Non weight-bearing bones were not affected. The PTN-Tg mice exposed to normal gravity presented a poorer trabecular organization then Wt mice, but interestingly, the expression of the PTN transgene during flight resulted in some protection against microgravity's negative effects. Moreover, osteocytes of the Wt mice, but not of PTN-Tg mice, acquired a round shape, thus showing for the first time osteocyte space-related morphological alterations in vivo. The analysis of specific bone formation and resorption marker expression suggested that the microgravity-induced bone loss was due to both an increased bone resorption and decreased bone deposition. Apparently, the PTN-Tg protection was the result of higher osteoblast activity in the flight mice (Travella 2012).

Effects of long-term spaceflight on erythrocytes and oxidative stress of Rodents

Several hematological modifications in humans were observed after microgravity exposure such as depression of T-cell lymphocyte activation and of our ability to fight infectious microorganisms. Moreover erythrocyte (red blood cell) hemolysis (breakdown) and hemoglobin loss was also observed after space missions. In addition, space radiations can induce generation of hydroxyl radicals, very reactive at the site of their formation, which can initiate a chain of reactions leading to lipid peroxidation (causing cell damage).

In the MDS mice, after landing, blood cell parameter showed a higher erythrocyte concentration (RBC) and RDW% with a hematocrit near or above 50%. Platelets were increased in both Wt and TG mice after flight, while hemoglobin content remained constant. These data are partially in accordance with human data after space mission and could probably be the consequence of body fluid shift and altered renal function.

After spaceflight, both Wt and Tg mice underwent oxidative stress and an increase of by-products of lipid peroxidation concentration. In parallel antioxidant and enzymes involved in the elimination of hydroperoxides from lipids were also enhanced with higher levels in Tg. After the MDS mission, mice erythrocytes presented modifications in the cell membrane composition and an increase of lipid peroxidation products. Despite their cellular activation, antioxidant defenses were not sufficient to prevent damages caused by oxidative stress (Rizzo 2012).

Adaptation of mouse skeletal muscle to long-term microgravity in the MDS mission

So far, the effect of microgravity on skeletal muscles has been examined in mice only after a short-term (5-20 day) exposition. It has been observed that spaceflight has adverse effects on muscles, including atrophy and partial shift of muscle fibres towards a faster, more glycolytic phenotype.

The MDS experiment gave the first opportunity to study long time exposure to microgravity effects on skeletal muscles. After the 91 day flight, muscle atrophy was observed in the fibres of the soleus muscle, but this atrophy was only slightly increased when compared to shorter periods in microgravity. Alterations were observed in the soleus and to a lesser extent in the extensor digitorum longus (EDL) muscle, in particular with regard to slow-to-fast fibre transition and ion channel activity.

Gene expression of the atrophy-related ubiquitin ligases was up-regulated in both soleus and EDL muscles from flight mice, whereas autophagy (self-degradation) was in the control range. In the same animals, various stress related genes were up-regulated in the EDL, but not in the soleus. Overall, gene expression results suggested that EDL muscle may resist microgravity-induced atrophy by activating compensatory and protective mechanisms and identified some molecular targets for the development of countermeasures (Sandona 2012).

MDS integrated inside the Double Payload Container. ASI image.

The impact of long-term exposure to space environment on adult mammalian organisims: A study on a mouse thyroid and testis

Human hormonal levels are known to change during spaceflight, but the underlying mechanisms are still unknown. To clarify this point, thyroid and testis/epididymis from the flight and ground control mice were analyzed both morphologically and functionally.

While Wt ground samples showed variable size and spatial orientation, spaceflight animals had a more homogenous thyroid tissue structure with a reduction in the interior spacing. In spaceflight animals, the follicular size in both Wt and Tg mice was greatly varied.

Structural modification correlated with altered thyroid functionality. Both Wt and Tg cells stimulated with thyrotropin enhanced cAMP production in ground cells. After spaceflight a more pronounced enhancement with Wt mice was observed. At the end of the MDS experiment, the thyrotropin receptor and caveolin-1 in the thyroid were overexpressed in the spaceflight mice.

In testes, the spaceflight mice showed severe degenerative changes, in some cases with tubules almost devoid of spermatozoa except for few spermatogonia. Tubular degeneration was not homogenous and differences were not seen between Wt and Tg mice. The expression of androgen and follicle stimulating hormone receptors increased while luteinizing hormone receptor levels were not changed.

These data indicate that several changes occur in relevant endocrine organs under the control of the pituitary gland and they could be responsible for variations of hormone levels in humans during space missions, significantly affecting the endocrine homeostasis of the body, as well as the reproductive function (Masini 2012).

Loss of parafollicular cells during gravitational changes (Microgravity, Hypergravity) and the secret effect of Pleiotrophin

Bone loss is one of the most important complications for crewmembers who are exposed to long-term microgravity. Changes in blood flow and systemic hormones were indicated as important contributing elements to the response of the mechanical loading experienced by osteoblast cells. Here, the possible biological involvement of thyroid C cells is being investigated.

This study has provided evidence that both microgravity and hypergravity induce similar loss of thyroid C cells with reduction of calcitonin production. Pleiotrophin over-expression results in some protection against negative effects of gravity change. To confirm these results it would be important to know blood levels of calcitonin in hypogravity and hypergravity environments and this could be an area of study for future missions (Albi-a 2012).

Observing the mouse thyroid Sphingomyelin under space conditions: A case study from the MDS Mission in comparison with hypergravity conditions

Histological examination of the thyroid gland revealed an increase in the average follicle size compared to that of 3 control animals and 3 animals exposed to hypergravity (2g) conditions in a centrifuge. Additional analysis detected an increase in two thyroid gland enzymes, sphingomyelinase and sphingomyelin-synthase1. In addition, sphingomyelinase, an enzyme traditionally confined to the cell nucleus in the control animals, was found in the mouse exposed to hypogravity to be homogenously distributed throughout the cell bodies (Albi-b 2012).

Evaluation of gene, protein and neutrophin expression in the brain of mice exposed to space environment for 91 days

While modification in the central nervous system are described in literature after short space missions, long-term inhibition of antigravity activity on the mouse brain are unclear. After the MDS experiment, the effects of the 3-month exposure to microgravity environment on the expression of genes and proteins in the mouse brain were studied.

Several genes related to the immune response, metabolic process, and/or inflammatory responses were up-regulated whereas several genes involved in various metabolic and catabolic processes were down-regulated. Two proteins, BDNF and NGF, which are involved in learning and memory performance, ageing-related disorders, and anxiety-like behavior were studied in the brain and adrenal gland. Expression on NGF in hippocampus, cortex, and adrenal gland of wild type animals tended to decrease following spaceflight, but together with BDNF it was not consistent suggesting only a transient response to spaceflight and not long-lasting effects. On the contrary CRMP1 was up-regulated in flight samples and, since the CRMP1 deficient mice showed an impaired spatial learning and memory, memory performance may be stimulated after spaceflight.

Exposure to space environment influenced the expression of a number of genes and proteins in the brain that have been shown to be involved in a wide spectrum of biological function and appears to interfere with expression of neuropeptides involved in psycho-neuro-endocrine adaptations that should need a deeper examination in a MDS re-flight (Masini 2012).

Evaluation of long term space permanence effects on other tissues of mice exposed to space environment for 3 months

Additional tissues are currently being processed and additional data collected by the different Principal Investigators.

PUBLICATION(S)

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Santucci D, Kawano F, Ohira T, et al. Evaluation of gene, protein, and neurotrophin expression in the brain of mice exposed to space environment for 91 days. *PLOS ONE.* 2012;7(7):e40112. doi: 10.1371/journal.pone.0040112.

Tavella S, Ruggiu A, Guiliana A, et al. Bone turnover in wild type and pleiotrophin-transgenic mice housed for 3 months in the International Space Station (ISS). *PLOS ONE*. 2012;7(9):e33179. doi: 10.1371/journal.pone.0033179.

This investigation is complete; however additional results are pending publication.

MOUSE ANTIGEN SPECIFIC CD4^{+} T CELL PRIMING AND MEMORY RESPONSE DURING SPACEFLIGHT (MOUSE IMMUNOLOGY)

Research Area: Animal Biology – Vertebrates
Expedition(s): 23 and 24
Principal Investigator(s):
- Millie Hughes-Fulford, PhD, University of California, San Francisco, California

RESEARCH OBJECTIVES

The Mouse Antigen-Specific CD4+ T Cell Priming and Memory Response during Spaceflight (Mouse Immunology) investigation studies specific mechanisms of immune system activation, and whether immune system cells exposed to challenges before flight retain the "memory" to fight challenges during spaceflight. Space Explorers on future long-duration space missions may require preflight vaccinations or other precautions to prevent infection during space travel if immune memory is not retained.

EARTH BENEFITS

Understanding the mechanisms of immune regulation is critical to the design of rational therapeutic interventions of these various disease processes. The immunosuppression observed during spaceflight provides important insight into the role of gravity in the generation of normal immune responses. Deciphering the mechanisms of spaceflight immunosuppression provides a more complete picture of the important factors necessary for successful immune responses that may be masked in Earth-based experiments in the presence of gravity. These gravity-sensitive factors may hold the key to our ability to manipulate the immune system and develop therapeutic interventions to treat the various disease processes affected by immunodysregulation. Dysregulated immune tolerance (overactive immune system) is linked to autoimmune diseases such as type I diabetes mellitus, systemic lupus erythematosus, psoriasis, rheumatoid arthritis, and multiple sclerosis. On the other hand, many disease processes result from immunosuppression (underactive immune system).

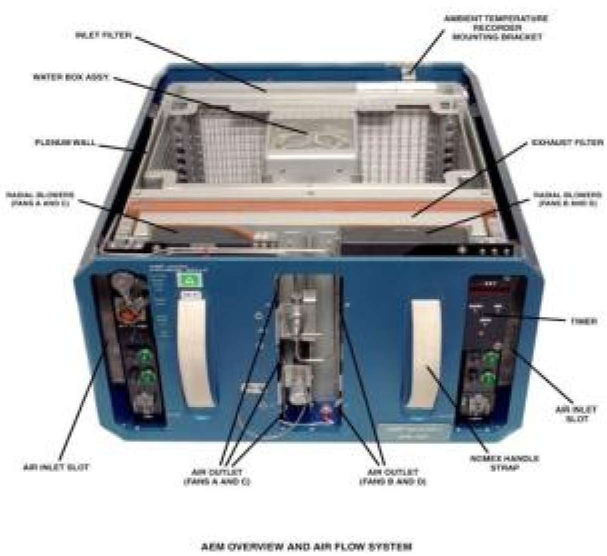

Image of the Animal Enclosure Module that houses the rodents used in the Mouse Immunology investigation. NASA's Ames Research Center image, Moffett Field, California.

SPACE BENEFITS

Spaceflight immunosuppression is a significant obstacle to long-term human space travel. Of foremost concern is whether space travelers may be able to generate effective protective immune responses against infections while in space. Using an innovative mouse experimental model, this set of experiments tests whether initial specific activation of T cells is intact and whether memory T cell function is maintained during spaceflight.

RESULTS

Results indicate that the process of hematopoietic and mesenchymal stem cell differentiation in bone marrow is profoundly altered under conditions of reduced mechanical load in microgravity, with retention of stem cell characteristics and a broad down-regulation in marrow differentiation capacity. This phenomenon is revealed in multiple cell types, including osteoclasts and osteoblasts required for bone remodeling and mineral homeostasis, erythrocytes required for the transport of oxygen and iron throughout the body, and megakaryocytes required for the formation of platelets. These results also suggest that under conditions of reduced gravitational mechanical load, such as physical inactivity, mechanical disuse conditions, and spaceflight, it is likely that differentiation of somatic stem cells, such as in bone and blood, may be inhibited, possibly resulting in serious regenerative health effects (Blaber 2013).

PUBLICATION(S)

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Martinez EM, Yoshida MC, Candelario TT, Hughes-Fulford M. Spaceflight and simulated microgravity cause a significant reduction of key gene expression in early T-cell activation. *American Journal of Physiology: Regulatory, Integrative, and Comparative Physiology*. March 15, 2015; 308(6):R480-R488. doi: 10.1152/ajpregu.00449.2014.

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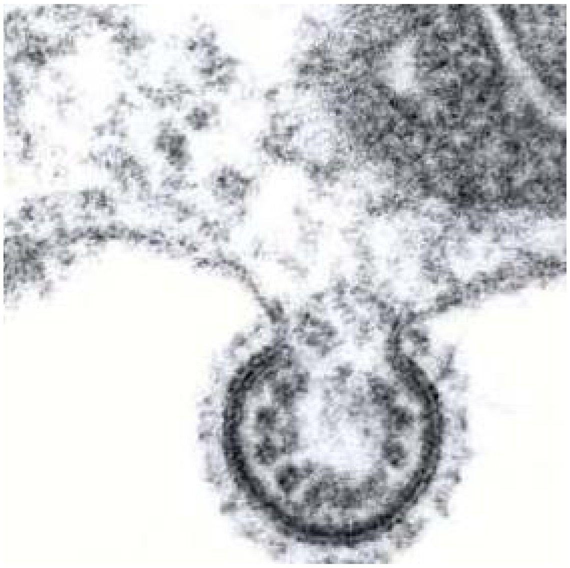
Zhao L, Tanjung N, Swarnkar G, Ledet E, Yokota H. Regulation of eIF2α phosphorylation in hindlimb-unloaded and STS-135 space-flown mice. *Advances in Space Research*. 2012;50(5):576-583. doi: 10.1016/j.asr.2012.05.024.

This investigation is complete and all results are published.

Effect of SpaceFlight on Innate Immunity to Respiratory Viral Infections (Mouse Immunology-2)

Research Area: Animal Biology – Vertebrates
Expedition(s): 25 and 26
Principal Investigator(s):
- Roberto P. Garofalo, MD, The University of Texas Medical Branch at Galveston, Galveston, Texas



Electron micrograph image of an RSV virion budding from an infected cell. Courtesy of Dr Roberto Garofalo, University of Texas Medical Branch, Galveston.

Research Objectives

The Effect of Spaceflight on Innate Immunity to Respiratory Viral Infections (Mouse Immunology-2) investigates the effects of microgravity on immune function to fight Respiratory Syncytial Virus (RSV). In microgravity, crew members experience changes in immune function. These studies help scientists determine the biological significance of spaceflight induced changes in immune responses.

Earth Benefits

Understanding the function of the immune system during spaceflight may have great relevance to our understanding of the process of aging and/or stress-related immunomodulation (adjustments in the level of an immune response) on Earth. In particular, studying the innate host response against pathogens during/after spaceflight provides novel data on the function of the respiratory mucosal response to viral pathogens.

Space Benefits

These investigations are expected to generate new scientific evidence of the immune pathways that are affected in antiviral host response during spaceflight and possible preventive or therapeutic approaches applicable to future space missions.

Results

This experiment has produced a significant amount of data and researchers are currently in the process of writing a manuscript to submit for peer review.

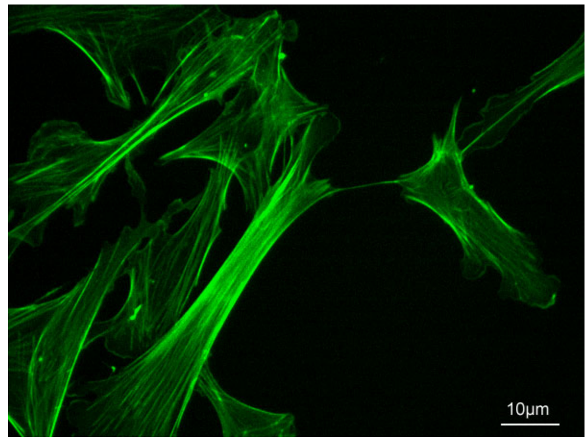
This investigation is complete; however additional results are pending publication.

Role of Weightlessness on Metabolism (Actin)

Research Area: Cellular Biology
Expedition(s): 8 and 9
Principal Investigator(s):
- Johannes Boonstra, Utrecht University, Utrecht, Netherlands

Research Objectives

The Role of Weightlessness on Metabolism (Actin) investigation studies the effect of weightlessness on the structure and metabolism of cellular actin microfilaments in mammalian cells. Actin is 1 of 2 proteins involved in muscle contraction and is found in both smooth and striated muscles. It also serves as an important structural molecule.



Actin cytoskeleton of mouse embryo fibroblasts, stained with Fluorescein isothiocyanate-phalloidin. Wikipedia image.

Results

Preliminary experiments were performed during two sounding rocket flights. The observed effects of microgravity on cell morphology suggested that the actin microfilament system was sensitive to gravity conditions. Analysis of the cells by fluorescence microscopy and by fluorometry revealed that the F-actin content of the cells was increased in microgravity conditions. These preliminary observations, however, clearly indicate that the actin microfilament system may represent a gravity-sensitive cell component.

Ground controls samples provided predictable results. Cells showed normal actin morphology and number of ruffles indicating that the cells survived the long period of starvation and exposure to room temperature during the experiment. Cells that were not stimulated showed abundant stress fibers and a pool of G-actin mainly localized around the nucleus. After stimulation with Platelet-Derived Growth Factor (PDGF) the number of stress fibers decreased and both F-actin and G-actin were found in circular ruffles indicating an extensive reorganization of actin. Unfortunately no flight results were obtained due to a combination of malfunctioning hardware and unfulfilled temperature requirements.

Publication(s)

Moes MJ. *Actin dynamics in microgravity*. Utrecht, Netherlands: University of Utrecht; 2012.

Moes MJ, Bijvelt JJ, Boonstra J. Actin dynamics in mouse fibroblasts in microgravity. *Microgravity Science and Technology*. September 2007;19(5-6):180-183. doi: 10.1007/BF02919477.

This investigation is complete and all results are published.

The Antibody V(D)J Recombination Machinery in Normal and Altered Gravity (Amphibody)

Research Area: Cellular Biology
Expedition(s): 13
Principal Investigator(s):
- Jean-Pol Frippiat, Lorraine University, Nancy, France

Research Objectives

The Antibody V(D)J Recombination Machinery in Normal and Altered Gravity (Amphibody) experiment studies whether antibody synthesis is affected when animal development occurs on the International Space Station (ISS) and, if so, which spaceflight-associated environmental modification has the greatest impact on antibody synthesis. Embryos of the amphibian *Pleurodeles waltl* are allowed to develop during 10 days of spaceflight in Mini-Aquaria, either in weightlessness or on a 1 g control centrifuge. Tissue samples are collected either immediately on return or 25 days postflight for analysis.

Results

This experiment revealed that Immunolglobin M (IgM) heavy-chain transcription was doubled at landing. To determine which space-related environmental modification was responsible for this change, environmental modifications encountered by embryos during their development on the ISS were recreated on ground. This approach demonstrated the fact that gravity changed during *Pleurodeles waltl* development, and induced a change in IgM heavy-chain transcription. Moreover, this change was associated with variations in nuclear factor kappa-light-chain-enhancer of activated β cells (NF-κβ) mRNA levels, which play a key role in regulating immune response. Given that *P. waltl* larvae were not immunized during the mission, data suggested that an alteration of B lymphocyte generation could occur if gravity is modified during *P. waltl* development.

The amounts of transcripts encoding NF-κβ molecules were increased in *P. waltl* embryos that developed at 3 g and were decreased in those that developed under simulated microgravity, as was shown in human T cells. Important immunological information can be deduced from space experiments performed with an amphibian species.

Finally, it can be shown that an immature vestibular system is transiently sensitive to microgravity exposure and that its exposure to hypergravity leads to a slowly growing vestibular sensitization.

Publication(s)

Frippiat J, Contribution of the urodele amphibian *Pleurodeles waltl* to the analysis of spaceflight-associated immune system deregulation. *Molecular Immunology*. December 2013;56(4):434-441. doi: 10.1016/j.molimm.2013.06.011.

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Gabriel M, Frippiat J, Frey H, Horn ER. The sensitivity of an immature vestibular system to altered gravity. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*. 2012;317(6):333-346. doi: 10.1002/jez.1727.

This investigation is complete and all results are published.

EFFECT OF SPACEFLIGHT FACTORS ON THE EXPRESSION OF PRODUCER STRAINS OF INTERLEUKIN 1A, 1B, AND ARYL (ARYL-1/ARYL-2), TWO INVESTIGATIONS

Research Area: Cellular Biology
Expedition(s): 16-24, 27-ongoing
Principal Investigator(s):
- Leonid N. Petrov, PhD, Biopreparat, Moscow, Russia

RESEARCH OBJECTIVES

The Effect of Spaceflight Factors on the Expression of Producer Strains of Interleukin 1α, 1β, and Aryl (Aryl) investigation develops a method of increasing the productivity of recombinant producer strains of interleukins 1α, 1β, and Aryl (interleukin antagonist) medication by incubating microorganism cultures in microgravity conditions and subsequently selecting the best cultures. The essence of the research is to identify possible changes in physical, chemical, morphological, and genetic properties of therapeutic and diagnostic bacteriophages exposed to spaceflight factors that could be used to obtain highly effective medicines with specific properties.

Conducting the ARIL experiment on the ISS RS. Roscosmos image.

EARTH BENEFITS

The material obtained will be used for selecting producer strains with enhanced properties (increased productivity and segregation stability) on Earth and subsequently introducing them into production. The selected high-productivity lines (clones) of producer strains of interferon, interleukins, and Aryl will be used in the production of biological medications at the State Scientific Research Institute of High Purity Biopharmaceuticals. The use in production of these strain medications with enhanced properties could have a significant economic impact.

SPACE BENEFITS

The essence of the research is the identification of possible changes in the physical, chemical, morphological, and genetic properties of therapeutic and diagnostic bacteriophages exposed to spaceflight factors that will be used to obtain highly effective medicines with specific properties.

RESULTS

During the Aryl-1, the culture retained the capability to synthesize recombinant protein (Aryl). Quantitatively speaking, the following differences were observed: when IPTG was used as the inducer, the amount of protein in the space experiment was lower than in ground conditions, while the opposite picture was observed when lactose was used. The maximum yield of *Escherichia coli* TGl (pPR-TGATG-hIL-1rα) biomass observed in microgravity conditions with induction by lactose was higher than in ground conditions. The result obtained can demonstrate the positive effect of microgravity on culture growth and on the high sensitivity of the culture to the nature of the inducer in these conditions.

In samples with lactose induction under microgravity conditions, a significant drop in the number of viable cells (CFU) was observed, which could be caused by both spaceflight factors and the oversaturation of cells by the target protein. This finding was confirmed in microscope observations and electrophoretic analysis.

The amount obtained in the space experiment of medication containing various forms of recombinant protein did not differ from that obtained under ground conditions. In the conditions of this experiment, most indicative were the initial cultivation doses of 107 and 109 cells/ml, at which the lowest degree of plasmid elimination was observed, and thus better synthesis of target protein by the cells of these cultures both on the ISS and on the ground.

In the Aryl-2 investigation, plasmid elimination in *Escherichia coli* BL21(DE3) (pAYC-ET-(hIFN-α2b)-lacI) strain cells was absent or minimal both on the ISS and in ground control samples, which distinguishes this strain from the *Escherichia coli* TG1 (pPR-TGATG-hIL-1rα) previously used.
The clones selected from the flight sample during ISS Expedition 29 demonstrated varying levels of target protein production, ranging from hyper production to almost complete absence.

Based on studying the growth pattern and microscopic picture, it can be stated that the addition to the culture medium of supernatant from the stationary growth phase of the Escherichia coli BL21(DE3) [pAYC-ET-(hIFN-α2b)-lacI] culture positively impacts survival in space conditions.

In order to clarify the mechanism of action of the supernatant, in subsequent experiments it would make sense to study the effect of a simulated mixture of compounds as the additive to reproduce the content of supernatant from the stationary phase of culture development (system of biologically active components of Aktoflor culture broth).

This investigation is ongoing and additional results are pending publication.

BIOKon In Space (BIOKIS), Seven Investigations

Research Area: Cellular Biology
Expedition(s): 27 and 28
Principal Investigator(s):
- Pier Luigi Ganga, Kayser Italia, Livorno, Italy

Research Objectives

BIOKon In Space (BIOKIS) involves the investigation of 7 experiments sponsored by the Italian Space Agency (ASI-Agenzia Spaziale Italiana) in the areas of cellular biology, radiation and radioprotection, aging, germination, and plant growth. These experiments aim to evaluate various biological species to determine genetic distinctions following short-duration spaceflight; also, BIOKIS utilizes a variety of dosimeters to monitor radiation.

S134E006385 – STS-134 Pilot Gregory Johnson working with the BIOKon in Space.

Earth Benefits

BIOKIS-BIOS-SPORE

This study inspires future scientists to pursue a career studying the influence of spaceflight on fertility, which can ultimately improve human existence in orbit.

BIOKIS - ArabidopS-ISS

This study inspires future scientists to pursue a career studying alterations in plant physiology associated with spaceflight, which can ultimately improve human existence in orbit.

BIOKIS - HiDOSE

This study can lead to further understanding of how radiation may affect human function on Earth as well as in space.

BIOKIS - PHOTO-EVOLUTION

The availability of regenerating an oxygen supporting system is of great relevance in space as well as on Earth. For environmental purposes, algae cultures could be applicable to the polluted water of civil and industrial wastewater biological oxidation processes. For medical applications, algae cultures could be used as an artificial lung that can replace the gas exchange function of a person's native lungs during recovery from injury or illness, or until donor lungs are available for transplantation.

BIOKIS - TARDIKISS

This study can improve human life and aging on Earth by engineering new molecules and metabolites for tissue and cell conservation, which can be used for developing countermeasures against radiation and aging.

BIOKIS - 3DISS
The same bio-dosimeters developed for this experiment in orbit can be used in Earth applications to develop more efficient radiation shielding.

BIOKIS - nDOSE
This research supports the study of neutron dosimetry concerning high-altitude flights; neutron dosimetry concerning high-altitude countries (eg, Bolivia); and generally, it provides accurate measurements of neutron dosimetry concerning medical physics and radiotherapy.

SPACE BENEFITS

BIOKIS - BioS-SPORE
These studies could be important when assessing the importance of spaceflight concerning generations of diversity and the birth of new species. Assessing viability of spores during spaceflight could be relevant to assessing the possibility of transporting terrestrial species to non-terrestrial ecosystems.

Image of the BIOKon hardware. ASI image.

BIOKIS - ArabidopS-ISS
This experiment elucidates the role of cytoskeleton in gravisensing and the genes involved in the ROS signaling chain. The International Space Station (ISS) is the only facility able to permit long-term microgravity conditions.

BIOKIS - HiDOSE
This experiment monitors primary cosmic radiation.

BIOKIS - PHOTO-EVOLUTION
For long-term space missions and permanence on space platforms such as the ISS, the isolation of microorganisms with improved tolerance to ionizing radiation represents a fundamental issue in order to be utilized as self-regenerating oxygen producing life supporting system. The exploitation of green algae compared to higher plants allows researchers to optimize the space utilization on ISS as a large algal biomass, which could be grown in relatively small-sized photobioreactors (plastic tubes exposed to sunlight).

BIOKIS – TARDIKISS
Since the exposure to the space environment can induce rapid changes in living systems, this study aims to define the countermeasures needed to protect sensitive organisms, including humans, which are not naturally able to withstand extreme stresses under space conditions; and for the study of future long-term explorations of the solar system.

BIOKIS - 3DISS
Absorbed radiation measurements are used to improve the safety of crew members and to develop more efficient radiation shielding.

BIOKIS - nDOSE
In the space environment, humans are exposed to a complex mixed radiation field. The evaluation of neutron components of the radiation environment in spacecraft, both in low-Earth orbits and in deep space, is of great importance because of their high LET (Linear Energy Transfer); especially in view of long-term space missions as on the ISS; whereby, neutrons can produce dramatic damages to the health of crew members as well as the instrumentation.

RESULTS

BIOKIS-BioS-SPORE
Sporulation of the yeasts included in the experiment was not found to be altered by the space environment. However, it was found that some species of *Saccharomyces* genus could not germinate in spaceflight, suggesting that germination is species and possibly strain dependent. There were also differences in spore viability suggesting that spaceflight affects hybrid viability and thus the formation of new species.

BIOKIS-ArabidopS-ISS
No differences in the germination rate were found in both the genotypes under flight and ground conditions. It was also noted that the hypocotyls (structures that eventually form the plant stems) were long due to the seeds being kept in darkness in all conditions and genotypes.

BIOKIS-HiDOSE
The preliminary results indicate that the dose equivalent rate due to space radiation exposure during the STS-134 mission is 320µSv/die (measured by TLD100 and TLD700) and 360µSv (measured by TLD600), according with the results obtained from long-duration flights.

BIOKIS-PHOTO-EVALUATION
After flight, the mutant cells displayed a higher photosynthetic performance and a faster rate of re-growth indicating a higher capacity of stress recovering. The enhanced capability to survive the cosmic adverse conditions has been related to a particular localization of the amino acid substitution in the D-1 structure.

BIOKIS-TARDIKISS
Flight tardigrades, small water-dwelling animals, of 2 species showed a very high postflight survival rate, unaffected by microgravity or cosmic radiation. Flight females laid eggs with normal shape that were able to hatch. Newborns exhibited normal morphology and behavior and also laid viable eggs at sexual maturity.

BIOKIS-3DISS
Work is in progress to analyze the DNA from the dosimeters and the Eppendorf vials and to measure the dose integrated by the diamond dosimeters.

BIOKIS-nDOSE

The average neutron dose of 17.2µSv/day ±20% has been estimated. The bismuth stack detector is still under analysis and the experimental results will be published in future papers.

All results presented in the listed publication are preliminary results and proved that the experiment was performed as expected. Analyses are on the way for each one of the experiment involved in BIOKIS.

PUBLICATION(S)

Rizzo AM, Altiero T, Corsetto PA, Montorfano G, Guidetti R, Rebecchi L. Spaceflight effects on antioxidant molecules in dry tardigrades: The Tardikiss experiment. *BioMed Research International*. 2015;2015:7. doi: 10.1155/2015/167642.

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Vukich M, Ganga PL, Cavalieri D, et al. BIOKIS: A model payload for multidisciplinary experiments in microgravity. *Microgravity Science and Technology.* December 1, 2012;24(6):397-409. doi: 10.1007/s12217-012-9309-6.

This investigation is complete; however additional results are pending publication.

Bone Proteomics (BOP)

Research Area: Cellular Biology
Expedition(s): 10 and 11
Principal Investigator(s):
- Aldaberto Costessi, University of Trieste, Trieste, Italy

Research Objectives

Bone Proteomics (BOP) investigates the possible role(s) of extracellular nucleotides in the molecular response of osteoblast cells to weightlessness conditions. BOP is the first student experiment from European Space Agency's (ESA) Space Station Utilization Contest Calls for European Student (SUCCESS) initiatives program and flew on the International Space Station (ISS) in 2005. Bone mass loss is a major consequence of extended periods of weightlessness. Many studies performed on astronauts and animals have shown that impaired maturation of osteoblast cells as well as a decrease of their bone-synthesizing activity, play key roles in bone mass loss in space.

Adalberto Costessi winner of the SUCCESS competition in 2002 student contest making final preparations for Bone Proteomics experiment prior to launch in 2005 on the Eneide Mission. ESA/Adalberto Costessi image.

Results

Preliminary analysis indicated that administration of ATP to MG-63 cells cultured in weightlessness conditions was able to increase extracellular-signal-regulated kinase (ERK) phosphorylation. Analysis of 2-D gels revealed several differentially regulated proteins in response to ATP treatment. To the best of our knowledge, BOP is the first proteomic study on mammalian cells cultured in space. The conclusion of the analysis will reveal new aspects of osteoblast biology and provide new insights into the molecular responses of human cells to weightlessness.

Publication(s)

Costessi A, Vascotto C, Pines A, et al. Bone Proteomics experiment (BOP): The first proteomic analysis of mammalian cells cultured in weightlessness conditions. *57th International Astronautical Congress*, Valencia, Spain; October 7, 2006.

This investigation is complete and all results are published.

CELLULAR BIOTECHNOLOGY OPERATIONS SUPPORT SYSTEMS (CBOSS), SEVEN INVESTIGATIONS

Research Area: Cellular Biology

Expedition(s): 3 and 4, 7 and 8, 10, 12 and 13

Principal Investigator(s):

- Timothy G. Hammond, MD, Durham Veterans Affairs Medical Center, Durham, North Carolina
- John Milburn Jessup, MD, National Cancer Institute, Bethesda, DC
- Jeanne L. Becker, PhD, National Space Biomedical Research Institute, Houston, Texas
- Peter I. Lelkes, PhD, Drexel University, Philadelphia, Pennsylvania
- Arthur J. Sytkowski, PhD, MD, Beth Israel Deaconess Medical Center, Boston, Massachusets
- Joshua Zimmerberg, PhD, National Institutes of Health, Bethesda, Maryland
- Joshua Zimmerberg, PhD, National Institutes of Health, Bethesda, Maryland

RESEARCH OBJECTIVES

Cells grown in microgravity grow and replicate into complex structures, unlike cells grown on Earth. The cells are to be returned to Earth and used in studies of several different diseases.

ISS0003E5276 – Image of a Quad Tissue Culture Module Assembly (QTCMA) 7 on International Space Station (ISS) Expedition 3 after activation of the cells. A syringe was used to inject cells into the pink nutrient growth media. The Biotechnology Specimen Temperature Controller (BSTC) can hold 8 of these QTCMAs, which are used to grow human cells on ISS. When the samples completed their growth cycle, the crew transferred the QTCMAs from the BSTC to the Biotechnology Refrigerator (BTR) where they were stored until they are examined at a ground-based laboratory.

CBOSS-01-02-RENAL (HAMMOND)

To better understand the mechanisms that cause several kidney disorders, human renal cortical epithelial (kidney) cell lines are grown on the International Space Station (ISS). Microgravity allows the cells to grow in 3-D structures that are similar to how they grow in the human body.

CBOSS-01-COLON (JESSUP)

To better understand the mechanisms that cause the differentiation of cells in microgravity, 6 cell lines of common human illnesses are grown on ISS. This study is important for understanding the mechanisms needed to fight colon cancer in humans.

CBOSS-01-Ovarian (Becker)

To better understand the mechanisms that cause the differentiation of cells in microgravity, a human ovarian tumor cell line is grown on ISS. This study aims to define mechanisms of ovarian cancer with the goal of developing new ovarian cancer treatments.

CBOSS-01-PC12 (Lelkes)

To better understand the mechanisms of neural regeneration and pain suppression, a neuroendocrine cell line is grown on ISS and then returned to Earth for analysis.

CBOSS-02-Erythropoietin (Sytkowski)

To better understand the mechanisms that cause the differentiation of cells in microgravity, 7 cell lines of common human illnesses are grown on the ISS. This study is important for understanding the mechanisms needed to fight immune dysfunction caused by microgravity.

CBOSS-02-HLT (Zimmerberg)

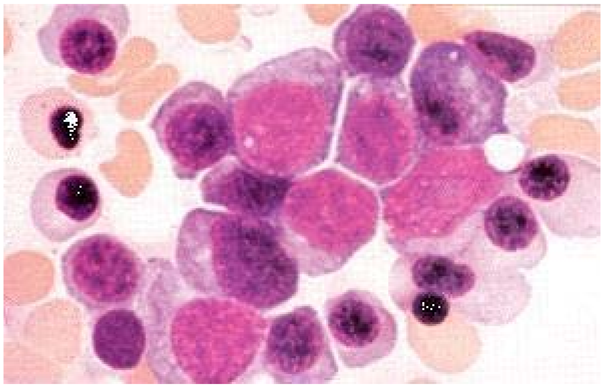
To better understand the mechanisms that cause the differentiation of cells in microgravity, 6 cell lines of common human illnesses are grown on ISS. This study is important for understanding the mechanisms needed to fight diseases of the human immune system.

CBOSS-FDI (Zimmerberg)

CBOSS-FDI optimizes the procedures for dispersion of cells and molecules in microgravity to enable future successes for growing cells in space. This investigation uses image analysis to assess how well the particles mix and if the size of particles causes distribution differences.

Earth Benefits

In the human body cells normally grow within a scaffolding of protein and carbohydrate fibers that help create a 3-D structure. This is how organs maintain their shape. Studying cells on Earth is difficult because outside the body cells tend to grow in flat sheets and are not capable of duplicating the structure they normally hold, which often makes them behave differently in the lab than they would in the body. Past research, however, has shown that cells grown in microgravity arrange themselves into 3-D shapes, more closely duplicating how they behave in the body.



Stained microscopy image of erythroleukemia cells.
NASA’s Marshall Space Flight Center image.

The CBOSS-FDI experiments allows for a better understanding of the physics of aqueous bubble-liquid interaction and the effects of gravity on surface tension.

Space Benefits

Development of techniques to reliably cultivate organisms under controlled conditions is essential to understanding the effect of microgravity and radiation on living organisms and creating environmental conditioning sources for long-term spaceflight.

The CBOSS-FDI experiments leads to a mixing protocol that is both optimal in providing uniform and reproducible mixing and convenient for the flight crew. In addition, these experiments promote interactive science between the flight crew and the ground team. These goals are accomplished by evaluating various mixing protocols using colored polystyrene microspheres, cytodex beads, and colored dyes in the Tissue Culture Module (TCM). Additionally, since bubble formation in the TCM can be deleterious to cells, the development of bubble removal procedures enhances culture conditions in the TCM. Optimizing fluid mixing and bubble removal techniques in orbit is essential to conduct cellular research in microgravity.

Results

The CBOSS hardware supported 6-cell culture investigations with different detailed scientific objectives. There were problems in the growth and preservation of all of the cell lines grown on Expeditions 3 and 4. The PC12 and erythroleukemia cells did not survive well in long-term culture, so no scientific results are expected from these experiments. It was found that there was more bubble formation than expected that may lead to cell death at the air-liquid interface. Although not well documented in this experiment, it was noted that poor mixing of cells/tissues and medium occurred in the other CBOSS payloads as well. Both the poor mixing and greater than expected bubble formation were important lessons learned that led to the addition of the CBOSS-Fluid Dynamics Investigation (CBOSS-FDI) to study mixing and bubble formation in microgravity on later Expeditions.

CBOSS-01-02-Renal

Renal cortical cells returned were treated with an RNA stabilizing agent (RNAlater-Ambion) that enabled analyses of both RNA and immunoreactive proteins. The space and ground control cell cultures exhibited similar immunoreactivity profiles for the antibodies tested. These data provide evidence that the techniques used can be generalized to other cell lines, and that RNAlater provides long-term storage of proteins at 4°C (39°F) for long-duration investigations (Hammond 2006).

CBOSS-01-Colon

Analyses of the returned colon carcinoma cells revealed that the cells had died in orbit. However, ground-based research led to an appreciation of a novel mechanism by which microgravity may kill cells as well as of the role of tumor marker carcinoembryonic antigen (CEA) on preventing cell death. It has been shown that CEA interacts with death receptors on the cell membrane to reduce cell death. Since CEA is important to many of the cancers that afflict men and women in the United States, this is a critical finding that was in large part initiated by studies of growth in simulated microgravity. These results are not yet published, but were presented by Jessup at the Keystone Symposium on “Stem Cells, Senescence, and Apoptosis” (Singapore 2005).

CBOSS-01-Ovarian

The LN1 ovarian cell cultures aboard station did not survive in long-term culture. However, the cells grown on ISS were found to have produced reduced amounts of cytokines (small secreted proteins that mediate and regulate immunity, inflammation, and hematopoiesis) compared to the ground controls. The proteins were recovered after the RNA had been removed from the cells via filtration. The novel proteins, vimentin and epithelial membrane antigen (EMA) proteins, were extracted from filtrate of the RNA extraction. Vimentin is the main intermediate filament protein in embryonic cells. It plays an important role in the differential diagnosis of undifferentiated neoplasms (abnormal tissue growths). EMA, which belongs to a family of proteins known as human milk fat globulemembrane proteins, is considered a broad spectrum antibody that is reactive against many types of adenocarcinomas. The data obtained from the protein extraction indicate the presence of the antigenic proteins, vimentin and EMA, in RNA-stabilized LN1 cells following long-duration storage at 4°C (39°F). The vimentin and EMA proteins showed similar profiles at different times between the flight and ground samples. These data provide confirmation that the techniques used can be generalized to other cell lines and that RNAlater provides long-term storage of proteins at 4°C (39°F) for long-duration investigations (Hammond 2005).

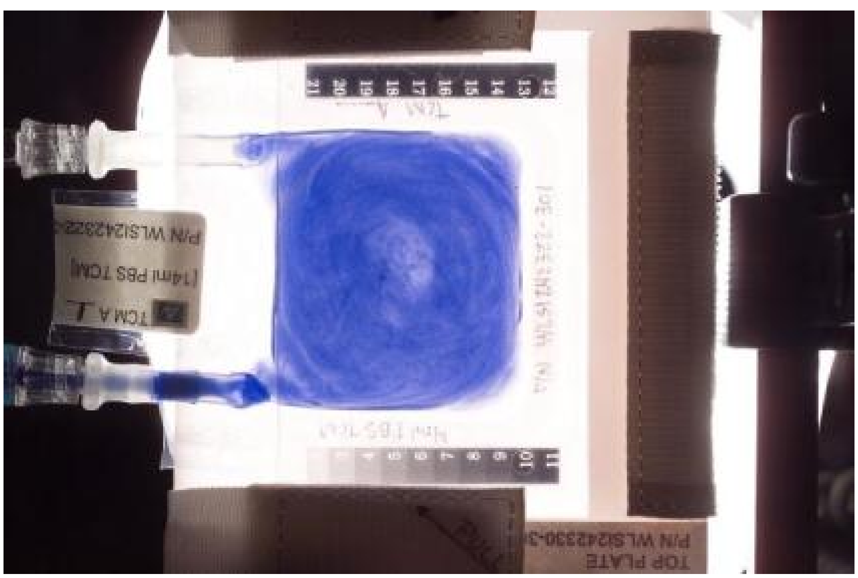
Analysis is ongoing, and additional results are expected to publish.

CBOSS-01-PC12

No results were found because the cells did not survive. This is most likely due to inadequate mixing or bubble formation.

CBOSS-02-Erythropoietin

No results were found because the cells did not survive. This is most likely due to inadequate mixing or bubble formation.



ISS008E09941 – This is a Cellular Biotechnology Operations Support Systems Fluid Dynamics Investigation Tissue Culture Module taken during Increment 8.

CBOSS-02-HLT

The human lymphoid tissue cultures were activated on board station but did not survive in longer-term culture. Early preliminary results, which were in agreement with rotating wall vesicle (RWV) ground studies (microgravity simulation), indicated that the human tonsil cell suspensions show impaired immune responses in microgravity and that the extent of impairment depended on the activation state of the cells. Cells in all conditions showed metabolic activity, indicating that they were alive. Cells that were activated in microgravity did not demonstrate any increases in antibody or cytokine production; however, if the cells were activated prior to exposure to microgravity, they did demonstrate such responses. These results indicated that microgravity suppresses humoral immune responses in a not dissimilar fashion to that of Human Immunodeficiency Virus on Earth, and that this phenomenon may reflect immune dysfunction observed in crew members during spaceflights (Fitzgerald 2006).

CBOSS-FDI

For CBOSS-FDI, a series of procedures was performed on Expeditions 8, 10, and 12 to optimize particle mixing and bubble removal. A mixing protocol for particles has been found that appears to be effective and time-efficient, and crew feedback has been very valuable in these studies. Two bubble removal methods were tested. Future experiments will help determine their effectiveness, and a protocol for bubble removal can be created for future tissue culture investigations. This investigation is critical for optimizing cell culture in space and ensuring the success of future investigations.

PUBLICATION(S)

Fitzgerald W, Chen S, Walz C, Zimmerberg J, Margolis L, Grivel J. Immune suppression of human lymphoid tissues and cells in rotating suspension culture and onboard the International Space Station. *Society for In Vitro Biology.* July 16, 2009;45:622-632. doi: 10.1007/s11626-009-9225-2.

Hammond DK, Elliott TF, Holubec K, et al. Proteomic retrieval from nucleic acid Depleted space-flown human cells. *Gravitational and Space Biology.* 2006;19(2).

Hammond DK, Becker JL, Elliott TF, Holubec K, Baker TL, Love JE. Antigenic protein in microgravity-grown human mixed mullerian ovarian tumor (LN-1) cells preserved in a RNA stabilizing agent. *Gravitational and Space Biology.* 2005;18(2): 99-100.

This investigation is complete; however additional results are pending publication.

STUDY ON THE DEVELOPMENT OF METHODS TO PRODUCE ARTIFICIAL CARTILAGE (CHONDRO)

Research Area: Cellular Biology
Expedition(s): 7 and 8
Principal Investigator(s):
- George Keller, Space Biology Institute, Zurich, Switzerland

Chondrocytes of hyaline cartilage. R.M. Hunt image.

RESEARCH OBJECTIVES

The Study on the Development of Methods to Produce Artificial Cartilage (Chondro) investigation helps improve medical treatment of cartilage injuries and provide insight into cartilage implants for medical use. Chondro compares the cartilage tissue cultured in normal gravity (1 g), RPM-simulated microgravity, and actual microgravity environments to validate whether Earth-based simulated microgravity systems are comparable to space microgravity. Cartilage from the hip joint of a pig was harvested, counted, and placed into 9 bioreactor chambers in culture chambers (CC).

RESULTS

All cartilage produced was soft, especially the tissue produced on International Space Station (ISS). Neocartilage formed in normal gravity was continuous in shape and form, while both the RPM and the ISS tissues were irregular. Although the ISS-produced cartilage had weaker extracellular matrix stains, it had higher gene expression levels of collagen type II/type I, which was comparable to normal cartilage. RPM- produced cartilage had the highest reduction in cell density, which in turn increased cell spacing. Although the data indicated the RPM system was not equivalent to real microgravity, the system did produce structural features and cellular spacing similar to ISS results, making it a viable tool for producing prefabricated collagen implants with fewer cells and without a scaffold.

PUBLICATION(S)

Stamenkovic V, Keller G, Nesic D, Cogoli A, Grogan SP. Neocartilage formation in 1g, simulated, and microgravity environments: Implications for tissue engineering. *Tissue Engineering*. Part A. 2010;16(5):1729-1736. doi: 10.1089/ten.tea.2008.0624.

Stamenkovic V, Keller G, Cogoli A, Grogan SP. Neo-cartilage formation in microgravity environment. *55th International Astronautical Congress*, Vancouver, Canada; 2004.

This investigation is complete and all results are published.

CONTROL OF CELL DIFFERENTIATION AND MORPHOGENESIS OF AMPHIBIAN CULTURE CELLS (DOMEGENE)

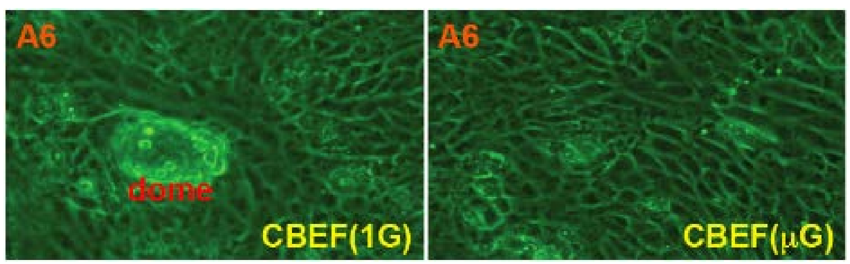
Research Area: Cellular Biology
Expedition(s): 18
Principle Investigator(s):
- Makoto Asashima, PhD, National Institute for Advanced Industrial Science and Technology, Tsukuba, Japan


JAXA astronaut Koichi Wakata is working on the Dome Gene experiment. JAXA image.

RESEARCH OBJECTIVES
Control of Cell Differentiation and Morphogenesis of Amphibian Culture Cells (DomeGene) is looking for upstream genes that respond to the gravitational changes and regulate downstream pathways such as the "dome" formation in kidney cells.

EARTH BENEFITS
DomeGene will establish innovative methodology in different scientific disciplines including organisms in physiology, cell biology, radiation biology, and developmental biology.

SPACE BENEFITS
Systematic study and detailed molecular mechanisms of the effect of microgravity on living cells are still lacking. To fully understand the effect of microgravity on human health it is important to study the microgravity response of cells of various organ origins.



Morphologic analyses of *Xenopus laevis* cells. The A6 cells were cultured under different gravitational conditions. For the A6 cells, dome formation was suppressed under microgravitational conditions (CBEF[μG]) as compared with the artificial 1G condition (CBEF[1G]). JAXA image.

RESULTS
Early results revealed that microgravity exerted little influence on the morphological characteristics of the cells or on their gene expression patterns, and that space radiation exerted a greater effect than microgravity, particularly in the aspects of organ and cancer development. Understanding the microgravity and space radiation effects on human health leads to the creation of effective countermeasures for future space life.

PUBLICATION(S)
Ikuzawa M, Asashima M. Global expression of simulated microgravity-responsive genes in *xenopus* liver cells. *Zoological Science*. August 2008; 25(8):828-837. doi: 10.2108/zsj.25.828.

This investigation is complete; however additional results are pending publication.

INVESTIGATION OF THE OSTEOCLASTIC AND OSTEOBLASTIC RESPONSES TO MICROGRAVITY USING GOLDFISH SCALES (FISH SCALES)

Research Area: Cellular Biology
Expedition(s): 23 and 24
Principle Investigator(s):
- Nobuo Suzuki, PhD, Kanazawa University, Kanazawa, Japan

RESEARCH OBJECTIVES

Investigation of the Osteoclastic and Osteoblastic Responses to Microgravity Using Goldfish Scales (Fish Scales) examines regenerating scales collected from anesthetized goldfish in microgravity. This investigation aims to elucidate the mechanism behind the decrease in bone mineral density in the human body during spaceflight and also to investigate the suppressive action of novel indole derivative (1-benzyl-2,4,6- tribromomelatonin) on the bone resorption of scales.

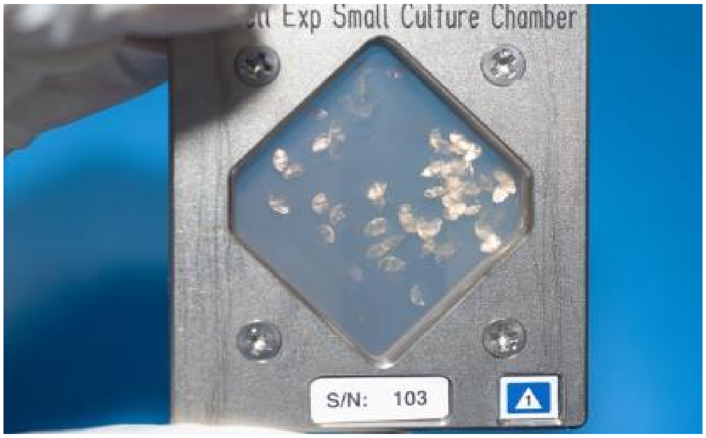


Image taken after culture in the CBEF in the ISS. Regenerating fish scales inside flight chamber. JAXA image.

EARTH BENEFITS

The results from Fish Scales can be the basis of a new pharmaceutical to treat bone disease.

SPACE BENEFITS

The results from Fish Scales can be utilized to maintain bone density in future space explorers during long-duration missions.

RESULTS

Fish Scales demonstrated that osteoclastic bone resorption occurred together with morphological changes of osteoclasts. In addition, it was also observed that 1-benzyl-2, 4, 6-tribromomelatonin increased the scale of osteoblastic marker expression but suppressed that of osteoclastic marker expression. On the ground basis experiment, the oral administration of this chemical augmented the total bone mineral density of the femoral metaphysis of ovariectomized rats. In rats fed a low-calcium diet, the total bone mineral density of the femoral metaphysis significantly increased following the oral administration of this melatonin derivative. In this space experiment, it was demonstrated that bone resorption was actually observed using the fish scales and indicated that a novel melatonin derivative may have a potential application in the treatment of bone diseases, such as those experienced in spaceflight.

JAXA astronaut Soichi Noguchi works on the Fish Scales experiment. JAXA image.

Publication(s)

Kakikawa M, Yamamoto T, Chowdhury VS, et al. Determination of calcium sensing receptor in the scales of goldfish and induction of its mRNA expression by acceleration loading. *Biological Sciences in Space*. 2012;26:26-31. doi: 10.2187/bss.26.26.

Omori K, Wada S, Maruyama Y, et al. Prostaglandin E_2 increases both osteoblastic and osteoclastic activity in the scales and participates in calcium metabolism in goldfish. *Zoological Science*. August 2012;29(8):499-504. doi: 10.2108/zsj.29.499.

Thamamongood TA, Furuya R, Fukuba S, Nakamura M, Suzuki N, Hattori A. Expression of osteoblastic and osteoclastic genes during spontaneous regeneration and autotransplantation of goldfish scale: A new tool to study intramembranous bone regeneration. *Bone*. June 2012;50(6):1240-1249. doi: 10.1016/j.bone.2012.03.021.

Yano S, Masuda D, Kasahara H, et al. Excellent thermal control ability of cell biology experiment facility (CBEF) for ground-based experiments and experiments onboard the Kibo Japanese Experiment Module of International Space Station. *Biological Sciences in Space*. 2012;26:12-20. doi: 10.2187/bss.26.12.

Suzuki N, Danks JA, Maruyama Y, et al. Parathyroid hormone 1 (1–34) acts on the scales and involves calcium metabolism in goldfish. *Bone*. May 2011;48(5):1186-1193. doi: 10.1016/j.bone.2011.02.004.

Kitamura K, Suzuki N, Satoh Y, et al. Osteoblast activity in the goldfish scale responds sensitively to mechanical stress. *Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology*. July 2010;156(3):357-363. doi: 10.1016/j.cbpa.2010.03.002.

Suzuki N, Kitamura K, Omori K, et al. Response of osteoblasts and osteoclasts in regenerating scales to gravity loading. *Biological Sciences in Space*. 2009;23(4):211-217. doi: 10.2187/bss.23.211.

Suzuki N, Omori K, Nakamura M, et al. Scale osteoblasts and osteoclasts sensitively respond to low-gravity loading by centrifuge. *Biological Sciences in Space*. 2008;22(1):3-7. doi: 10.2187/bss.22.3.

Suzuki N, Somei M, Kitamura K, Reiter RJ, Hattori A. Novel bromomelatonin derivatives suppress osteoclastic activity and increase osteoblastic activity: Implications for the treatment of bone diseases. *Journal of Pineal Research*. April 2008;44(3):326-334. doi: 10.1111/j.1600-079X.2007.00533.x.

Suzuki N, Somei M, Seki A, Reiter RJ, Hattori A. Novel bromomelatonin derivatives as potentially effective drugs to treat bone diseases. *Journal of Pineal Research.* October 2008;45(3):229-234. doi: 10.1111/j.1600-079X.2008.00623.x.

Suzuki N, Kitamura K, Nemoto T, et al. Effect of vibration on osteoblastic and osteoclastic activities: Analysis of bone metabolism using goldfish scale as a model for bone. *Advances in Space Research*. January 2007;40(11):1711-1721. doi: 10.1016/j.asr.2007.04.104.

This investigation is complete; however additional results are pending publication.

Bone Cell Mechanosensitivity in Weightlessness (FLOW)

Research Area: Cellular Biology
Expedition(s): 8 and 9
Principal Investigator(s):
- Jenneke Klein Nulend, ACTA-Free University Amsterdam, Amsterdam, Netherlands
- Rommel G. Bacabac, ACTA-Free University Amsterdam, Amsterdam, Netherlands
- Jack van Loon, ACTA-Free University Amsterdam, Amsterdam, Netherlands

Research Objectives

The Bone Cell Mechanosensitivity in Weightlessness (FLOW) investigation tests whether near-weightlessness decreases the sensitivity of chicken osteocytes for mechanical stress through a decrease in early signaling molecules that are involved in the mechanical loading-induced osteogenic response (formation of bone). Osteocytes, the bone mechanosensitive cells, will be compared with osteoblasts (the bone forming cells) and periosteal fibroblasts (cells found around or near bones, from which connective tissue develops).

Results

Due to unforeseen hardware complications, results from in-flight cultures are considered lost. Ground control experiments showed an accumulative increase of nitric oxide in medium for osteocytes (as well as for osteoblasts and periosteal fibroblasts). Data from the online-nitric oxide sensor showed that the nitric oxide produced in medium by osteocytes increased sharply after pulse shear stress stimulations. COX-2 mRNA expression revealed high levels in osteoblasts compared to the other cell types tested. In conclusion, preparations for the FLOW experiment and preliminary ground results indicate that the FLOW setup is viable for a future flight opportunity.

Publication(s)

Bacabac RG, van Loon JJ, Blieck-Hogervorst JM, et al. Microgravity and bone cell mechanosensitivity: FLOW experiment during the DELTA mission. *Microgravity Science and Technology*. September 2007;19(5-6):133-137. doi: 10.1007/BF02919468.

This investigation is complete and all results are published.

FISCHER RAT THYROID LOW SERUM 5 (FRTL5)

Research Area: Cellular Biology
Expedition(s): 10 and 11
Principal Investigator(s):
- Francesco Curcio, University of Udine, Udine, Italy

RESEARCH OBJECTIVES

The Fischer Rat Thyroid Low Serum 5 (FRTL5) assesses the effects of microgravity and radiation on rat thyroid cells. This experiment should provide further indications that may help in understanding why the sensitivity of the cells to radiation damage is related to their cell cycle and to the kinetics of the radiation. Furthermore, it will help improve our knowledge of the effect of the space environment on the human body, especially on long-duration missions.

RESULTS

Overall cell number was lower in the cultures exposed to space environment as compared to the ground controls reproducing the temperature conditions during the ENEIDE mission. This phenomenon was most likely related to a slower growth rate in proliferative state. This slow growth rate was reversible, as demonstrated by the results of the growth curves, the plating and cloning efficiencies measured on the samples once they were returned to our laboratory in Udine; and mostly related to space effects as indicated by additional control in a clinostat. More experiments of this kind are needed to verify and validate these data and to investigate the molecular mechanisms underlying the phenomenon.

PUBLICATION(S)

Albi E, Ambesi-Impiombato FS, Villani M, et al. Thyroid cell growth: Sphingomyelin metabolism as non-invasive marker for cell damage acquired during spaceflight. *Astrobiology*. 2010;10(8):811-820. doi: 10.1089/ast.2010.0461.

Meli A, Perrella G, Toller M, et al. Ambesi-Impiombato FS, FRTL-5 experiment during ENEIDE mission. *Microgravity Science and Technology*. September 2007;19(5-6):175-179. doi: 10.1007/BF02919476.

This investigation is complete and all results are published.

Expression of Microbial Genes in Space (Gene Expression)

Research Area: Microbiology

Expedition(s): 7 and 8

Principal Investigator(s):
- Roberto Marco, Instituto de Investifaciones Biomedicas, Madrid, Spain

Research Objectives

The Expression of Microbial Genes in Space (Gene Expression) investigation initiates the characterization of the modifications occurring in the gene expression pattern of a complex organism (*Drosophila* in this case) when exposed to the space environment. This investigation will demonstrate the establishment of how extensive the changes in gene expression patterns are when a complex multicellular organism is exposed to the space environment.

Results

When compared to the parallel ground control samples, the spaceflight samples showed a relatively large amount of genes had significant expression level alterations. Furthermore, when the gene expression patterns in the controls that had been exposed to a similar period of exposure to 14ºC as the flight samples (parallel controls) were compared to pupae from the same flies not exposed to this cold step, many genes were also modified by such a treatment. It is interesting to note that both treatments (exposure to 14ºC or to the space conditions) had been previously found compatible with a normal development of flies that kept successfully breeding after these treatments. It turned out that the 2 treatments showed some kind of synergism.

In fact, the genes modified by the exposure to the space conditions actually fall into 3 categories. Group 1 of genes (317) that had been previously modified by the cold treatment and that in microgravity were returning to the normal conditions much faster than the samples not exposed to this environmental change. Group 2 of genes (77) that were modified by the microgravity treatment even more than by the cold treatment alone, ie, increased/decreased even more than in the parallel controls. Group 3 of genes (894) not significantly modified by the cold treatment were changing in microgravity. They can be assimilated to the other 2 groups since most of them (879) change in opposite direction in both treatments, and only 15 (similar to group 2) change in the same direction. There are reasons to believe that the synergism between the 2 treatments is responsible for the changes in group 2.

Publication(s)

Herranz R, Benguria A, Laván DA, et al. Spaceflight-related suboptimal conditions can accentuate the altered gravity response of *Drosophila* transcriptome. *Molecular Ecology*. October 2010;19(19):4255-4264. doi: 10.1111/j.1365-294X.2010.04795.x.

Khairul-Bariah A, Then SM, Rageshwary R, et al. Changes in gene expression of hepG2 cells exposed to microgravity. *Gravitational and Space Biology*. 2010;23(2):91-92.

Herranz R, Laván DA, Medina F, van Loon JJ, Marco R. *Drosophila* GENE experiment in the Spanish Soyuz Mission to the ISS: II. Effects of the containment constraints. *Microgravity Science and Technology*. 2008;21(4):299-304. doi: 10.1007/s12217-008-9097-1.

Herranz R, Laván DA, Benguria A, et al. The "gene" experiment in the Spanish Soyuz mission to the ISS. Effects of the cold transportation step. *Microgravity Science and Technology*. 2007;19(5-6):196-200. doi: 10.1007/BF02919481.

Herranz R, Benguria A, Fernandez-Pineda E, et al. Gene expression variations during *Drosophila* metamorphosis in space. The GENE experiment in the Spanish Cervantes Mission to the ISS. *Journal of Gravitational Physiology*. 2005;12(1).

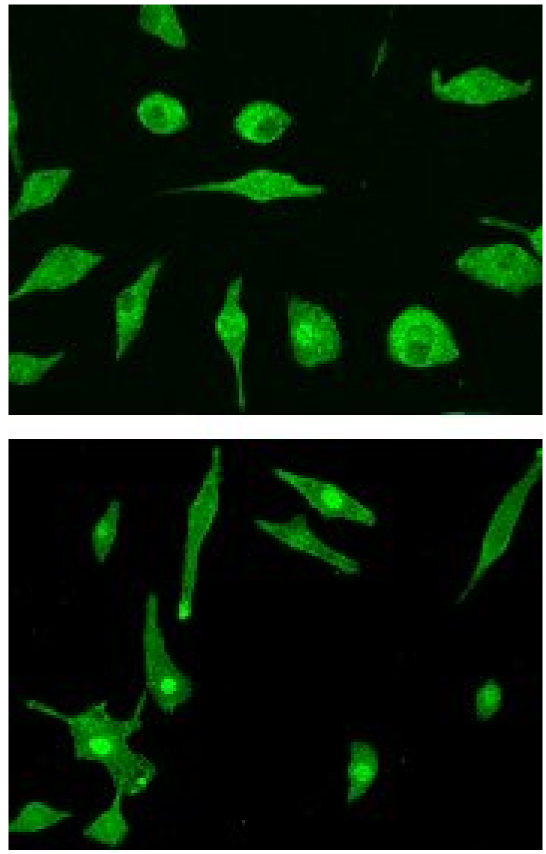
This investigation is complete; however additional results are pending publication.

FIRST INTERNATIONAL CAENORHABDITIS ELEGANS EXPERIMENT: PHYSIOLOGICAL AND INFLUENCE OF WEIGHTLESSNESS ON THE ACTIVATION OF NF-κB PROTEINS (KAPPA)

Research Area: Cellular Biology
Expedition(s): 8 and 9
Principal Investigator(s):
- Maikel Peppelenbosch, Erasmus Medical Center, Rotterdam Netherlands

RESEARCH OBJECTIVES

The main scientific objectives of the Influence of Weightlessness on the Activation of NF-κβ Proteins (Kappa) experiment are to establish whether in weightlessness phagocytic cells of the myeloid lineage either retain or lose the capacity to react to lipopolysaccharide from gram-negative bacteria with the activation of nuclear factor kappa B (NF- κβ).



Immunostaining of NF- κβ in unstimulated blood cells (top) or LPS-stimulated cells (bottom). M. Peppelenbosch image.

RESULTS

Data analysis from this investigation is ongoing.

This investigation is complete; however additional results are pending publication.

Role of Interleukin-2 Receptor in Signal Transduction and Gravisensing Threshold of T-Lymphocytes (Leukin-2)

Research Area: Cellular Biology
Expedition(s): 14
Principal Investigator(s):
- Isabelle Walther, PhD, Swiss Federal Institute of Technology, Space Biology, Zurich, Switzerland
- August Cogoli, PhD, Zero-g Tec GmbH, Zurich, Switzerland
- Proto Pippia, University of Sassari, Sassari, Italy
- Millie Hughes-Fulford, PhD, University of California, San Francisco, California

Research Objectives

The Role of Interleukin-2 Receptor in Signal Transduction and Gravisensing Threshold of T-Lymphocytes (Leukin-2) experiment studies the signal transduction pathway of the activation of T-lymphocytes. This investigation determines if loss of the Interleukin-2 receptor (IL-2) expression is the cause of inhibition. Microgravity is used as an inhibitor of activation.

Earth Benefits

Determining the factors that cause IL-2 suppression can help scientists on Earth better treat immunosuppressed patients.

Space Benefits

Leukin-2 may help scientists better understand the depression of the immune system, which occurs during spaceflight and, therefore, to devise more adequate preventive or corrective measures for crew members during long-duration missions.

Results

Human T cells were stimulated with Con A and anti-CD28 aboard the International Space Station (ISS) to induce immune responses. Microarray expression analysis after 1.5 hours of activation demonstrated that the T cells activated in microgravity (during flight on the ISS) had distinct patterns of global gene expression that differed from those activated in a 1-g centrifuge during spaceflight (control or normal gravity that can be run during spaceflight). Forty-seven genes were identified that were significantly differentially down-regulated in T cells exposed to microgravity compared with T cells exposed to microgravity in a 1-g centrifuge. Activation of Rel/NF-κB, CREB (a transcription factor that is known for its role in cell proliferation, differentiation, and survival), and serum response factor gene targets, genes important in immune cell function pathways, was down-regulated. These data suggest that the tumor necrosis factor (TNF) pathway is a major early downstream effector pathway inhibited in microgravity, and this could lead to ineffective, pro-inflammatory host defenses against infections during long-term spaceflight. These results may suggest that there could be a direct effect of microgravity on the expression of genes controlling immune cell function.

PUBLICATION(S)

Chang TT, Walther I, Li C, et al. The Rel/NF-κB pathway and transcription of immediate early genes in T cell activation are inhibited by microgravity. *Journal of Leukocyte Biology*. 2012;92(6):1133-1145. doi: 10.1189/jlb.0312157.

This investigation is complete and all results are published.

Detection of Changes in LOH Profile of TK mutants of Human Cultured Cells (LOH)

Research Area: Cellular Biology
Expedition(s): 18
Principle Investigator(s):
- Fumio Yatagai, PhD, Institute of Physical and Chemical Research, Wako, Japan

Research Objectives

Detection of Changes in LOH Profile of TK Mutants of Human Cultured Cells (LOH) addresses genetic alterations in immature immune cells. LOH uses lymphoblastoid (immature immune) cells to detect potential changes on the chromosome after exposure to cosmic radiation.

Earth Benefits

The developed system for mutation (LOH) analysis is suggested to be applicable for evaluating various cellular responses to low-dose, low-dose-rate ionizing radiation, therefore providing a better estimation of the influence radiation exposure has on crew member health.

The Monitoring of the LOH Experiment in the International Space Station from Earth. JAXA image.

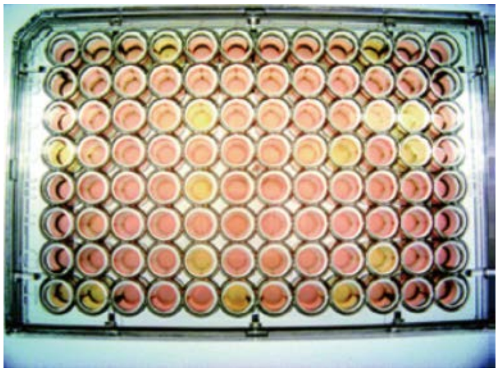
Space Benefits

Future crew members can benefit from the data obtained in this investigation by understanding the effects of radiation on human cells and may lead to the development of new countermeasures. Furthermore, researchers expect to obtain a better understanding of DNA repair mechanisms under such condition.

Results

Researchers observed an increase (2.3-fold) in thymidine kinase deficient (TK^-) mutations. Loss of heterozygosity (LOH) analysis on the mutants also demonstrated an increase in proportion of the large deletion (beyond the *TK* locus) events, 6/41 (in-flight samples) and 1/17 (ground control). Furthermore, in-flight samples exhibited 48% of the ground-control level of TK^- mutation frequency upon exposure to a subsequent 2 Gy X-rays, suggesting a tendency of radioadaptation when compared with the ground control samples. The tendency of radioadaptation was also supported by the post-flight assays on DNA double-strand break repair: a 1.8- and 1.7-fold higher efficiency of in-flight samples compared to ground control via non-homologous end-joining and homologous recombination, respectively. These observations suggest that this system can be used as a biodosimeter because DNA damage generated by space radiation is thought to accumulate in the preserved cells during the mission.

Certain cell samples were incubated for 8 days under 1G or microgravity in a CO_2 incubator, then refrozen, returned to Earth, and compared to ground control samples to determine the influence of microgravity on cell survival and mutation induction. The results for both conditions varied from experiment to experiment, yielding a large standard deviation, but the microgravity sample results differed significantly from the 1G sample results for each of 2 experiments, with the mean ratio of microgravity to 1G being 0.55 for the concentration of viable cells and 0.59 for the fraction of TK^- mutants. Among the mutants, point mutations were less frequent (31%) after microgravity incubation than after 1G incubation, which might be explained by the influence of microgravity on cellular metabolic or physiological function. Additional experiments are needed to clarify the effect of microgravity interferes on DNA repair.



Detection of LOH by color-changing of culture medium on 96-well microplate. The frozen cells returned from ISS were cultured at 37 °C in a CO_2 incubator. After 2-3 days, the exponentially growing cells were plated in each well of a fresh 96-well plate by the limiting dilution method. The medium color of the cells lost heterozygosity, changes to yellow from red after incubating cells on 96-well microplate for 2 weeks. JAXA image.

PUBLICATION(S)

Yatagai F, Honma M, Ukai A, et al. Preliminary results of space experiment: Implications for the effects of space radiation and microgravity on survival and mutation induction in human cells. *Advances in Space Research*. 2012;49(3):479-486. doi: 10.1016/j.asr.2011.10.015.

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Gordon A, Halliday JA, Blankschien MD, Burns PA, Yatagai F, Herman C. Transcriptional infidelity promotes heritable phenotypic change in a bistable gene network. *PLOS Biology*. 2009;7(2):e1000044. doi: 10.1371/journal.pbio.1000044.

Yatagai F, Takahashi A, Honma M, et al. LOH analyses for biological effects of space radiation: Human cell culture in Kibo of International Space Station. Biological Sciences in Space. 2009;23(1):11-16. doi: 10.2187/bss.23.11.

This investigation is complete and all results are published.

Cell to Cell Interaction of Monocytes and T-Lymphocytes in Microgravity (MIA)

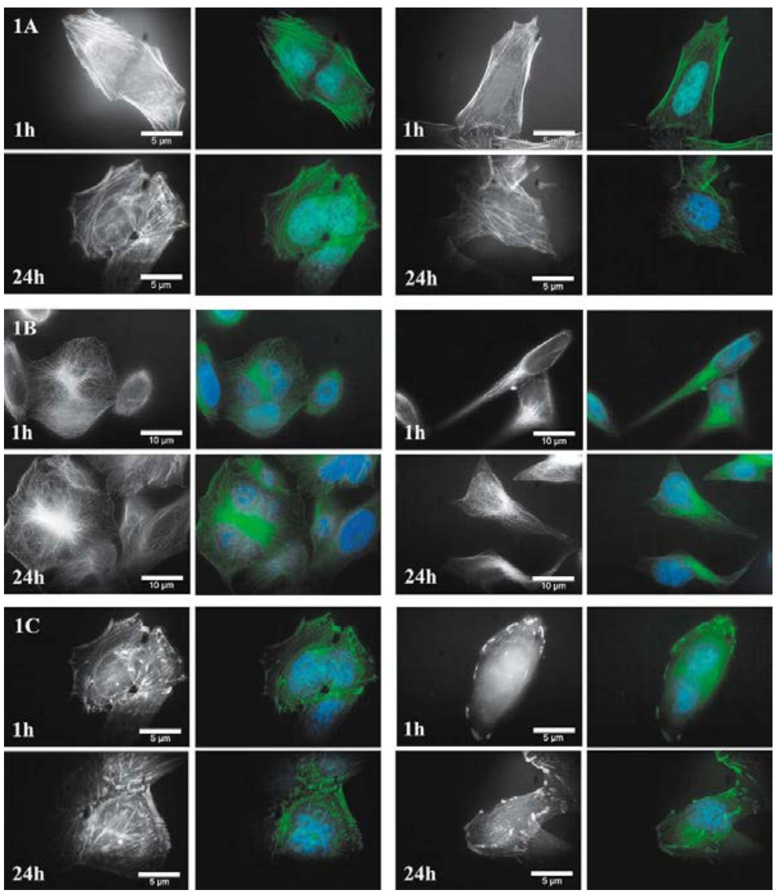
Research Area: Microbiology

Expedition(s): 13

Principal Investigator(s):
- Marianne Cogoli-Greuter, Swiss Federal Institute of Technology, Zurich, Switzerland

Research Objectives

The Cell to Cell Interaction of Monocytes and T-Lymphocytes in Microgravity (MIA) investigation determines the effect of microgravity on both the ability of adherent monocytes to migrate on a surface (motion), as well as to interact with T-cells (interact).



Immunofluorescence images of F-actin (A), β-tubulin (B), and vinculin (C) in cultured J-111 cells. Right panels, monochromatic and merge images of samples exposed to RPM for 1 and 24 h. Left panels, 1g control samples. ESA image.

Results

The MIA investigation demonstrated that adherent monocytes are not motile in microgravity; the cytoskeletal structures of F-actin, β-tubulin and vinculin are altered in cells exposed for 24 hours to microgravity conditions, also in microgravity an interaction between T-cells and monocytes takes place, although to a much lesser extent. The cytoskeleton played a major role in the locomotion of adherent cells but also in the clustering of the adhesion proteins LFA-1 and ICAM-1. The fact that several cytoskeletal structures are altered in microgravity may explain why these cells had a highly reduced ability of locomotion and a reduced interaction between monocytes and T-cells as observed by the colocalization of ICAM-1 with LFA-1.

The hypothesis that there is no interaction between T-cells and monocytes in microgravity could not be confirmed. Despite the fact that monocytes lost their locomotion ability we still observed an interaction. In earlier investigations we have found that T-cells are highly motile in microgravity. From the results we can conclude that also in microgravity an interaction between T-cells and monocytes takes place, although to a much lesser extent. In follow-up investigations in simulated microgravity we are now studying this interaction with a quantitative method to get a clearer picture on this important step in the activation of T-lymphocytes.

Publication(s)

Meloni MA, Galleri G, Pani G, Saba A, Pippia P, Cogoli-Greuter M. Spaceflight affects motility and cytoskeletal structures in human monocyte cell line J-111. *Cytoskeleton.* February 2011; 68(2):125-137. doi: 10.1002/cm.20499.

This investigation is complete and all results are published.

Effects of Microgravity on Expression of Calcium Channels in Myocytes (Myocyte)

Research Area: Cellular Biology

Expedition(s): 13

Principal Investigator(s):
- Jean-Luc Morel, Physiologie Cellulaire et Pharmacologie Moleculaire, Bordeaux, France
- Jean Mironneau, Physiologie Cellulaire et Pharmacologie Moleculaire, Bordeaux, France

Research Objectives

Effects of Microgravity on Expression of Calcium Channels in Myocytes (Myocyte) experiment is designed to investigate whether isolated vascular smooth muscle cells are directly sensitive to altered gravitational forces and, second, whether sustained blood pressure changes act on the same molecular target.

Results

Exposure to microgravity during 8 days in the International Space Station induced the decrease of ryanodine receptor subtype 1 expression in primary cultured myocytes from rat hepatic portal vein. Identical results were found in portal vein from mice exposed to microgravity during an 8-day shuttle spaceflight. To evaluate the functional consequences of this physiological adaptation, evoked calcium signals obtained in myocytes from hindlimb unloaded rats, in which the shift of blood pressure mimics the one produced by the microgravity, were compared with those obtained in myocytes from rats injected with antisense oligonucleotide directed against ryanodine receptor subtype 1. In both conditions, calcium signals implicating calcium-induced calcium release were significantly decreased. In contrast, in spontaneous hypertensive rat, an increase in ryanodine receptor subtype 1 expression was observed as well as the calcium-induced calcium release mechanism. Taken together, the results have shown that myocytes were directly sensitive to gravity level and that they adapt their calcium signaling pathways to pressure by the regulation of the ryanodine receptor subtype 1 expression.

Publication(s)

Dabertrand F, Porte Y, Macrez N, Morel J. Spaceflight regulates ryanodine receptor subtype 1 in portal vein myocytes in the opposite way of hypertension. *Journal of Applied Physiology*. February 1, 2012;112(3):471-480. doi: 10.1152/japplphysiol.00733.2011.

This investigation is complete and all results are published.

Cbl-b-Mediated Protein Ubiquitination Downregulates the Response of Skeletal Muscle Cells to Growth Factors in Space (MyoLab)

Research Area: Cellular Biology
Expedition(s): 23 and 24
Principle Investigator(s):
- Takeshi Nikawa, MD, PhD, The University of Tokushima, Tokushima, Japan

Research Objectives

Cbl-b-Mediated Protein Ubiquitination Downregulates the Response of Skeletal Muscle Cells to Growth Factors in Space (MyoLab) studies a rat muscle gene modified cell line to determine the effects of microgravity.

Earth Benefits

The number of bedridden elderly people in Japan is remarkably increasing, which can be considered a serious social problem. However, there is no effective countermeasure for muscle atrophy (decrease in muscle mass), which is a main cause for bedridden conditions. The few countermeasures for unloading mediated muscle atrophy include: rehabilitation, diet, and drugs. The MyoLab investigation focuses on the inhibition of Cbl-b-mediated ubiquitination (enzyme found in humans) to improve IGF-1 (insulin-like growth hormone) resistance of skeletal muscle cells. Ubiquitin ligase Cbl-b is inhibited by focusing on the competitively inhibitory function of oligopeptides (molecules containing a small number of peptides).

Space Benefits

The data collected during this investigation may lead to the discovery of the underlying mechanism behind muscle atrophy caused by microgravity. Novel countermeasures (ubiquitin ligase inhibitors and nutrients) against muscle atrophy are being examined in order to allow crew members to stay in space and perform various projects without muscle atrophy.

Results

Researchers investigated the transcription factors that regulate Cbl-b expression using rat L6 myoblasts and differentiated myotubes. The biological relevance of Cbl-b expression as a sensor of unloading is strengthened by the findings that both oxidative stress and 3-D-clinorotation induced Cbl-b expression in L6 myoblasts and myotubes. These findings suggest that increased levels of ROS link mechanical stress to downstream signaling pathways. In the present study, we observed that H_2O_2 treatment promoted the binding of Egr to the 5'-franking region of Cbl-b gene. Moreover, 3-D-clinorotation and H_2O_2 each induced the expression of Cbl-b in a manner accompanied by the early expression of Egrs 1-3. This is consistent with the findings of another laboratory using Egr-2 or Egr-3 knockout mice. The results obtained in Egr knockdown studies (siRNA) confirm that Egr transcription factors play a major role in 3-D-clinorotation-mediated Cbl-b induction. Together, these data uncover the molecular mechanism through which mechanical unloading is transduced into biochemical signaling in skeletal muscle.

ISS023E025830-Expedition 23 flight engineer and Japan Aerospace Exploration Agency (JAXA) astronaut Soichi Noguchi is photographed with hardware for the Molecular Mechanism of Microgravity-Induced Skeletal Muscle Atrophy (MyoLab) experiment in the Kibo Japanese Experiment Pressurized Module (JPM). JAXA image.

Several lines of evidence in diverse cell types point to the involvement of Egr transcription factors in the response to mechanical stress. Egr expression induced by 3-D-clinorotation occurs within 90 minutes of stimulation, indicating that the Egr genes are in close temporal proximity to the mechanical stress “receptor.” Consistent with the role of oxidants as the second messengers of Egr activation and downstream unloading responses, the ERK1/2 pathway, a common target of oxidative signaling, was activated by 3-D-clinorotation and H_2O_2. Together, these results are consistent with the findings of other laboratories; they showed that immobilization or tail suspension increased oxidative stress-dependent signaling in rat skeletal muscles. Recent studies have identified several signaling molecules, such as ASK1, that mediate oxidative stress-dependent activation of MAPK signaling. An important area for further investigation will be to identify the molecules that regulate ROS production in distinct cellular compartments (plasma membrane, mitochondria) in response to unloading. It is anticipated that these molecules may be the direct receptors/sensors for unloading stress. This hypothesis is supported by previous finding that the disrupted expression of cytoskeletal genes, especially mitochondria-anchoring protein genes, is associated with large imbalances in the expression of genes encoding diverse members of the electron transport system in the mitochondria of space-flown skeletal muscle.

PUBLICATION(S)

Abe T, Hirasaka K, Kagawa S, et al. Cbl-b is a critical regulator of macrophage activation associated with obesity-induced insulin resistance in mice. *Diabetes*. January 24, 2013;62(6):1957-1969. doi: 10.2337/db12-0677.

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Teshima-Kondo S, Ochi A, Kohno S, et al. Spaceflight/bedrest immobilization and bone development of inhibitors for atrophy caused by unloading stress. *Clinical Calcium*. December 2012;22(12):1879-1885. doi: CliCa121218791885.

Nishisho T, Yukata K, Matsui Y, et al. Angiogenesis and myogenesis in mouse tibialis anterior muscles during distraction osteogenesis: VEGF, its receptors, and myogenin genes expression. *Journal of Orthopaedic Research*. November 2012;30(11):1767-1773. doi: 10.1002/jor.22136.

Mukai R, Horikawa H, Fujikura Y, et al. Prevention of disuse muscle atrophy by dietary ingestion of 8-prenylnaringenin in denervated mice. *PLOS ONE*. September 19, 2012;7(9):e45048. doi: 10.1371/journal.pone.0045048.

Tanaka H, Shimazawa M, Kimura M, et al. The potential of GPNMB as novel neuroprotective factor in amyotrophic lateral sclerosis. *Scientific Reports*. August 13, 2012;2(573):11 pp. doi: 10.1038/srep00573.

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Kohno S, Yamashita Y, Abe T, et al. Unloading stress disturbs muscle regener ation through perturbed recruitment and function of macrophages. *Journal of Applied Physiology*. March 1, 2012;112(10):1773-1782. doi: 10.1152/japplphysiol.00103.2012.

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Utsunomiya K, Owaki K, Okumura Y, et al. An intracellular fragment of osteoactivin formed by ectodomain shedding translocated to the nucleoplasm and bound to RNA binding proteins. *Bioscience, Biotechnology, and Biochemistry*. 2012;76(12):2225-2229. doi: 10.1271/bbb.120515.

Yano S, Masuda D, Kasahara H, et al. Excellent thermal control ability of cell biology experiment facility (CBEF) for ground-based experiments and experiments onboard the Kibo Japanese Experiment Module of International Space Station. *Biological Sciences in Space*. 2012;26: 12-20. doi: 10.2187/bss.26.12.

This investigation is complete; however additional results are pending publication.

EFFECTS OF MICROGRAVITY ON THE HAEMOPOIETIC SYSTEM: A STUDY ON NEOCYTOLYSIS (NEOCYTOLYSIS)

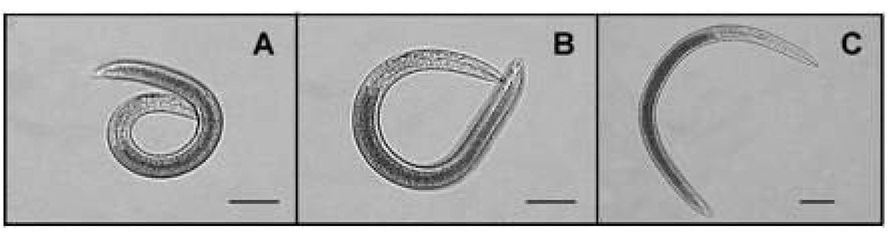
Research Area: Cellular Biology
Expedition(s): 14-16
Principal Investigator(s): ● Angela Rizzo, PhD, University of Udine, Udine, Italy

RESEARCH OBJECTIVES

The objective of the Effects of Microgravity on the Haemopoietic System: A Study on Neocytolysis (Neocytolysis) experiment is to better characterize the neocytolytic process in space and investigate some variations of young red cells mediated by exposure to microgravity, which could explain their apparently selective lysis. This study could strengthen the hypothesis that neocytolysis is involved in a number of hematologic disorders.

RESULTS

After spaceflight, mean corpuscular volume, mean corpuscular hemoglobin, mean corpuscular hemoglobin concentration, red blood cell counts, and hematocrit values were not significantly different from those measured before flight. In 3 astronauts the reticulocyte counts were lower than before the flight. The hematochemical analysis disclosed a mean increase of 1,54+1,1 times in ferritin plasma level in 3 subjects. As expected, the percentage of recently generated red blood cells (young and a fraction of middle aged red blood cells) was decreased after the flight. Moreover, the percentage of middle aged, old and, to a greater extent, young red blood cells, exposing phosphatydilserine on the outer membrane leaflet was increased. Finally, the young cells had lost viability, as measured by calcein fluorescence, and the expression of CD55 and CD47 proteins by neocytes was decreased both in term of the number of positive cells (from 91.25+7 and 96+2.7 to 86.35+4.4 and 87 +8.58, respectively), and in term of level of expression (fluorescence intensity). No significant changes were observed in control subject's red blood cell population.



Healthy red blood cells (upper left) are smooth and round. Hemolytic red blood cells (lower right). The Cleveland Clinic, Cleveland, Ohio image.

The consistency in the differences observed for some of the hematological parameters and red blood cell features, prompt some conclusions, although the number of subjects analyzed in this study was small. Erythrocyte destruction likely occurred during the spaceflight, as indicated by the increase in plasma ferritin. Hemolysis occurred most likely due to destruction of neocytes, because young erythrocyte counts in blood samples drawn after the flight were lower than before the flight. The exposure of phosphatydilserine, the loss of viability and the decreased expression of CD47 in some of the still surviving young red blood cells support this view, indicating that an "apoptotic-like" phenotype could trigger ingestion by macrophages. A similar phenotype could be shared by pathological red cells, such as thalassemic or sickle erythrocytes.

PUBLICATION(S)

Rizzo AM, Turello M, Antonutto G. Effects of spaceflight on erythropoiesis a study on neocytolysis. *2008 Life in Space for Life on Earth Symposium, Angers*, France. June 22-27, 2008;48.

This investigation is complete and all results are published.

BIOLOGICAL EFFECTS OF SPACE RADIATION AND MICROGRAVITY ON MAMMALIAN CELLS (NEURO RAD)

Research Area: Cellular Biology
Expedition(s): 23 and 24
Principle Investigator(s):
- Hideyuki J Majima, DDS, PhD, Kagoshima University, Kagoshima, Japan

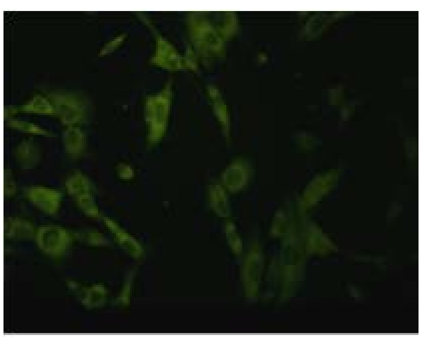
RESEARCH OBJECTIVES

Biological Effects of Space Radiation and Microgravity on Mammalian Cells (Neuro Rad) studies the effects of space radiation on the human neuroblastoma cell (nerve cell containing a tumor) line in microgravity. Neuro Rad evaluates the risk factors of long-term spaceflight by investigating the ability to recover from radiation damage in microgravity. In addition, this experiment focuses on changes in the mitochondria-related gene expression, since the mitochondria is well known for having a crucial role in apoptosis (programmed cell death).

EARTH BENEFITS

The Neuro Rad experiment studies space radiation effects using human nerve cells. The radiation effects are critical for biological creatures. The data collected during this investigation may lead to a greater understanding of how the radiation defense system is affected by space radiation and the microgravity environment. The data obtained could be applied to the development of new treatments and preventative measures for the effects of radiation, life-style related diseases, and aging.

Astronauts at work on the Neuro Rad experiment. JAXA image.



A picture of oxidative stress level stained with free radical detection probe HPF (Indo et al. Mitochondrion 2007) using laser confocal microscope. JAXA image.

SPACE BENEFITS

The data collected during this investigation may lead to a greater understanding of how the radiation defense system is affected by different factors from space radiation and the microgravity environment. The data could be applied to develop new treatments and preventative measures for the effects of radiation, and to further investigate the effects of long-duration human stays in space.

RESULTS

The space radiation dose aboard the International Space Station (ISS) was monitored using the on-board Passive Dosimeter for Life Science Experiments in Space (PADLES) hardware. The monitored data was estimated at 0.48±0.08 mSv/day. Gene expression analysis has been undertaken, and mitochondrial impairment also has been examined for the “fixed” cells.

ISS short- and long-term cultured cells grew faster than the ground control cells. And, in both cases, no differences were observed between microgravity and 1G.

ISS cultured cells generated more intracellular reactive oxygen species (ROS) and increased the expression of heat shock proteins (HSPs) and antioxidant enzymes compared with the control cells. The results suggest that oxidative stress occurs in cells in low-Earth orbit.

PUBLICATION(S)

Indo HP, Nakanishi I, Ohkubo K, et al. Comparison of in vivo and in vitro antioxidative parameters for eleven food factors. *RSC Advances*. 2013;3(14):4535. doi: 10.1039/c3ra22686g.

Indo HP, Inanami O, Koumura T, et al. Roles of mitochondria-generated reactive oxygen species on X-ray-induced apoptosis in a human hepatocellular carcinoma cell line, HLE. *Free Radical Research*. August 2012;46(8):1029-1043. doi: 10.3109/10715762.2012.698012.

Majima HJ, Indo HP, Suenaga S, Matsui H, Yen H, Ozawa T. Mitochondria as possible pharmaceutical targets for the effects of vitamin E and its homologues in oxidative stress-related diseases. *Current Pharmaceutical Design*. July 1, 2011;17(21):2190-2195. doi: 10.2174/138161211796957490.

This investigation is complete; however additional results are pending publication.

Eyespots and Macular Pigments Extracted from Algal Organisms Immobilized in Organic Matrix with the Purpose to Protect Astronaut's Retina (Night Vision)

Research Area: Cellular Biology

Expedition(s): 27 and 28

Principal Investigator(s):
- Maria Teresa Giardi, PhD, Institute of Crystallography, Rome, Italy

Research Objectives

Eyespots and Macular Pigments Extracted from Algal Organisms Immobilized in Organic Matrix with the Purpose to Protect Astronaut's Retina (Night Vision) is a study on the response of microalgae strains (that contain eye spots similar to the human retina) to space radiation in order to obtain results applicable to future nutrition programs for crew members.

Earth Benefits

The results of the Night Vision experiment can be transferred to a food integration program that promotes the consumption of foods necessary to prevent conditions that damage the eyes (eg, Macular Degeneration).

Image of the unicellular green alga *Chlamydomonas reinhardtii*. ASI image.

Space Benefits

The experiment is important since it addresses a possible future nutrition program for the crew members against oxidative damage in the space environment.

Results

Results are in publication.

Publication(s)

Vukich M, Ganga PL, Cavalieri D, et al. BIOKIS: A model payload for multidisciplinary experiments in microgravity. *Microgravity Science and Technology*. December 1, 2012;24:397-409. doi: 10.1007/s12217-012-9309-6.

Giardi MT, Scognamiglio V, Rea G, et al. Optical biosensors for environmental monitoring based on computational and biotechnological tools for engineering the photosynthetic D1 protein of Chlamydomonas reinhardtii. *Biosensors and Bioelectronics.* October 2009;25(2):294-300. doi: 10.1016/j.bios.2009.07.003.

Scognamiglio V, Raffi D, Lambreva M, et al. Chlamydomonas reinhardtii genetic variants as probes for fluorescence sensing system in detection of pollutants. *Analytical and Bioanalytical Chemistry*. 2009;394(4):1081-1087. doi: 10.1007/s00216-009-2668-1.

Rea G, Esposito D, Damasso M, et al. Ionizing radiation impacts photochemical quantum yield and oxygen evolution activity of Photosystem II in photosynthetic microorganisms.

International Journal of Radiation Biology. 2008;84(11):867-877. doi: 10.1080/09553000802460149.

Tibuzzi A, Rea G, Pezzotti G, Esposito D, Johanningmeier U, Giardi MT. A new miniaturized multiarrays biosensor system for fluorescence detection. *Journal of Physics: Condensed Matter*. 2007;19:395006. doi: 10.1088/0953-8984/19/39/395006.

This investigation is complete; however additional results are pending publication.

Natural Killer Cell Activity in Microgravity (NKA)

Research Area: Cellular Biology

Expedition(s): 13

Principal Investigator(s):
- Lyudmila Buravkova, Institute of Medical and Biological Problems of Russian Academy of Sciences, Russia

Research Objectives

The objective of the Natural Killer Cell Activity in Microgravity (NKA) flight experiment is to assess NK cytotoxic activity during co-cultivation of lymphocytes and myoblast K-562 cells under microgravity.

Results

The level of natural killer (NK) cytotoxic activity was measured during co-cultivation of human lymphocytes and target cells (K- 562) in microgravity. Flight experiments were carried out using special instrumentation, the Fibroblast-1 cassettes, in the frame of Russian scientific program during 6 International Space Station (ISS) missions, which involved cooperation with European Space Agency (ESA). Lymphocyte suspensions from human venous blood were used in experiments during short-term flights on 6 ISS missions. Russian crew members performed the experiments after Soyuz docking. The first step was mixing lymphocytes and 3H-labeled K-562 cells and their incubation at 37°C during 24 hours; the second step was filtration of the cell suspension. The frozen medium and filters were analyzed for the cytokine level and cytotoxic activity after landing. It was found that lymphocytes with different basal levels of cytotoxic activity kept the ability of recognizing and lysing malignant cells. In microgravity, cytotoxity increased to 160% of the basal levels. Donor individual features modulated the magnitude of the increase. The measurement of interleukin levels (TNF-α, IL-1, IL-2) in medium showed that synthesis of TNF-α increased during cell co-cultivation in microgravity. The level of IL-2 was very low in flight and ground control samples. The production of IL-1 by lymphocytes decreased after in-flight incubation. The results indicate that microgravity did not disturb the cytotoxic function of immune cells in vitro during 24-hour incubation with specific target cells.

Publication(s)

Buravkova LB, Grigorieva OV, Rykova MP, Grigoriev AI. Cytotoxic activity of natural killer cells in vitro under microgravity. *Biological Sciences*. July-August 2008;421:275-277. doi: 10.1134/S0012496608040169. [Also: Grigorieva OV, Buravkova LB, Rykova MP. *Cytotoxic activity of NK lymphocytes in vitro under microgravity.* 26th Annual International Gravitational Physiology Meeting, Cologne, Germany; 2005.]

Buravkova LB, Grigorieva OV, Rykova MP. The effect of microgravity on the in vitro NK cell function during six International Space Station Missions. *Microgravity Science and Technology*.2007;19(5-6):145-147. doi: 10.1007/BF02919470.

Buravkova LB, Romanov Y, Rykova MP, Grigorieva OV, Merzlikina N. Cell-to-cell interactions in changed gravity: Ground-based and flight experiments. *Acta Astronautica*. July 2005;57(2-8):67-74. doi: 10.1016/j.actaastro.2005.03.012. [Also: Buravkova LB, Romanov Y, Grigorieva OV, Rykova MP. *Cell-to-cell interactions in changed gravity: ground-based and flight experiments. 55th International Astronautical Congress*, Vancouver, Canada; 2004.]

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This investigation is complete and all results are published.

NATIONAL LABORATORY PATHFINDER-CELLS (NLP-CELLS), TWO INVESTIATIONS

Research Area: Cellular Biology

Increment(s): 18, 21-28

Principal Investigator(s):

- Neil C. Talbot, PhD, Agricultural Research Services, Beltsville, Maryland
- Wagner Vendrame, PhD, University of Florida, Homestead, Florida

RESEARCH OBJECTIVES

NLP-CELLS (TALBOT)

National Lab Pathfinder-Cells (NLP-Cells) comprises 2 experiments conducted by the United States Department of Agriculture (USDA). One experiment assesses the effects of spaceflight on cellular replication and differentiation in cattle cells. The other experiment examines the effects of spaceflight on the normal differentiation and function of liver cells and bile duct (opens into the small intestine from the liver) epithelium (lining).

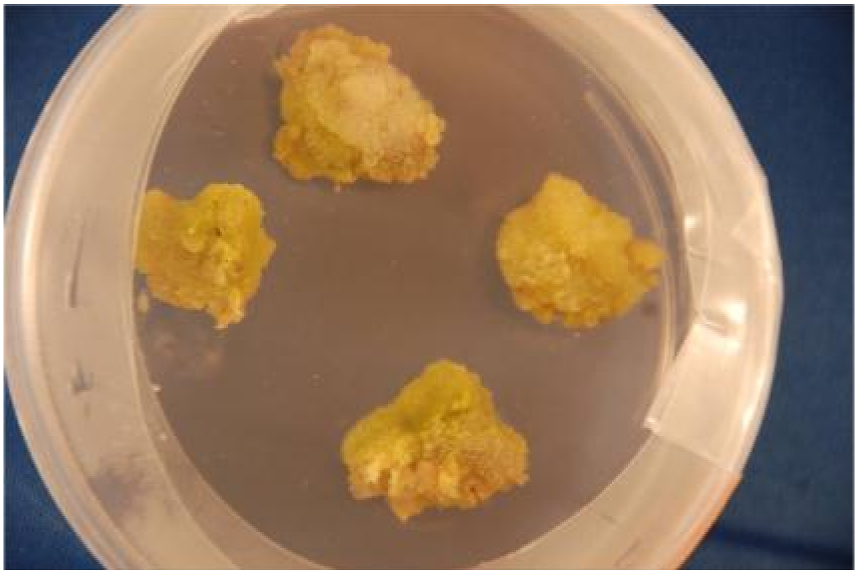
In this image shows the Group Activation Packs placed into the Commercial Generic Bioprocessing Apparatus that provides environmental controls from cold stowage to incubation temperatures. BioServe Space Technologies image, University of Colorado, Boulder, Colorado.

NLP-CELLS-JATROPHA BIOFUELS (VENDRAME)

National Lab Pathfinder-Cells-*Jatropha* Biofuels (NLP-Cells-Jatropha Biofuels) assesses the effects of microgravity on formation, establishment, and multiplication of undifferentiated cells of the *Jatropha (Jatropha curcas)*, a biofuel plant, using different tissues as explant sources from different genotypes of *Jatropha*. Specific goals include the evaluation of changes in cell structure, growth and development, genetic changes, and differential gene expression. Postflight analysis identifies significant changes that occur in microgravity, which could contribute to accelerating the breeding and genetic improvement processes for the development of new cultivars of this biofuel plant.

EARTH BENEFITS

The long-term goal of this project is to enhance the ability to introduce new genetic information into cells and to examine the effects of spaceflight on the normal differentiation and function of undifferentiated plant cells. The *J. curcas* plant, which is also known as the “physic nut” is a small tree from the Euphorbiaceae family that produces seeds from which oil can be extracted for use as biofuel. It has been demonstrated that *J. curcas* is a feasible species for the commercial production of biodiesel. The oil is of excellent quality and amenable also for jet fuel mixes. *J. curcas* is a tropical plant with an oil content of about 38% within the seeds. However, *J.*



Fluid Processing Apparatus (FPA) containing cell suspensions of *J. curcas*. The FPAs are assembled into the Group Activation Pack, which is transported to the International Space Station for microgravity studies. Dr. Wagner A. Vendrame image, University of Florida, Homestead, Florida.

curcas is not currently being cultivated as a crop, since no commercial cultivars exist. Therefore the development of *J. curcas* cultivars with improved characteristics is highly desirable. Such studies can contribute to the development of US-based new cultivars of an alternative energy crop that can be readily available to U.S. farmers while contributing towards energy independence from fossil fuel sources. Microgravity might be able to induce genetic changes that result in positive characteristics for the development of superior *Jatropha* cultivars. That would be a means of accelerating the breeding and genetic improvement of *Jatropha* towards the commercialization of such superior *jatropha* cultivars.

Space Benefits

This investigation is a part of a series of investigations to be conducted aboard the International Space Station (ISS) to provide the foundation for use of the ISS as a National Laboratory following assembly complete.

Results

NLP-Cells

NLP-Cells assessed the effects of spaceflight on the liver's characteristic cells to differentiate into either monolayers of liver cells or cells lining the vessels that carry bile. In comparing flight vs. ground control cultures, no differences were found between the cultures with the exception being that some genes were differentially expressed. By light microscopy both young and older cultures, flight and ground, had grown and differentiated normally in the Opticell culture vessels. The PICM-19 cells grew to approximately 75% confluency (coverage of the petri dish), with few signs of cell death. The cells differentiated into either monolayer patches of liver cells with bile ducts visible between the cells or into 3-D bile ducts with well-defined lumens, the inside space of a tubular structure. Structural features between flight and ground samples were similar with PICM-19 cells. Flight PICM-19 cells produced more urea in response to added ammonia, although there was no apparent difference when compared to the ground control culture samples. The enzyme activities investigated were also found to be similar between ground and flight samples.

Researchers noted the nature of the PICM-19 cells was not obviously changed by exposure to the space environment. However, the study's results should be viewed as preliminary because a greater number of observations are needed for additional statistical analyses. Also, different types of cell culture platforms other than the one used in this study (3-D spheroid culture vs 2-dimensional culture) might be tested. Finally in neither the immediately assayed PICM-19 cells nor the PICM-19 cells continuously cultured postflight did there appear to be any new unique cellular characteristics, permanent or transient, that would enhance their utility for biotechnological purposes, such as their use in an artificial liver support device (Talbot 2010).

NLP-Cells-Jatropha

This study aimed to compare the in vitro growth of plant cultures from 3 different plant parts, cotyledon, leaf, and stem sections, derived from *Jatropha* from different geographic locations (Brazil, India, and Tanzania) outside and inside the petriGAP. Cell growth was observed for all *Jatropha* accessions both inside and outside the petriGAP for all evaluated plant materials. Growth parameters were affected by geographic origin, plant part type and environment. The type of plant part type influenced the type of cell growth and subsequent plantlet regeneration capacity. Overall growth showed no abnormalities. The current study shows *Jatropha* in vitro cell cultures are suitable for growth inside petriGAPs for a period of 12 weeks. The parameters evaluated in this study provide the basic ground work and preflight assessment needed to justify a model for microgravity studies with *Jatropha* in vitro cell cultures. Future studies should focus on results of experiments performed with J*atropha* in vitro cultures in microgravity, including culture growth and potential genetic changes and differential gene expression (Vendrame 2013).

Publication(s)

Vendrame WA, Pinares A. Characterizing parameters of *Jatropha Curcas* cell cultures for microgravity studies. *Advances in Space Research*. 2013;51(11):2069-2074. doi:10.1016/j.asr.2012.12.019.

Talbot NC, Caperna TC, Blomberg L, Graninger PG, Stodieck LS. The effects of spaceflight and microgravity on the growth and differentiation of PICM-19 pig liver stem cells. *In Vitro Cellular & Developmental Biology – Animal*. 2010;46:502–515. doi:10.1007/s11626-010-9302-6.

This investigation is complete; however additional results are pending publication.

Pathway Different Activators (PADIAC)

Research Area: Cellular Biology
Expedition(s): 25 and 26
Principal Investigator(s):
- Isabelle Walther, PhD, Swiss Federal Institute of Technology, Space Biology, Zurich, Switzerland

Research Objectives

The Pathway Different Activators (PADIAC) experiment will test the hypothesis that the inhibition of interleukin-2 (IL-2) receptor expression on T cells (mature white blood cells from the thymus) in microgravity is due to a sensitivity of the CD28 (molecule required for T-Cell stimulation) co-stimulatory pathway to microgravity and determine how microgravity affects the expression of genes mediated by CD28 activation.

Pathway Different Activators hardware. ESA image.

Results

The quality of data for the 4-hour samples was excellent, though a few more ground studies are needed on the 4-hour samples to determine signal transduction under the 3 methods of activation to complete the picture. The data for the 24-hour samples was less striking most likely due to the fact that the RNA from the 24-hour samples was in low amount.

The data are excellent for the 4-hour data with changes seen in IL2Rα, Xcl2, EGR-1, GMCSF and IFNγ for each activation. In most cases, the ConA/CD28 and the more physiological CD3/CD28 activations were comparable, confirming that all previous work with ConA/CD28 is reliable. We had thought by bypassing the IL-2 step would eliminate the suppression of spaceflight, but that was not the case. The effectiveness of the 3 activations demonstrated that all 3 stimulations were effective suggesting that IL2 is not the only limiting factor in microgravity. These experiments help to understand immune system activation by introducing the variable of gravity. As in mathematics, the elimination of a variable many times can eventually solve the equation. Spaceflight causes changes in the ability of the T cells to respond to a simulated infection. The central hypothesis was that this effect was solely dependent on IL-2, however, this experiment showed that IL-2 was not the only factor.

This investigation is complete; however additional results are pending publication.

Mechanisms and Functional Consequences of Protein Kinase C Isoform Translocation in Monocytes Exposed to Microgravity (PKinase)

Research Area: Cellular Biology

Expedition(s): 16

Principal Investigator(s):

- Millie Hughes-Fulford, PhD, University of California, San Francisco, California
- Jack J.W.A. van Loon, Free University, Amsterdam, Netherlands
- Isabelle Walther, PhD, Swiss Federal Institute of Technology, Space Biology, Zurich, Switzerland

Research Objectives

The Mechanisms and Functional Consequences of Protein Kinase C Isoform Translocation in Monocytes Exposed to Microgravity (PKinase) investigates the effects of microgravity on the development of monocytes (infection-fighting white blood cells) into macrophages. Since all terrestrial life began in a gravity field, this study examines alterations of early T-cell activation, whereby microgravity gives us the unique opportunity to examine the role of Earth's gravity in immune function. The PKinase study shows the regulation of the earliest signals that cause the T cell to activate and the role of normal Earth's gravity in that signaling. PKinase helps scientists understand the immune-suppression that occurs during spaceflight and can facilitate the development of preventive and corrective measures for long duration missions.

Earth Benefits

Since all terrestrial life began in a gravity field, this study examines alterations of early T-cell activation, whereby microgravity gives us the unique opportunity to examine the role of Earth's gravity in immune function. The PKinase study shows the regulation of the earliest signals that cause the T cell to activate and the role of normal Earth's gravity in that signaling.

PKinase inside the transportable Kubik incubator. ESA image.

Space Benefits

PKinase helps scientists understand the immunosuppression that occurs during spaceflight and can facilitate the development of preventive and corrective measures for long-duration missions.

Results

PKC activation was conducted using phorbol 12,13-dibutyrate (PDBu) under normal and altered gravity in the PKinase experiment on the International Space Station. Examination of differentiation of monocytes under real microgravity and normal gravity showed significant changes in the molecular function gene expression during early signaling as well as in expression of differentiation of the monocyte.

PDBu causes differentiation of the monocyte and results in adhesion of the cells within 24 hours. Cumulatively, these results suggest that activation of early signal transduction is regulated in part by gravity.

In true microgravity (µg), significant changes were seen in gene expression of the monocyte between activation of the µg samples and the 1-g in-flight samples. These changes in gene expression suggest a role of gravity in regulation of immune function in human monocytes.

PUBLICATION(S)

Hughes-Fulford M, Chang TT, Li C. Effect of gravity on monocyte differentiation. *2008 Life in Space for Life on Earth Symposium*, Angers, France; 2008.

This investigation is complete and all results are published.

GENE EXPRESSION OF P53-REGULATED GENES IN MAMMALIAN CULTURED CELLS AFTER EXPOSURE TO A SPACE ENVIRONMENT (RAD GENE)

Research Area: Cellular Biology
Expedition(s): 18
Principle Investigator(s):
- Takeo Ohnishi, PhD, Nara Medical University, Kashihara, Japan

RESEARCH OBJECTIVES

Rad Gene studies the expression of *p53*-regulated genes in human cultured mammalian cells during and after spaceflight. This data contributes to the knowledge of physiological protection against the serious effects of space radiation on crew members during long-duration missions in space.

EARTH BENEFITS

These techniques are quite useful for the dosimetry of low dose rate and low dose radiation. Data obtained from Rad Gene are applicable to the accidents such as Fukushima nuclear power plant following the 2011 tsunami. The measurement of DSBs induced by heavy-ion beams can also be applied to heavy-ion cancer therapy.

SPACE BENEFITS

Results obtained from this investigation hope to add important details on how to protect against space radiation during long-term spaceflight.

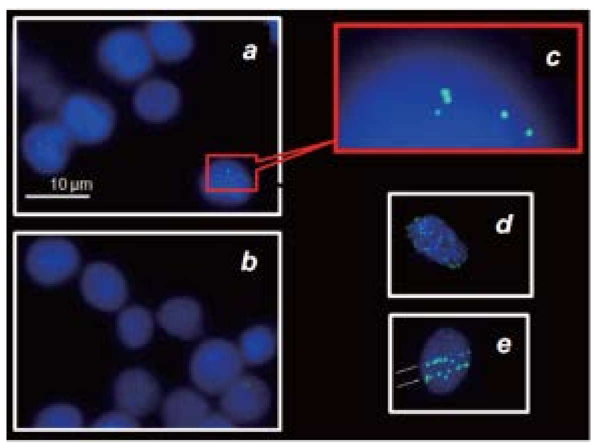
RESULTS

PHYSICAL DOSIMETRY

The total dose was about 66.5 mSv for 133 days in space evaluated by small dosimeters: thermoluminescence (TLD) and CR39. The dose rate was about 0.5 mSv per day, though that has been understood to be about 1.0 mSv (1).

SPACE RADIATION-INDUCED DSBS IN NUCLEI

In the frozen cells, researchers determined that DSBs were detected as γH2AX-positive foci with the shape of tracks. From the induced frequency of γH2AX-positive foci, scientists measured about 93.1 mSv as the total dose. The dose rate was about 0.7 mSv per day. This value is very close to the value of 0.5 mSv per day noted by the physical dosimetry.



Visualization of ionizing radiation tracks in nucleus by Gamma-H2AX staining. ***a***, space samples; ***b***, ground controls; ***c,*** large scale(x 5) of ***a***; ***d***, ground samples irradiated by X-rays (3 Gy); ***e***, ground samples irradiated by 20 kev/mm Fe-ion beams (0.5 Gy). ***a***-***c***, wt*p53*; ***d*** and ***e***, m*p53* cells. JAXA image.

p53-Dependent Induced and Depressed Genes in Space Cultured Cells

Researchers previously published the induction of *p53* gene products in the muscles and skin of a space-flown rat. The *p53* gene product is understood to control apoptosis, cell cycle, and DNA repair as a genome guardian that depresses gene instability and induction of mutation, chromosome aberration, and carcinogenesis. Scientists prepared 2 kinds of human-cultured cell lines of lymphoblastoid cells bearing wt*p53* and m*p53* gene statuses. Researchers found many new kinds of *p53*-regulated genes induced by space radiations, by microgravity, and the space environment, though the induction of *p53* gene product itself was never understood. In addition, space radiations synergistically induced 209 genes by microgravity, while 166 synergistic depression genes altered by microgravity.

p53-Dependent Induced and Depressed Proteins in Cultured Cells in Space

Scientists also analyzed *p53*-dependent protein synthesis using protein chips of the space cultured cells. These reports were the first findings in the world.

p53-Dependent Induced and Depressed Genes That Were Exposed to Space Radiations

The flight samples were exposed to space radiations for 133 days in space in a frozen state. After spaceflight, the cells were cultured on the ground. Researchers analyzed the *p53*-dependent gene expression in these cells. Induced and depressed genes were 50 and 94, respectively. Heat shock protein (HSP) genes were also found and were induced by low doses of radiations (4).

Radio-Adaptive Response in Space-Flown Cells in a Frozen State

The flight samples were exposed to space radiations for 133 days in space in a frozen state. After spaceflight, the cells were cultured on the ground and then irradiated by X-rays at 2 Gy. Thereafter, the cells were cultured again for measurements of a radio-adaptive response of cell survival, apoptosis, and chromosomal aberration. Scientists detected the radio-adaptive response in wt*p53* cells but not in m*p53* cells. These results suggested that the flown cells in space were exposed to space radiations in the range of 20-100 mSv because reports already revealed that the radio-adaptive response was found in those specific radiation doses.

Publication(s)

Takahashi A, Suzuki H, Omori K, et al. Expression of p53-regulated proteins in human cultured lymphoblastoid TSCE5 and WTK1 cell lines during spaceflight. *Journal of Radiation Research.* 2012;53(2):168-175. doi: 10.1269/jrr.11140.

Takahashi A, Suzuki H, Omori K, et al. Expression of p53-regulated genes in human cultured lymphoblastoid TSCE5 and WTK1 cell lines after spaceflight in a frozen state. *Advances in Space Research*. March 15, 2011;47(6):1062-1070. doi: 10.1016/j.asr.2010.11.002.

Takahashi A, Nagamatsu A, Su X, et al. The first life science experiments in ISS: Reports of “Rad Gene” - Space radiation effects on human cultured cells. *Biological Sciences in Space*. 2010;24(1):17-41.

Takahashi A, Su X, Suzuki H, et al. P53-dependent adaptive responses in human cells exposed to space radiations. *International Journal of Radiation Oncology, Biology, Physics.* November 15, 2010;78(4):1171-1176. doi: 10.1016/j.ijrobp.2010.04.062.

Takahashi A, Suzuki H, Omori K, et al. The expression of p53-regulated genes in human cultured lymphoblastoid TSCE5 and WTK1 cell lines during spaceflight. *International Journal of Radiation Biology*. August 2010;86(8):669-681. doi: 10.3109/09553001003789596.

Ohnishi T, Takahashi A, Nagamatsu A, et al. Detection of space radiation-induced double strand breaks as a track in cell nucleus. *Biochemical and Biophysical Research Communications.* December 18, 2009;390(3):485-488. doi: 10.1016/j.bbrc.2009.09.114.

This investigation is complete and all results are published.

Signalling through Rho GTPases in microgravity (Rho Signalling)

Research Area: Cellular Biology
Expedition(s): 5
Principal Investigator(s): ● Betty V. Nusgens, University of Liège, Liège, Belgium

Research Objectives

The main objective of the Signalling through Rho GTPases in microgravity (Rho Signalling) experiment is to analyze by immune-morphological procedures distinct cellular processes (cytoskeleton and focal adhesions organization, GTPases translocation to the membrane, translocation of activated signaling molecules) depending on Rho GTPases activity. The Rho GTPases (RhoA, Rac1 & Cdc42) are molecular switches in the signaling pathways that relay the information collected by most transmembrane receptors to modulate the mechanical and phenotypic expression of the cells.

Results

The Rho Signaling experiment was located in a vacuum-tight aluminum container (B-container), providing 2 levels of containment for the plunger box unit (PBU) and their contents. Upon inspection of the PBUs after landing, it turned out that 2 plungers had been correctly activated to make the exchange of culture medium 6 hours after reaching 37°C in the incubator. Four plungers had not been activated causing the loss of biological samples. Postflight debriefing revealed that the B-container was disconnected and removed from the Aquarius, 5 minutes before termination of the experiment just before the activation of the plungers. As such, additional security should be applied in the future to prevent avoidable failure.

Publication(s)

Nusgens B, Lambert C, Lapiere C. Signaling through rho gtpases in microgravity (rho signaling) on ISS (soyuz tma-1) Belgian soyuz mission "Odissea". *Microgravity Science and Technology*. September 2007;19(5-6):184-186. doi: 10.1007/BF02919478.

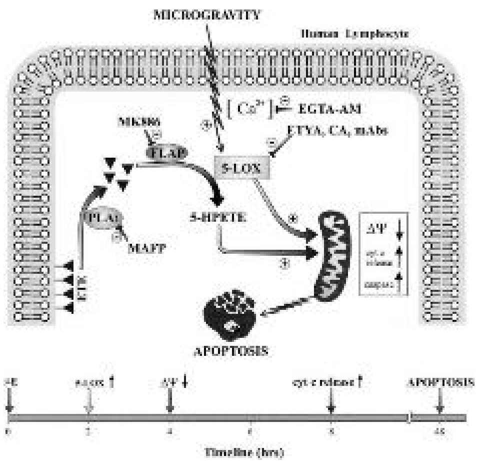
This investigation is complete and all results are published.

Role of Apoptosis in Lymphocyte Depression (ROALD)

Research Area: Cellular Biology

Expedition(s): 18

Principal Investigator(s):
- Mauro Maccarrone, N. Battista , University of Teramo, Teramo, Italy
- Natalia Battista, PhD, University of Teramo, Teramo, Italy



Model of microgravity-induced apoptosis in human lymphocytes. ESA image.

Research Objectives

Role of Apoptosis in Lymphocyte Depression (ROALD) will determine the contribution of programmed apoptosis (cell death) in loss of T-lymphocyte (white blood cells originating in the thymus) activity in microgravity.

Results

In the postflight analysis, the following parameters directly correlated to programmed cell death were tested:

- Gene expression of calpain and p53
- 5-LOX protein expression and activity
- DeoxyriboNucleic Acid **(**DNA) fragmentation

The results demonstrated that exposure of human lymphocytes to microgravity for 48 hours aboard the International Space Station (ISS) remarkably increased apoptotic hallmarks such as Deoxyribonucleic acid (DNA) fragmentation (~3-fold compared to ground-based controls) and cleaved-poly (ADP-ribose) polymerase (PARP) protein expression (~3-fold), as well as mRNA levels of apoptosis-related markers such as p53 (~3-fold) and calpain (~4-fold); these changes were paralleled by an early increase of 5-LOX activity (~2-fold). These findings provided a molecular background for the immune dysfunction observed in astronauts during space missions, and revealed potential new markers to monitor health status of ISS crew members.

Publication(s)

Battista N, Meloni MA, Bari M, et al. Five-Lipoxygenase-dependent apoptosis of human lymphocytes in the International Space Station: Data from the ROALD experiment. *Federation of American Societies for Experimental Biology Journal.* 2012;26(5):1791-1798. doi: 10.1096/fj.11-199406.

This investigation is complete and all results are published.

Role of Apoptosis in Lymphocyte Depression-2 (ROALD-2)

Research Area: Cellular Biology
Expedition(s): 29 and 30
Principal Investigator(s):
- Natalia Battista, PhD, University of Teramo, Teramo, Italy
- Mauro Maccarrone, University of Teramo, Teramo, Italy
- Natalia Battista, University of Teramo, Teramo, Italy

Research Objectives


European Space Agency astronaut Andre Kuipers, Expedition 30 flight engineer, works with the Role of Apoptosis in Lymphocyte Depression-2 experiment in the KUBIK-3 incubator located in the Columbus laboratory of the International Space Station in December 2011. NASA/ESA image.

The goal of the Role of Apoptosis in Lymphocyte Depression-2 (ROALD-2) project experiment is to investigate the “endocannabinoid system,” (that is, an ensemble of receptors, metabolic enzymes, and transporters of bioactive lipids collectively termed “endocannabinoids”), in human peripheral lymphocytes exposed to microgravity aboard the International Space Station (ISS). The project aim is to determine possible alterations of the activity and expression of endocannabinoid system elements in weightlessness, and their impact on the regulation of immune cell cycle, growth and death.

Results

Peripheral Blood Mononuclear Cells (PBMCs) isolated from human donors on the ground were sent to the ISS on the Soyuz. The experimental activities, performed in the KUBIK incubator, were stopped at different time points and the experimental containers were stored in the Minus Eighty Degrees Celsius Laboratory Freezer for the ISS (MELFI) facility. The preliminary postflight analysis, using quantitative real time-polymerase chain reaction (qRT-PCR) and western blot techniques, showed that microgravity alters the expression, at transcriptional and translational level, of the main AEA-synthesizing and -degrading enzymes. The project will disclose a potential engagement of endocannabinoid signalling in lymphocyte apoptosis and immunodepression already documented in space.

Publication(s)

Battista N, Meloni MA, Bari M, et al. Five-Lipoxygenase-dependent apoptosis of human lyphocytes in the International Space Station: Data from the ROALD experiment. *Federation of American Societies for Experimental Biology Journal*. 2012;26(5):1791-1798. doi: 10.1096/fj.11-199406.

This investigation is complete and all results are published.

SPACEFLIGHT OF HUVEC: AN INTEGRATED EXPERIMENT (SPHINX)

Research Area: Cellular Biology
Expedition(s): 25 and 26
Principal Investigator(s):
- Silvia Bradamante, University of Milan, Milan, Italy

RESEARCH OBJECTIVES

The SPaceflight of Huvec: an Integrated eXperiment (SPHINX) examines growth changes in Human Umbilical Vein Endothelial Cells (HUVEC), ie, the cells that line the interior of blood vessel, when exposed to microgravity. This 10-day study which consisted of 12 in-flight and 12 ground-based control modules is important to maintaining crew health during long-duration space exploration.

RESULTS

Postflight microarray analysis revealed 1 023 significantly modulated genes, the majority of which are involved in cell adhesion, oxidative phosphorylation, stress responses, cell cycle, and apoptosis. Thioredoxin-interacting protein was the most up-regulated (33-fold), heat-shock proteins 70 and 90 the most down-regulated (5.6-fold). Ion channels (TPCN1, KCNG2, KCNJ14, KCNG1, KCNT1, TRPM1, CLCN4, CLCA2), mitochondrial oxidative phosphorylation, and focal adhesion were widely affected. Cytokine detection in the culture media indicated significant increased secretion of interleukin-1α and interleukin-1β. Nitric oxide was found not modulated. Our data suggest that in cultured HUVECs, microgravity affects the same molecular machinery responsible for sensing alterations of flow and generates a pro-oxidative environment that activates inflammatory responses, alters endothelial behavior, and promotes senescence.

PUBLICATION(S)

Versari S, Longinotti G, Barenghi L, Maier JA, Bradamante S. The challenging environment on board the International Space Station affects endothelial cell function by triggering oxidative stress through thioredoxin interacting protein overexpression: The ESA-SPHINX experiment. *Federation of American Societies for Experimental Biology Journal*. November 2013;27(11):4466-4475. doi: 10.1096/fj.13-229195.

Versari S, Maier JA, Norfini A, Zolesi V, Bradamante S. SPaceflight of Huvec: An Integrated eXperiment - SPHINX onboard the ISS. *2012 Life in Space for Life on Earth Symposium*, Aberdeen, United Kingdom; June 18-22, 2012.

This investigation is complete and all results are published.

STELSYS LIVER CELL FUNCTION RESEARCH (STELSYS)

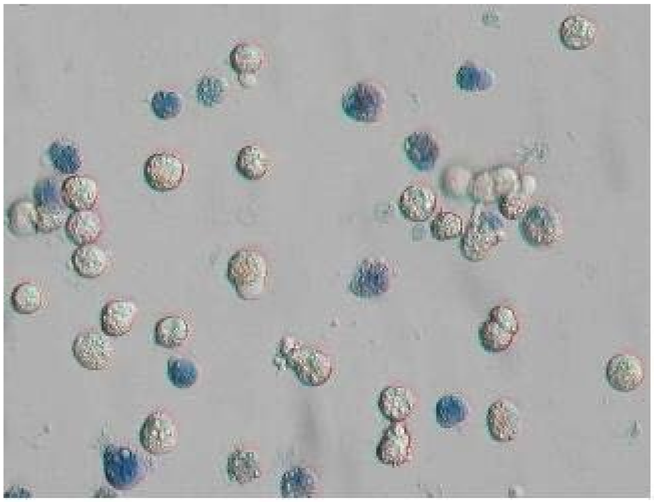
Research Area: Cellular Biology
Expedition(s): 5
Principal Investigator(s):
- Albert Li, PhD, StelSys LLC, Baltimore, Maryland

RESEARCH OBJECTIVES

StelSys Liver Cell Function Research (StelSys) tests human liver cell functionality in microgravity and compares the results to the typical function of duplicate cells on Earth.

EARTH BENEFITS

Human liver cells grown on Earth using traditional techniques typically form flat colonies that only function for 1 or 2 days at best. However, liver cells grown on Earth in NASA's Rotating Bioreactor form 3-D colonies that maintain their function for at least several weeks. These cell colonies closely resemble and function like natural cells in the human body, which makes them excellent candidates for research concerning drug metabolism and general cell function. Scientists believe that cells grown in a microgravity environment also develop in a 3-D form that resembles cells in the human body. This enables researchers to isolate and study the multiple factors that influence cellular function in microgravity and then compare the results to ground-based data obtained from the Rotating Bioreactor.



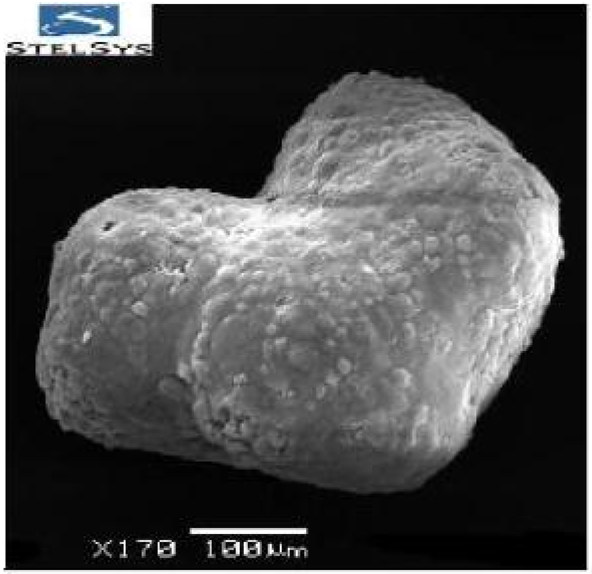
Human liver cells at the completion of a ground-control experiment. A stain has been applied to indicate the live versus dead (blue-colored) cells. NASA Johnson Space Center image.

The Rotating Bioreactor is being used in the investigator's laboratory to perform drug metabolism studies. These studies are useful for determining how the human body processes a drug. In addition, quantities of drug metabolites are produced, and these are required in various pharmacokinetic and toxicology studies during the course of drug development. The ultimate goal is to speed up the process that is used to make new drugs available for patients in need.

The data obtained from this investigation could also aid in the development of a liver-assist device, a machine very similar to a kidney dialysis machine. Such a device would be used to sustain the life of a patient with advanced liver disease waiting for an organ transplant.

SPACE BENEFITS

This experiment gives insight on how liver cells function in microgravity. The results help in developing measures to further protect the health of crewmembers on extended exploration missions.



A 3-D aggregate composed of thousands of liver cells. This aggregate has been grown in the investigator's laboratory for 8 days in the NASA Rotating Bioreactor. StelSys image.

RESULTS

The samples returned from space were analyzed by specialized mass spectrometry equipment to determine the amount of drug metabolites formed by the liver cells from the drug substances added. Overall this analysis showed the rate of metabolism by the liver cells in space was lower than that of the liver cells maintained under similar conditions on Earth. This was true for all of the drug substances tested as well as for cells from 3 different liver donors. These results indicate that microgravity may well retard the rate of drug metabolism in the human liver, although the mechanism for this effect is yet unknown.

Returned samples were also analyzed by gene array to determine whether genetic expression differed for cells in microgravity. Differences were found, including 9,200 of 13,000 genes that had at least 2-fold greater expression in space as compared to Earth and 9,800 genes that had decreased expression in space. This large body of data is being analyzed for clues as to how liver cell function changes in specific ways in the microgravity environment of space.

This investigation is complete and all results are published.

Space Tissue Loss (STL), Five Investigations

Research Area: Cellular Biology

Expedition(s): 23 and 24, 27 and 28

Principal Investigator(s):
- Rasha Hammamieh, PhD, United States Army, Ft Detrick, Maryland
- Cheryl A. Nickerson, PhD, Arizona State University, Tempe, Arizona
- Eduardo Almeida, PhD, Ames Research Center, Moffett Field, California
- Eduardo Almeida, PhD, Ames Research Center, Moffett Field, California
- H. Joon Paek, PhD, Tissue Genesis, Inc, Honolulu, Hawaii

Pilot Jeffrey S. Ashby works with the Space Tissue Loss-B middeck experiment locker.

Research Objectives

STL-MRMC (Hammamieh)

Space Tissue Loss is a Department of Defense (DoD) Space Test Program payload flying both DoD and NASA science using cell and tissue cultures in microgravity to study the effects of tissue regeneration and wound healing in space.

STL-Microbial Immunity (Nickerson)

Space Tissue Loss - Microbial Immunity (STL-Microbial Immunity) is a Department of Defense Space Test Program payload examining how human cells respond to bacterial infections in space and if normal processes seen on Earth occur in the space environment. This experiment could yield valuable knowledge leading to advances in vaccine development and other therapeutics for treatment, prevention, and control of infectious diseases on Earth.

STL-Regeneration (Almeida)

Space Tissue Loss - Stem Cell Regeneration (STL-Regeneration) is a Department of Defense Space Test Program payload studying stem cell regeneration in mouse cell culture in microgravity examining the effects of tissue regeneration in space. Cell culture in microgravity serves as a model system for understanding necrosis of tissue following severe injuries on Earth.

STL-Regeneration-Keratinocytes (Almeida)

Space Tissue Loss - The Effects of Microgravity on Stem Cell-Based Tissue Regeneration: Keratinocyte Differentiation in Wound Healing (STL-Regeneration-Keratinocytes) is a Department of Defense (DoD) Space Test Program payload flying both NASA and DoD science using cell and tissue cultures in microgravity to study the effects of tissue regeneration and wound healing in space.

STL-TATRC2 (Paek)

Space Tissue Loss is a DoD Space Test Program payload flying both DoD and NASA science using cell and tissue cultures in microgravity to study the effects of tissue regeneration and wound healing in space.

Earth Benefits

Wound healing is considered a major clinical challenge in surgical and military units; the related concerns have been mounting recently, triggered by an aging population and increasing rates of diabetes, obesity, and cancer treatment side effects. To better understand the physiological cascade of the healing model, the present plan intends to temporally obtain in vitro biological samples associated with endotoxin insulted dermal cells and identify molecular signatures using an integrated pan-omics platform. We project the earth based pan-omic study may reveal true EARLY (or "immediate onset") indicators of the healing cascade; but, perhaps more importantly, a demonstrable understanding of the regulatory nodes/networks cascading into successful wound healing. The application spans both military and civilian injuries and immune response on Earth.

S118E10350 – Seen in this image is the hardware that houses the Cell Culture Module - Immune Response of Human Monocytes in Microgravity (CCM-Immune Response) and the Cell Culture Module - Effect of Microgravity on Wound Repair: In Vitro Model of New Blood Vessel Development (CCM-Wound Repair) experiments. The experiments were flown on STS118/13A August 1, 2007.

Space Benefits

Prolonged residence in a space shuttle causes immunocompromisation; therefore the crew members not only suffer from a delayed healing process, they also become particularly vulnerable to bacterial infection. This study is designed to identify certain early molecular signatures and/or therapeutic targets associated with the compromised healing cascade.

RESULTS

All results are pending further analysis or upcoming publication.

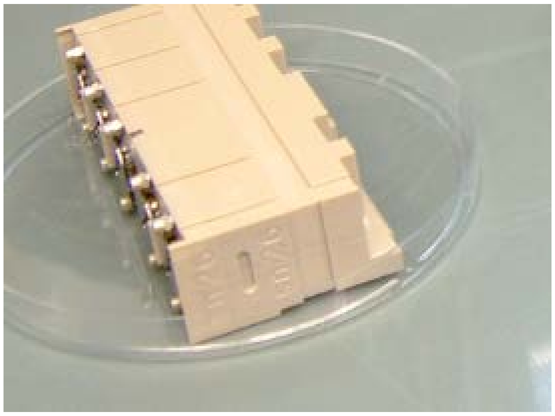
This investigation is complete; however additional results are pending publication.

Bone Marrow Stroma Cell Differentiation and Mesenchymal Tissue Reconstruction in Microgravity (Stroma-2)

Research Area: Cellular Biology
Expedition(s): 13
Principal Investigator(s):
- Ranieri Cancedda, MD, University of Genoa, Genoa, Italy

Research Objectives

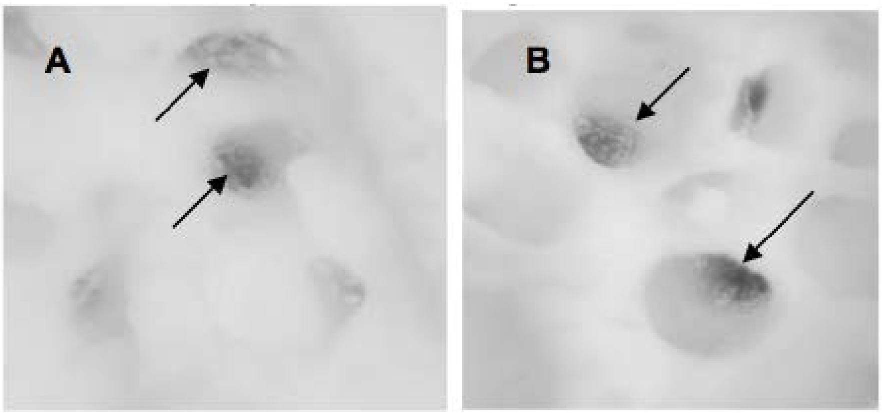
The Bone Marrow Stroma Cell Differentiation and Mesenchymal Tissue Reconstruction in Microgravity (Stroma-2) investigation studies the potentially osteogenic murine bone marrow stromal cells in a 3-D culture system.



Stroma-2 hardware. ESA image.

Results

The study involved 4 groups of cells/Skelite constructs: Flight Experiment, FE, (spaceflight, static on orbit, in bioreactors), Flight Control, FC, (spaceflight, artificial 1 g in orbit, in bioreactors), Ground Control, GC, (ground 1 g, static, in bioreactors), and Laboratory Control, LC, (ground 1 g, static in petri dishes). Half of the constructs of each group were maintained in normal growth medium (BMSC cultures), and the other half was stimulated with osteo-inductive medium (BOI cultures). Inspection by stereo-microscope showed vigorous cell growth in all BMSC/Skelite constructs recovered at the end of the experiment; cells grew into a veil-like network, filling pores and frequently forming snowflake-like aggregates. No major difference in morphology was seen between BMSC and BOI cultures in all groups.



Postflight visual inspection of BMSC (A) and BMSC-osteoinducted (B) by stereo-microscope. Arrows indicate BMSC grown into the skelite pores. ESA image.

To maximize yield, since cells maintained in RNAlater solution tended to detach from the scaffold, RNA was extracted from the BMSC/Skelite constructs and from the solution recovered from the bioreactor cell chamber. Half the amount of total RNA was obtained from the FE respective to the GC samples, and a comparable amount was obtained from BMSC and BOI cultures.

Differences in total RiboNucleic Acid (RNA) extracted suggested that cell proliferation was inhibited in flight samples. Affymetrix technology revealed that 1 599 genes changed expression after spaceflight exposure. A decreased expression of cell-cycle genes confirmed the inhibition of cell proliferation in space. Unexpectedly, most of the modulated expression was found in genes related to various processes of neural development, neuron morphogenesis, transmission of nerve impulse and synapse, raising the question on the lineage restriction in BMSC.

Publication(s)

Monticone M, Liu Y, Pujic N, Cancedda R. Activation of nervous system development genes in bone marrow derived mesenchymal stem cells following spaceflight exposure. *Journal of Cellular Biochemistry*.July 23, 2010;111(2):442-452. doi: 10.1002/jcb.22765.

This investigation is complete; however additional results are pending publication.

EFFECTS OF MICROGRAVITY ON THE ACTION OF VITAMIN D IN OSTEOBLASTS (VITAMIN D)

Research Area: Cellular Biology

Expedition(s): 5

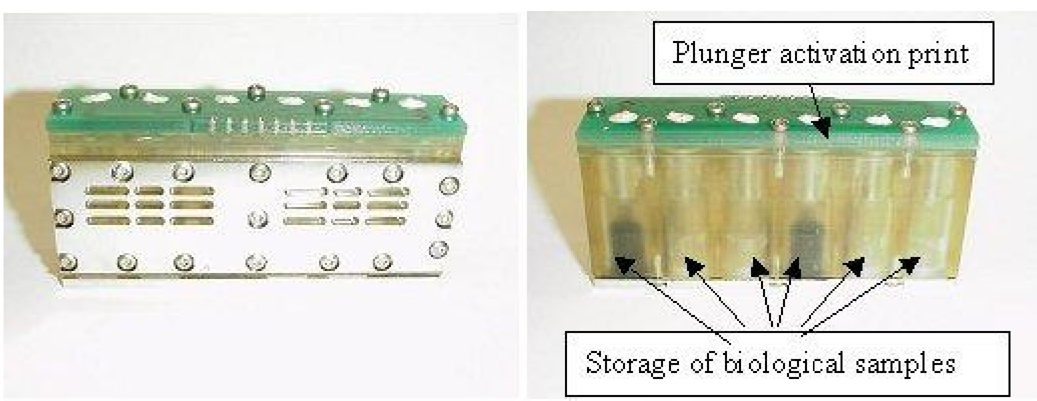
Principal Investigator(s):
- Roger Bouillon, Katholieke Universiteit Leuven, Leuven, Belgium

RESEARCH OBJECTIVES

The first objective of the Effects of Microgravity on the Action of Vitamin D in Osteoblasts (Vitamin D) is to elucidate whether space-induced alterations in 1, 25(OH) 2vitaminD3 regulated gene expression is a generalized phenomenon or species-specific. The second objective is to study the mechanisms underlying space-related alterations in gene expression in osteoblasts.

RESULTS

After transfection and selection, 3 MC3T3-VDRE colonies showed a time- and dose-dependent increase in growth hormone release following treatment with 1,25(OH)2D3. Noteworthy, the induction of growth hormone was less in the stable transfectants than after transient transfection, most likely because less copies of the construct were present in the former. The growth hormone response of the selected MC3T3-VDRE cell line was not manifestly altered when cells were cultured in the plunger box units and when the temperature profile of the spaceflight was applied. The preparation and course of both spaceflight and ground experiment went uncomplicated.



Vitamin D plunger box unit. ESA image.

Five days of microgravity during the Odissea mission (Soyuz 5S/Soyuz 4S exchange) did not affect the level of 1, 25(OH) 2D3-induced growth hormone expression per cell, which was used as reporter. It has, however, to be remarked that no 1-g centrifuge was present during the flight. An inflight 1-g experiment remains the ideal control as gravity is at that moment the only parameter differing between the 2 conditions. These data indicate that in this model where only certain aspects of the 1, 25(OH) 2D3 signaling cascade are analyzed, the endpoint of the 1, 25(OH) 2D3 signaling cascade, namely gene transcription and protein synthesis of a reporter gene, was not altered by microgravity. However changes in the different aspects of the 1, 25(OH) 2D3 signaling pathway, namely the passage of 1, 25(OH) 2D3 through the plasma membrane, its binding to the vitamin response (VDR), transport to the nucleus, and the binding of the heterodimer VDR-RXR to its response element cannot be excluded although they did not result in altered production of the reporter.

These data suggested that other factors in the promoter beside VDRE can affect 1, 25(OH) 2D3-induced gene expression during microgravity. Recently, it has become evident that chromatin modifications outside the binding sites for transcription factors contribute to gene transcription and this has also been observed for vitamin D-regulated gene expression. It therefore remains possible that 1, 25(OH) 2D3-induced gene transcription was impaired under microgravity due to chromatin modifications.

PUBLICATION(S)

Coenegrachts L, Stockmans I, Segers I, Bouillon R, Carmeliet G. The effect of microgravity on 1, 25-dihydroxyvitamin d3 signaling in osteoblasts. *Microgravity Science and Technology*. September 2007;19(5-6):154-158. doi: 10.1007/BF02919472.

This investigation is complete and all results are published.

ADVANCED PROTEIN CRYSTALLIZATION FACILITY (APCF) , EIGHT INVESTIGATIONS

Research Area: Macromolecular Crystal Growth

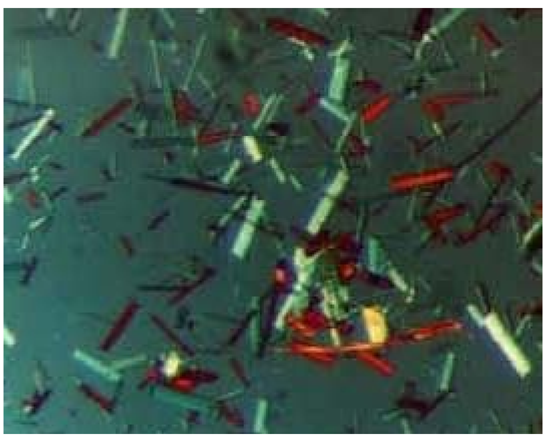
Expedition(s): 3

Principal Investigator(s):

- Lode Wyns, PhD, Free University, Brussels, Belgium
- Sevil Weinkauf, PhD, Technische Universität München, München, Germany
- Richard Giege, PhD, Center National Research Science, Strasbourg, France
- Manfred W. Baumstark, MD, University of Frieburg, Frieburg, Germany
- Fermin Otalora Munoz, University of Granada, Granada, Spain
- Joseph Martial, Université de Liège, Liège, Belgium
- Adriana Zagari, PhD, University of Naples, Naples, Italy
- Willem J. de Grip, PhD, University Nijmegen, Nijmegen, Netherlands

RESEARCH OBJECTIVES

The Advanced Protein Crystal Facility is a specialized microgravity facility offering researchers several different crystal growth options in a controlled environment enabling undisturbed nucleation (beginning of chemical changes at discrete points in a system) and growth of proteins to obtain large crystals for analysis on Earth. Understanding the results obtained from the crystals can lead to advances in manufacturing and biological processes.



Camelid crystals grown by diffusion under microgravity aboard STS-95 during October, 1998. NASA Johnson Space Center image.

EARTH BENEFITS

Biotechnology and pharmaceutical researchers carry out the process of protein crystallization in order to grow large, well-ordered crystals for use in X-ray diffraction studies. However, on Earth, the protein crystallization process is hindered by forces of sedimentation and convection since the molecules in the crystal solution are not of uniform size and weight. This leads to many crystals of irregular shape and small size that are unusable for X-ray diffraction. X-ray diffraction is a complex process that requires several months to several years to complete, and the quality of data obtained about the 3-D structure of a protein is directly dependent on the degree of perfection of the crystals. Thus, the structures of many important proteins remain a mystery simply because researchers are unable to obtain crystals of high enough quality or large enough size. Consequently, the growth of high quality macromolecular crystals for diffraction analyses has been of primary importance for protein engineers, biochemists, and pharmacologists. Fortunately, the microgravity environment aboard the ISS is relatively free from the effects of sedimentation and convection and provides an exceptional environment for crystal growth. Crystals grown in microgravity could help scientists gain detailed knowledge of the atomic, 3-D structure of many important protein molecules used in pharmaceutical research for cancer treatments, stroke prevention, and other diseases. The knowledge gained could be instrumental in the design and testing of new drugs.

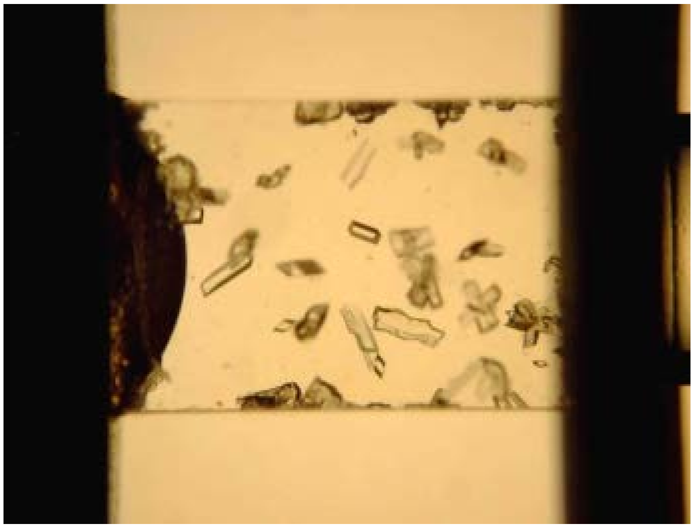
Space Benefits

The crystals grown in microgravity are able to grow larger and more organized than those grown on Earth. The results from this investigation may further human space exploration efforts by creating technological and biological advancements as a direct result from this research.

Results

Initial analysis of crystals returned from station support the findings of earlier APCF flights: comparative crystallographic analysis indicates that space-grown crystals are superior in every way to control-group crystals grown on Earth under identical conditions (except the critical space environment). Crystals grown in microgravity generally have improved morphology, larger volume, higher diffraction limit, and lower mosaicity as compared to Earth-grown crystals. The researchers reported that the electron-density maps calculated from diffraction data contained considerably more detail, allowing them to produce more accurate 3-D models (Vergara 2005).

The APCF hardware performed well during International Space Station (ISS) Expedition 3 with very few anomalies. APCF-Camelids, APCF-Crystal Quality, APCF-Growth, APCF-Lysozyme, APCF-Octarellins and APCF-PPG10 all produced excellent quality crystals that had better resolution and other optical properties than those grown on Earth. APCF-Lipoprotein successfully produced crystals, but they did not achieve the expected level of resolution. APCF-Rhodopsin had slight technical problems that prevented the formation of suitable crystals.



Camelid crystals, complexed with lysozyme, grown in the Advanced Protein Crystallization Facility during International Space Station Expedition 3. NASA Johnson Space Center image.

Well-diffracting crystals prepared in space have 2 purposes: understanding the gravity-dependent phenomena (such as nucleation and growth mechanisms) and structural determination. Each new high-resolution structure may become the start of a cascade of investigations to unravel the complexity of the cellular events like growth, division, differentiation, communication, motility, death, and their role in the development of multicellular organisms. This may accelerate the structure-based design and redesign of drugs targeting pathogens, diseases, and degenerative cellular processes as well as of protein and nucleic acid leading to custom enzymes, ribozymes, or inhibitors to treat diseases.

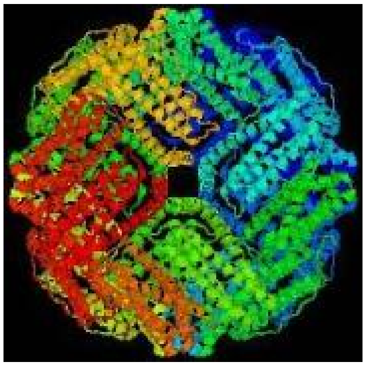
APCF-CAMELIDS (WYNS)

Four of the 6 reactors used for APCF-Camelids produced crystals. Optical analysis and interferometry were used to determine the crystals' properties that included a maximum resolution of 1.2A. This was much better than crystals grown under similar conditions on Earth and comparable to the best resolution ever achieved for crystals grown in hanging-drop experiments aboard the shuttle.

APCF-CRYSTAL GROWTH (WEINKAUF)

After their return to Earth, the ferritin crystals were found to have better diffraction than Earth-grown crystals but the data collection was incomplete. The lumazin synthase crystals had diffraction properties equal to those grown on Earth.

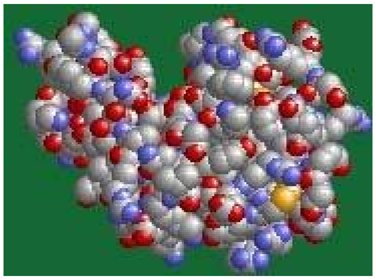
APCF-CRYSTAL QUALITY (GIEGE)



Computer generated image of a ferritin molecule. NASA image.

Crystallographic analysis indicates that the space-grown crystals are superior to the control-group crystals grown on Earth. Crystals grown in microgravity generally have improved morphology, larger volume, better optical properties, higher diffraction limit, and lower mosaicity when compared to Earth-grown crystals. Several space-grown crystals including Aspartyl-tRNA Synthetase and thaumatin have a common feature; an increased number of ordered hydrogen-bound water molecules in the hydration layer of the protein. This may be responsible for the enhanced stability of the protein crystals (Vergara 2005).

Well-diffracting crystals prepared in space have 2 purposes: understanding the gravity-dependent phenomena (such as nucleation and growth mechanisms) and structural determination. Each new high-resolution structure may become the start of a cascade of investigations to unravel the complexity of the cellular events like growth, division, differentiation, communication, motility, death, and their role in the development of multicellular organisms. This may accelerate the structure-based design and redesign of drugs targeting pathogens, diseases and degenerative cellular processes as well as of protein and nucleic acid leading to custom enzymes, ribozymes, or inhibitors to treat diseases.



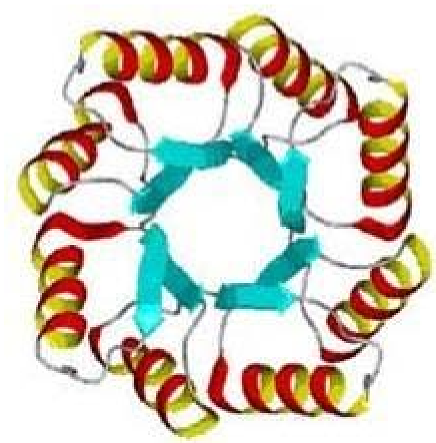
Computer generated image of a lysozyme molecule. NASA image.

APCF-LIPOPROTEIN (BAUMSTARK)

Although APCF-Lipoprotein successfully produced crystals, the main objective of achieving a significant improvement in resolution (compared to Earth-grown crystals) was not accomplished. However, there was some indication that parameters like mosaicity and the signal/noise ratio were in fact improved.

APCF-Lysozyme (Munoz)

Initial analysis of crystals returned from station support the findings of earlier APCF flights: comparative crystallographic analysis indicates that space-grown crystals are superior in every way to control-groups crystals grown on Earth under identical conditions (except the critical space environment). Crystals grown in microgravity generally have improved morphology, larger volume, higher diffraction limit, and lower mosaicity as compared to Earth-grown crystals. The researchers reported that the electron-density maps calculated from different diffraction data contained considerably more detail, allowing them to produce more accurate 3-D models (Vergara 2005).



Ribbon Structure showing the main chain de novo design o the idealized alpha/beta-barrel. This scaffold has been used for the design of the next generation octarellin. NASA image.

The APCF hardware performed well during ISS Expedition 3 with very few anomalies. APCF-Camelids, APCF-Crystal Quality, APCF- Crystal Growth, APCF- Lysozyme, APCF-Octarellins and APCF-PPG10 all produced excellent quality crystals that had better resolution and other optical properties than those grown on Earth. APCF-Lipoprotein successfully produced crystals but they did not achieve the expected level of resolution. APCF-Rhodopsin had slight technical problems that prevented the formation of suitable crystals. The more recently developed Granada Crystallization Facility (GCF) makes it possible to carry out a larger number of experiments. To optimally use the results from these experiments, it was necessary to visualize the crystal development throughout the forming process. The Protein Microscope for the International Space Station (PromISS) was developed for observation by digital holography. This method enabled researchers to evaluate the initial appearance of crystals, their growth rates, and the movement of crystals. Adjustments need to be made to reduce the sensitivity of the PromISS to vibrations aboard the ISS and also to have the crystals form within the observation time.

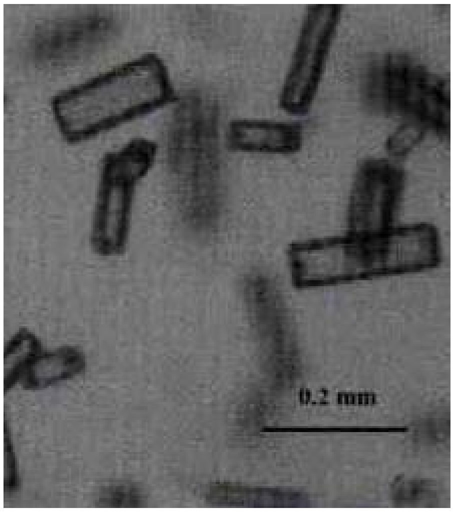
Well defracting crystals prepared in space have 2 purposes: understanding the gravity-dependent phenomena (such as nucleation and growth mechanisms) and structural determination. Each new high-resolution structure may become the start of a cascade of investigations to unravel the complexity of cellular events like growth, division, differentiation, communication, motility, death, and their role in the development of multicellular organisms. This may accelerate the structure-based design and redesign of drugs targeting pathogens, diseases, and degenerative cellular processes as well as of protein and nucleic acid leading to custom enzymes, ribozymes, or inhibitors to treat diseases.

APCF-Octarellins (Martial)

Data for this investigation was inconclusive.

APCF-PPG10 (Zagari)

Early published results have come out for crystals of (Pro-Pro Gly) 10 (PPG10). PPG10 is a collagen protein found in many tissues. This collagen is particularly concentrated in the skin, joints, and bones. Video that was collected during Expedition 3 showed the small movements within the crystallizing solutions. A direct correlation between crystal motion and acceleration from events on station (such as docking, venting, and crew movement) was determined for the first time. The PPG10 crystals were independently studied by X-ray diffraction in various labs; the best resolution attained for microgravity-grown crystals from ISS was 1.5A, superior to the 1.7A obtained on the ground. The teams of APCF scientists are combining data from previous spaceflights, the ground, and the station to get the best possible information on protein structures for applications in pharmaceutical and physiological research (Vergara 2005).



PPG10 crystals grown in microgravity, in reactor number 612 containing agarose gel. NASA image.

PPG10 crystals grown aboard the ISS were observed to move coherently and followed parallel trajectories, which was different from movements observed aboard the shuttle. These movements have been linked to large-scale acceleration events such as the undocking of the shuttle, change in ISS attitude, and the venting of water and air. Final distribution of the crystals in solution was strongly affected by this motion. Crystal appearance time and growth rate was comparable in all crystal environments (agarose gel in microgravity, solution on Earth and agarose gel on Earth). These observations suggest that the crystal growth mechanism is kinetically controlled (Vergara 2002, Berisio 2002).
Using 2 other experiment aboard ISS Microgravity Acceleration Measurement System (MAMS)—which measured residual gravity on the experiment—and Space Acceleration Measurement System (SAMS)—which measured acceleration caused by space craft docking and undocking, change in ISS attitude, venting, and crew movement—a direct correlation between crystal motion and acceleration was determined for the first time. However, this paper reports that there is no apparent correlation between the resulting crystal motions and crystal quality.

APCF-Rhodopsin (de Grip)

Even though the reactors successfully produced small crystals on Earth, they did not perform well during their stay on ISS Expedition 3. Apparently, slight technical problems developed that lead to minor leakage of the protein chamber. Slow destabilization of the rhodopsin protein occurred that prevented formation of suitable crystals (One Year Postflight Report).

Publication(s)

Vergara A, Lorber B, Sauter C, Giege R, Zagari A. Lessons from crystals grown in the Advanced Protein Crystallisation Facility for conventional crystallization applied to structural biology. *Biophysical Chemistry*. 2005;118(2-3):102-112. doi: 10.1016/j.bpc.2005.06.014.

Castagnolo D, Piccolo C, Carotenuto L, Vergara A, Zagari A. Crystalization of the collagen-like polypeptide (PPG)10 aboard the International Space Station. 3. Analysis of residual acceleration-induced motion. *Acta Crystallographica Section D: Biological Crystallography*. 2003;59(pt4): 773-776.

Berisio R, Vitagliano L, Vergara A, Sorrentino G, Mazzarella L, Zagari A. Crystallization of the collagen-like polypeptide (PPG) 10 aboard the International Space Station. 2. Comparison of crystal quality by X-ray diffraction. *Acta Crystallographica Section D: Biological Crystallography*. 2002;58:1695-1699.

Garcia-Ruiz JM, Gonzalez Ramirez LA, Gavira JA, Otalora Munoz F. Granada crystallisation box: A new device for protein crystallisation by counter-diffusion techniques. *Acta Crystallographica Section D: Biological Crystallography*. September 26, 2002;58:1638-1642. doi: 10.1107/S0907444902014464.

Vergara A, Corvino E, Sorrentino G, et al. Crystallization of the collagen-like polypeptide (PPG)10 aboard the International Space Station. 1. Video observation. *Acta Crystallographica Section D: Biological Crystallography*. 2002;58:1690-1694.

This investigation is complete and all results are published.

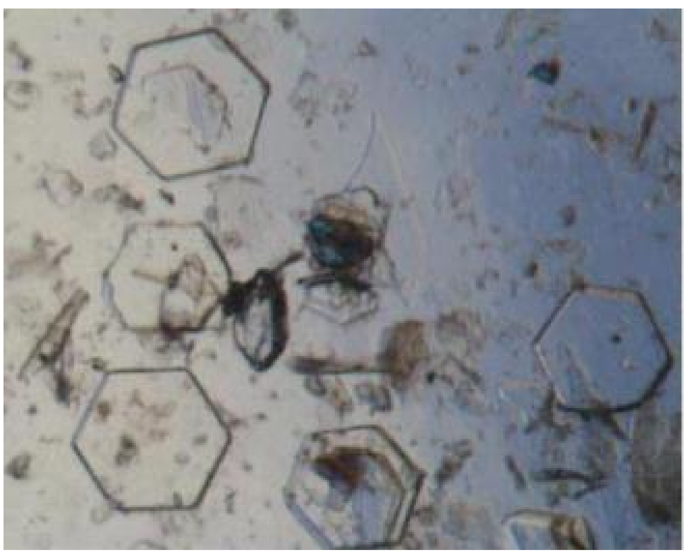
COMMERCIAL PROTEIN CRYSTAL GROWTH-HIGH DENSITY (CPCG-H)

Research Area: Macromolecular Crystal Growth
Expedition(s): 2 and 4
Principal Investigator(s):
- Lawrence J. DeLucas, OD, PhD, University of Alabama at Birmingham, Birmingham, Alabama

RESEARCH OBJECTIVES

Commercial Protein Crystal Growth - High Density (CPCG-H) tests hardware using a variety of protein crystal growth methods. Researchers aim to determine the most appropriate type of hardware for each experiment and which type of hardware could be permanently added to or removed from International Space Station (ISS) facilities for future protein crystal experiments. Protein crystal growth experiments aid the generation of computer models of carbohydrates, nucleic acids and proteins, and further advance the progress of biotechnology. Understanding these results can lead to advances in manufacturing and biological processes, both in medicine and agriculture.

EARTH BENEFITS



Thermus flavus crystals of the 7bp helix B1 grown on the International Space Station Expedition 2. Image provided by Acta Crystallographica. Section D, Biological Crystallography. Crystallization and Structure Analysis of *Thermus flavus* 5S rRNA helix B.

Knowledge of precise 3-D molecular structure is a key component in biotechnology fields such as protein engineering and pharmacology. In order to obtain accurate data on the 3-D structure of protein crystals or other macromolecules, scientists employ a process called X-ray crystallography. Crystallographers construct computer models that reveal the complex structures of a protein molecule. In order to generate an accurate computer model, crystallographers must first crystallize the protein and analyze the resulting crystals by a process called X-ray diffraction. Precise measurements of thousands of diffracted intensities from each crystal help scientists map the probable positions of the atoms within each protein molecule. This complex process requires several months to several years to complete.

The quality of structural information obtained from X-ray diffraction methods is directly dependent on the degree of perfection of the crystals. Thus, the structures of many important proteins remain a mystery simply because researchers are unable to obtain crystals of high enough quality or large enough size. Generally, crystals must have dimensions of approximately 0.3 mm to 1.00 mm, and the protein molecules must be arranged in an orderly, repeating pattern. Consequently, the growth of high quality macromolecular crystals for diffraction analyses has been of primary importance for protein engineers, biochemists, and pharmacologists.

On Earth, the crystallization process is hindered by forces of sedimentation and convection since the molecules in the crystal solution are not of uniform size and weight. This leads to many crystals of irregular shape and small size that are unusable. However, the microgravity environment aboard the ISS is relatively free from the effects of sedimentation and convection and provides an exceptional environment for crystal growth.

Space Benefits

The crystals grown in microgravity are able to grow larger and more organized than those grown on Earth. The results from this investigation may further human space exploration efforts by creating technological and biological advancements as a direct result from this research.

Results

Preliminary analysis indicated that at least 65% of the macromolecules flown in the CPCG-H experiments produced diffraction-sized crystals. X-ray diffraction studies of these crystals were conducted, and the data were used to determine and refine the 3-D structures of these macromolecules. Three benchmark proteins, ML-I, *Thermus flavus* 5S RNA, and BARS, were flown to validate the performance of the hardware. Diffraction-quality crystals, which were obtained from all of these proteins, yielded X-ray diffraction data comparable to those previously collected on Earth-grown crystals. Since the structure of each of the benchmark proteins is known to high resolution, these results indicate that the new HDPCG assembly worked very well, successfully producing high-quality crystals of the benchmark proteins.

ISS004E10827 – Astronaut, Carl Walz works with CPCG-H in US Laboratory during International Space Station Expedition 4.

Synchrotron diffraction data, collected from the space crystals of the BARS protein, were comparable in resolution but more intense and showed significantly less mosaicity than data from Earth-grown crystals. This indicates that the space-grown crystals had a higher order at the molecular level, and the X-ray diffraction data from the space crystals produced a more complete data set. These results contributed significantly to the structural study of BARS (Nardini 2002).

ML-I is an enzyme that has the ability to inactivate ribosomes and inhibit cell replication. It is a target for new cancer treatments. Crystals of the protein attached to adenine (2 of 5 building blocks of DNA or RNA) were flown, and these crystals yielded X-ray data to 1.9 angstrom. These data were used to refine the structure of the complex and were especially valuable in refining the active site conformation (Krauspenhaar 2002). Perhaps the most exciting results from the macromolecular crystallization experiments conducted in the CPCG-H hardware were obtained from the *Thermus flavus* 5S rRNA [ribosomal ribonucleic acid] experiments. These experiments involved a synthetic RNA duplex of 5S rRNA, which is a model system for the study of the binding of ribosomal RNA to proteins. Crystallization under microgravity provided crystals of significantly higher quality than those grown in one-g. The space crystals diffracted to a maximum resolution of 2.6 angstrom in contrast to the best Earth-grown crystals, which diffracted to 2.9 angstrom. The improved X-ray data facilitated the completion of the structure of the RNA segment (Vallazza 2002).

To understand the true function of a protein, the structure must be determined. The model of the structure must be accurate to allow scientists to create compounds that bind to the protein. The understanding of the protein structure is of major importance with complex proteins (proteins that have significant folding). The 3-D structure of the triple mutant protein Mb-YQR was solved by growing the protein on ISS during Expeditions 2 and 4. Following return to Earth, 3-D models were created of the Mb-YQR proteins grown in space using X-ray crystallography techniques (Miele 2004).

Structural studies of microgravity-grown crystals have provided important information for the development of new drugs. For example, previous studies conducted using crystals grown on shuttle flights have been used in the design of inhibitors, which may serve as broad-spectrum antibiotics. The CPCG-H payload offers a great increase in the amount of space available for protein crystal growth, enhancing the space station’s research capabilities and commercial potential.

Publication(s)

Miele AE, Federici L, Sciara G, Draghi F, Brunori M, Vallone B. Analysis of the effect of microgavity on protein crystal quality: The case of a myoglobin triple mutant. *Acta Crystallographica Section D: Biological Crystallography*. 2004;D59: 928-988.

Krauspenhaar R, Rypniewski W, Kalkura N, et al. Crystallisation under microgravity of mistletoe lectin I from Viscum album with adenine monophosphate and the crystal structure at 1.9 angstrom resolution. *Acta Crystallographica Section D: Biological Crystallography.* 2002;58:1704-1707.

Nardini M, Spano S, Cericola C, et al. Crystallization and preliminary X-ray diffraction analysis of brefeldin A-ADP ribosylated substrate (BARS). *Acta Crystallographica Section D: Biological Crystallography*. 2002;58: 1068-1070.

Vallazza M, Banumathi S, Perbandt M, et al. Crystallization and structure analysis of thermus flavus 5S rRNA helix B. *Acta Crystallographica Section D: Biological Crystallography*. 2002;58:1700-1703.

This investigation is complete and all results are published.

DYNAMICALLY CONTROLLED PROTEIN CRYSTAL GROWTH (DCPCG)

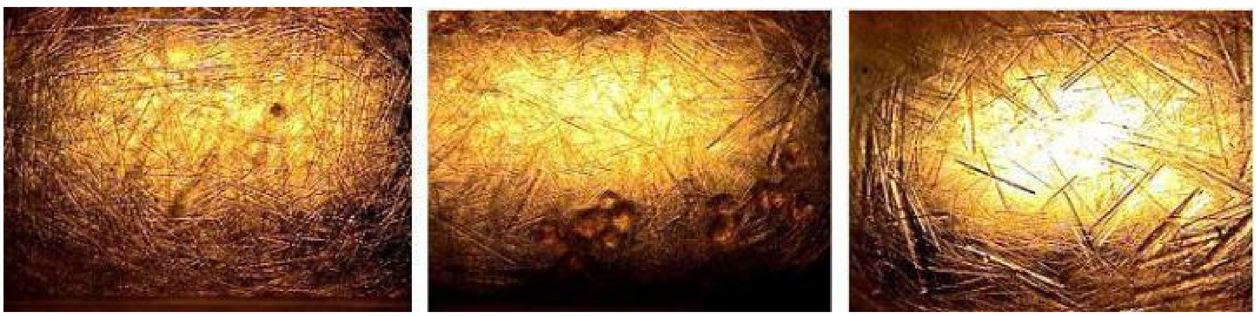
Research Area: Macromolecular Crystal Growth

Expedition(s): 3

Principal Investigator(s):
- Lawrence J. DeLucas, OD, PhD, University of Alabama at Birmingham, Birmingham, Alabama

RESEARCH OBJECTIVES

Dynamically Controlled Protein Crystal Growth demonstrates significant advances in the ability of researchers to control protein crystal growth processes. Previous research demonstrated that macromolecular crystals grown in microgravity are frequently larger and more perfectly formed than their Earth grown counterparts. Understanding the results obtained from the crystals can lead to advances in manufacturing and biological processes.



Glucose Isomerase crystals from Dynamically Controlled Protein Crystal Growth on International Space Station Expedition 3. From left to right, fast evaporation rate, medium evaporation rate and slow evaporation rate. NASA image.

EARTH BENEFITS

Proteins play a key role in the living world around us. They are the building blocks for humans and other animals and they regulate the biochemical processes of plants. Knowledge of the structure and design of proteins helps researchers design new drugs, combat disease, and improve agricultural products, such as pesticides. Researchers are unlocking this knowledge by studying protein crystals, their growth, and 3-D atomic structure. For the most part, drugs are not so much discovered anymore, they are designed. Scientists can now target a specific protein of a pathogen, be it bacterial or viral, to maximize a drug’s effectiveness while at the same time minimizing possible side effects. This method, known as rational drug design, has one major downside. The exact structure of the target protein must be determined, down to the last molecule. To uncover this molecular structure, scientists use X-ray crystallography. A crystal of the protein is bombarded with X-rays to produce a pattern, which, much like a fingerprint, reveals the identity of the protein’s atomic structure. But to get an accurate pattern, the crystal must be as free of imperfections as possible. Growing such crystals can be extremely difficult, even impossible, on Earth because gravity causes the crystals to settle on top of one another resulting in structural flaws.

The DCPCG system demonstrates significant advances in the ability of researchers to gain control of the protein crystal growth process and provides tremendous opportunities for both terrestrial and microgravity research. Large, high-quality crystals are necessary for the determination of the molecular structure of macromolecules by X-ray diffraction analysis. Previous research has demonstrated that macromolecular crystals grown in microgravity are frequently larger and more perfectly formed than their Earth grown counterparts. This improvement in size and quality translates into X-ray diffraction data of higher resolution and intensity, yielding better structural information about the molecule.

Space Benefits

The crystals grown in microgravity are able to grow larger and more organized than on Earth. The research done on these crystals may further human space exploration efforts by technological and biological advancements developed as a direct result from this research.

Results

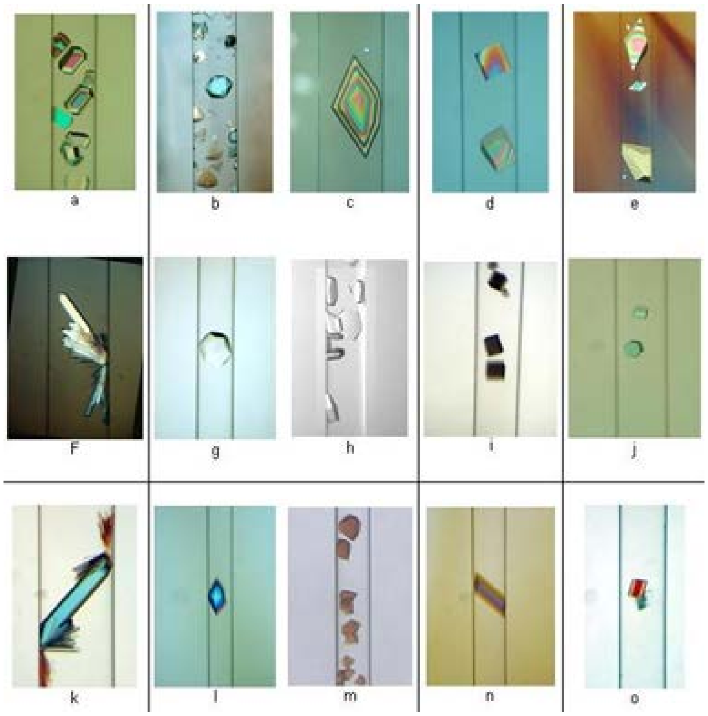
DCPCG was the first flight test of an apparatus designed to control the crystal growth process by controlling the rate of evaporation. The apparatus worked in orbit, and crystals were grown for the test proteins; however, the investigators determined that the growth could have been better. The same apparatus was used in extensive testing on the ground. Researchers tested a selection of protein solutions, including insulin (a hormone produced by the pancreas to regulate the metabolism and use of sugar), serum albumin, and lysozyme (an enzyme that attacks bacteria) and found that a slower evaporation rate yielded better results than a more rapid evaporation rate. While the results of the ground tests were published, the DCPCG experiment investigators did not seek to publish any structures from crystals grown in orbit.

Additional flights were originally scheduled for this investigation until funding was removed. Due to the loss of funding, no additional analysis was performed.

This investigation is complete and all results are published.

Granada Crystallisation Facility (GCF)

Research Area: Macromolecular Crystal Growth
Expedition(s): 3, 5, 6-10, 12, 14-17
Principal Investigator(s):
- Juan Manuel Garcia-Ruiz, PhD University of Granada, Granada, Spain



Example of proteins crystallized in the Andromede mission a) Lysozyme; b) Dehydroquinase; c,e) Thaumatin; d) Concanavalin A; f,k,n) Anti lysozyme camel antibody; g) Insulin; h) Lumazine synthase; i) Catalase; j,o) Factor XII; l) Saicar synthase; m) Ferritin. LEC, Granada, Spain images.

Research Objectives

The Granada Crystallisation Facility (GCF) experiment concerns the crystallization of proteins in space by the counter-diffusion technique. The major objective is to produce a detailed analysis and quantitative interpretation of the relationship between the quality of the crystals and the environment in which they were produced. The secondary objective of the project is to compare identical experiments performed in space with free protein solutions on one hand, and on the ground in gelled protein solutions on the other hand.

Results

Most of the molecules did crystallize, both in space and on the ground and correspond to those molecules in which crystallization conditions were adequately optimized. Owing to the very short time available to prepare this project, the optimal crystallization conditions could not be found for some molecules, and they did not crystallize, either in space or on ground.

Both on ground and microgravity grown crystals showed very good I/sigma(I) values for the crystallographic analysis performed postflight. For the model proteins, the values were comparable to the best obtained by other techniques.

An analysis of the slight differences in crystal quality in terms of I/sigma(I) as a function of the resolution revealed the inexistence of a clear and consistent pattern that led to conclude which environment yields the best crystals. The effect of redundancy on I/sigma(I) was clearly observed in the thaumatin: data sets collected at room temperature from crystals grown in space with gel, without gel, and on ground share similar multiplicity and yield similar crystal quality in terms of I/sigma(I). Interestingly, the differences in crystal quality that appeared between the data sets collected at 100 Kelvin and their counterpart collected at room temperature can be correlated with differences in redundancy.

In some cases, crystal quality was evaluated by X-ray diffraction. Regarding the crystal quality, the preliminary analysis of the data sets collected with synchrotron radiation showed that the crystals grown with the counter-diffusion technique shared excellent global indicators of X-ray data quality with no obvious difference between crystals grown under reduced convection conditions in space and crystals grown under convection free conditions on ground.

It is noticeable that due to unexpected logistic and safety problems, the data recorder could not be used with the space GCF. Therefore, it is impossible to know if the temperature profile during the mission and the one on the GCF on ground were similar enough to permit a reasonable crystal quality comparison.

PUBLICATION(S)

Maes D, Decanniere K, Zegers I, et al. Protein crystallization under microgravity conditions: What did we learn on TIM crystallization from the Soyuz missions. *Microgravity Science and Technology*. 2007;XIX-5/6:90-94.

Garcia-Ruiz JM. Counter diffusion methods for macromolecular crystallization. *Methods in Enzymology*. 2003;368:130-154. doi: 10.1016/S0076-6879(03)68008-0.

Garcia-Ruiz JM, Gonzalez Ramirez LA, Gavira JA, Otalora Munoz F. Granada Crystallization Box: A new device for protein crystallization by counter-diffusion techniques. Acta Crystallographica Section D: *Biological Crystallography*. September 26, 2002;58(10):1638-1642. doi: 10.1107/S0907444902014464.

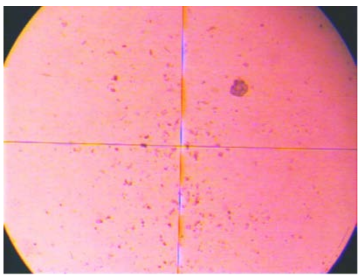
This investigation is complete and all results are published.

Identifying and Investigating Surface Glycoproteins E1-E2 of Alphaviruses on Earth and in Space (Glikoproteid)

Research Area: Macromolecular Crystal Growth
Expedition(s): 11-13 and 16-17
Principle Investigator(s):
- Grigoriy Y. Shcherbakov, MD, PhD, Biopreparat, Moscow, Russia

Research Objectives

The Identifying and Investigation Surface Glycoproteins E1-E2 of Alphaviruses on Earth and in Space (Glikoproteid) obtains data on the atomic structure of glycoprotein biomolecules with the highest possible resolution to create effective and safe new generation vaccines and to develop new antiviral medications and diagnostic systems.



Results of the experiment during ISS-13. Microscopic video imagery of the contents of the crystallization cells in chamber 4 of bio-crystallization cassette No.5 containing glycoprotein. The linear dimensions of the largest crystals are 35 - 85 micron. Roscosmos image.

Earth Benefits

The surface glycoprotein E of the West Nile virus is the main target for virus neutralizing antibodies. The accurate spatial mapping of neutralizing virus epitopes is of fundamental importance for the development of antiviral medications, vaccines, and diagnostic tests. The project implementation provided fundamentally new information on the structure of a new type of viral proteins and combined the accumulated information on the organization of the virions of an entire family of warm-blooded animal viruses.

Space Benefits

The space grown crystals will be used to determine the 3-dimensional structure of the protein. This will facilitate the continuation of the refinement of the technology for obtaining bio-crystals in microgravity and the development of crystallographic research in space in order to obtain high-quality protein crystals.

Results

As a result of the Glikoproteid experiment, in most cases, the presence of small prism-shaped crystals was identified with a maximum size of approximately, 100 micron in the presence of amorphous deposits. The development relates to the following aspects. First, to the principal role of the E1 and E2 glycoproteins in the development of the infection process and the generation of an immune response to an alphavirus infection. Second, to the prevalence of alphavirus infections among pets and humans. Third, to the structural specifics of viral proteins, which as a rule, are typical for a group of viruses and usually differ greatly from other proteins.

This investigation is complete; however additional results are pending publication.

JAPAN AEROSPACE EXPLORATION AGENCY – GRANADA CRYSTALIZATION FACILITY HIGH QUALITY PROTEIN CRYSTALLIZATION EXPERIMENT (JAXA-GCF), 238 INVESTIGATIONS

Research Area: Macromolecular Crystal Growth
Expedition(s): 7-10, 12, 14, and 15-17
Principle Investigator(s):
- Masaru Sato, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

The primary objective of JAXA-GCF is to provide a low-cost, simple experiment platform for the production of high quality protein crystals in the microgravity environment in order to understand the relationship between protein structure and function.

EARTH BENEFITS

Biotechnology and pharmaceutical researchers carry out the structural analysis of proteins as part of their research process. However, it is difficult to obtain high quality protein crystals on Earth because the sedimentation and convection caused by gravity adversely affects the protein crystal growth. This makes it difficult to obtain suitable crystals for X-ray diffraction experiments. The quality of the 3-D structural information of a protein depends on the quality of the crystals. Thus, the structures of many important proteins remain unknown due to difficulties obtaining high quality and/or large size crystals. Consequently, the high-quality macromolecular crystals obtained for diffraction analysis are still important for protein engineers, biochemists, and pharmacologists.

ISS014E20129 – A close-up view of the JAXA-Granada Crystallization Facilities (GCF) in the Thermo Biological Universal (TBU) during Expedition 14. JAXA image.

SPACE BENEFITS

The results from this investigation may further human space exploration efforts by creating technological and biological advancements.

RESULTS

Through the first, second, and third space experiments, JAXA launched alpha-amylase and lysozyme proteins to validate the developed crystallization technique. As a result, high-quality protein crystals were successfully obtained (eg, up to 0.9 Å in alpha-amylase) and the structural analysis was carried out closely and carefully.

JAXA was able to obtain the highest resolution data from some of the proteins (eg, sleeping and allergy material synthetase and proteins related to symptoms of parasite infection) provided by different user organizations. We expect these results will lead to new drug development in the future.

PUBLICATION(S)

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Kuranova IP, Smirnova E, Abramchik YA, et al. Crystal growth of phosphopantetheine adenylyltransferase, carboxypeptidase T, and thymidine phosphorylase on the International Space Station by the capillary counter-diffusion method. *Crystallography Reports*. September 2011;56(5):884-891. doi: 10.1134/S1063774511050154.

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Takahashi S, Tsurumura T, Aritake K, et al. High-quality crystals of human haematopoietic prostaglandin D synthase with novel inhibitors. *Acta Crystallographica Section F: Structural Biology and Crystallization Communications.* 2010;66(Pt. 7):846-850. doi: 10.1107/S1744309110020828.

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Crystallographica Section F: Structural Biology and Crystallization Communications. January 17, 2007;63(2):69-73. doi: 10.1107/S1744309106054625.

Aritake K, Kado Y, Inoue T, Miyano M, Urade Y. Structural and functional characterization of HQL-79, an orally selective inhibitor of human hematopoietic prostaglandin D synthase. *Journal of Biological Chemistry.* 2006;281(22):15277-15286. doi: 10.1074/jbc.M506431200.

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Tanaka H, Yoshizaki I, Takahashi S, et al. Diffusion coefficient of the protein in various crystallization solutions: The key to growing high-quality crystals in space. *Microgravity Science and Technology*. 2006;18(3/4):91-94.

Kinoshita T, Maruki R, Warizaya M, Nakajima H, Nishimura S. Structure of a high-resolution crystal form of human trisephosphate isomerase: Improvement of crystals using the gel tube method. *Acta Crystallographica Section F: Structural Biology and Crystallization Communications*. 2005;61:346-349. doi: 10.1107/S1744309105008341.

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This investigation is complete; however additional results are pending publication.

Japan Aerospace Exploration Agency Protein Crystal Growth (JAXA PCG), 114 Investigations

Research Area: Macromolecular Crystal Growth
Expedition(s): 19-ongoing
Principle Investigator(s):
- Kazunori Ohta, Japan Aerospace Exploration Agency, Tsukuba, Japan

Research Objectives

The Japan Aerospace Exploration Agency Protein Crystal Growth (JAXA PCG) studies the growth crystals of biological macromolecules using the counter-diffusion technique. JAXA PCG creates high-quality protein crystals in a microgravity environment to apply to structural biology and pharmaceutical activities.

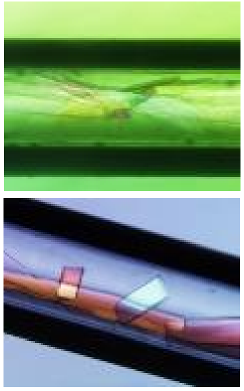
ISS028E49720 – ISS crewmembers Satoshi Furakawa (L) and Sergei Volkov (R) holding the JAXA PCG during ISS Expedition 28.

Earth Benefits

This investigation may contribute to society by creating new drugs for diseases and new catalysts for the environment or for energy production.

Space Benefits

This investigation is applied to new knowledge and not specifically to advances in space exploration.



Crystal photo of alpha-amylase (upper:grown on ground, lower: grown in space). JAXA image

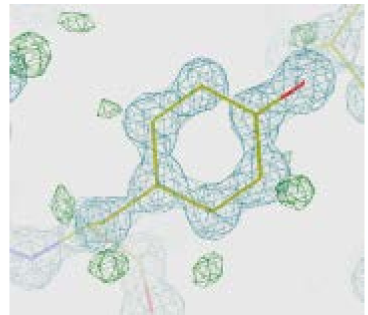
Results

The JAXA PCG studies have been performed for more than 20 years. JAXA has conducted protein crystallization experiments aboard the International Space Station (ISS) since 2003. In this experiment, over 300 protein samples were launched in order to obtain high-quality crystals in space. In the past PCG missions, 60-70% of the proteins experimented were crystallized as single crystals. Excellent diffraction data used to determine the precise structure of proteins were obtained for several different proteins. Detailed structural analysis of those proteins are currently being conducted.

In microgravity, the incorporation of molecules into the crystal highly depends on diffusion. The incorporated molecules may be allocated in order and the incorporation of impurity may be suppressed. Consequently, these nature of microgravity environment brings the growth of the highly ordered crystals. It is assumed that the formation of a protein depletion zone (PDZ) and an impurity depletion zone (IDZ) around growing crystals under a microgravity environment is due to the suppression of a convection flow. The combination of the crystal size (R), the diffusion coefficiency of the protein molecule (D), and the kinetic coefficiency for the protein molecule (β), Rβ/D, could be an index of the extent of these depletion zones. Larger 'Rβ/D' are favorable to maximize the effect of microgravity environment. 'D' can be decreased by using high-viscous reagent such as polyethylene glycol (PEG) 8000 for crystallization solution, and 'β' can be increased by using highly purified protein sample for crystallization. Researchers now become able to estimate microgravity effects and optimize the crystallization condition prior to performing microgravity experiments by referring to this β/D value.

Here are some results of the successful crystallization experiments in space.

The crystals of *Aspergillus oryzae* alpha-amylase were obtained as cluster-like crystals that diffracted up to 1.4 Å resolution on the ground so far. However, after the further purification of the protein sample using FPLC and changing the precipitant from salt to high viscous polyethylene glycol (PEG) 8000, high-quality crystals were obtained. These crystals diffracted up to 0.79 Å resolution by visual inspection; and a full X-ray diffraction dataset could be obtained up to 0.92 Å resolution. After the data analysis, the electron density corresponding to hydrogen atoms were visualized.



Electron density map of alpha-amylase Image courtesy of Professor Nakagawa, Osaka University.

Hematopoietic prostaglandin D synthase (H-PGDS) and Lipocalin-type prostaglandin D synthase (L-PGDS) are both clinically important drug target proteins provided by Professor Urade of University of Tsukuba.

H-PGDS was crystallized in space 12 times with more than 20 inhibitors since 1997. It was difficult to obtain good crystals of H-PGDS initially. Accordingly, scientists used the same strategy, which applied to the crystallization of alpha-amylase, to the crystallization of H-PGDS (using PEG as a high-viscous precipitant and highly purified protein sample). Afterward, investigators were able to obtain high-quality crystals of H-PGDS with novel inhibitors that diffracted X-ray waves up to 1.1 Å. Those novel inhibitors are expected to be candidates for novel drug designs.

L-PGDS with a C65A mutation was previously crystallized with citrate or malonate as a precipitant, and the X-ray crystal structure was determined at 2.0 Å resolution. Then, scientists attempted to obtain high-quality crystals of the C64A mutant under microgravity environment by using the same conditions as used in the previous study, but they could not obtain a satisfactory results. Therefore the same strategy as mentioned above was used, and then high-quality crystals could be obtained in microgravity, which diffracted at around 1.0 Å resolution. The crystal quality was markedly improved through the use of a high-viscosity precipitant solution in microgravity, in combination with the use of a highly purified protein.

These examples are a part of JAXA's procedure for growing high-quality protein crystals. From the purification of a protein sample to the high-resolution X-ray data collection, including the optimization of crystallization condition on the ground, JAXA has established a sequence of experimental steps for successful crystallization in space.

PUBLICATION(S)

Timofeev V, Smirnova E, Chupova L, Esipov R, Kuranova IP. X-ray study of the conformational changes in the molecule of phosphopantetheine adenylyltransferase from Mycobacterium tuberculosis during the catalyzed reaction. *Acta Crystallographica Section D: Biological Crystallography*. November 9, 2012;68(12):1660-1670. doi: 10.1107/S0907444912040206.

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Inaka K, Tanaka H, Takahashi S, et al. Numerical analysis of the diffusive field around a growing protein crystal in microgravity. *Defect and Diffusion Forum*. April 2012;323-325:565-569. doi: 10.4028/www.scientific.net/DDF.323-325.565.

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Rahman RN, Ali MS, Leow TC, Salleh AB, Basri M, Matsumura H. The effects of microgravity on thermostable T1 lipase protein crystal. *Gravitational and Space Biology*. 2010;23(2):89-90.

This investigation is ongoing and additional results are pending publication.

PROTEIN CRYSTALLIZATION DIAGNOSTICS FACILITY - INFLUENCE OF MASS TRANSPORT AND SURFACE GROWTH PROCESSES ON PROTEIN CRYSTAL PERFECTION (PCDF)

Research Area: Macromolecular Crystal Growth
Expedition(s): 18-20
Principal Investigator(s):
- Fermin Otalora Munoz, University of Granada, Granada, Spain

RESEARCH OBJECTIVES

The specific overall goal of the Protein Crystallization Diagnostics Facility (PCDF) project is to investigate mass-transport phenomena that control crystal quality: super saturation level and fluctuation, impurity incorporation and nucleation in homogeneous fluids. Such phenomena are strongly affected by buoyancy being accompanied by concentration and, consequently, density gradients that indeed promote buoyancy driven convective instabilities.

Front view of Crystallization Diagnostics Facility hardware. ESA image.

EARTH BENEFITS

Without the convection and sedimentation effects induced by Earth's gravity, the experiments carried out in the PCDF will help to understand the fundamental processes that occur during crystallization. Understanding the process of protein crystallization can help to obtain better quality crystals. This in turn will help improve their function in various applications, such as in protein-based medicines where they are a means of controlling the release rate of an active compound, or of increasing shelf-life.

SPACE BENEFITS

Zero gravity on the International Space Station helps to prevent the occurrence of negative sedimentation impacts known from ground experiments and supports undisturbed crystal formation. Precise knowledge of the nucleation process is crucial to grow sufficiently homogeneous and large crystals, which may provide information on the protein molecule. The results from this investigation may further human space exploration efforts by creating technological and biological advancements as a direct result of this research.

RESULTS

The corrected and reprocessed Dynamic Light Scattering data obtained in the experiment indicated the presence of 3 main particle populations during the experiment: the glucose isomerase tetramer at approximately 6 nm, particles with an apparent radius around 200 nm, and a third population with apparent size between 2 and 30 µm. For each of these, the apparent size of the particle changed with reactor temperature during the nucleation experiment. The reactor also contained glucose isomerase precipitate, complicating the analysis. Nevertheless, the 200 nm particles seemed to fit well with the hypothesis of metastable dense liquid clusters in pre-nucleation conditions.

Further investigation of the pre-nucleation behavior of glucose isomerase on ground showed that the presence of the 200 nm particles is the result of specific interactions between protein and precipitant. In addition, data indicated that the apparent size of the glucose isomerase depended on both specific interactions with the precipitant and on total ionic strength.

PUBLICATION(S)

De Smet L, Klai S, Decanniere K, Haumont E. Successful PCDF PROTEIN mission in ISS after meticulous preparation and on-the-fly flexibility. *SpaceOps 2010*, Huntsville, Alabama; April 25-30, 2005:10.

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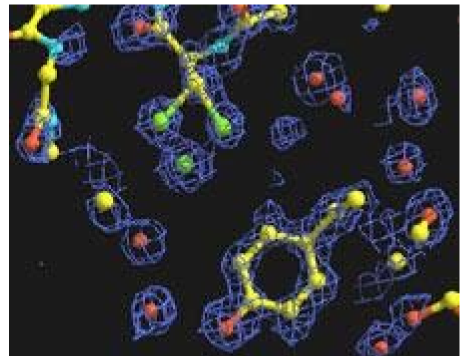
This investigation is complete and all results are published.

Protein Crystal Growth-Enhanced Gaseous Nitrogen Dewar (PCG-EGN), Thirty Investigations

Research Area: Macromolecular Crystal Growth
Expedition(s): 0-2 and 4
Principal Investigator(s):
- Alexander McPherson, PhD, University of California at Irvine, Irvine, California

Research Objectives

The Protein Crystal Growth-Enhanced Gaseous Nitrogen Dewar (PCG-EGN) experiment tests proteins and protein solutions to determine if they can tolerate the freeze-thaw mechanism used to initiate protein crystal experiments. Understanding these results can lead to a better selection process for later protein crystal experiments on the International Space Station (ISS).



Electron density map of thaumatin crystal grown on the International Space Station on Increment 2. NASA Marshall Space Center image.

Earth Benefits

Knowledge of precise 3-D molecular structure is a key component in biotechnology fields such as protein engineering and pharmacology. In order to obtain accurate data on the 3-D structure of protein crystals or other macromolecules, scientists employ a process called X-ray Crystallography. Crystallographers construct computer models that reveal the complex structures of a protein molecule. However, in order to generate accurate computer models crystallographers must first crystallize the protein and analyze the resulting crystals by a process called X-ray diffraction. Precise measurements of thousands of diffracted intensities from each crystal help scientists map the probable positions of the atoms within each protein molecule. This complex process requires several months to several years to complete.

On Earth, the crystallization process is hindered by forces of sedimentation and convection since the molecules in the crystal solution are not of uniform size and weight. This leads to many crystals of irregular shape and small size that are unusable. However, the microgravity environment aboard the ISS is relatively free from the effects of sedimentation and convection and provides an exceptional environment for crystal growth.

Space Benefits

Hardware that provides low-cost and low-crew maintenance crystal production in the microgravity environment is extremely beneficial to scientific studies on Earth. The crystals that are grown in microgravity grow larger and are better organized than those grown on Earth. The research that is done on these crystals may further human space exploration efforts by technological and biological advancements developed as a direct result of this research.

Results

The PCG-EGN experiment was a platform that provided an economical and potential high-volume avenue to produce biological protein crystals in microgravity. The samples used in the EGN Dewar were placed into individual tubes, flash frozen, and allowed to warm to the ambient temperature aboard the ISS. Crystals produced in microgravity when compared to their counterparts grown on Earth are usually larger and more defined in structure making them better candidates for X-ray diffraction studies. The X-ray diffraction studies show researchers the structure of the molecules in the proteins, and once the structure is understood, the active sites can be determined, which may lead to improvement in medical treatment for certain conditions.

Catalase crystals grown in microgravity during International Space Station Expedition 4. NASA Marshall Space Center image.

Successful crystallization rates were as follows: Expedition 0 (prior to permanent human occupation of ISS), 10 of 24 proteins and viruses; Expedition 1, 4 of 23 proteins and viruses; Expedition 2, 6 of 8 proteins and both viruses; Expedition 4, 3 of 9 proteins and 0 of 2 viruses. Major crystals obtained included Bence-Jones protein, Bromegrass Mosaic Virus, canavalin, lysozyme, pea lectin, thaumatin, trypsin, and 4a-hydroxy-tetrahydropterin dehydratase (DcoH). Overall the rate of successful crystallizations was not as high as expected. Although many of the crystals produced were no better than those obtained in the ground laboratory, there were still some significant structural results. When compared to their Earth-grown counterparts, the space-grown thaumatin crystals diffracted to a higher resolution, and some crystals showed as much as 40% more intensity during the diffraction process. This resulted in a more accurate protein structure model (electron density map) being produced from the space-grown crystal data. The pea lectin crystals also diffracted to higher resolution than their Earth-grown counterparts. Data from the space-grown crystals were the best obtained, giving rise to the highest resolution structure for pea lectin. A refinement for the structural model of pea lectin is in progress. DcoH crystals grown on Expedition 1 also appeared to be of better quality than those grown on Earth.

Student investigations across the 4 Expeditions were successful in crystallizing a number of proteins. Although many of the crystals did not appear to be better than previously analyzed crystals, some of the crystals from Expedition 2 were used for microscopic observation and X-ray examination.

Publication(s)

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This investigation is complete and all results are published.

Protein Crystal Growth-Single Locker Thermal Enclosure System (PCG-STES), Nine Investigations

Research Area: Macromolecular Crystal Growth

Expedition(s): 2, 4-11

Principal Investigator(s):

- Craig E. Kundrot, PhD, NASA's Johnson Space Center, Houston, Texas
- Geoffrey Chang, PhD, Scripps Research Institute, La Jolla, California
- Gloria E.O. Borgstahl, PhD, University of Toledo and University of Nebraska Medical Center, Toledo, Ohio
- Ronald Kaplan, PhD, Chicago Medical School, Chicago, Illinois
- Bill Thomas, Universities Space Research Association, Huntsville, Alabama
- Barbara L. Golden, PhD, Purdue University, West Lafayette, Indiana
- Gerald Bunick, PhD, Oak Ridge National Laboratory, Oak Ridge, Tennessee
- Daniel C. Carter, PhD, New Century Pharmaceuticals, Inc, Huntsville, Alabama
- Aniruddha Achari, PhD, Raytheon, Huntsville, Alabama

Research Objectives

Protein crystals are grown in a temperature controlled environment.

Image shows crystals from the plant protein thaumatin that were grown onboard the International Space Station. NASA Marshall Space Center image.

PCG-STES-IDQC (Kundrot)

This investigation obtains high-quality crystal for ground-based research. Study of protein crystals is essential for visualizing proteins and developing new drugs and agricultural products.

PCG-STES-IMP (Chang)

This investigation's primary objective is to grow high-quality crystals for ground-based research, which are to be used in understanding the structure of transporter proteins within cells.

PCG-STES-MM (Borgstahl)

This investigation's primary objective is to grow high-quality, large crystals for ground-based research, which are used in X-ray diffraction studies to discern the function and structure of the proteins.

PCG-STES-MMTP (Kaplan)
This investigation grows high-quality crystals for ground-based research, which examines the proteins that are used in transporting carbon into cells.

PCG-STES-MS (Thomas)
This investigation grows high-quality crystals for ground-based research, which examines 2 proteins, 1 used in the food industry, and the other is used in gene expression.

PCG-STES-RDP (Golden)
This investigation's primary objective is to grow high-quality crystals for ground-based research, which are used in X-ray crystallography of the active site of ribonucleic acid (RNA) enzyme.

PCG-STES-RGE (Bunick)
This investigation grows high-quality crystals for ground-based research, which examines 2 proteins, 1 used in the food industry, and the other is used in gene expression.

PCG-STES-SA (Carter)
This investigation focuses on the PCG-STES hardware and its ability to provide an environment to produce high-quality crystals.

PCG-STES-VEKS (Achari)
This investigation obtains high-quality crystal for ground-based research. Study of protein crystals is essential for visualizing proteins and developing new drugs and agricultural products.


ISS005E21531 – Astronaut Peggy A. Whitson, Expedition 5 science officer, works the PCG-STES hardware aboard the International Space Station.

Earth Benefits
Biotechnology and pharmaceutical researchers carry out the process of protein crystallization in order to grow large, well-ordered crystals for use in X-ray diffraction studies. However, on Earth, the protein crystallization process is hindered by forces of sedimentation and convection since the molecules in the crystal solution are not of uniform size and weight. This leads to many crystals of irregular shape and small size that are unusable for X-ray diffraction. X-ray diffraction is a complex process that requires several months to several years to complete, and the quality of data obtained about the 3-D structure of a protein is directly dependent on the degree of perfection of the crystals. Thus, the structures of many important proteins remain a mystery simply because researchers are unable to obtain crystals of high quality or large size. Consequently, the growth of high-quality, macromolecular crystals for

diffraction analysis have been of primary importance for protein engineers, biochemists, and pharmacologists.

Fortunately, the microgravity environment aboard the International Space Statoin (ISS) is relatively free from the effects of sedimentation and convection and provides an exceptional environment for crystal growth. Crystals grown in microgravity could help scientists gain detailed knowledge of the atomic, three-dimensional structure of many important protein molecules used in pharmaceutical research for cancer treatments, stroke prevention, and other diseases. The knowledge gained could be instrumental in the design and testing of new drugs.

Protein crystal growth experiments aid the generation of computer models of carbohydrates, nucleic acids and proteins, and further advance the progress of biotechnology. Understanding these results can lead to advances in manufacturing and biological processes, both in medicine and agriculture.

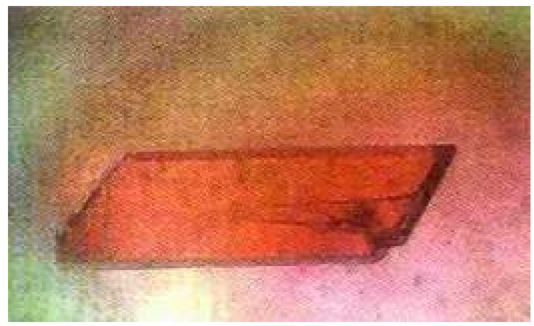


Image from Vahedi-Faridi, A. Acta Crystallographica, Section D, Biological Crystallography, 2003. Shows a Manganese Superoxide dismutases crystal grown in microgravity. The pink color is a result from the oxidized manganese in the active site.

SPACE BENEFITS

The crystals grown in microgravity are able to grow larger and more organized than those grown on Earth. The results from this investigation may further human space exploration efforts by creating technological and biological advancements as a direct result from this research.

RESULTS

PCG-STES is a suite of 9 experiments with additional shared samples for associated investigators. Samples were taken to and from station five times for crystallization during Expeditions 2, 4, 5, and 6. The logistical considerations of spaceflight affected some of the results, as flight delays compromised some samples, and a jarring drop of the hardware shortly after return on 11A/STS-113 probably destroyed any larger crystals that had formed during that set of runs. PCG-STES samples in DCAM were in orbit prior to the Space Shuttle *Columbia* accident and then spent an unprecedented 981 days (November 2002 - August 2005) on ISS before being returned on the next space shuttle flight.

PCG-STES-IDQC

The PCG-STES-IDQC operated on the ISS during Expedition 2. The experiment used 2 types of protein samples, basic fibroblast growth factor (bFGF) and thaumatin, used to grow crystals and was active for 22 days. The bFGF samples were originally supposed to be loaded into 45 PCAM chambers. Due to regulations that are related to flight, the original formulation of chemicals was declared ineligible for fight. After a new set a chemical formulations were created, 18 chambers were loaded with the samples. Of the 18 chambers 8 produced crystals. The largest crystal was about 80 micrometers x 50 micrometers. The thaumatin samples were originally to be loaded into 23 PCAM chambers. Due to flight regulations, one compound (hexadecyltimethyl ammonium bromide) in the sample was not eligible for flight. A new formulation was created to replace the original sample and was used to fill 45 chambers. There was a clerical error during the transcribing of the recipe and this affected 4 sample chambers. Of the remaining chambers, 9 produced crystals. The crystals that were produced in microgravity were large needle splays (Kundrot, Increment Two One Year Postflight Report).

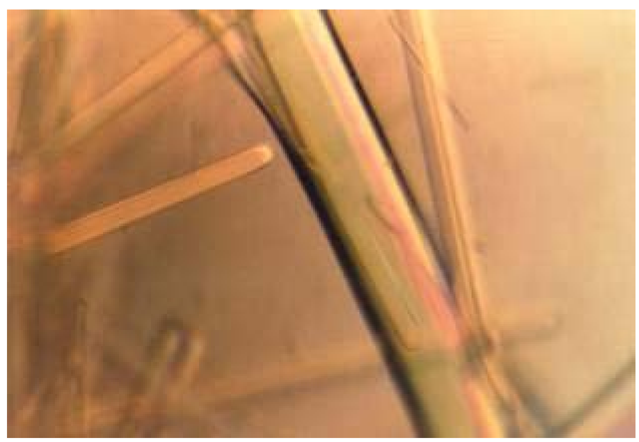
PCG-STES-IMP

The PCG-STES-IMP operated on ISS during Expedition 5. The *E. coli* MsbA and EmrE membrane protein samples used did not produce crystals. Previous ground tests indicated that crystal growth was possible. Upon examining the pedestals (part of the PCAM trays where the sample was originally loaded) it was found that the protein drops were no longer present. The drops also contained a detergent that is used in crystallization experiments. These drops had a lower surface tension and were more sensitive to displacement than proteins that do not contain the detergent. An explanation for the displacement of the drops is that the trays, PCAMs, or the entire STES unit was bumped or jolted at some point before the experiment was initiated.

The investigator has concluded that new recipes for crystallization that use detergents are needed in order to raise the surface tension of the protein drops so they can survive the normal movements associated with STES unit during the round trip from ground to orbit (Chang, One Year PostflightReport, 2003).

PCG-STES-MM

Not surprisingly, given the wide array of materials and objectives, some samples did produce large crystals, while other samples produced crystals no better than those produced on Earth. Yet other samples failed to crystallize at all.



Crystallized structure of a nucleosome core particle that was grown during a previous DCAM mission on *Mir*. NASA Marshall Flight Space Center image.

Crystals of MnSOD, produced during Expedition 4, exhibited an 80-fold volume increase when compared to the crystals produced on Earth. The crystals that were produced in orbit ranged from small, needle-like crystals to large 3-D crystals. These crystals were used for Synchrotron X-ray analysis, the use of a high-energy, adjustable particle beam used for crystal diffraction. Through this analysis it was determined that the diffraction resolution and quality of data for the crystals produced in microgravity were increased when compared to the diffraction resolution of the crystals grown on Earth (Vahedi-Faridi 2003).

PCG-STES-MMTP
The PCG-STES-MMTP operated on the International Space Station during Expedition 5. The experiment used Mitochondrial Metabolite Transport Proteins samples to grow crystals. This investigation suffered sample loss from the sample pedestals during the mission. Even though there was a loss of some of the sample, crystals did grow in 4 out of the 28 wells. Unfortunately, these crystals were too small and poor quality to perform X-ray diffraction.

PCG-STES-MS
The PCG-STES-RGE operated on the International Space Station during Expeditions 6 through 11. This mission was launch in November 2002 and was returned in August 2005. This was the longest running crystal experiment to date aboard the ISS.

PCG-STES-RDP
PCG-STES-RDP operated on ISS during Expedition 5 during 2 separate runs. The experiment used an engineered RNA enzyme sample to grow crystals. Crystals were not obtained from the first run of this investigation. This was attributed to using the precipitant MPD (hexylene glycol), which is now known to evaporate more than expected in the PCAMs. This investigation began in June 2002 and was concluded in October 2002. During the post analysis, it was discovered there was an increase in the concentration of magnesium chloride in the samples, which may have led to the degradation of the samples. (One Year Postflight Report, 2003)

The second run of this investigation began in October 2002 and concluded in December 2002. The detailed examination of the PCAM trays revealed that tiny crystals had grown in the trays. They may have been overlooked in the initial examination when the samples were returned to Earth. It is not known whether the crystals grew in orbit or post-landing. Upon further examination, it appeared that the samples had been disturbed. An explanation of the disturbance is that the STES unit had been dropped or jolted during transport with enough force to displace the samples or shatter crystals.

These experiments lead to an optimization of growing the ribozyme in ground laboratories. Crystals are now more reproducible. The rate of growth has increased from 4% to 50% (One Year Postflight Report, 2003).

PCG-STES-RGE
No information gathered.

PCG-STES-SA
Not surprisingly, given the wide array of materials and objectives, some samples did produce large crystals while other samples produced crystals no better than those produced on Earth. Yet other samples failed to crystallize at all. Crystals of MnSOD, produced during Expedition 4, exhibited an 80-fold volume increase when compared to the crystals produced on Earth. The crystals that were produced in orbit ranged from small, needle-like crystals to large 3-D crystals. These crystals were used for Synchrotron X-ray analysis, the use of a high-energy, adjustable particle beam used for crystal diffraction. Through this analysis it was determined that the

diffraction resolution and quality of data for the crystals produced in microgravity were increased when compared to the diffraction resolution of the crystals grown on Earth (Vahedi-Faridi 2003).
High-resolution structural data were also obtained from human albumin and human antithrombin III crystals.

PCG-STES-VEKS

The PCG-STES-VEKS operated on the ISS during Expeditions 2, 4, 5. The experiment used precipitants of ammonium sulfate, sodium chloride, 2-methyl-2,4-pentanediol, and polyethylene glycol. The samples that used ammonium sulfate and sodium chloride showed that activation of 4 days provides equilibrium, while activation for 2 days provides 90% equilibrium. This indicates that shuttle missions of 10 days are long enough to allow salt samples to reach equilibrium. For the remaining samples, time to equilibrium is dependent on the drop volume; at the highest volume, it takes approximately 10 days to reach equilibrium. (Achari, Increments 2 and 4 One Year Postflight Reports).

Protein Crystallization Apparatus for Microgravity (PCAM). NASA's Marshall Flight Space Center image.

Expedition 5 used 9 trays in PCAM 6 on flight STS-111/UF2. The sample in 7 of the 9 trays lost volume during the experiment. The space shuttle mission was unexpectedly extended, which might explain the loss of volume in the trays. Due to the loss of volume, the kinetics data was not obtained (Achari, Increment 5 One Year Postflight Report).

PUBLICATION(S)

Vahedi-Faridi A, Porta J, Borgstahl GEO. Improved three-dimensional growth of manganese superoxide dismutase crystals on the International Space Station. *Acta Crystallographica Section D: Biological Crystallography*. 2003;59(Pt 2):385-388. doi: 10.1107/S0907444902020310.

This investigation is complete and all results are published.

Protein Crystal Growth Monitoring by Digital Holographic Microscope for the International Space Station (PROMISS-1, -2, -3 and -4), Four Investigations

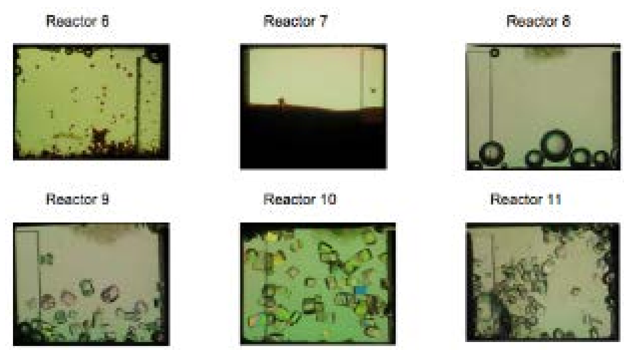
Research Area: Macromolecular Crystal Growth
Expedition(s): 5, 7-9, 12
Principal Investigator(s):
- Juan M. Garcia-Ruiz, PhD, University of Granada, Granada, Spain
- Fermin Otalora Munoz, University of Granada, Granada, Spain
- Ingrid Zegers, PhD, Free University, Brussels, Belgium

Research Objectives

The major objective of the Protein Crystal Growth Monitoring by Digital Holographic Microscope for the International Space Station (PROMISS-1,-2,-3,-4) experiments is to produce a detailed analysis and a quantitative interpretation of the relationship between the quality of the obtained crystals and the environment in which they are produced by the method of digital holography. The experiment aims to investigate the protein growth processes in weightless conditions using the counter diffusion technique in order to measure the parameters of the growing protein crystals and to measure the composition changes (depletion zone) of liquid around the growing protein crystals.

Results

The following results are based on the first 3 series of PromISS experiments, which were performed on 6 proteins: the complex of the variable domain of a camelid heavy chain antibody with lysozyme (cablys3*lysozyme), Thermotoga marirtima triose phosphate isomerase (TIM), pike parvalbumin, hen egg white lysozyme, equine spleen ferritin, and lumazine synthase. For 12 out of the 18 reactors flown (6 reactors per mission), crystals were obtained in the right time frame.



Images of the activated reactors at their return to Brussell's. ESA image.

The results showed that counter diffusion experiments can be useful not only for producing crystals of higher quality, but also in cases where one wants to obtain a different crystal form with improved (diffraction) properties. The effect of diffusive conditions was very extensively investigated for the proteins TIM and cablys3*1ysozyme. For TIM, more than 100 datasets were collected from crystals grown either in non-convective environments (in microgravity or in gels on the ground) or by conventional techniques prone to convection. The results show that there is a clear effect of diffusion, and the crystal perfection was higher for crystals grown in a non-convective environment. Analysis of crystal growth rates and mass transport showed that the depletion zone model cannot explain this, as TIM crystals essentially grew in a regime controlled by surface growth rates. Diffusion is not rate-limiting and no depletion zone was formed. For other proteins like cablys3*lysozyme the influence of a diffusive environment was negligible.

Results from the PromISS experiments have shown that protein crystallization is one of the processes found in the very complex landscape of phase behavior of protein at high concentrations. To better understand the effect of crystal growth conditions on crystal quality requires the continued ground and microgravity research on the thermodynamics and kinetics of these processes.

PUBLICATION(S)

Evrard C, Maes D, Zegers I, et al. TIM crystals grown by capillary counter diffusion: Statistical evidence of quality improvement in microgravity. *Crystal Growth and Design*. 2007;7(11):2161-2166. doi: 10.1021/cg700687t.

This investigation is complete; however additional results are pending publication.

Structural Research on Protein Candidates for an AIDS Vaccine in Earth and Space Conditions (Vaktsina-K)

Research Area: Macromolecular Crystal Growth
Expedition(s): 9-11, 13, and 16-17
Principle Investigator(s):
- Grigoriy Y. Shcherbakov, MD, PhD, Biopreparat, Moscow, Russia

Research Objectives

The Structural Research on Protein Candidates for an AIDS Vaccine in Earth and Space Condition (Vaktsina-K) investigation aims to create a new generation of vaccines against viral infections based on artificial proteins with predetermined antigenicity and immunogenicity. Analysis of the spatial structure provides information on the conformation of the active center and on the efficacy of the protein construction, and allows necessary changes to be introduced in order to increase the biological activity of artificial proteins.

Activation of the crystallization process in the Luch-2 hardware. Roscosmos image.

Earth Benefits

As a result of Vaktsina-K, the spatial structure of the protein monocrystals obtained are being studied, the mechanism of their action is being determined, and the possibility of using the information obtained to create new pharmaceuticals is being assessed to facilitate the creation of new vaccines against harmful viral diseases.

Space Benefits

Improvements in the technology for producing biocrystals in microgravity and development of crystallographic research in space will make it possible to obtain high-quality protein crystals.

Results

As a result of the use of several types of precipitants for crystallizing TBI protein in microgravity, monocrystals were obtained that were several times greater in size than those grown on Earth. In a number of instances, the total dimensions of the crystals permitted testing of their quality (reflective capability) using X-ray diffraction methods. Vaktsina-K resulted in crystals of rod-like or tubular shape, or without defined facets with a maximum size of about 200 µm in the presence of amorphous precipitation.

This investigation is complete; however additional results are pending publication.

Development of Methods and Onboard Equipment to Assure Aseptic Conditions Performing Biotechnology Experiments During Manned Spaceflight (Aseptik)

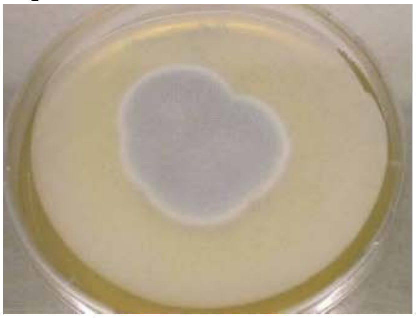
Research Area: Microbiology
Expedition(s): 21-ongoing
Principle Investigator(s):
- Tatiana K. Krasheninnikova, PhD, Biokhimmash, Moscow, Russia

Research Objectives

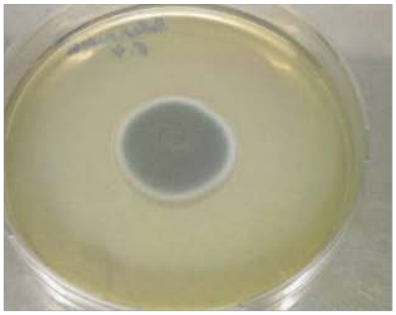
The Development of Methods and Onboard Equipment to Assure Aseptic Conditions Performing Biotechnology Experiments During Manned Spaceflight (Aseptik) investigation onducts an experimental assessment of the reliability and efficiency of methods and equipment, for assuring aseptic (sterile) conditions for biological investigations performed on board ISS.

Earth Benefits

Performance of this investigation makes it possible to expand the circle of tasks for space biotechnology experiments in the direction of solving the issue of obtaining biological end-products in an integrated technological chain and refine stage-by-stage processes during orbital flight.



Poverkhnost 6.1



Poverkhnost 6.4

Poverkhnost 6.5

Photographs of cultures grown in Poverkhnost samplers after the Aseptik experiment was conducted. Poverkhnost 6.1 and Poverkhnost 6.4 show green mold; Poverkhnost 6.5 shows cocci.

Space Benefits

The Glovebox-S apparatus makes it possible to assure the sterility and cleanliness of experiments being conducted, and prevents contamination of the ISS Russian Segment, thus assuring crew safety. The use of this equipment is the first step on the path to creating a bio-lab module on board an orbital station that will be the site of laboratory production of biological preparations and target biologically active substances for long-term interplanetary flights and planetary stations.

Results

During the course of the Aseptik investigation it was revealed that the interior air space of the glovebox was not sterile for bacteria. Moreover, this experiment also revealed the non-sterility of the internal surface of the Glovebox-S apparatus. The same varieties of fungi and bacteria were encountered fairly frequently when the non-sterility of the Glovebox-S apparatus, both inside and out, was revealed.

It was possible to determine that the surface of the Glovebox-S apparatus was non-sterile in 2 places: the surface of the lower loading hatch after the performance of the Kaskad experiment and after sterilization, and the surface of the loading port. Using the data obtained, one may conclude that the hypothesis concerning the introduction of contaminating microflora through the placement into the glovebox of equipment necessary for biotechnology experiments being conducted on board the ISS Russian Segment was justified.

The mold cultivated belongs to the genus *Penicillium*, and the bacterial colony belongs to the *cocci*. Since these types of fungi and bacteria have been found before when the Glovebox-S apparatus was found to be non-sterile, one may conclude that the glove box may get contaminated during the transfer of equipment necessary for biotechnology experiments being conducted on board the ISS RS.

Based on the data, it seems wise to treat equipment being transferred into the glovebox with sterilizing wipes, and to perform additional treatment of the glovebox surface after conducting biotechnology experiments, paying particular attention to hard-to-reach areas.

This investigation is ongoing and additional results are pending publication.

CULTIVATING *ESCHERIA COLI* PRODUCER OF CAF1 PROTEIN IN WEIGHTLESSNESS (ASTROVAKTSINA)

Research Area: Microbiology
Expedition(s): 16 and 19 -24
Principle Investigator(s):
- Grigoriy Y. Shcherbakov, MD, PhD, Biopreparat, Moscow, Russia
- Anatoliy M. Vasilyev, PhD, Institute of Engineering Immunology, Moscow, Russia

RESEARCH OBJECTIVES

The Cultivating *Escheria coli* Producer of CAF1 Protein in Weightlessness (Astrovaktsina) studies the effect of spaceflight factors on the processes of biosynthesis, secretion, capsule formation, and the biological properties of the *E. coli* producer of the genetically engineered CAF1 antigen protein of *Yersinia pestis* during its exposure to microgravity.

EARTH BENEFITS

The results of the experiment may be used on Earth to obtain highly pure preparation of V antigen blended with polyhistidine peptide as the main component of a new-generation molecular vaccine against yersiniosis, as well as for the targeted creation of new medicines, including medicine for treating Acquired Immune Deficiency Syndrome and a number of tumor diseases.

SPACE BENEFITS


Location of the Bioekologiya kit for the Astrovaktsina experiment in the ISS Russian Segment Service Module. Roscosmos image.

Incubation in spaceflight conditions followed by selection on Earth may be used as a method for obtaining lines of productive strains with an elevated number of copies of plasmids controlling the synthesis of targeted products. This data is important for developing the biotechnology of molecular vaccines against yersiniosis and other infectious diseases in humans and animals, and also for developing a program of life-support systems for cosmonauts during long-term spaceflights.

RESULTS

Displaying of working cultures on agar slants to microgravity conditions, and the effect of other orbital flight factors, led recombinant *Escherichia coli* HB101/pVHB62 to synthesize an increased amount of the target product at a level 30% ± 10% greater than that of control samples located on Earth (for example, 12.3 mg/ml and 9.8 mg/ml). Lyophilically dried culture samples did not differ in the level of V gene synthesis in the experimental or control cultures.

V-antigen isolated from cells of the recombinant strain *Escherichia coli* HB101/pVHB62 exposed to microgravity was identical in terms of molecular mass, spectral properties, and immunochemical properties to V341 antigen obtained from control cultures kept on Earth.

PUBLICATION(S)

Abramov VM, Khlebnikov VS, Vasiliev AM, et al. A study of the interaction of *Yersinia Pestis* virulence factors with 1L-1R/TLR recognition system. Totowa, NJ: *National Institute of Allergy and Infections Diseases*, NIH; 2008.

Abramov VM, Khlebnikov VS, Vasiliev AM, et al. Attachment of LcrV from *Yersinia Pestis* at dual binding sites to human TLR-2 and human IFN-gamma receptor. *Journal of Proteome Research*. June 2007;6(6):2222-2231. doi: 10.1021/pr070036r.

Mueller CA, Broz P, Mueller SA, et al. The V-Antigen of Yersinia forms a distinct structure at the tip of injectisome needles. *Science*. October 28, 2005;310:674-676.

Derewenda U, Mateja A, Devedjiev Y, et al. The structure of *Yersinia Pestis* V-Antigen, an essential virulence factor and mediator of immunity against plague. *Structure*. 2004;12:301-306. doi: 10.1016/j.str.2004.01.010.

This investigation is complete; however additional results are pending publication.

Study of the Effects of Spaceflight Factors on Bacteriophages (Bakteriofag/Bakteriofag-L), Two Investigations

Research Area: Microbiology
Expedition(s): 21-24 and 27-ongoing
Principle Investigator(s):
- Grigoriy Y. Shcherbakov, MD, Biopreparat, Moscow, Russia

Research Objectives

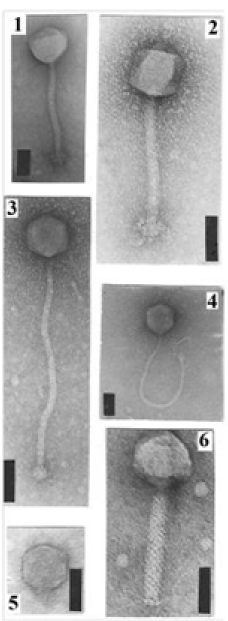
The Study of the Effects of Spaceflight Factors on Bacterophages (Bakteriofag/Bakteriofag-L) investigation examines the therapeutic, diagnostic, and genetic properties of bacteriophages to discover possible changes in the physical, chemical, morphological, and genetic properties of therapeutic and diagnostic bacteriophages exposed to microgravity.

Earth Benefits

Bacteriophages are used to prevent and treat certain bacterial infections. Due to their specific lytic action on bacteria, they are an alternative to antibiotics. They are strictly specific, and live in the human body in the presence of specific bacterial flora, then due to the absence of a substrate, they die and the body self-cleans.

Space Benefits

During the long-term presence of crewmembers in space station conditions, human microflora infiltrates the structure, equipment, and materials which cause conditions similar to the development of hospital based infections. On Earth, the battle with these infections is fought using harsh disinfectants that cannot be used in spaceflight conditions. In these conditions, bacteriophage preparations will turn out to be indispensable; the treatment with them may be similar to wet cleaning, and after inactivation of microorganisms, the bacteriophages themselves die. Such specific sterilizing preparations will also help to eliminate dispersed microorganisms destroying materials and equipment. Therefore, during long-term autonomous spaceflight conditions, having such preparations on board the vehicle is promising.

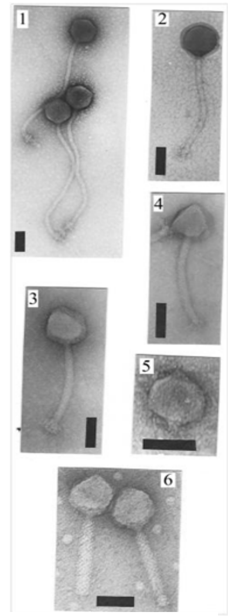


Electron micrographs of bacteriophages after 4 months in space from ISS Expedition 30. Roscosmos image.

Results

Bakteriofag

Of the lyophilically dried bacteriophages exposed on the ISS one, *Staphylococcus aureus* bacteriophage exhibited increased lytic activity. Data indicated that in the lyophilically dried forms of bacteriophages exposed to space factors, the structure of particles was unchanged and the heads of the phage particles contain DNA. The biological properties of the bacteriophages (morphology of negative colonies, spectrum of lytic action, and stability under the influence of fluctuating pH levels) do not change relative to initial data. All studied bacteriophages retained their viability and biological activity after being in space for 3 months. However, it was noted that the concentration of bacteriophages was an order of magnitude lower than the initial concentration.



Electron micrographs of bacteriophages after 6 months in space from ISS Expedition 31. Roscosmos image.

BAKTERIOFAG-L

Experiment results showed that bacteriophages in lyophilically dried form do not change their biological properties over the course of 3 months under spaceflight conditions. The study of the properties of bacteriophages after 3-month and 6-month exposures to spaceflight showed that in lyophilically dried bacteriophages exposed to long-term spaceflight, the lytic spectrum reduces by 1.5 – 2 times, the lytic activity reduces by 5 orders of magnitude, and resistance to temperature factors and pH fluctuations also decreases. The obtained results show that gel-form bacteriophages exposed to spaceflight for 1 month do not reduce lytic activity, maintain their resistance to temperature and pH fluctuations, and this specific timeframe is acceptable for their storage. Improving the environment for retaining therapeutic bacteriophages in long-term spaceflight requires further experimentation.

This investigation is complete; however additional results are pending publication.

Bacterial Acclimation and Adaptation to the Space Environment Conditions-A (BASE-A)

Research Area: Microbiology
Expedition(s): 14
Principal Investigator(s):
- Natalie Leys, MD, Belgium Nuclear Research Center, Mol, Belgium
- Max Mergeay, D. Sc, Belgium Nuclear Research Center, Mol, Belgium

Research Objectives

The Bacterial Acclimation and Adaptation to the Space Environment Conditions-A (BASE-A) investigation studies the effects of space conditions such as microgravity and cosmic radiation aboard the International Space Station (ISS) on physiological and metabolic processes in bacteria. The bacteria used for MESSAGE and BASE experiments included R. rubrum S1H as MELiSSA bacterium and Cupriavidus metalidurans CH34 as an example of a bacterium adapted to a variety of harsh environments, including the clean rooms where satellites are built.

Example of Kubik incubator with centrifuge configuration loaded with experiment containers. ESA image.

Results

Growth, spontaneous mutants, and viable counts were similar to ground experiments. Proteomic data show limited effects of spaceflight conditions, especially for *C. metallidurans*, although some uncommon proteins involved in acetone metabolism, were found to be over-expressed in space. Transcriptomic data were mainly obtained for *R. rubrum* and provided information about the importance of experimental design and the effect of low doses of cosmic radiation. This effect was mainly revealed in the BASE-A spaceflight experiment where various over-expressed genes matched those found during ground tests of ISS radiation. Thus, for the first time, studies showed a low dose of ionizing radiation (2 mGy) can induce a significant response at the transcriptomic level, although no change in cell viability was observed. This experiment will surely stimulate further studies of effects of low-dose ionizing radiation in bacteria. These will be paramount for implementation of bioreactors in spaceflight and on planetary stations.

Publication(s)

Leys N, Baatout S, Rosier C, et al. The response of *Cupriavidus Metallidurans* CH34 to spaceflight in the International Space Station. *Antonie van Leeuwenhoek*. 2009;96:227-245. doi: 10.1007/s10482-009-9360-5.

Mastroleo F, Van Houdt R, Leroy B, et al. Experimental design and environmental parameters affect Rhodospirillum rubrum S1H response to spaceflight. *International Society for Microbial Ecology*. 2009;3(12):1402-1419. doi: 10.1038/ismej.2009.74.

Vanhavere F, Genicot JL, O'Sullivan D, et al. DOsimetry of Biological EXperiments in SPace (DOBIES) with luminescence (OSL and TL) and track etch detectors. *Radiation Measurements*. 2008;43(2-6):694-697. doi: 10.1016/j.radmeas.2007.12.002.

This investigation is complete and all results are published.

BACTERIAL ACCLIMATION AND ADAPTATION TO THE SPACE ENVIRONMENT CONDITIONS-B/-C (BASE-B/-C), TWO INVESTIGATIONS

Research Area: Microbiology

Expedition(s): 18

Principal Investigator(s):
- Natalie Leys, MD, Belgium Nuclear Research Center, Mol, Belgium
- Max Mergeay, Belgium Nuclear Research Center, Mol, Belgium

RESEARCH OBJECTIVES

The Bacterial Acclimation and Adaptation to the Space Environment Conditions-B/-C (BASE-B/C) investigations are a continuation of BASE-A that studies the effects of space conditions such as microgravity and cosmic radiation aboard the International Space Station (ISS) on physiological and metabolic processes in bacteria.

Kubik experiment hardware. ESA image.

RESULTS

The preliminary results indicated that none of the 4 test bacteria samples were able to proliferate in space during the incubation. The reason remains unclear, as all cells were viable, present in the culture medium and temperature data indicated 28°C. In addition, all parallel ground control cultures did grow. Only one of the bacteria samples that were packed for return showed growth in the non-fixed cultures. It is suspected that growth occurred in these samples after incubation during the 16.5 hours additional storage at ambient temperature in the Soyuz before return. As 4 different bacteria and different culture media were involved, a "biological" cause of failure can be excluded. The 4 different bacteria and different culture media prepared by different research groups used in the flight experiment units were checked postflight and have proven to be correct. In addition, samples were prepared by different science teams, minimizing also the potential of human error as cause of experiment failure. Although the experiment failure root cause could not be identified, it is suspected that perhaps a possible error in the timeline, which may have caused a too-short incubation time between automatic activation and fixation or removal from the incubator, may have limited the cell proliferation. Unfortunately, as no bacteria proliferated during flight, insufficient biomass was obtained to continue cell and molecular analysis. Thus the samples from the BASE-B and BASE-C flight experiment cannot be exploited any further and no trustable scientific data could be obtained.

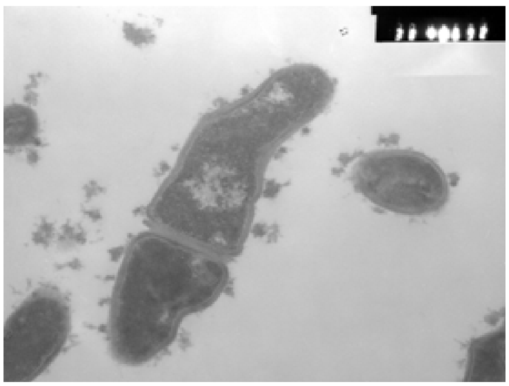
This investigation is complete; however no publications are expected.

Study of the Effects of Spaceflight Factors on the Technological and Biomedical Characteristics of Bifidobacteria (Bif)

Research Area: Microbiology
Expedition(s): 21-24, 27-30, 33 and 35
Principle Investigator(s): ● Igor V. Nyn, PhD, Biopreparat, Moscow, Russia

Research Objectives

The Study of the Effects of Spaceflight Factors on the Technological and Biomedical Characteristics of Bifidobacteria (Bif) investigation identifies the specifics of metabolism and morphology of different phenotypes of one strain of the *Bifidobacteria* caused by microgravity in order to obtain probiotics with improved biomedical properties and to increase the efficiency of production.



Electron-microscopic structure of the *Bifidobacterium bifidum* 1. Roscosmos image.

Earth Benefits

A comparative analysis of the morpho-physiological dissociation of the bifidobacteria on Earth and in microgravity, assuming appropriate procedures, will facilitate identification of the specifics of metabolism and morphology of different phenotypes of one strain, which will provide new opportunities to raise the efficiency of producing bifido-containing probiotics with improved biomedical characteristics.

Space Benefits

The spaceflight factors may only serve as the main starting point for selecting organisms with modified properties. Subsequent work with them on Earth may assist scientists in obtaining technologically important material.

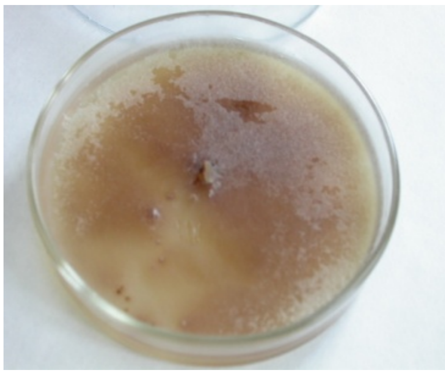
Results

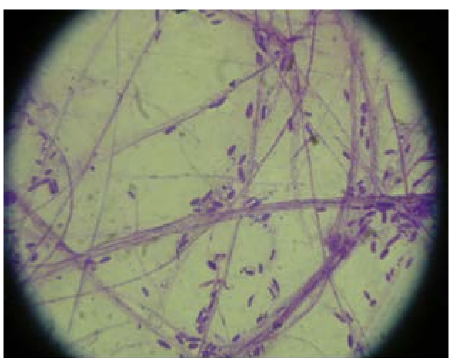
Bif utilized the *Bifidobacterium bifidum* 1 and *Bifidobacterium adolescentis MC-42* strains to observe onboard the ISS. Bif showed once again that microorganisms undergo phenotypic changes during cultivations under the influence of different environmental factors. The obtained results confirm that possibly, the changes in microorganisms' activity types, which occur on board of a space vehicle under condition of microgravity are not often due to genetic or chromosomal mutations. And these are the very ones that define the stability of the newly obtained properties of organisms and transmission of these properties from generation to generation. Spaceflight factors, the most significant of which, microgravity, impossible to simulate on Earth, may serve only as the most important starting point for the selection of organisms with modified properties. Subsequent work with them on the ground may assist scientists in obtaining technologically important material.

This investigation is complete and additional results are pending publication.

Obtaining Highly-Efficient Strains of Microorganisms for the Production of Biological Petroleum Degrading Compounds, Organophosphate Substances, Plant Protection Means, and Exopolysaccharides used in the Petroleum Industry (Bioekologiya-M/Bioekologiya-R), Two Investigations

Research Area: Microbiology
Expedition(s): 7-16
Principle Investigator(s):
- Tatiana K. Krasheninnikova, PhD, Biokhimmash, Moscow, Russia





Top: Colonies of *Cylindrocarpon radicicola Wollenweber HTH-10* producers of plant biostimulants which were exhibited in a space experiment on a dense nutrient Heltzer medium inside test tubes. Bottom: Cells of *Cylindrocarpon radicicola Wollenweber HTH-10 cells* Roscosmos image.

Research Objectives

The Obtaining Highly-Efficient Strains of Microorganisms for the Production of Biological Petroleum Degrading Compounds, Organophosphate Substances, Plant Protection Means, and Exopolysaccharides used in the Petroleum Industry (Bioekologiya) investigations have 2 goals. The goal of Bioekologiya-M is to obtain strains of high performance microorganisms for production of growth-promoting hormones. The goal of Bioekologiya-R is to obtain high performance strains of microorganisms for the production of components of oil biodegradation.

Earth Benefits

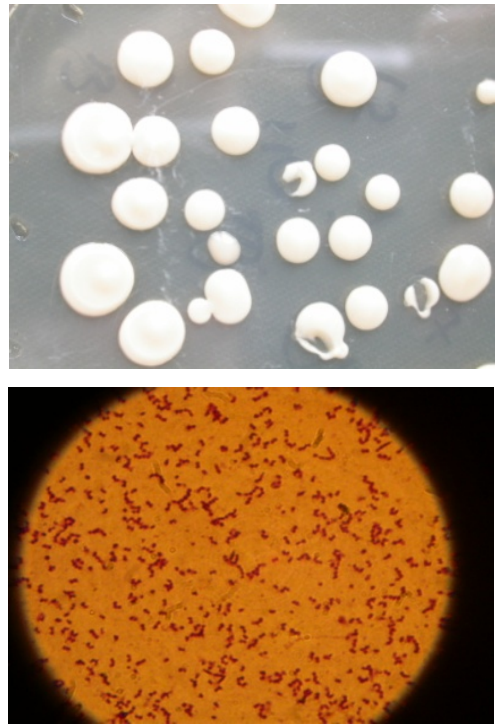
The aim of the Bioekologiya is to obtain highly efficient strains of microorganisms to be used in Russian domestic industry for the production of growth hormone and biological petroleum degrading compounds.

Results

The biological compound Mitsefit was created for use to stimulate plant growth and development and to enhance its reproductive potential based on the new highly active strains of endophytic fungi obtained in the space experiment.

The compound Rodart was created to decontaminate soil and bodies of water from petroleum pollution when the concentration is up to 20%. Rodart contains new highly active bacterial strains that were obtained in the space experiment.

Feasibility studies, technical provisions, technological regulations, and instructions on the use of the biological compounds Rodart and Mitsefit were developed. A pilot fermentation line was created to obtain these compounds.



Top: Colonies of *Arthrobacter sp.* OC-1 (A1) producers of oil biodegradation components which were exposed in a space experiment on a dense nutrient Heltzer medium inside test tubes and in freeze-dehydrated condition in ampoules. Bottom: Cells *Arthrobacter sp.* OC-1 (A1). Roscosmos image.

PUBLICATION(S)

BIOEKOLOGIYA-M

Zhemchuzhina NS, Kofnova IN, Krasheninnikova TK, et al. Results of experiments conducted by Biokhimmash Space Biotechnology Laboratory. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2007;49(4):103-107.

Ukraintsev AD, Krasheninnikova TK, Kofnova IN, et al. Influence of factors of spaceflight on properties of bacterial and mushroom cultures at long stay in space in structure of equipment "Bioecology." *6th International Scientific-Practical Conference Manned Spaceflights,* Moscow, Russia; November 10-11, 2005.

BIOEKOLOGIYA-R

Sinitsyn AN, Krasheninnikova TK, Sinchurina EV, Smolyanaya GL. Advanced biological products for oily wastes disposal and contaminated land phytoremediation. *International Congress (Waystack)*, Moscow, Russia; 2007.

These investigations are complete and all results are published.

GROWTH AND SURVIVAL OF COLORED FUNGI IN SPACE-A (CFS-A)

Research Area: Microbiology

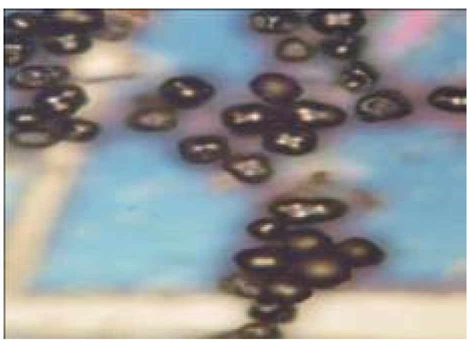
Expedition(s): 25-28

Principal Investigator(s):

- Dumitru Hasegan, , Romanian Institutes of Space Science and Biology, Bucharest, Romania
- George Mogildea, Romanian Institutes of Space Science and Biology, Bucharest, Romania
- Elias Chatzitheodoridis, National Technical University of Athens, Greece

RESEARCH OBJECTIVES

Growth and Survival of Colored Fungi in Space-A (CFS-A) determines the effect of microgravity and cosmic radiation on the growth and survival of colored fungi species. The fungal species chosen for experiments belong to 4 genera selected as organic material decomposers, possible contaminants of materials destined for interplanetary travel, aggressive biodeteriogens of artworks, and wooden buildings.



Colored fungi. ESA image.

RESULTS

Different growth rates were observed for the aerial and for the submerged mycelium. Growth of aerial mycelium has a high rate in flight and ground controls up to Flight Day 5, then becomes lower and stops between Flight Day 8-9. Sporulation takes place in flight and ground, but it is less abundant compared to ground and laboratory control.

Integration of the microcapsules in the biocontainers showed a negative effect on the growth and on the sporulation in comparison with the laboratory control; new ground experiments will be made to acquire more information.

Microgravity reduced the rate of growth of aerial mycelium and stimulates the growth of submerged mycelium. The CFS-A experiment demonstrated that fungi as biodeteriogens and biodegraders are able to grow in microgravity, such as inside the International Space Station (ISS) where substrates are humid.

For the dry spore samples the spores chosen for the CFS-A experiment were still viable after 5 months in microgravity. *Ulocladium chartarum* spores are more resistant from a viability point of view then *Basipetospora halophila* and *Cladosporium herbarum* spores but less than *Aspergillus niger* spores. *Aspergillus niger* spores were more than 91% viable on all types of wafers.

Basipetospora halophila spores had a lower viability on ISS than on the ground, which could suggest that white spores are more sensitive to the ISS environment than black spores.

Basipetospora *halophila* spores also showed a lower viability on the silica wafers than on plastic wafers, and no viability on iron wafers was probably due to a strong oxidation of iron wafer in contact with salts removed from the nutrient.

PUBLICATION(S)

Gomoiu I, Chatzitheodoridis E, Vadrucci S, Walther I. The effect of spaceflight on growth of *Ulocladium chartarum c*olonies on the International Space Station. *PLOS ONE*. April 24, 2013; 8(4):e62130. doi: 10.1371/journal.pone.0062130.

This investigation is complete and all results are published.

INTERNATIONAL SPACE STATION HIGH EFFICIENCY PARTICLE FILTER ANALYSIS (ISS HIGH EFFICIENCY PARTICLE FILTER ANALYSIS)

Research Area: Microbiology

Expedition(s): 25, 26, 27 and 28

Principal Investigator(s):

- Robert Friedman, PhD, J. Craig Venter Institute, San Diego, California

RESEARCH OBJECTIVES

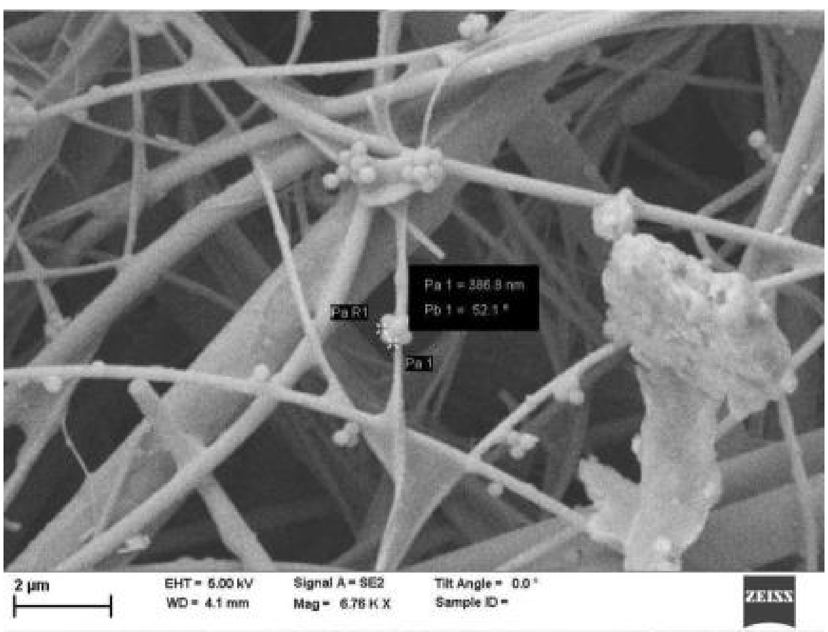
Microbes are the most abundant life forms on Earth, but the least well characterized and understood. International Space Station High Efficiency Particle Filter Analysis (ISS High Efficiency Particle Filter Analysis) studies the microbes present in the air of the International Space Station (ISS) by examining those trapped on the ISS air filter. The goal is to characterize the enormous diversity of microbes that are normally present in indoor environments.

EARTH BENEFITS

Humans spend the majority of their lives in indoor environments, but little is known about the microorganisms living along with us, including in the air we breathe. This research identifies and helps us understand the vast diversity of microorganisms present in indoor air. Many of these are beneficial to humans, some are harmful, but most are merely co-inhabitants.

SPACE BENEFITS

In order to maintain crew health aboard the ISS, it is essential to ensure crew members have clean air to breathe. Identifying and understanding the microorganisms present on the ISS HEPA filters allows for mitigation of any potential hazards that may result from this very specialized microgravity environment.



Scanning Electron Microscope image of the International Space Station High Efficiency Particle Filter Analysis (HEPA) filter displaying collected bacterial cells and debris particles. J. Craig Venter Institute image.

RESULTS

Single microbial cells are currently frozen and waiting to be sequencing. The analysis portion of this experiment is not funded and is awaiting spare capacity on an additional run to be conducted.

This investigation is ongoing and additional results are pending publication.

Microbial Drug Resistance and Virulence (MDRV)

Research Area: Microbiology

Expedition(s): 16

Principal Investigator(s):

- Barry Pyle, PhD, Montana State University, Bozeman, Montana
- Cheryl A. Nickerson, PhD, Arizona State University, Tempe, Arizona
- David W. Niesel, PhD, University of Texas Medical Branch, Galveston, Texas
- Michael McGinnis, PhD, University of Texas Medical Branch, Galveston, Texas

Research Objectives

Microbial Drug Resistance and Virulence (MDRV) evaluates microbial drug resistance and the mechanisms of virulence (infection potential) in microbial cultures.

Dominic Gorie, STS-123 commander, watches Group Activation Pack float, containing Microbial Drug Resistance Virulence. Photo was taken during STS-123/Expedition 16 joint operations.

Earth Benefits

By understanding the unique spectrum of microbial genetic and virulence changes induced by spaceflight, this experiment could yield valuable knowledge leading to advances in vaccine development and other therapeutics for treatment, prevention, and control of infectious diseases on Earth as well as in space.

Space Benefits

Results from these experiments could provide important information on the threat of pathogens in the space environment. This could assist with development of diagnostic tools to monitor the atmosphere, water and surfaces for the presence of these microbes as well as developing countermeasures to manage infections. Understanding the molecular responses of these organisms to spaceflight is a necessary step that significantly contributes improved systems for keeping crewmembers safe. Furthermore, identification of the changes caused by spaceflight to gene expression and proteins could provide novel targets for pharmacological intervention to prevent and control infectious disease, which ultimately facilitates safe and productive long-term exploration of the moon and Mars.

Results

The Microbe experiment aboard STS-115 was the first spaceflight experiment to show increased virulence of the pathogen, *Salmonella enterica*, *serovar Typhimurium* (*S.*

Lead investigator Cheryl Nickerson with colleagues Jennifer Barrila and Aurélie Crabbé.

Typhimurium) in response to spaceflight culture. As a follow-up experiment, the MDRV experiment was performed in March 2008 during the STS-123/1JA mission to the International Space Station to reproduce and confirm the Microbe findings (Wilson 2008). MDRV expanded the scope of Microbe by culturing *S. Typhimurium* in 3 different growth conditions, which included a rich medium, a minimal, high inorganic salt medium, and the rich media supplemented with key inorganic salts. This experiment confirmed the Microbe findings, as *S. Typhimurium* grown in a rich medium exhibited increased virulence compared to identically grown bacteria on Earth. Interestingly, the *S. Typhimurium* grown in either the minimal, high inorganic salt medium or the rich media supplemented with key inorganic salts did not display this increased virulence. Subsequent ground-based testing using the NASA designed spaceflight analogue Rotating Wall Vessel (RWV) bioreactor supported this finding and indicated that the key inorganic salt which was influencing the changes in *S. Typhimurium* was inorganic phosphate.

Both Microbe and MDRV have prompted new studies using spaceflight analogues and true spaceflight. One example includes the study of bacterial genes that were identified as a part of the spaceflight response but have not had their function previously identified. These genes are of particular importance to determine if they play a role in mediating bacterial responses to low fluid shear and/or have additional functions that influence bacterial physiology in general. The study in collaboration with the Microbe/MDRV team (Jennings 2011) investigated the gene *ydcI*, which was found to be differentially regulated when cultures grown in the RWV were compared to controls. The *ydcI* gene is a highly conserved DNA binding protein found in multiple Gram-negative bacteria, including *S. Typhimurium*; however, the function was previous not well understood. From this study, *ydcI* was found to be a part of the *rpoS* regulon, which is responsible for a variety of stress responses in *S. Typhimurium*. Future experiments will be aimed to identify the genes that are members of a potential "*ydcI* regulon" and how they are linked to stress resistance, host cell interactions, biofilm formation, and other bacterial characteristics. The results of MDRV and future follow-up studies should continue to provide newfound knowledge to keep crew members safe during space exploration and to identify novel targets for vaccines and therapeutic development.

Publication(s)

Jennings ME, Quick L, Soni A, et al. Characterization of the Salmonella enterica serovar Typhimurium ydcI gene which encodes a conserved DNA binding protein required for full acid stress resistance. *Journal of Bacteriology*. 2011;193(9):2208-2217. doi: 10.1128/?JB.01335-10.

Sarker SF, Ott CM, Barrila J, Nickerson CA. Discovery of spaceflight-related virulence mechanisms in Salmonella and other microbial pathogens: Novel approaches to commercial vaccine development. *Gravitational and Space Biology*. 2010;23(2):75-78.

Wilson JW, Ott CM, Quick L, et al. Media ion composition controls regulatory and virulence response of Salmonella in spaceflight. *PLOS ONE*. 2008;3(12). doi: 10.1371/journal.pone.0003923.

Nickerson CA, Ott CM, Wilson JW, Ramamurthy R, Pierson DL. Microbial responses to microgravity and other low-shear environments. *Microbiology and Molecular Biology Reviews*. June 2004;68:345-361. doi: 10.1128/MMBR.68.2.345-361.2004.

This investigation is complete; however additional results are pending publication.

Microbiological Experiment on Space Station About Gene Expression-1 and 2 (MESSAGE-1 and MESSAGE-2), Two Investigations

Research Area: Microbiology
Expedition(s): 5, 7 and 8
Principal Investigator(s):
- Max Mergeay, DSc, Belgium Nuclear Research Center, Mol, Belgium
- Natalie Leys, Belgium Nuclear Research Center, Boeretang, Belgium

Research Objectives

The main objective of the Microbiological Experiment on Space Station About Gene Expression-1 and 2 (MESSAGE-1 and MESSAGE-2) experiments is to study the effects of space conditions aboard the International Space Station (ISS) on physiological and metabolic processes in bacteria. *Ralstonia metallidurans CH34* is a proteobacterium that can survive in harsh environmental conditions. *Rhodospirillum rubrum S1H* (only used in MESSAGE-2) is of major importance for a future bioregenerative life support system called MELiSSA under development at the European Space Agency (ESA).

Results

The results showed that space conditions can significantly change the physiology and metabolism of bacteria. The differences in bacterial survival and growth observed between space and ground cultures of *R. metallidurans CH34* in the MESSAGE-1 experiment were not observed in MESSAGE-2. Also the *R. rubrum S1H* cell survival count indicated no significant difference between space and ground-grown cultures. It should be noted that a more stable temperature control was possible in the MESSAGE-2 experiment. The motility of *R. metallidurans CH34* showed no significant differences between ground and space cultures, though this was based on pure visual analysis and did not allow good quantitative analysis. Flow cytometry data did not show any significant difference between *R. metallidurans CH34* cells grown in space or on ground for cells size and shape, membrane integrity and potential, intracellular pH, and intracellular concentrations of reactive oxygen species. For *R. rubrum S1H*, significant differences in cell physiology were observed. Space-grown cells showed a change in cell size and shape in space conditions. Cell permeability was increased and membrane potential was reduced under space conditions, indicating a lower viability of cells grown in space conditions. The transcriptomic analysis of R. rubrum S1H showed 372 genes that were significantly up-regulated under space conditions. Typical genes related to oxidative stress were identified: H_2O_2 detoxification, SOS response (a global response to DNA damage in which the cell cycle is arrested and DNA repair and mutagenesis are induced), iron transport, and metabolism. Induction of genes related to chemotaxis, flagellum structure and metabolism, cobalamin metabolism, and nitrogen regulation system were also observed.

Publication(s)

Leys N, Baatout S, Rosier C, et al. The response of *Cupriavidus metallidurans* CH34 to spaceflight in the International Space Station. *Antonie van Leeuwenhoek*. 2009;96:227-245. doi: 10.1007/s10482-009-9360-5.

Goossens O, Vanhavere F, Leys N, et al. Radiation dosimetry for microbial experiments in the International Space Station using different etched track and luminescent detectors. *Radiation Protection Dosimetry*. April 27, 2006;120(1-4):433-437. doi: 10.1093/rpd/nci652.

Leys N, Baatout S, De Boever, et al. Gene expression in Ralstonia metallidurans CH34 in spaceflight. *European Symposium on Environmental Biotechnology*; 2004.

These investigations are complete and all results are published.

Gravitational Effects on Biofilm Formation During Spaceflight (Micro-2) & Microbial biofilm formation during spaceflight (Micro-2A), Two Investigations

Research Area: Microbiology
Expedition(s): 23, 24, 27, and 28
Principal Investigator(s):
- Cynthia H. Collins, PhD, Rensselaer Polytechnic Institute, Troy, New York

The Group Activation Pack - Fluid Processing Apparatuses is essentially a microgravity test tube that allows controlled, sequential mixing of 2 or 3 fluids in a weightless environment. BioServe Space Technologies, University of Colorado - Boulder, Colorado image.

Research Objectives

The Gravitational Effects on Biofilm Formation during Spaceflight (Micro-2) experiment studies how gravity alters biofilm (aggregation of microorganisms) formation with the goal of developing new strategies to reduce their impact on crew health and to minimize the harmful effects of biofilms on materials in space and on Earth.

Earth Benefits

According to the Center for Disease Control (CDC), hospital-acquired infections are the fourth leading cause of death in the United States behind stroke, cancer, and heart disease. Furthermore, it is estimated that more than 65% of all bacterial infections are associated with biofilms. A greater understanding of biofilms is essential if we are to find effective methods to combat their formation. Furthermore, the low-shear conditions microbes experience in microgravity are similar to those found in the human body that are difficult to study. This work may provide new insights into the role of shear and other physical effects, such as convection, on biofilm formation.

Space Benefits

Understanding the different effects of microgravity on biofilm formation may provide new insights into combating biofilm formation in space and may lead to better management and treatment of infections if they occur. Also, novel antimicrobial surfaces are tested for their potential to reduce the impact of biofilms in future spacecraft design.

Results

While planktonic cultures (grown under constant mixing) of microbes have indicated that spaceflight can lead to increases in growth and virulence, the effects of spaceflight on biofilm development and physiology remain unclear. To address this issue, *Pseudomonas aeruginosa* was cultured during 2 Space Shuttle *Atlantis* missions: STS-132 and STS-135, and the biofilms formed during spaceflight were characterized. Micro-2 reveals the first evidence of spaceflight affecting the biofilm formation of *P. aeruginosa*. An increased number of viable cells, increased biomass, and increased thickness were observed in spaceflight biofilms when compared to ground controls regardless of phosphate concentration or carbon source. Results also show *P. aeruginosa* forming column-and-canopy shaped biofilms during spaceflight and flagella-driven motility plays a key role in the formation of this unique structure, where flagella are structures that enable cells to move in liquids by "swimming." The findings indicate that altered biofilm production during spaceflight may have detrimental impacts on long-term spaceflight missions, where increases in biofouling and microbial-induced corrosion could have profound impacts on mission success. Furthermore, it is important to explore the effects of such changes on human health through pathogenic and beneficial interactions between humans and microbes during spaceflight (Kim 2013).

Side view of a Group Activation Pack (GAP) containing eight Fluid Processing Apparatuses each holding yeast cell cultures, growth medium, and fixative for the U.S. sponsored GAP Yeast experiment being conducted during Expedition 8.

PUBLICATION(S)

Kim W, Tengra FK, Young Z, et al. Spaceflight promotes biofilm formation by Pseudomonas Aeruginosa. *PLOS ONE*. 2013;8(4):e62437. doi: 10.1371/journal.pone.0062437.

Kim W, Tengra FK, Shong J, et al. Effect of spaceflight on *Pseudomonas aeruginosa* final cell density is modulated by nutrient and oxygen availability. *BMC Microbiology*. November 6, 2013;13:241. doi: 10.1186/1471-2180-13-241.

These investigations are complete; however additional results are pending publication.

Genotypic and Phenotypic Changes in Yeast Related to Selective Growth Pressures Unique to Microgravity (Micro-4)

Research Area: Microbiology
Expedition(s): 27/28
Principal Investigator(s):
- Timothy G. Hammond, MBBS, Durham Veterans Affairs Medical Center, Durham, North Carolina

Research Objectives

The Genotypic and Phenotypic Changes in Yeast Related to Selective Growth Pressures Unique to Microgravity (Micro-4) study investigates how yeast cells adapt to the unique aspects of the space environment by using the yeast deletion series; a collection of yeast strains where every gene has been individually knocked out. In this manner, the selective growth of every strain in the yeast deletion series can be analyzed.

Enhanced microscopic image of the yeast fungi *Saccharomyces cerevisiae*. NASA image.

Earth Benefits

Fundamental Space Biology (FSB) uses the space environment to probe the fundamental nature of life on Earth in order to enhance the understanding of how life responds to physical forces on Earth and in space.

Space Benefits

Direct assessment of selective pressures on cell populations through generations using the yeast deletion series is a critical experiment to directly address risks to biological integrity and life-based support systems for long-term occupation in space. Results from this study allow researchers to gain a global perspective to the genes that play a role in survival, in regards to microgravity conditions and allows for a more thorough understanding of the effects of microgravity on a model organism. The expectation is that what is observed in yeast is likely to have a comparable effect in mammalian cells. This is supported by the observation that regulatory mechanisms are largely conserved between yeast and mammalian cells.

Results

Results are pending publication.

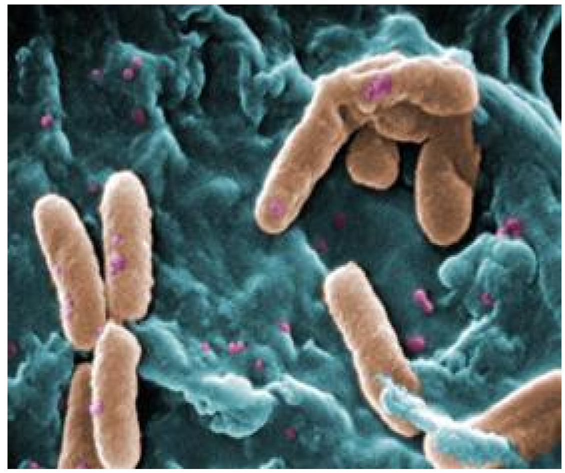
This investigation is complete; however additional results are pending publication.

Effect of Spaceflight on Microbial Gene Expression and Virulence (Microbe)

Research Area: Microbiology
Expedition(s): 13
Principal Investigator(s):
- Cheryl A. Nickerson, PhD, Arizona State University, Tempe, Arizona

Research Objectives

The Microbe experiment investigates the effects of the spaceflight environment on virulence (ability to infect) of 3 model microbial pathogens: *Salmonella typhimurium*, *Pseudomonas aeruginosa*, and *Candida albicans*, that have been identified as potential threats to crew health based upon previous spaceflight missions.



Colorized scanning micrograph (SEM) of Pseudomonas aeruginosa. Janice Haney Carr, CDC image.

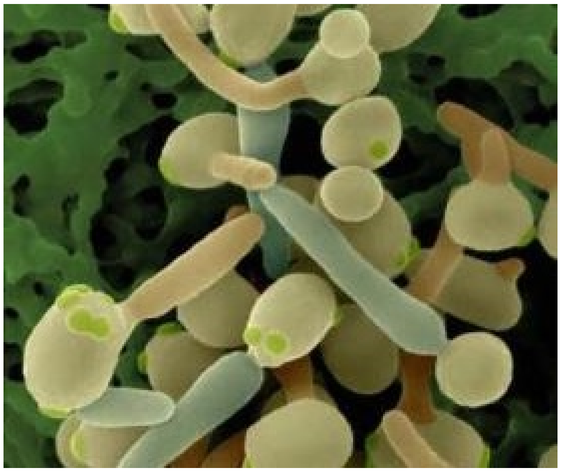
Earth Benefits

By understanding the unique spectrum of microbial genetic and virulence changes induced by spaceflight, this experiment can yield valuable knowledge leading to advances in vaccine development and other therapeutics for treatment, prevention and control of infectious diseases on Earth as well as in space.

Color enhanced scanning electron micrograph showing Salmonella typhimurium (red) invading cultured human cells. Rocky Mountain Laboratories, NIAAD, NIH image.

Space Benefits

Results from this single flight experiment can provide important information on the threat of pathogens in the space environment, which assists with the development of diagnostic tools to monitor the atmosphere, water, and surfaces for the presence of these microbes. Understanding the molecular responses of these organisms to spaceflight is a necessary step that significantly contributes to the development of systems that meet requirements for supplying and storing potable water that is free of microbial contaminants. Furthermore, identification of the changes caused by spaceflight to genes and proteins provides novel targets for pharmacological intervention to prevent and control infectious disease, which ultimately facilitates safe and productive long-term exploration of the moon and Mars.



Candida albicans. Dennis Kunkel Microscopy Inc image.

RESULTS

A human presence in space, whether permanent or temporary, is accompanied by the presence of microbes. However, the response of microorganisms to growth during a spaceflight mission is not completely understood. While several spaceflight studies have investigated changes in microbial characteristics when cultured during spaceflight, the Microbe experiment was the first to investigate changes in virulence and gene expression in several microbes that are pertinent to both crew members and the general public on Earth. The organisms investigated were, *Salmonella enterica, Salmonella Typhimurium, Pseudomonas aeruginosa*, and *Candida albicans*.

Within a few hours after return to Earth aboard STS-115, the *S. Typhimurium* grown in space was used to infect mice to determine the disease-causing potential (virulence) of the organism. Mice infected with bacteria cultured in space displayed a decreased time to death and increased percent mortality compared with those infected with ground controls (Wilson 2007). To better understand why the spaceflight-grown cultures were more virulent, an analysis of the gene expression was performed. The *S. Typhimurium* grown in space expressed a total of 167 genes differently compared to the identically grown cultures on Earth. Surprisingly, many genes that are commonly associated with increased virulence were not differentially regulated. Perhaps the most interesting finding was that a regulatory protein, Hfq, appeared to play a role in the alteration in gene expression in response to spaceflight culture. This finding was the first to identify a potential mechanism by which a microorganism was being altered when grown in space. One additional finding detected alterations in microbial morphology grown during spaceflight. Greater cellular aggregation and the formation of an extracellular matrix associated with bacterial biofilms were displayed. Because extracellular matrix formation can help to increase survival of bacteria under various conditions, this biofilm phenotype indicated a change in bacterial responses that are related to increased virulence.

Also grown aboard STS-115 were cultures of *P. aeruginosa* (Crabbé 2011). A comparison of spaceflight grown cultures to those grown identically on Earth indicated that 167 genes were differentially regulated, with many being different than those seen with *S. Typhimurium*. However, one key similarity was that when analysis of the data was performed, Hfq was again identified as a key regulator for many of the differentially regulated genes. This finding reinforced the role for Hfq in microbial response to spaceflight and also suggested that this response may be evolutionarily conserved between species. The differentially regulated gene expression data also indicated that many *P. aeruginosa* virulence characteristics may increase in response to spaceflight culture. The results for *C. albicans* are still being evaluated and prepared for publication.

Both during the preparation for spaceflight experiments and to fully understand the results after the experiment, scientists used spaceflight analogues, like the rotating wall vessel (RWV) and the random position machine (RPM) to mimic spaceflight growth conditions in order to gain insight into the potential behavior *P. aeruginosa* in microgravity (Nickerson 2004). For Microbe, microarray analysis samples of *P. aeruginosa* grown in a RWV were compared to samples grown in normal gravity controls (Crabbé 2010). The results revealed an alteration in a regulatory role of the sigma factor AlgU, which consequently led to an increase in production of the extracellular substance alginate. This change in gene regulation and increased production of alginate resulted in an increase in heat and oxidative stress resistance. Perhaps most interesting was the involvement of Hfq in response to culture in the RWV, consistent with Microbe spaceflight findings in *S. Typhimurium* and *P. aeruginosa*.

The Microbe experiment had far reaching implications. It clarified the mechanisms behind the observations of microbial spaceflight experiments over the past 40 years and initiated studies to understand how these findings impact risk assessment to crew health. In addition, the knowledge gained from spaceflight research has been the focus of commercial and academic entities toward the discovery of novel therapeutic and vaccine approaches leading to the implementation of new strategies for translation of this research into health benefits for the general public (Sarker 2010).

PUBLICATION(S)

Crabbe A, Nielson-Preiss S, Woolley CM, et al. Spaceflight enhances cell aggregation and random budding in *Candida albicans*. *PLOS ONE*. December 4, 2013;8:e80677. doi: 10.1371/journal.pone.0080677.

Crabbe A, Schurr MJ, Ott CM, et al. Transcriptional and proteomic responses of Pseudomonas aeruginosa PAO1 to spaceflight conditions involve Hfq regulation and reveal a role for oxygen. *Applied and Environmental Microbiology*. 2011;77(4):1221-1230. doi: 10.1128/AEM.01582-10.

Crabbe A, Pycke B, Van Houdt R, et al. Response of Pseudomonas aeruginosa to low shear modeled microgravity involves AlgU regulation. *Environmental Microbiology*. 2010;12(6):1545-64.

Sarker SF, Ott CM, Barrila J, Nickerson CA. Discovery of spaceflight-related virulence mechanisms in *Salmonella* and other microbial pathogens: Novel approaches to commercial vaccine development. *Gravitational and Space Biology.* 2010;23(2):75-78.

Nauman EA, Ott CM, Sander E, et al. A novel quantitative biosystem to model physiological fluidsShear stress on cells. *Applied and Environmental Microbiology*. February 2007;73(3):699-705.

Sittka A, Pfeiffer V, Tedin K, Vogel J. The RNA chaperone Hfq is essential for the virulence of Salmonella typhimurium. *Molecular Microbiology.* 2007;63(1):193-217. doi: 10.1111/j.1365-2958.2006.05489.x.

Wilson JW, Ott CM, Honer zu Bentrup K, et al. Spaceflight alters bacterial gene expression and virulence and reveals a role for global regulator. *Proceedings of the National Academy of Sciences of the United States of America*. 2007;104(41):16299-16304. doi: 10.1073/pnas.0707155104.

Nickerson CA, Ott CM, Wilson JW, Ramamurthy R, Pierson DL. Microbial responses to microgravity and other low-shear environments. *Microbiology and Molecular Biology Reviews*. 2004;68(2):345-361.

This investigation is complete and all results are published.

Microbial dynamics in International Space Station (Microbe-I/II), Two Investigations

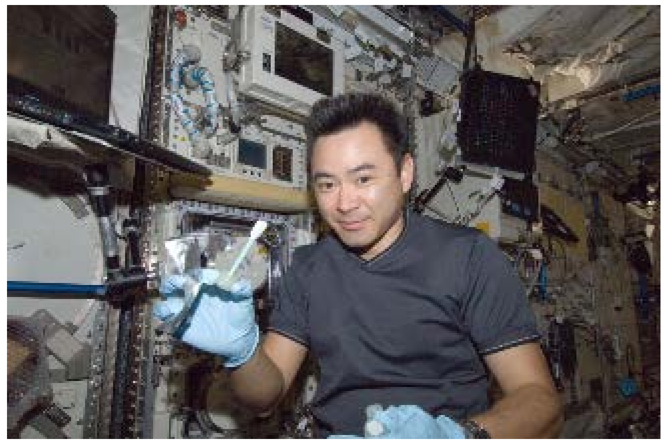
Research Area: Microbiology
Expedition(s): 19, 20 and 23-26
Principle Investigator(s):
- Koichi Makimura, MD, PhD, Teikyo University, Tokyo, Japan
- Masao Nasu, PhD, Osaka University, Osaka, Japan

Research Objectives

The Microbe investigations are a set of activities used to monitor the abundance and diversity of fungi and bacteria in Kibo (the Japanese Experiment Module) of the International Space Station (ISS).

Earth Benefits

This experiment contributes to the establishment of a standard microbial sampling method that pharmaceutical and food industries can use. These industries require strict microbial control and could greatly benefit from such techniques. Microbe can also contribute to a better microbial quality control of freshwater, a fundamental part of daily life.



ISS033E012541 – Japan Aerospace Exploration Agency (JAXA) astronaut Akihiko Hoshide, Expedition 33 flight engineer, performs microbial white tube sampling in the JEM Pressurized Module with wet wipes and sampling sheets for the JAXA MICB (Microbe-III) experiment. JAXA image.

Space Benefits

Periodically monitoring microbial activity in the JEM module secures microbial hygiene and can be used in other closed habitat systems, such as the relatively constant environment of space ships.

Results

Fungal populations (Makimura)

Samples were collected from 3 sites in Kibo (air diffuser, handrail, and surfaces) for analysis of fungal biota approximately 1 year after the module had docked to the ISS. Samples taken from Kibo before launch and from our laboratory were used as controls. In the case of Kibo, both microbe detection sheet (MDS) and swab culture tests of orbital samples were negative. The MDS were also examined by field emission-scanning electron microscopy; no microbial structures were detected. However, fungal DNAs were detected by real-time PCR and analyzed by the clone library method; *Alternaria* and *Malassezia* spp. were the dominant species before launch and in space, respectively. The dominant species found in specimens from the air conditioner diffuser, lab bench, door push panel, and facility surfaces on the laboratory (ground controls) were *Inonotus*, *Cladosporium*, *Malassezia*, and *Pezicula*, respectively. The fungi in Kibo were probably derived from contamination due to humans, while those in the laboratory came from the environment (eg, the soil). In conclusion, the cleanliness of Kibo was equivalent to that in a clean room environment on the ground.

***Bacterial populations* (NASU)**

Microbiological monitoring is important to assure microbiological safety especially in long-duration space habitation. Researchers have continuously monitored the abundance and diversity of bacteria in the ISS-Kibo to accumulate knowledge on microbes in the ISS. In this study, we used a new sampling device, the microbe-collecting adhesive sheet developed in our laboratory. This adhesive sheet has high operability, needs no water for sampling, and is easy to transport and store. We first validated the adhesive sheet as a sampling device used in space habitat, with regard to stability of bacterial number on the sheet during prolonged storage of up to 12 months. Bacterial abundance on the surfaces in the Kibo was then determined, and it was lower than that on the surfaces in our laboratory (10^5 cells $[cm^2]^{-1}$), except for the return air grill, and bacteria detected in the Kibo were a part of the human skin microflora. From these studies of microbial abundance and their phylogenetic affiliation, scientists concluded that the Kibo has been microbiologically well maintained; however, microbial abundance may increase with prolonged stay of crew members. To ensure crew safety and understand bacterial dynamics in space habitation environments, continuous bacterial monitoring in the Kibo is required.

Publication(s):

Ott CM, Pierson D, Shirakawa M, et al. Space habitation and microbiology: Status and roadmap of space agencies. *Microbes and Environments.* 2014;29(3):239-242. doi: 10.1264/jsme2.ME2903rh.

Venkateswaran K, La Duc MT, Horneck G. Microbial existence in controlled habitats and their resistance to space conditions. *Microbes and Environments.* 2014;29(3):243-249. doi: 10.1264/jsme2.ME14032.

Yamaguchi N, Roberts M, Castro S, et al. Microbial monitoring of crewed habitats in space—Current status and future perspectives. *Microbes and Environments.* 2014;29(3):250-260. doi: 10.1264/jsme2.ME14031.

Ichijo T, Hieda H, Ishihara R, Yamaguchi N, Nasu M. Bacterial monitoring with adhesive sheet in the International Space Station “Kibo”, the Japanese experiment module. *Microbes and Environments.* April 20, 2013;28(2):264-268. doi: 10.1264/jsme2.ME12184.

Satoh K, Nishiyama Y, Yamazaki TQ, et al. Microbe-I: Fungal biota analyses of Japanese experimental module “Kibo,” International Space Station which passed for about four hundred sixty days. *Microbiology and Immunology*. December 2011;55(2):823-829. doi: 10.1111/j.1348-0421.2011.00386.x.

This experiment is complete; however additional results are pending publication.

Microbial life in Space: Response to environmental factors in a space vehicle (Microspace)

Research Area: Microbiology
Expedition(s): 10 and 11
Principal Investigator(s):
- Francesco Canganella, Universitá della Tuscia, Viterbo, Italy

Research Objectives

Microorganisms are well known for their capabilities to withstand extreme environmental conditions such as elevated temperature, high salinity, hydrostatic pressure, and toxic compounds. The exposure to radiation, vacuum, electricity, and magnetic waves has been investigated in the past, but still little information is available about the effects of the space environment on microorganisms. The Microbial life in Space: Response to environmental factors in a space vehicle (Microspace) research studies the response of representative nonpathogenic microorganisms to the environment inside the space vehicle and at different mission stages.

Microspace experiment pouch. ESA image.

Results

The response of microorganisms was investigated in terms of survival rates, cell structure modifications, and genomic damages. The survival of cells was affected by both radiation doses and intrinsic cell features. As expected, only samples kept on the International Space Station (ISS) for 226 days showed significant levels of mortality. As far as the effect on cell structures, these samples also showed remarkable morphological changes, particularly for Escherichia coli, Enterococcus faecium, and Saccharomyces cerevisiae. The data collected allowed for new insights into the biological traits of microorganisms exposed to space environment during spaceflight. Moreover, the result obtained may be important for the improvement of human conditions aboard space vehicles (nutraceuticals for astronauts and disinfections of ISS modules) and also for the potential development of closed systems devoted to vegetable productions and organic recycling.

Publication(s)

Canganella F, Bianconi G. Survival of microorganisms representing the three domains of life inside the International Space Station. *Microgravity Science and Technology*. 2007;19(5-6):148-153. doi: 10.1007/BF02919471.

This investigation is complete and all results are published.

Passive Observatories for Experiments Microbial Systems (POEMS)

Research Area: Microbiology

Expedition(s): 13 and 14

Principal Investigator(s):

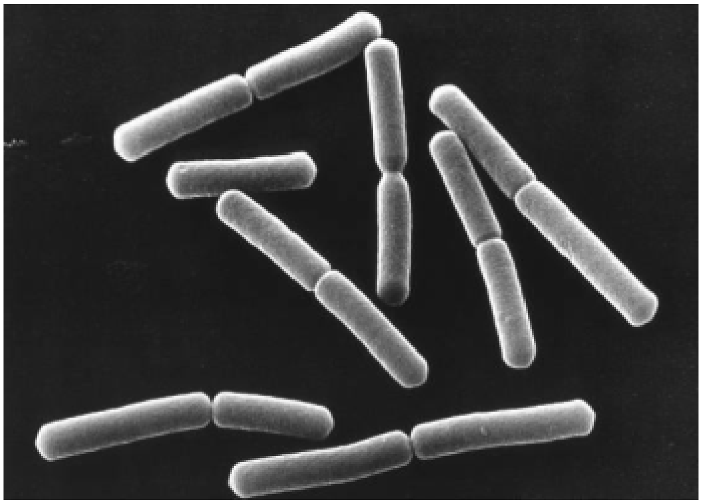
- Michael S. Roberts, PhD, Dynamac Corporation, Cape Canaveral, Florida

Research Objectives

This experiment evaluates how exposure to space leads to genetic changes and variation using model microbe cultures.

Earth Benefits

The research objective is to develop and test passive observatories for experimental microbial systems (POEMS) for the long-term, multi-generation monitoring of microbial community development in isolated biological systems such as humans on long-term space missions. However, the results of this study may be applicable to other isolated biological systems found on Earth, including those that incorporate humans, such as cruise ships and submarines. Results may also provide insight into the mechanisms of DNA repair and acquisition of exogenous genetic information in microorganisms, which is important to understanding the spread of such genetic-based traits as antibiotic resistance.

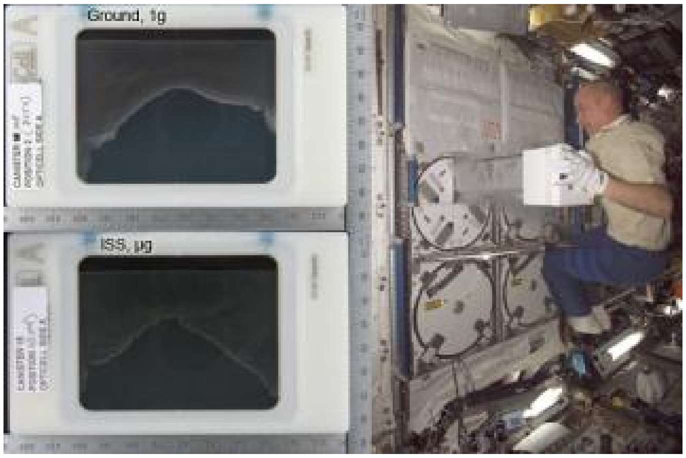


Scanning Electron Micrograph of gram positive *Bacillus subtilis* bacteria that is studied by the Passive Observatories for Experiments Microbial Systems (POEMS) investigation. POEMS looks for genetic changes that might occur in these bacteria as a result of exposure to the space environment. SCIMAT image.

Space Benefits

Extension of human habitation into space results in humans carrying with them the microorganisms with which they coexist on Earth. This proposal seeks to develop simple, ground-based experimental systems with low manpower, mass, volume, and energy requirements that enable exploration of the ecology and evolution of microbiological communities in the space environment. Given the potential for rapid change in populations of microorganisms under space conditions, it is essential to the NASA mission to understand both the mechanisms and consequences of microbial evolution in space. Just as on Earth, the survival of humans on long-term missions is inextricably linked to their microbial companions. Passive experimental microbial systems (POEMS) are an enabling technology to address fundamental questions in the ecology and evolution of microbes in the insulated ecosystem of the space environment.

RESULTS



ISS013E64639 - Image on the left shows ground control and a flight sample of bacteria cultures growing through the solid media agar, and scientists can sample the genetic changes across multiple generations by sampling different places in the growth medium. Image on the right shows NASA International Space Station Science Officer, Jeff Williams inserting one of the Passive Observatories for Experiments Microbial Systems samples into the Minus Eighty-Degree Laboratory Freezer for ISS freezer.

POEMS performed as expected, and data (temperature, thermal offsets, and humidity) has been recovered from data-loggers. Bacterial cells and genetic transformants were recovered in all returned canisters. Fixed gases and volatile organic compound analyses of canister headspace are underway.

The investigation team continues to isolate and characterize rifampicin-resistant bacteria and to enumerate auxotroph mutants (lysine methionine tryptophan) that were recovered from sortie mission canisters (5 canisters) and 3 canisters from the International Space Station (ISS) mission returned on STS-115. Viable cell and spore counts are completed; total direct counts and genetic characterization of transformants is ongoing. Transformation efficiency was lower than expected in both flight and ground experiments, but rates were sufficient to yield >102 *rpo*B transformants. Data analysis continues for 6 months after recovery of all POEMS canisters from ISS.

Trends in early analyses suggest that microbe population densities and transformation rates may be slightly elevated in flight samples compared to ground controls, but the preliminary conclusion is that the effects of the space environment on the rate of horizontal gene transfer are not statistically significant for Bacillus subtilis. Full data analysis is pending.

PUBLICATION(S)

Roberts MS, Reed DW, Rodriguez JI. Passive observatories for experimental microbial systems (POEMS): Microbes return to flight. *34th International Conference on Environmental Systems*, Colorado, Springs, CO; July 2005.

This investigation is complete; however additional results are pending publication.

STREPTOCOCCUS PNEUMONIAE EXPRESSION OF GENES IN SPACE I AND II (SPEGIS I AND SPEGIS II), TWO INVESTIGATIONS

Research Area: Microbiology
Expedition(s): 15, 21, and 22
Principal Investigator(s):
- David W. Niesel, PhD, University of Texas Medical Branch, Galveston, Texas

A scientist loads a vial into the Streptococcus Pneumoniae Expression of Genes in Space canister. In the background, the vials are stored in a four degree C Labtop cooler. NASA's Ames Research Center, Dominic Hart image.

RESEARCH OBJECTIVES

Streptococcus pneumoniae Expression of Gene in Space (SPEGIS) examines the behavior and growth of bacteria in microgravity and investigates the effects of the space environment on the gene expression, protein production, and virulence of the bacteria *Streptococcus pneumoniae*. The data collected also provides insight on what types of bacterial infections may occur during long-duration space missions and the risks to crew members.

S118E06158 - Missions Specialist, Astronaut Barbara Morgan is inserting the samples for the SPEGIS investigation into the Minus Eighty-Degree Laboratory Freezer for ISS for storage during the mission.

EARTH BENEFITS

Analyzing and understanding the mechanisms utilized by *S. pneumoniae* to adapt to microgravity can lead to the development of novel methods to combat newly emerging drug-resistant strains, which could greatly assist in disease prevention and management on Earth.

SPACE BENEFITS

Identification of the global genetic responses undergone by *S. pneumoniae* in reaction to space enables this single-flight experiment to determine if the spacecraft environment exerts a selective pressure on microbial contaminants, leading to increased virulence and contributing to increased health risks to the crew. Results from SPEGIS also provides information on the threat of opportunistic pathogens in the space environment, which assists in the development of diagnostic tools to monitor the atmosphere and surfaces (air, soil, and food) for the presence of these microbes. Further, identification of spaceflight alterations to genes and proteins involved in bacterial proliferation and mutation provides targets for pharmacological intervention, which can ultimately facilitate long-term exploration of the moon and Mars.

RESULTS

SPEGIS is undergoing bioinformatics analysis, and final results are pending.

These investigations are complete; however additional results are pending publication.

eVALUATIOn AND MONITORING OF MICROBIOFILMS INSIDE INTERNATIONAL SPACE STATION (VIABLE ISS)

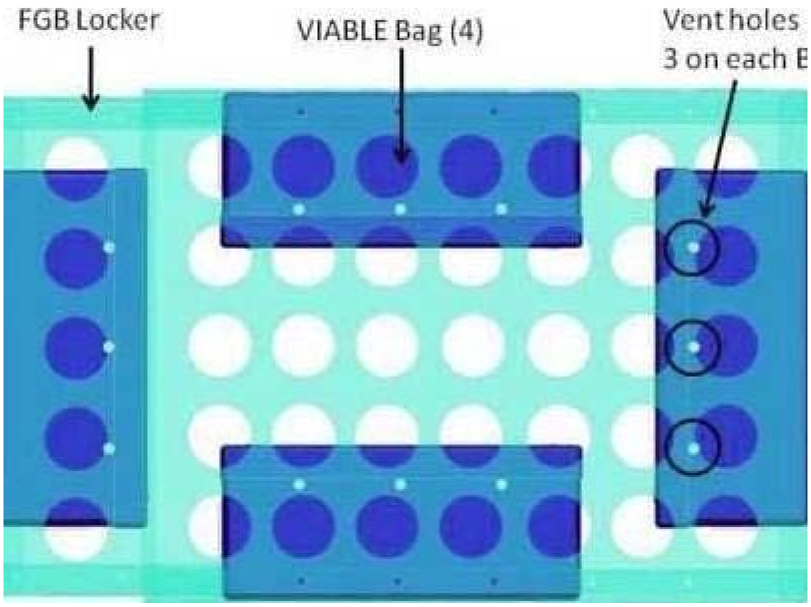
Research Area: Microbiology
Expedition(s): 27-30
Principal Investigator(s):
- Francesco Canganella, University of Tuscia, Viterbo, Italy

RESEARCH OBJECTIVES

The eValuatIon and Monitoring of MicroBiaL Biofilms InsidE ISS (VIABLE ISS) study involves the evaluation of the microbial biofilm development on space materials. Both metallic and textile space materials, either conventional or innovative, are located inside and on the cover of Nomex pouches placed inside the International Space Station (ISS).

EARTH BENEFITS

The potential application of novel methodologies and products to treat space materials may lead to improve the environmental quality of manned confined habitats on space; but also specific bases and modules on Earth where humans have to stay long-term, particularly for scientific purposes.



Planned configuration of the four VIABLE pouches inside the Functional Cargo Block (FGB) locker. ASI image.

SPACE BENEFITS

The present investigation may supply interesting data related to the biosafety and health quality of crew members as well as to the maintenance of ISS hardware. Microbial biofilms are well known for causing damage and contamination on both MIR and ISS. The potential application of novel methodologies and products to treat space materials may lead to improve the environmental quality of manned confined habitats on space.

RESULTS

Data analysis of VIABLE ISS is ongoing.

This investigation is ongoing and additional results are pending publication.

YEAST IN NO GRAVITY - THE INFLUENCE OF MICROGRAVITY ON CELLULAR ADHESIONS, BIOFILM FORMATION AND IN INVASIVE GROWTH IN THE MODEL EUKARYOTE SACCHAROMYCES CEREVISIAE (YEAST-B: PART 2)

Research Area: Microbiology
Expedition(s): 19 and 20
Principal Investigator(s):

- Ronnie Willaert, PhD, Vrije Universiteit Brussel, Brussels, Belgium
- Freddy Delvaux, PhD, Katholieke Universiteit, Heverlee, Belgium
- Jens Nielsen, PhD, Technical University of Denmark, Kongens Lyngby, Denmark
- Lode Wyns PhD, Free University, Brussels, Belgium

RESEARCH OBJECTIVES

Yeast In No Gravity - The Influence of Microgravity on Cellular Adhesions, Biofilm Formation and In Invasive Growth in the Model Eukaryote Saccharomyces cerevisiae (Yeast-B: Part 2) will determine the effect of microgravity on expression and functionality of Flo proteins from *Saccharomyces cerevisae*, which are involved in cell surface interactions on solid substrate and cell-cell interactions in liquid media. The final goal is to obtain information on the importance of gravity on the formation of organized cell structures (flocculation, biofilm, invasion) and the entire "Flo processes" itself.

RESULTS

The colony growth rate of the agar invasive *S. cerevisiae* Σ1278b strain was reduced as well as its agar invasiveness. Postflight growth experiments of a brewer's top yeast strain showed an increase in G2/M and a decrease in Sub-G1 cell population; an increased viability, a decreased lipid peroxidation level, increased glycogen content, and changes in carbohydrate metabolic enzyme activities were also observed. Using the *S. cerevisiae* BY4741 deletion collection, genes that provide a survival advantage in space, were identified in a batch growth experiment; no difference in growth rate was observed. Freeze-dried strains showed significant changes in the cell wall thickness. Spaceflight unique gene expression changes were observed in stress response element (STRE) genes with transcription regulation involving Sfp1 (which is involved in the TOR pathway) and Msn4. Some of the components of the ribosome biogenesis (which is under the control of Sfp1) as well as components of the proteasome were down regulated in microgravity. Recent results indicate that microgravity

ISS020E044456 – Astronaut Frank De Winne, Expedition 20 flight engineer, works with the Yeast-B Part 2 experiment container in the Biolab incubator located in the Columbus module.

imposes a “microgravity” stress on the cells, which has the characteristics of an osmotic stress. Cellular energy is directed towards protective measures such as cell wall biosynthesis (cell wall integrity pathway activation) and the production of compounds (glycerol, trehalose) that increase the osmotolerancy (HOG pathway).

This investigation is complete; however additional results are pending publication.

Yeast-Group Activation Packs (Yeast-GAP)

Research Area: Microbiology
Expedition(s): 8 and 13
Principal Investigator(s):
- Cheryl A. Nickerson, PhD, Arizona State University, Tempe, Arizona

S115E07274 - Astronaut Heidemarie M. Stefanyshyn-Piper, STS-115 mission specialist, works with the Yeast-Group Activation Packs (Yeast-GAP) on the middeck of Space Shuttle *Atlantis*. Yeast-GAP experiment studies the effects of genetic changes of yeast cells exposed to the space environment. The results help scientists to understand how cells respond to radiation and microgravity.

Research Objectives

Yeast-Group Activation Packs (Yeast-GAP) studies the effects of genetic changes of yeast cells exposed to the space environment. The results help scientists understand how cells that respond to radiation and microgravity impact the determination of health remedies and increase the basic understanding of cell biology.

Earth Benefits

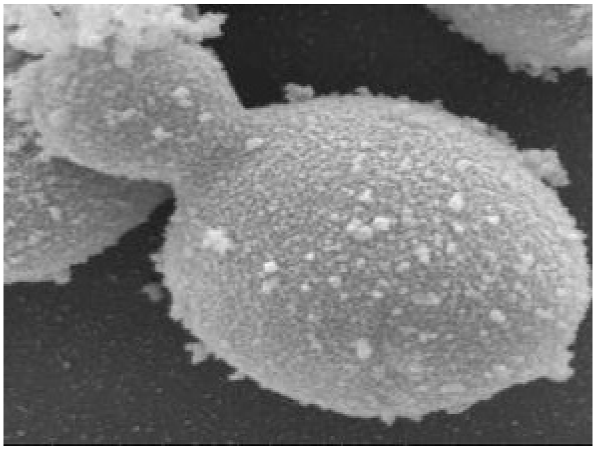
Any insight into the genetic controls of a single-celled organism like yeast or certain bacteria can yield tremendous benefits on Earth, including increased antibiotic production as well as further insight into general cell biology. Research, such as Yeast-GAP, can lead to further developments in cancer research.

Space Benefits

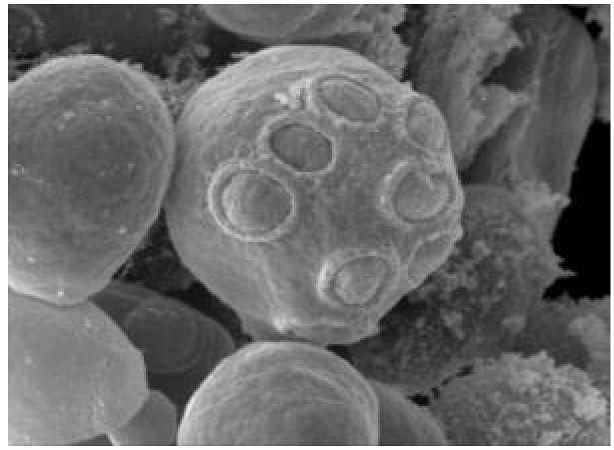
Understanding how microbes reproduce and mutate in space may lead to the development of additional countermeasures to protect crew members on future long-duration missions.

Results

Yeast-GAP was sent to space in October 2002 and September 2006 to determine the effects microgravity has on *S. cerevisiae*. More specifically, this experiment was conducted to determine which genes impart a survival advantage and which a disadvantage under the unique environmental conditions associated with microgravity. To accomplish this, a gene deletion series of yeast strains were combined and grown in the same media and identical growth conditions both in flight and on the ground.



Scanning electrograph image of *Saccharomyces cerevisiae* cells grown on Earth.



Scanning electrograph image of *Saccharomyces cerevisiae* cells grown on the International Space Station.

It was found that indeed select key genes are necessary for robust growth during spaceflight (deletion leads to poor growth) while others appear to inhibit growth in microgravity (deletion leads to enhanced growth). Spaceflight cultures exhibited survival advantages in strains with deletions in their catalytic active genes. In comparison to ground controls, flight cultures held were disadvantaged with deletions dealing with strains lacking transporter, antioxidant, and catalytic activity. Yeast-GAP further identified specific genes critical for survival in space (Johanson 2007).

Yeast-GAP was able to identify Stress Response Element (STRE) genes associated with microgravity. STRE genes are activated in response to specific stresses, including osmotic stress, heat shock, and environmental stresses such as microgravity. This experiment investigated the gene expression changes of the STRE genes SSA4, YIL052C, and YST2, with transcription regulation involving Sfp1 and Msn4. Results show that spaceflight significantly decreased expression of most genes, with only one left unaffected. Next, transcriptional regulation of YIL052C and SSA4 were explored. Genes were stripped of one of their transcriptional factors and evaluated to determine each gene's dependence on the corresponding factor. Both genes lacking Msn4 decreased expression while genes lacking Sfp1 did not experience any change. This suggests that the cellular effects of the space environment are at least in part mediated by the transcription factor Sfp1. This is significant because it demonstrates the importance of true microgravity experimentation (in contrast to ground simulations of microgravity), which can lead to a better understanding of the mechanisms behind cellular responses to this unique environment (Coleman 2008).

Finally, phenotypic variations were observed as assessed by scanning electron microscopy (SEM). Yeast cells grown under ground-based conditions revealed a normal budding pattern with buds developing adjacent to previous bud scars. Yeast cells exposed to microgravity exhibited random and more numerous budding patterns (Johanson 2007).

These early investigations were designed to be launched on an unmanned spacecraft (Progress) well in advance of processing aboard the International Space Station and remain stable for months before return to Earth and analysis. The results obtained demonstrate the robustness of studies utilizing *S. cerevisiae* as a model for eukaryotic cell studies. These studies demonstrate that the yeast gene deletion series is a powerful tool to assess the effects of microgravity and other environmental factors on cellular level responses, which is likely to be relevant to more complex organisms including humans.

PUBLICATION(S)

Coleman CB, Allen PL, Rupert M, et al. Novel Sfp1 transcriptional regulation of Saccharomyces cerevisiae gene expression changes during spaceflight. *Astrobiology*. 2008;8(6):1071-1078. doi: 10.1089/ast.2007.0211.

Johanson K, Allen PL, Gonzalez-Villaobos RA, et al. Haploid deletion strains of Saccharomyces cerevisiae that determine survival during spaceflight. *Acta Astronautica*. 2007;60(4-7):460-471. doi: 10.1016/j.actaastro.2006.09.011.

This investigation is complete and all results are published.

YEAST IN NO GRAVITY - THE INFLUENCE OF MICROGRAVITY ON CELLULAR ADHESIONS, BIOFILM FORMATION AND IN INVASIVE GROWTH IN THE MODEL EUKARYOTE SACCHAROMYCES CEREVISIAE (YING-A: PART 1)

Research Area: Microbiology

Expedition(s): 14

Principal Investigator(s):

- Ronnie Willaert, PhD, Vrije Universiteit Brussel, Brussels, Belgium
- Freddy Delvaux, PhD, Katholieke Universiteit, Heverlee, Belgium
- Jens Nielsen, PhD, Technical University of Denmark, Kongens Lyngby, Denmark
- Lode Wyns PhD, Free University, Brussels, Belgium

RESEARCH OBJECTIVES

Yeast In No Gravity - The Influence of Microgravity on Cellular Adhesions, Biofilm Formation and In Invasive Growth in the Model Eukaryote Saccharomyces cerevisiae (YING-A: Part 1) studies the influence of microgravity on Flo proteins of the yeast *Saccharomyces cerevisiae*, which are involved in cell surface interactions on solid substrate and cell-cell interactions in liquid media. The final goal is to obtain information on the importance of microgravity on the formation of organized cell structures (flocculation, biofilm, invasion) and the entire “Flo processes” itself.

RESULTS

Yeast cells were grown on Yeast extract Peptone Dextrose (YPD) agar plates during 300 hour at an average temperature of 19.28°C. Colony morphology was assessed by photographing the plates at 2 time points in orbit, after 97.5rh and 216.3hr. For the ground reference experiments, photographs were taken every day. Both the CMBSESA1 and Σ1278b yeast colonies covered a larger surface on 0.8% agar than on 2% agar throughout the experiment, which is in accordance with previous studies. Two-dimensional spreading of the yeast colonies grown on semi-solid agar medium was reduced under microgravity in the Σ1278b laboratory strain but not in the CMBSESA1 industrial strain. This was supported by the Σ1278b proteome map under microgravity conditions, which revealed up-regulation of proteins linked to anaerobic conditions. The Σ1278b strain showed a reduced invasive growth in the center of the yeast colony. Bud scar distribution was slightly affected with a switch toward more random budding. Together, microgravity conditions disturb spatially programmed budding patterns and generate strain-dependent growth differences in yeast colonies on semi-solid medium. Proteomics analysis showed that the Σ1278b WT showed a more anaerobic fermentative growth in microgravity compared to the ground samples, since many enzymes involved in the Krebs cycle were less abundant in microgravity, which indicates a higher request for energy in microgravity.

PUBLICATION(S)

Van Mulders SE, Stassen C, Daenen L, et al. The influence of microgravity on invasive growth in Saccharomyces cerevisiae. *Astrobiology*. 2011;11(1):45-55. doi: 10.1089/ast.2010.0518.

This investigation is complete and all results are published.

MICROENCAPSULATION ELECTROSTATIC PROCESSING SYSTEMS (MEPS)

Research Area: Microencapsulation
Expedition(s): 5
Principal Investigator(s):
- Dennis R. Morrison, PhD, Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

A single-step process forming a tiny liquid-filled, biodegradable, micro-balloons containing various drug solutions (a process called microgravity micro-encapsulation) has been shown to provide better drug delivery and new medical treatments for solid tumors and resistant infections. Recent testing in mouse models has shown that these unique microcapsules can be injected into human prostate tumors to inhibit tumor growth or can be injected following cryo-surgery (freezing) to improve the destruction of the tumors much better than freezing or local chemotherapy alone. The microcapsules also contain a contrast agent that enables C-T, X-ray or ultrasound imaging to monitor the distribution within the tissues to insure that the entire tumor is treated when the microcapsules release their drug contents.

Micro-balloons containing anti-tumor drugs and small amounts of radio-contrast oil were created during Microencapsulation Electrostatic Processing Systems operations on STS-95. The radio-contrast oil is traceable by radiograph and allows doctors to follow the microcapsules as they travel to the tumor. The permeable outer skin releases the drug slowly, giving the microcapsule plenty of time to reach its destination. This slow release prevents artery damage as the drug travels to its destination. NASA's Johnson Space Center image.

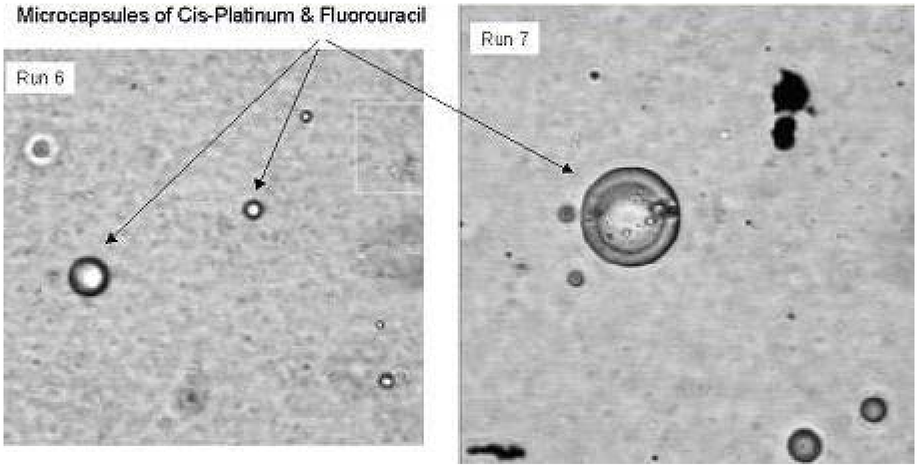
EARTH BENEFITS

The utilization of microcapsules can benefit the treatment of several diseases here on Earth. Microcapsules can be inhaled to deliver antibiotic and immune stimulant drugs to treat inhaled bacterial infections of the lungs. These unique microcapsules can be injected directly into solid tumors to provide local, sustained release, of anti-cancer drugs. The microcapsules can be imaged with C-T scans or ultrasound to insure that the release combinations of medications slowly over 12-14 days, which can be delivered directly to the target tumors. Since the drug release is local, using these mirocapsules reduces the unwanted side effects of systemic (intravenous) chemotherapy, which involves large amount of drugs producing major side effects throughout the entire body.

SPACE BENEFIT

MEPS expands our understanding of the use of microgravity to enable development of new drug delivery devices. These new discoveries can help protect crew members on long-duration space missions and provide alternative delivery routes and countermeasures to injured or sick crew members.

RESULTS



The images shows some microcapsules produced on the International Space Station in Microencapsulation Electrostatic Processing Systems during the UF-2 mission (July 18-19,2002). NASA Johnson Space Center image.

The MEPS experiment on the International Space Station consisted of 8 samples processed using various methods to mix dissimilar liquids to form micro-balloons/microcapsules. The recovered micro-balloons were analyzed for size and drug content. Additionally, studies included the effects of temperature and mixing fluid shear on the size of the micro-balloons and payload concentration of contrast and concentrated drug. ON UF-2 several combinations of anti-cancer drugs, photodynamic therapy drugs, and a DNA construct were successfully encapsulated. These results led to the invention and NASA Patent for a Pulse Flow Microencapsulation Processing System that has been used to make these microcapsules for ground-based studies on human tumors grown in a mouse model. Pre-clinical investigations revealed that when only a few doses of microcapsules containing 5-Fluorouracil are injected directly into human prostate tumors, the growth can be inhibited by up to 51% within 3 weeks. When chemotherapy microcapsules are injected following cryo-surgery, the combined treatment can greatly inhibit the growth of 1-2cm size prostate tumors by 72% in just 3 weeks (Morrison 2009). Other studies using 2 doses of 5-FU microcapsules injected into A549 human lung tumors inhibited growth by 45% and destroyed 18% of the lung tumors after 4 weeks of sustained release. In a parallel study, only 2 doses injected of microcapsules containing Paclitaxel, injected on Day 0 and Day 7 produced macroscopic necrosis in 43% of the tumors. After 26 days of sustained Paclitaxel release, lung tumor growth was inhibited by 82% and 28% of the tumors had completely disappeared (Morrison 2013, in press).

A further study was carried out aiming to confirm the increased growth inhibition of human prostate tumors produced by an intentionally palliative combination treatment of cryochemotherapy (partial cryoablation followed by intratumor partial chemotherapy with injection of microencapsulated 5-fluorouracil at the ice ball periphery). The results of this study extend and confirm previous findings (Le Pivert 2009). The addition of 5-fluorouracil focal chemoablation to partial cryoablation of a fast growing hormone resistant prostate cancer enhances the directional destructive effect of cryosurgery and inhibits growth in peripheral unfrozen tumor tissues (Le Pivert 2004*).*

PUBLICATION(S)

Le Pivert PJ, Morrison DR, Haddad RS, et al. Percutaneous tumor ablation: Microencapsulated echo-guided interstitial chemotherapy combined with cryosurgery increases necrosis in prostate cancer. *Technology in Cancer Research and Treatment*. 2009;8(3):207-216.

Le Pivert PJ, Haddad RS, Aller A, et al. Ultrasound guided, combined cryoablation and microencapsulated 5-fluorouracil, inhibits growth of human prostate tumors in xenogenic mouse model assessed by fluorescence imaging. *Technology in Cancer Research and Treatment*. 2004;3(2):135-142.

Morrison DR, Haddad RS. Microencapsulation of drugs: New cancer therapies and improved drug delivery derived from microgravity research. *40th Space Congress*, Cape Canaveral, FL; 2003.

PATENT(S)

Morrison DR, Mosier B, inventors; Externally triggered microcapsules. United States Patent and Trademark Office 7,968,117. June 28, 2011.

Morrison DR, inventor; Microencapsulation system and method. United States Patent and Trademark Office 7,588,703. September 15, 2009.

Morrison DR, inventor; Microparticle analysis system and method. United States Patent and Trademark Office. 2007.

Morrison DR, inventor; Microencapsulation system and method. United States Patent and Trademark Office 7,094,045. August 22, 2006.

This investigation is complete; however additional results are pending publication.

ADVANCED ASTROCULTURE™ (ADVASC)

Research Area: Plant Biology
Expedition(s): 2, 4 and 5
Principal Investigator(s):
- Weijia Zhou, PhD, University of Wisconsin, Madison, Wisconsin

RESEARCH OBJECTIVES

Understanding the effects of gravity on plant life is essential in preparation for future interplanetary exploration. The ability to produce high energy, low-mass food sources during spaceflight enables the maintenance of crew health during long-duration missions while having a reduced impact on resources necessary for long-distance travel. Additional applications of a plant growth chamber include using plants as components of regenerative life support systems for travel to the moon and Mars.

ISS004E8727 - Interior view of the Advanced Astroculture (ADVASC) experiment plant growth chamber showing the emergence of mustard seedlings. The ADVASC experiment is located in Expedite the Processing of Experiments to the Space Station rack 4 in the Destiny U.S. Laboratory during Expedition 4.

EARTH BENEFITS

ADVASC contributes to National Security, cancer-fighting pharmaceuticals and educational tools for students. Bio-KES, a device that uses ultraviolet light to convert ethylene into carbon dioxide and water, to remove the ethylene from plant growth chamber, can be used to kill pathogens like anthrax. The light, used to simulate photosynthesis in the growth chambers, heals wounds and increases the effectiveness of cancer-fighting drugs *in vitro*. The Orbital Laboratory is an Internet-based multimedia tool that allowed students and educators to conduct their own ground-based plant experiments and to analyze data returned from the ADVASC units in their classrooms on Earth.

SPACE BENEFITS

ADVASC explores the benefits of using microgravity to create customized crops that withstand disease and inhospitable conditions, resist pestilence, and need less space to grow. These qualities benefit space explorers and earth inhabitants. Plant growth and development in microgravity can provide a natural air and water filtration system and large-scale plant growth systems. Furthermore, ADVASC is a precursor for growing plants during extended space expeditions to the moon and Mars.

RESULTS

ISS005E07209 - Astronaut Peggy A. Whitson, Expedition 5 NASA ISS science officer, displays a first crop of soybeans growing inside the AdvAsC. Photos of the growing plant have been a useful tool for the ground-based science team, which uses them to determine optimal time for cross-pollination and harvesting.

Arabidopsis thaliana was successfully grown from seed to seed on the International Space Station (ISS). During a 2-month growth period, the plants progressed from seed hydration to germination, vegetative, and reproductive stages, producing mature seeds. Ninety percent of the seeds germinated in space, although only 70 percent of the plants grew to maturity. Some of the seeds that were harvested from the plants grown in microgravity were planted in a ground study. These seeds produced typical plants without any visible abnormalities (Link 2003). During a second ADVASC run, second-generation seeds were produced and tissues were harvested and preserved for RNA and complementary deoxyribonucleic acid (cDNA) analysis. Detailed results of the germination and harvesting of space-grown seeds in the ADVASC growth chamber in the U.S. Destiny Laboratory have not been released. In the third ADVASC run, which took place over approximately 95 days on ISS, soybeans were grown from seed to seed for the first time in space. Biomass production in the space seeds was approximately 4% larger than ground controls. Flight and ground controls produced nearly identical numbers of seeds, but the space seeds were larger on average. Scientists found that the seeds produced in space were healthy, the germination rates were comparable to those on Earth, and no major morphological differences were evident. Phytochemical analysis of commercially important components such as oils, amino acids, proteins, carbohydrates, and phytoestrogens have not yet been released.

PUBLICATION(S)

Link BM, Busse JS, Stankovic B. Seed-to-seed-to-seed growth and development of *Arabidopsis* in microgravity. *Astrobiology*. October 2014;14:866-875. doi: 10.1089/ast.2014.1184.

Link BM, Durst SJ, Zhou W, Stankovic B. Seed-to-seed growth of Arabidopsis Thaliana on the International Space Station. *Advances in Space Research*. 2003;31(10):2237-2243. doi: 10.1016/S0273-1177(03)00250-3.

Zhou W, Durst SJ, DeMars M, et al. Performance of the advanced ASTROCULTURETM plant growth unit during ISS-6A/7A mission. *SAE Technical Paper*. 2002;2002-01-2280. doi: 10.4271/2002-01-2280. [Paper # 02ICES-267].

Patent(s)

Burstyn J, Ellis AB, Green O, Smith NA, inventors; Photoluminescent ethylene sensors. United States Patent and Trademark Office 7,105,274. September 12, 2006.

This investigation is complete and all results are published.

ADVANCED PLANT EXPERIMENTS - CAMBIUM (APEX-CAMBIUM)

Research Area Plant Biology
Expeditions 20-21
Principal investigator(s):
- Rodney Savidge, PhD, University of New Brunswick, Fredericton, New Brunswick, Canada

RESEARCH OBJECTIVES

Canadian Space Agency astronaut and Expedition 20/21 crew member Bob Thirsk poses with the Canadian willow trees used for the Advanced Plant Experiments - Cambium experiment. NASA image.

Astronauts on the International Space Station engage in the unusual task of bending weeping willow (*Salix babylonica*) stems into loops to determine the role gravity plays in forming different kinds of wood.

Parts of a tree that are not vertical typically grow one kind of wood on one side and another kind on the other. This is known as "reaction wood," and the mix of different kinds of this wood in trees influences their suitability for different uses, such as construction or paper. Scientists believe reaction wood is a response to gravity, but they haven't been able to prove it. APEX-Cambium determines if reaction wood forms to the same extent, and in the same position as in trees grown on Earth.

EARTH BENEFITS

Understanding the fundamental processes by which plants produce cellulose and lignin in their tissues is of great interest in the realm of forestry and industry. Trees used for paper production are selected for maximum cellulose production and minimal lignin production. Conversely, trees used to make structural lumber are selected for maximum lignin content. However, due to the complex relationship of these 2 biosynthesis processes, researchers do not yet know how to genetically alter such plants to further boost their productivity. Gravity is suspected to strongly affect the formation of reaction wood, and this experiment determines if this is true.

SPACE BENEFITS

APEX-Cambium along with the Advanced Biological Research System hardware demonstrates the capabilities of providing the correct environment for plant growth aboard spacecraft. For future long-duration exploration, crews will need to be able to grow plants for a variety of applications.

RESULTS

Data analysis for this investigation is ongoing; no results have been published to date.

This investigation is complete; however additional results are pending publication.

Advanced Plant Experiment - Canadian Space Agency 2 (APEX-CSA2)

Research Area Plant Biology
Expeditions 23-24
Principal investigator(s):
- Jean Beaulieu, PhD, Natural Resources Canada, Canadian Wood Fibre Centre, Quebec City, Quebec, Canada

ISS023E036876 – NASA astronaut T.J. Creamer, Expedition 23 flight engineer, services the Advanced Plant Experiments - Canadian Space Agency 2 experiment in the Destiny laboratory of the International Space Station.

Research Objectives

The Advanced Plant Experiment - Canadian Space Agency 2 (APEX-CSA2) investigation examines white spruce, *Picea glauca*, to understand the influence of gravity on plant physiology, growth, and on the genetics of wood formation.

Earth Benefits

Gravitational pull influences the quality of wood that is produced by the tree. Depending on their composition, some types of wood are not appropriate for specific industrial applications. By growing trees in weightlessness, the investigator identifies candidate genes involved in the production of these different types of wood. These candidate genes are used to select trees that produce the wood of interest for different industrial applications. These trees are used in breeding and reforestation programs in Canada, with the aim of improving industrial competitiveness and forest sustainability.

Space Benefits

The experiment defines the best growth conditions for trees using the Advanced Biological Research System habitat and opens the way to more basic plant research in the space environment, as well as better biological life support systems to sustain human presence in space.

Results

At the end of the experiment, the leading shoot from 3 plantlets from each line tested was collected and fixed in a RNA stabilization solution. The expression levels for 27 candidate genes and 3 reference genes were determined by quantitative real-time polymerase chain reaction (qRT-PCR) on the 9 seedlings grown at 0 g and 1 g. While close to 20 genes displayed some up-regulation in microgravity conditions, only 3 genes showed statistically significant up-regulation at 0 g. The function of these 3 genes was linked to crucial processes such as cell propagation, development, and response to stress, and their up-regulation is very likely to influence seedling growth patterns in microgravity. Further analysis of plant tissues clearly demonstrated an increase in leaf growth as compared to ground-based plants, with needles less inclined towards the stem base. Cellular components involved in gravity sensing were also altered in the ISS environment.

PUBLICATION(S)

Rioux D, Lagace M, Cohen LY, Beaulieu J. Variation in stem morphology and movement of amyloplasts in white spruce grown in the weightless environment of the International Space Station. *Life Sciences in Space Research*. 2015;4:67-78. doi: 10.1016/j.issr.2015.01.004.

Beaulieu J, Giguère I, Deslauriers M, Boyle B, Mackay J. Differential gene expression patterns in white spruce newly formed tissue on board the International Space Station. *Advances in Space Research*. 2013;52(4):760–772. doi: 10.1016/j.asr.2013.05.004.

This investigation is ongoing and additional results are pending publication.

Arabidopsis thaliana in Space: Perception of Gravity, Signal Transductions and Gravitresponse in Higher Plants (AT-Space)

Research Area: Plant Biology
Expedition(s): 16
Principal Investigator(s):
- Alexander Dovzhenko, PhD, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- Klause Palme, PhD, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

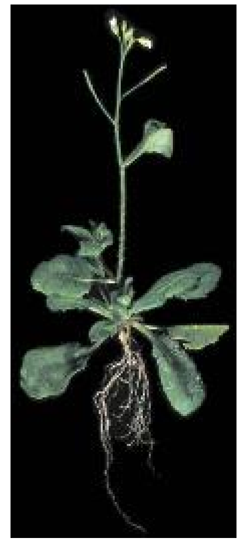


Image of *Arabidopsis thaliana* plant used in the AT-Space investigation. ESA image.

Research Objectives

The *Arabidopsis thaliana* in Space: Perception of Gravity, Signal Transductions and Gravitresponse in Higher Plants (AT-Space) experiment identifies plant gravity perception and signal transduction pathways on a molecular level. This comprehensive research should reveal the crucial factors controlling the gravity signal transduction cascade in *arabidopsis thaliana*, or thale cress, a plant that is genetically related to soybeans, cotton, vegetables, and oil seed crops

Results

Data analysis of AT-Space samples revealed numerous genes affected by microgravity. Gene network analysis revealed a hormonal cross-talk between auxin, abscisic acid (ABA) and ethylene signaling pathways in meadiating microgravity triggered stress responses, such as osmotic stress and water deprivation and lipid metabolic changes in particular.

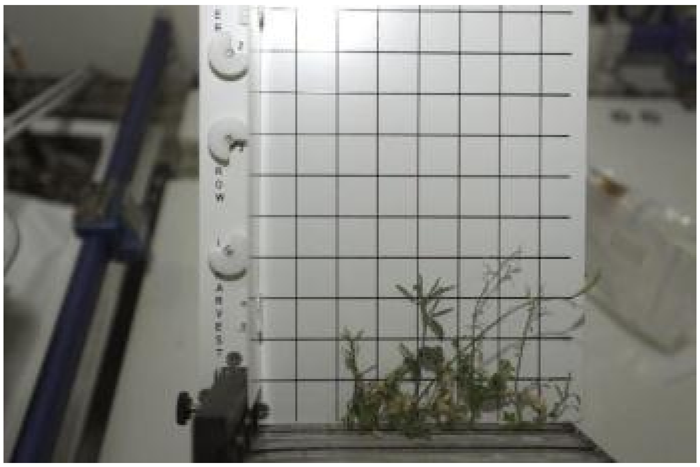
This investigation is complete and all results are published.

Biomass Production System (BPS)

Research Area: Plant Biology
Expedition(s): 4
Principal Investigator(s):
- Robert C. Morrow, PhD, Orbital Technologies Corporation, Madison, Wisconsin

Research Objectives

The Biomass Production System (BPS) environmental control subsystems provide a complete growing environment for plants in microgravity. Results can lead to the development of regenerative life support systems on future exploration missions to the moon or Mars.



ISS004E11721 – View of Brassica plants from plant growth chamber 2 being harvested as part of the technical validation test of the Biomass Production System conducted during International Space Station Expedition 4.

Earth Benefits

As less fertile land becomes available to grow food, alternative agricultural systems that efficiently produce greater quantities of high-quality crops are increasingly important. Data from the operation of the BPS can advance greenhouse and controlled-environment agricultural systems and help farmers produce better, healthier crops in a small space using the optimum amount of nutrients.

Space Benefits

The amount of food necessary to sustain a crew during a long-duration mission to Mars would prohibitively increase the mass of spacecraft and the overall cost of the mission. Some of the crew's food would need to come from a selection of renewable crops grown in biomass production systems. The biomass production systems may also be used as a filtration system for water and atmospheric gases. Plant growth chambers would also offer a comforting, green reminder of Earth to a crew a long way from home.

Video screen shot of *Brassica rapa*, 36 days after planting on International Space Station during Increment 4. NASA image.

Results

Thirty-two germinating *Brassica rapa* plants were launched inside the BPS for the TVT of the hardware. The *Brassica rapa* plants were grown over 2 growth cycles on International Space Station (ISS). *Brassica rapa* tissue from BPS was analyzed for general morphology, seed anatomy and storage reserves, foliar carbohydrates, and chlorophyll and root zone hypoxia analysis. Some of the wheat plantings were evaluated for growth, germination, weight, chlorophyll concentration and root appearance (Morrow 2004). By the end of the 73-day experiment, BPS TVT produced a total of 8 harvests, 7 primings, and a plant tissue archive of more than 300 plants.

Gross measure of growth, leaf chlorophyll, starch, and soluble carbohydrates confirmed comparable performance by the plants on the station with ground controls. Of particular interest were the differences between the immature seedlings. Immature seeds from station had higher concentrations of chlorophyll, starch, and soluble carbohydrates than the ground controls. Seed protein was significantly lower in the ISS material. Also, microscopy of immature seeds fixed on ISS showed embryos to be at a range of developmental stages, while ground control embryos had all reached the same stage of development. These differences could be attributable to differences in water delivery or reduced gas exchange due to lack of convection. These results suggest that the microgravity environment may affect flavor and nutritional quality on potential space produce (Musgrave 2005).

An ancillary study tested for bacterial and fungal communities in the BPS chambers and root modules, and these cultures were compared to ground control bacterial and fungal growth. Analysis indicated more species of both bacteria and fungus were identified in the flight samples than the ground samples. The populations were common airborne species found on Earth. The significance of the difference is uncertain (Frazier 2003).

PUBLICATION(S)

Allen J, Bisbee PA, Darnell RL, et al. Gravity control of growth form in Brassica rapa and Arabidopsis thaliana (Brassicaceae): Consequences for secondary metabolism. *American Journal of Botany*. 2009;96(3):652-660.

Stutte GW, Monje O, Hatfield RD, Paul A, Ferl RJ, Simone CG. Microgravity effects on leaf morphology, cell structure, carbon metabolism and mRNA expression of dwarf wheat. *Planta*. 2006;224:1038-1049. doi: 10.1007/s00425-006-0290-4.

Monje O, Stutte GW, Chapman DK. Microgravity does not alter plant stand gas exchange of wheat at moderate light levels and saturating CO2 concentration. *Planta*. 2005;222(2):336-345. doi: 10.1007/s00425-005-1529-1.

Musgrave ME, Kuang A, Tuominen LK, Levine LH, Morrow RC. Seed storage reserves and glucosinolates in Brassica rapa L. Grown on the International Space Station. *Journal of the American Society for Horticultural Science*. 2005;130(6):848-856.

Stutte GW, Monje O, Goins GD, Tripathy BC. Microgravity effects on thylakoid, single leaf, and whole canopy photosynthesis on dwarf wheat. *Planta*. 2005:1-11. doi: 10.1007/s00425-005-0066-2.

Morrow RC, Iverson JT, Richter RC, Stadler JJ. Biomass Production System (BPS) technology validation test results. *International Conference on Environmental Systems*, Colorado Springs, CO; July 19, 2004 1061-1070.

Stutte GW, Monje O, Anderson S. Wheat (Triticum Aesativum L. cv. USU Apogee) growth onboard the International Space Station (ISS): Germination and early development. *Plant Growth Regulation Society of America*. 2003;30:64-69.

Frazier CM, Simpson JB, Roberts MS, et al. Bacterial and fungal communities in BPS chambers and root modules. *SAE Technical Paper*. 2003; 2003-01-2528. doi: 10.4271/2003-01-2528.

Iverson JT, Crabb TM, Morrow RC, Lee MC. Biomass production system hardware performance. *SAE Technical Paper*. 2003; 2003-01-2484. doi: 10.4271/2003-01-2484.

This investigation is complete and all results are published.

Biological Research in Canisters-16 (BRIC-16), Three Investigations

Research Area: Plant Biology

Increment(s): 23 and 24

Principal Investigator(s):
- John Z. Kiss, PhD, Miami University, Oxford, Ohio
- Anna-Lisa Paul, PhD, University of Florida, Gainesville, Florida
- Elison Blancaflor, PhD, Samuel Roberts Noble Foundation Incorporated, Ardmore, Oklahoma

S135E012252 - Mission specialist Rex Walheim poses for a photo while working with a Biological Research in Canisters experiment.

Research Objectives

BRIC-16-Cytoskeleton (Kiss)

Biological Research in Canisters - 16: Investigations of the plant cytoskeleton in microgravity with gene profiling and cytochemistry (BRIC-16-Cytoskeleton) studies the effects of microgravity on the structure and organization of the actin cytoskeleton in plants using the model plant *Arabidopsis*. The specific aims of this research are: to investigate plastid position in statocytes (the gravity-perceiving cells) in microgravity; to determine the effect of microgravity on the actin cytoskeletal organization in gravity-perceiving cells and to study the microgravity effects on actin cytoskeleton-related gene expression in plant cells.

BRIC-16-DNA (Paul)

Biological Research in Canisters - 16: The impact of spaceflight on Arabidopsis: Deep sequencing and DNA Arrays as Collaborative Readouts of the Transcriptome of Arabidopsis Seedlings and Undifferentiated Cells in Space (BRIC-16-DNA) compares and contrasts the gene expression responses within 2 forms of Arabidopsis: whole, etiolated seedlings and undifferentiated cells in culture. The comparison of intact plants with cultures of undifferentiated cells shows that cells can detect spaceflight and gravity in the absence of tissue or organized developmental structures.

BRIC-16-Regulation (Blancaflor)

Biological Research in Canisters - 16: Actin Regulation of Arabidopsis Root Growth and Orientation During Spaceflight (BRIC-16-Regulation) studies how actin cytoskeleton dictates root growth orientation during spaceflight and conducts an extensive set of genome-wide microarray studies to unravel actin-dependent gene regulatory networks that modulate root growth and orientation during spaceflight.

EARTH BENEFITS

The microgravity of space is used to investigate and clarify plant-related phenomena that cannot be studied in the presence of gravity. The fundamental knowledge gained through these investigations can aid in the understanding of basic plant processes that can eventually increase our ability to better control plant use on Earth in agriculture (and other) applications.

Image of Biological Research in Canisters (BRIC) - 16 middeck payload hardware and final packing of locker MR28K. BRIC Canister A-D, only A is fully assembled. NASA image.

SPACE BENEFITS

The fundamental knowledge gained by growing plants under microgravity conditions can contribute to resolving the following risks:

- providing and maintaining biodegenerative life support systems
- maintaining food quantity and quality
- maintaining acceptable atmosphere
- managing waste
- providing and recovering potable water

RESULTS

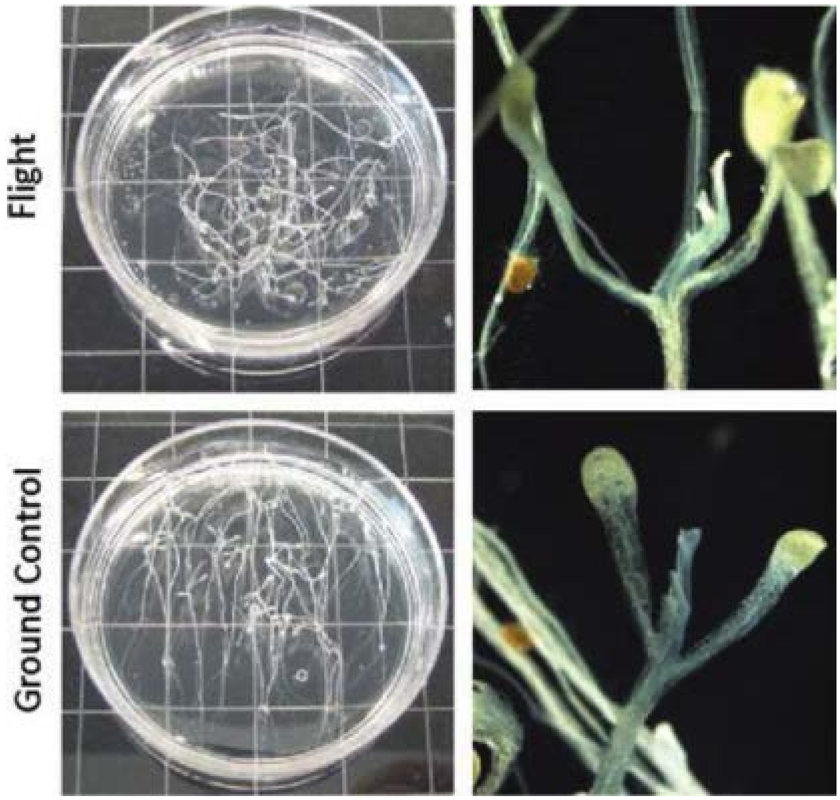
BRIC-16-CYTOSKELETON

The BRIC-16-Cytoskeleton experiment was carried into space on April 5, 2010, and returned April 20, 2010, aboard orbiter *Discovery* on space shuttle mission STS-131 as part of the BRIC-16 suite of investigations. A total of 13 Petri Dish Fixation Unit (PDFU) samples were studied in flight and on ground. These samples were allotted approximately 309 hours in total darkness to grow in microgravity and then fixated for later observation. The primary focus of this experiment is to focus on the changes in composition of the seedlings in microgravity. Seedling morphology did not develop with any major discrepancies. With controlled temperatures, averaging within 22-25°C, seedling germination between the ground and flight controls remained comparable with 90.9% for the ground controls and 89.0% for the flight controls. When comparing ground and flight experiments, both exhibited an etiolated appearance, elongated hypocotyls, which is typical for plants grown in darkness.

The BRIC-16-Cytoskeleton experiment found 2 major differences of note between ground and in flight samples. The first difference arose in the morphology found in the roots systems of the seedlings. Extreme skewing was observed at the root apex and proximal root. The roots skewed only slightly on the ground controls in comparison to flight controls. This leads to the conclusion that plants have endogenous growth patterns that are largely masked in normal 1 g conditions found on Earth. Another major difference was noted between the amount of adventitious roots (roots formed from shoot tissues) found on the flight and ground samples. This adds to the idea that microgravity produces an increase in mitosis in the pericycle, thus producing a larger number of adventitious roots. It is also believed that with previous and present experiments that microgravity may induce alterations in essential cell functions that may be related to cell cycle regulation (Millar 2011).

BRIC-16-DNA

Previous studies determined that plants exhibit adaptive behaviors in response to spaceflight. One specific study looked to determine if cell cultures of *Arabidopsis thaliana* were able to perceive and respond to spaceflight. This study determined that only under constant clinorotation (rotation about an axis) were these cells able to induce heat shock proteins. This led to the conclusion that even nondifferentiated cells are able to sense and react to gravity (Zupanska 2012).



Spaceflight and Ground Control biology after landing. Representative pictures of the plant materials removed from their respective Petri Dish Fixation Units.

BRIC-16-DNA addressed these issues by producing replicable results in order to answer fundamental questions using current gene profiling technologies. Seedlings and cell cultures both respond to microgravity by altering specific gene expressions in entirely different responses. A possible explanation for the differences between cultured cells and seedlings is due to the fact that seedlings use their organs to sense and sample their environment, and that undifferentiated cell cultures, lacking such organs propagate inappropriate stress responses. Another possibility is that all the cells in the culture were responding unanimously, while distinct tissue-types in the seedlings responded differently (Paul 2012).

BRIC-16-Regulation

Results are pending publication.

PUBLICATION(S)

Johnson CM, Subramanian A, Edelmann RE, Kiss JZ. Morphometric analyses of petioles of seedlings grown in a spaceflight experiment. *Journal of Plant Research*. November 2015;128:1007-1016. doi: 10.1007/s10265-015-0749-0.

Kwon T, Sparks JA, Nakashima J, Allen SN, Tang Y, Blancaflor E. Transcriptional response of *Arabidopsis* seedlings during spaceflight reveals peroxidase and cell wall remodeling genes associated with root hair development. *American Journal of Botany*. January 1, 2015;102:21-35. doi: 10.3732/ajb.1400458.

Zupanska AK, Denison FD, Ferl RJ, Paul A. Spaceflight engages heat shock protein and other molecular chaperone genes in tissue culture cells of Arabidopsis thaliana. *American Journal of Botany*. 2013;100(1):235-248. doi: 10.3732/ajb.1200343.

Paul A, Zupanska AK, Ostrow DT, et al. Spaceflight Transcriptomes: Unique responses to a novel environment. *Astrobiology*. January 2012;12(1):40-56. doi: 10.1089/ast.2011.0696.

Millar KD, Johnson CM, Edelmann RE, Kiss JZ. An endogenous growth pattern of roots is revealed in seedlings grown in microgravity. *Astrobiology*. October 2011;787-797(8):1-12. doi: 10.1089/ast.2011.0699.

These investigations are complete; however additional results are pending publication.

BIOLOGICAL RESEARCH IN CANISTERS SYMBIOTIC NODULATION IN A REDUCED GRAVITY ENVIRONMENT (BRIC-SYNRGE)

Research Area: Plant Biology
Expedition(s): 27/28
Principal Investigator(s):
- Gary W. Stutte, PhD, Dynamac Corporation, Cape Canaveral, Florida

Medicago truncatula (barrel medic) leaf sample; brown markings show beneficial nodulation due to bacterial inoculation. NASA image.

RESEARCH OBJECTIVES

Biological Research in Canisters Symbiotic Nodulation in a Reduced Gravity Environment (BRIC-SyNRGE) investigates microgravity effects associated with microbe-host interactions and cell-cell communication using a plant-bacteria model system. *Medicago truncatula* (barrel medic) seedlings are grown in orbit in the presence of genetically marked strains of nitrogen-fixing bacteria of the species *Sinorhizobium meliloti*. These bacteria are able to form a mutualistic symbiosis (relationship between different species in which both benefit) with leguminous plants. On Earth, this symbiotic plant-bacteria relationship benefits both crops for humans and livestock.

EARTH BENEFITS

Plant-bacteria symbiosis accounts for a large percentage of human and livestock food production on Earth, particularly in nitrogen-depleted soil. BRIC-SyNRGE adds to the knowledge base of this plant-bacteria mechanism.

SPACE BENEFITS

Medicago truncatula (barrel medic) seedlings grown inside a Biological Research In Canisters Petri Dish Fixation Unit. NASA image.

BRIC-SyNRGE directly addresses the impact of the space environment on microbial virulence in a constructed ecosystem. The establishment of a controlled environment, legume-rhizobium ecosystem, to utilize biological fixation to recycle nitrogen and reduce food resupply benefits long-duration transit and planetary surface habitation missions. Preliminary work has indicated that establishment of the legume-rhizobium ecosystem enables Martian regolith (loose material covering rock) stimulants to support plant growth. The *M. truncatula*-*S. meliloti* system is a well-defined biological model system for studying plant/microbe interactions and the biological and genomic tools are available to determine whether the virulence of *S. meliloti* is increased in the space environment. BRIC-SyNRGE is designed to directly test the hypothesis that the virulence of *S. meliloti* is increased in microgravity. BRIC-SyNRGE is designed to use molecular, biochemical, and microscopic tools to determine whether a change in virulence is due to reduced resistance of the host, increased virulence of the microorganism, or changes in the signal transduction pathway.

This investigation is complete; however additional results are pending publication.

Reverse Genetic Approach to Exploring Genes Responsible for Cell Wall Dynamics in Supporting Tissues of Arabidopsis Under Microgravity Conditions (Cell Wall)

Research Area: Plant Biology
Expedition(s): 16 and 17
Principle Investigator(s):
- Kazuhiko Nishitani, DSc, Tohoku University, Sendai, Japan

Research Objectives

The Reverse Genetic Approach to Exploring Genes Responsible for Cell Wall dynamics in Supporting Tissues of Arabidopsis Under Microgravity Conditions (Cell Wall) investigation explores the molecular mechanism by which the cell wall (rigid outermost layer) construction in *Arabidopsis thaliana* (a small plant of the mustard family) is regulated by gravity. The results of this investigation support future plans to cultivate plants on long-duration exploration missions.

Earth Benefits

Data gathered from the Cell Wall study aims to further the understanding of how plant growth and development at a molecular level can lead to significant advancements in agricultural production on Earth

Space Benefits

The Cell Wall experiment aims to explore the molecular mechanism by which the cell-wall construction of supporting tissues in land plants is regulated via a gravitational signal, which can benefit space explorers.

Results

The Cell Wall portion of the experiment in orbit was incomplete due to a failure of the water supply system in the European Modular Cultivation System.

This image taken from inside the European Modular Cultivation System shows the in-orbit growth of *Arabidopsis thaliana* for the Cell Wall experiment. JAXA image.

Publication(s)

Kamada M, Omori K, Nishitani K, et al. Germination and growth test in four strains of *Arabidopsis thaliana* in the reference model of European Modular Cultivation System. *Japan Society of Microgravity Application*. 2009;26(3):249-254.

Koizumi K, Yokoyama R, Nishitani K. Mechanical load induces upregulation of transcripts for a set of genes implicated in secondary wall formation in the supporting tissue of *Arabidopsis thaliana. Journal of Plant Research*. July 7, 2009;122(6):651-659. doi: 10.1007/s10265-009-0251-7.

Nishitani K, Yokoyama R, Koizumi K. Cell wall-related genes involved in supporting tissue formation and transcriptional regulation in *Arabidopsis thaliana*. *Biological Sciences in Space*. 2009;23(3):121-129.

Kamada M, Omori K, Nishitani K, Hoson T, Shimazu T, Ishioka N. JAXA space plant research on the ISS with European Modular Cultivation System. *Biological Sciences in Space*. 2007;21(3):62-66. doi: 10.2187/bss.21.62.

Koizumi K, Yokoyama R, Kamada M, et al. Reverse genetic approach to exploring genes responsible for cell-wall dynamics in supporting tissues of *Arabidopsis thaliana* under microgravity conditions. *Biological Sciences in Space*. 2007;21(3):48-55. doi: 10.2187/bss.21.48.

This investigation is complete and all results are published.

REGULATION BY GRAVITY OF FERULATE FORMATION IN CELL WALLS OF RICE SEEDLINGS (FERULATE)

Research Area: Plant Biology
Expedition(s): 23 and 24
Principle Investigator(s):

- Kazuyuki Wakabayashi, PhD, Osaka City University, Osaka, Japan

RESEARCH OBJECTIVES

Regulation by Gravity of Ferulate Formation in Cell Walls of Rice Seedlings (Ferulate) tests the hypothesis that microgravity decreases the mechanical strength of cell walls of rice plants by modifying the levels of abscisic acid.

EARTH BENEFITS

The cell wall is an essential organelle in maintaining the plant life cycle. The data obtained from this investigation may greatly improve the understanding of how gravitational stimuli affect the formation of cell wall architecture in higher plants. Furthermore, the basic mechanism behind the formation of cell wall phenolic components are clarified in this investigation and may contribute to the development of an efficient method for breeding gramineous (cereal) plants.

SPACE BENEFITS

The information obtained from this investigation could be applied to develop efficient plant production systems in an altered gravity environment. The data may also contribute to improve the experimental procedures for cultivating plants in orbit.

ISS023E056378 - NASA astronaut, Tracy C. Dyson, is working on the Regulation by Gravity of Ferulate Formation in Cell Walls of Rice Seedlings experiment.

RESULTS

The sterilized rice seeds were planted on an agar medium, placed in a black polycarbonate culture dish, and stored in a refrigerator to prevent germination before and during the flight until the start of growth experiment in the Kibo module of the International Space Station (ISS). In orbit, seeds were transferred to the Cell Biology Experiment Facility (CBEF) and allowed to germinate and grow under 1*G* and microgravity conditions in the dark. After incubation, seedlings were frozen and returned to Earth. The CBEF has 2 incubator compartments, a microgravity compartment and an artificial gravity compartment with a centrifuge. The facility allowed for plant samples to be grown under microgravity and artificial 1 *G* conditions simultaneously in orbit.

The germination rate was more than 90% in both in-orbit 1*G* and microgravity conditions. The length of 1*G*-grown rice shoots substantially increased from day 4 to day 5. Microgravity did not affect the shoot growth. Analysis of the mechanical properties in the cell walls showed that shoot cell walls obtained from seedlings grown under microgravity conditions for 5 days were loosened as compared with those under 1*G* conditions. On day 5, the levels of cell wall-bound mono-phenolic acids, such as ferulic acid (FA), in microgravity grown shoots were almost comparable to those in 1 *G*-grown shoots, while the levels of diferulic acid (DFA) were lower in microgravity grown shoots. Furthermore, cell wall peroxidases activity measurements showed that the activity obtained from micro *G*-grown shoots was lower than that from 1*G*-grown shoots. These results suggest that microgravity conditions reduce the activity of cell wall peroxidases in rice shoots, resulting in the suppression of DFA formation, which in turn, may cause the reduction of mechanical strength in shoot cell walls.

PUBLICATION(S)

Wakabayashi K, Soga K, Hoson T. Phenylalanine ammonia-lyase and cell wall peroxidase are cooperatively involved in the extensive formation of ferulate network in cell walls of developing rice shoots. *Journal of Plant Physiology*. February 2012;169(3):262-267. doi: 10.1016/j.jplph.2011.10.002.

Wakabayashi K, Soga K, Hoson T. Cell wall oxalate oxidase modifies the ferulate metabolism in cell walls of wheat shoots. *Journal of Plant Physiology*. November 2011;168(16):1997-2000. doi: 10.1016/j.jplph.2011.05.010.

This investigation is complete; however additional results are pending publication.

Gravity Related Genes in Arabidopsis - A (Genara-A)

Research Area: Plant Biology

Expedition(s): 23 and 26

Principal Investigator(s):

- Eugenie Carnero-Diaz, PhD, Universite Pierre et Marie Curie, Paris, France
- Francisco-Javier Medina, Centro de Investigaciones Biológicas, Madrid, Spain

Research Objectives

Gravity Related Genes in *Arabidopsis* - A (Genara-A) seeks to provide an understanding of microgravity induced altered molecular activities, which will help to find plant systems that compensate the negative impact on plant growth in space. Twelve-day-old seedlings are grown either in space, in the European Modular Cultivation System (EMCS) under microgravity, on a 1-g reference centrifuge, or on the ground. Proteins associated with membranes were selectively extracted from microsomes and identified and quantified through Liquid Chromatography-tandem Mass spectrometry (LC-MS-MS) using a label-free method, ie, a method in mass spectrometry that aims to determine the relative amount of proteins in biological samples.

Layout for germinated seeds in 1 Culture Chamber after 10 days of cultivation (on Earth). ESA image.

Results

Among the 1484 proteins identified and quantified in the 3 conditions mentioned above, 80 membrane-associated proteins were significantly more abundant in seedlings grown under microgravity in space than under 1 g and 69 were less abundant. Clustering of these proteins according to their predicted function indicated that proteins associated with auxin metabolism and trafficking were depleted in the microsomal fraction in microgravity space conditions, whereas proteins associated with stress responses, defense, and metabolism were more abundant in microgravity than under 1 g indicating that microgravity is perceived by plants as a stressful environment. These results clearly indicate that a global membrane proteomics approach can give a snapshot of the cell status and its signaling activity at a given time in response to microgravity and highlight the major processes affected.

Publication(s)

Mazars C, Briere C, Grat S, et al. Microgravity induces changes in microsome-associated proteins of Arabidopsis seedlings grown on board the International Space Station. *PLOS ONE*. March 11, 2014;9(3):e91814. doi: 10.1371/journal.pone.0091814.

Valbuena MA, Manzano AI, van Loon JJ, et al. Auxin transport and ribosome biogenesis mutant/reporter lines to study plant cell growth and proliferation under altered gravity. *The Joint Life Science Symposium*, Aberdeen, United Kingdom; June 18-22, 2012.

Manzano AI, Matia I, Gonzalez-Camacho F, et al. Germination of arabidopsis seed in space and in simulated microgravity: Alterations in root cell growth and proliferation. *Microgravity Science and Technology*. 2009;21(4):293-297.

This investigation is complete and all results are published.

STUDY INTO THE INTERACTION OF EFFECTS OF LIGHT AND GRAVITY ON THE GROWTH PROCESS OF PLANTS (GRAPHOBOX)

Research Area: Plant Biology
Expedition(s): 8 and 9
Principal Investigator(s):
- Karel Buizer, University of Utrecht, Utrecht, Netherlands

RESEARCH OBJECTIVES

The Study into the Interaction of Effects of Light and Gravity on the Growth Process of Plants (GraPhoBox) experiment investigates the presence of a link between phototropism (growth towards a light source) and gravitropism (growth towards the gravitational vector) in wild-type and mutant seeds of *Arabidopsis thaliana*. The results obtained from the GraPhoBox experiment can give new insights to the interactions between the mechanisms underlying the formation of the basic architecture of the plant, and can also give rise to new ideas in how plants respond to their environment.

ESA astronaut André Kuipers works on the GraPhoBox experiment aboard the International Space Station. ESA image.

RESULTS

The angle of directional growth of roots and shoots was assessed. Light is—even in the absence of gravity—the most important environmental cue for directional growth of shoots, while for roots, gravity is by far the most important cue, and light is only a very minor factor due to their poor phototropic capacity. Compared to roots, shoots were deviated more than roots in microgravity and therefore less gravity-dependent. All results together suggested that environmental cues were perceived differently by roots and shoots, which also adapt differently. Furthermore, environmental cues were probably transferred little or none to the opposite side of the plant.

PUBLICATION(S)

Buizer K. GraPhoBox: Gravitropism and phototropism in *Arabidopsis thaliana*. *Microgravity Science and Technology*. September 2007;19(5-6):239-243. doi: 10.1007/BF02919490.

This investigation is complete and all results are published.

Threshold Acceleration for Gravisensing-1 (Gravi-1)

Research Area: Plant Biology
Expedition(s): 14
Principal Investigator(s):
- Dominique Driss-Ecole, PhD, Université Pierre-et-Marie Curie, Paris, France

Research Objectives

Threshold Acceleration for Gravisensing-1 (Gravi-1) grows lentil seedling roots under various gravity conditions aboard the International Space Station (ISS) to determine the amount of acceleration force sufficient to stimulate the direction of root growth. In the first part of the experiment, seedlings are grown in weightlessness following hydration for 15 hours and then centrifuged for almost 14 hours. In the second part of the experiment, seedlings are grown for 21.5 hours in weightlessness followed by 9 hours of induced gravity by centrifuge.

Earth Benefits

These goals will provide insight into the fundamental organization and operation of the gravity response system of plants and determine if, other than the root cap, other parts of the plant require cues for directional growth.

Space Benefits

Although this is primarily a basic research study, understanding how plants respond to partial gravity environments may be useful for growing plants on the moon or Mars.

Cultivation chambers from the Gravi-1 experiment in the US laboratory, carries out research to determine the gravity perception threshold in lentil seedlings. NASA image.

Results

The imagery showed that the embryonic roots curved away from the cotyledons and then slowly straightened from 17 hours to 30 hours after hydration. Due to this straightening the root tip was oriented close to an optimal angle of curvature (120-135°) during a 2-hour period of centrifugation. One interesting point is that lentil roots grown in weightlessness were more sensitive to stimulation than lentil roots grown under 1-g conditions. The gravity threshold perceived by these plants was determined to be between 0 and 0.002g. In addition by using a hyperbolic model, the gravity threshold was estimated to be 1.4 x 10-5 g.

Publication(s)

Driss-Ecole D, Legue V, Carnero-Diaz E, Perbal G. Gravisensitivity and auto morphogenesis of lentil seedling roots grown on board the International Space Station. *Physiologia Plantarum*. 2008;134(1):191-201. doi: 10.1111/j.1399-3054.2008.01121.x.

This investigation is ongoing and additional results are pending publication.

Gravigen

Research Area: Plant Biology

Expedition(s): 18

Principal Investigator(s):

- Annick Graziana, Universite Paul Sabatier Toulouse, Castanet-Tolosan, France
- Christian Mazars, Universite de Toulouse UPS, Castanet-Tolosan, France
- R. Rangeva, Universite Paul Sabatier Toulouse, Castanet-Tolosan, France
- Gilbert Gasset, Université Paul Sabatier, Toulouse, France
- Didier Chaput, MEng, Centre National d'Estudes Spatiales, Paris, France

Research Objectives

The Gravigen experiment examines how gene expression in germinating *Brassica napus* seedlings is modified by microgravity in order to elucidate the mechanisms of gravity perception and transduction in plant roots. Seedlings are grown either in microgravity or 1-g conditions, and the expression of some genes between the two samples is compared.

Results

No exploitable results were obtained due to lack of germination in all but one of the culture chambers.

This investigation is complete and all results are published.

Hydrotropism and Auxin-Inducible Gene Expression in Roots Grown under Microgravity Conditions (Hydro Tropi)

Research Area: Plant Biology
Expedition(s): 25
Principle Investigator(s):
- Hideyuki Takahashi, PhD, Tohoku University, Sendai, Japan

Research Objectives

Hydrotropism and Auxin-Inducible Gene Expression in Roots Grown under Microgravity Conditions (Hydro Tropi) uses the microgravity environment of space to separate hydrotropism from gravitropism and to dissect its mechanism in cucumber roots. This experiment aims to demonstrate that gravitropism interferes with hydrotropism. Second, it clarifies the differential auxin response that occurs during the respective tropisms by investigating the auxin-inducible gene expression. Lastly, it shows whether hydrotropism can be used in controlling root growth orientation in microgravity.

Earth Benefits

Water availability is a critical matter for plant growth and survival. For example, crop cultivation and yields are indeed restricted under drought conditions in an arid area. The results of Hydro Tropi provides additional knowledge to develop new technology that enables plants to efficiently uptake water.

Space Benefits

Hydro Tropi demonstrates a plants ability to respond to moisture gradients. It also aims to provide basic information for creating new plants suitable for the hydrotropism-assisted plant growth unit or developing a hydrotropism-controlled growth unit itself for future space exploration.

ISS025E0077880 - Astronaut, Shannon Walker, is working on the Hydro Tropi experiment in Kibo module. JAXA image.

Results

The on-board experiments were successfully carried out and researchers measured the growth and curvature of the seedling roots and analyzed *CsIAA1* expression by in situ hybridization. The results showed that roots hydrotropically bent toward the moistened plastic foam under microgravity conditions, whereas they grew straight along the direction of gravitational force under 1*G* conditions. The hydrotropic response in microgravity appeared to be greater in the NaCl chamber compared with that in H_2O chamber, but they did not differ statistically. Furthermore, *CsIAA1* gene differentially expressed in the hydrotropically bending roots; the expression was much greater on the concave side than on the convex side. On the other hand, no asymmetric expression of *CsIAA1* in the roots grown under 1*G* conditions were detected. These results revealed that roots become very sensitive to moisture gradients in microgravity and that auxin redistribution and differential auxin response take place during hydrotropic response. Also, the results imply that the hydrotropic response can be used as a means of root growth regulation for plant production in space.

PUBLICATION(S)

Moriwaki T, Miyazawa Y, Kobayashi A, Takahashi H. Molecular mechanisms of hydrotropism in seedling roots of *Arabidopsis thaliana (Brassicaceae). American Journal of Botany*. 2013;100(1):25-34. doi: 10.3732/ajb.1200419.

Miyazawa Y, Moriwaki T, Uchida M, Kobayashi A, Fujii N, Takahashi H. Overexpression of MIZU-KUSSEI1 enhances the root hydrotropic response by retaining cell viability under hydrostimulated conditions in *Arabidopsis thaliana*. *Plant and Cell Physiology*. September 25, 2012;53(11):1926-1933. doi: 10.1093/pcp/pcs129.

Moriwaki T, Miyazawa Y, Fujii N, Takahashi H. Light and abscisic acid signaling are integrated by MIZ1 gene expression and regulate hydrotropic response in roots of *Arabidopsis thaliana*. *Plant, Cell and Environment*. August 2012;35(8):1359-1368. doi: 10.1111/j.1365-3040.2012.02493.x.

Nakayama M, Kaneko Y, Miyazawa Y, et al. A possible involvement of autophagy in amyloplast degradation in columella cells during hydrotropic response of Arabidopsis roots. *Planta*. April 25, 2012;236(4):999-1012. doi: 10.1007/s00425-012-1655-5.

Watanabe C, Fujii N, Yanai K, et al. Gravistimulation changes the accumulation pattern of the CsPIN1 auxin efflux facilitator in the endodermis of the transition zone in cucumber seedlings. *Plant Physiology*. January 2012;158(1):239-251. doi: 10.1104/pp.111.188615.

Yamazaki T, Miyazawa Y, Kobayashi A, Moriwaki T, Fujii N, Takahashi H. MIZ1, an essential protein for root hydrotropism, is associated with the cytoplasmic face of the endoplasmic reticulum membrane in *Arabidopsis* root cells. *FEBS Letters*. February 2012;586(4):398-402. doi: 10.1016/j.febslet.2012.01.008.

This investigation is complete; however additional results are pending publication.

VALIDATING VEGETABLE PRODUCTION UNIT (VPU) PLANTE, PROTOCOLS, PROCEDURES AND REQUIREMENTS (P3R) USING CURRENTLY EXISTING FLIGHT RESOURCES (LADA-VPU-P3R)

Research Area: Plant Biology
Expedition(s): 18, 19, 20, 21, and 22
Principal Investigator(s):
- Gail E. Bingham, PhD, Utah State University, North Logan, Utah

RESEARCH OBJECTIVES

ISS013E84325 – View of Spaceflight Participant, Anousheh Ansari, posing for a photo with barley in a root tray from the Lada greenhouse, which is part of the Rasteniya experiment.

Validating Vegetable Production Unit (VPU) Plants, Protocols, Procedures and Requirements (P3R) Using Currently Existing Flight Resources (Lada-VPU-P3R) is a study to advance the technology required for plant growth in microgravity and to research related food safety issues. Lada-VPU-P3R also investigates the non-nutritional value to the flight crew of developing plants in orbit. The Lada-VPU-P3R uses the Lada hardware on the ISS and falls under a cooperative agreement between NASA and the Russian State Space Corporation (Roscosmos).

EARTH BENEFITS

As less fertile land is available to grow food, alternative agricultural systems that efficiently produce greater quantities of high-quality crops are increasingly important. Data from the operation of this investigation can advance greenhouse and controlled-environment agricultural systems and help farmers produce better, healthier crops in a small space using the optimum amount of water and nutrients.

SPACE BENEFITS

Plants not only provide food, but for many they provide comfort and relaxation, a diversion from the stress of required activities. For many people, plants provide significant non-nutritional benefits during long-duration spaceflight. These values are currently based only on anecdotal and untested observations that need verification. Part of the benefit may be a small fresh food source, which makes food safety issues important.

Results

Creation of an effective life support system (LSS) is one of the main obstacles faced by engineers in order to support long-duration spaceflight. Experiments with higher plants conducted on board MIR and the Russian segment of the ISS, showed plant organisms are capable of long-duration normal growth, full development and reproduction without deviations under real spaceflight environment. These results allowed researchers to assume that properly engineered greenhouses are potential candidates for biological subsystem and may be included in the LSS for interplanetary spaceflight. Successful inclusion of greenhouse equipment in the spacecrafts required a number of actions to the existing LSS, redistribution of material streams inside an LSS, and increased functional load. Furthermore, involvement of a greenhouse in a LSS of an interplanetary spacecraft required a number of technical tasks to be cleared, such as selection of plant species and larger scale hardware development. To resolve the mentioned tasks, real spaceflight-based and ground-based experiments are being conducted in the frame of Russian Scientific Program (Sychev 2008).

ISS005E20305 - View of Cosmonaut Valery G. Korzun, Expedition 5 mission commander, posing at the Rasteniya-2 plant growth experiment in the Service Module (SM)/Zvezda on the International Space Station.

Previous experiments revealed that plants are capable of normal growth, development and proliferation if they are provided with everything essential for life. However, the absence of phenotypic (observable characteristics) and genotypic changes (DNA changes) in plants grown in microgravity for several generations does not mean plants do not experience some stresses during these conditions. The genomic expression patterns analyzed revealed over 500 genes changed more than two-fold. The results demonstrate an increase in the transcription of eliminating genes and circumstantially indicate the presence of oxidative stress-causing factors aboard the International Space Station. These factors are yet to be identified and their elimination could improve productivity (Shagimardanova 2010).

PUBLICATION(S)

Sugimoto M, Oono Y, Gusev OA, et al. Genome-wide expression analysis of reactive oxygen species gene network in Mizuna plants grown in long-term spaceflight. *BMC Plant Biology*. 2014;14:21. doi: 10.1186/1471-2229-14-4.

Shagimardanova E, Gusev O, Bingham GB, et al. Oxidative stress and antioxidant capacity in barley grown under space environment. *Bioscience, Biotechnology, and Biochemistry*. 2010;74:1479 - 1482. doi:10.1271/bbb.100139.

Sychev VN, Levinskikh MA, Podolsky IG. Biological component of life support systems for a crew in long-duration space expeditions. *Acta Astronautica.* 2008;63:1119-1125. doi: 10.1016/j.actaastro.2008.01.001.

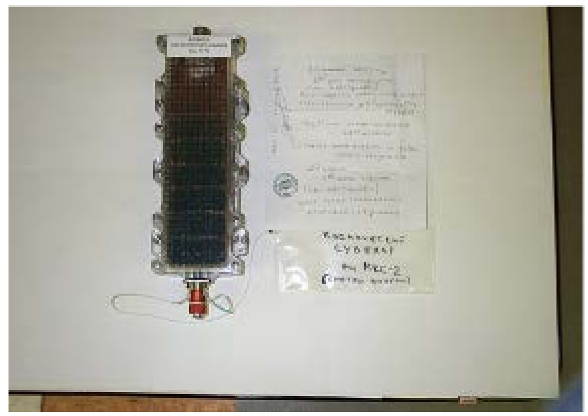
This investigation is complete; however additional results are pending publication.

Study of Mass-Exchange Properties of Capillary-Porous Bodies, Root Habitable Media, in Spaceflight Conditions (Massoperenos)

Research Area: Plant Biology
Expedition(s): 2
Principal Investigator(s):
- Vladimir N. Sychev, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

The Study of Mass-Exchange Properties of Capillary-Porous Bodies, Root Habitable Media, in Spaceflight Conditions (Massoperenos) investigation studies the particulars of moisture transfer in capillary-porous bodies—soil substitutes—in microgravity. Massoperenos examines the movement of liquid when pores are partially filled and, subsequently, with the active participation of capillary forces, since microgravity conditions are primarily evident where capillary forces start prevailing.



Massoperenos experimental cuvette following completion of the investigation and return to Earth.

Space Benefits

Results of this study are used to design space greenhouses (such as the Lada greenhouse) that are proposed for use on near-Earth orbital stations. In addition, all the particulars discovered are important for designing modules for researching substrates and for various space technologies using porous bodies.

Results

The results showed that the gravitation factor played an important role in the formation of a different level of moisture content in root habitable media when cultivating plants. For the first time, the dynamics of capillary sorption by root habitable medium in microgravity were determined, and the coefficient of capillary diffusion of moisture was determined experimentally in microgravity for root habitable medium with limited capillary saturation. In order to study the particulars of moisture migration in the root module (RM) for spaceflight conditions, a comparison of the hydrophysical characteristic was made during the root habitable medium drying phase.

In order for liquid to move via capillary forces in capillary RM (drying process) in spaceflight conditions, greater potential is required than for gravitational conditions (roughly up to 10 times greater for humidity of 70-60%); thus, the value of rheon is significantly higher in spaceflight conditions than in gravitational conditions. These data coincide with previous data on the possibility of creating localized weakly diffusing zones of moisture in RM for spaceflight conditions.

The dispersion in the readings of hydrophysical characteristics obtained in spaceflight conditions indicated the heterogeneous nature of RM drying, which is not observed in gravitational conditions. The difference in moisture for a potential of -60 mm of water may reach 17% (62.58% and 45.87%).

Massoperenos demonstrated the possibility of using the proposed method for studying the dynamics of capillary sorption in root habitable medium in microgravity conditions, as well as the possibility of applying the method in the experimental determining of the coefficient of capillary diffusion of moisture in microgravity conditions for root habitable medium with limited capillary saturation.

PUBLICATION(S)

Souza KA, Ilyin EA, Sychev VN, Jahns GC. Space biology and medicine - U.S. and Russian cooperation in space biology and medicine. *Biological Research in Space. Joint U.S.-Russian Publication.* 2009;(1):1-43.

Sychev VN, Levinskikh MA, Guryeva TS, Podolsky IG. Biological life support systems for space crews: Some results and prospects. *Human Physiology*. December 22, 2011;37(7):784-789. doi: 10.1134/S0362119711070292. [Original Russian Text © Sychev VN, Levinskikh MA, Gurieva TS, Podolsky IG, 2008, published in Aviakosmicheskaya i Ekologicheskaya Meditsina, 2008, Vol. 42, No 6, pp 92–97.]

Podolsky IG, Bingham GE. Hydrophyscial characteristics of greenhouse root habitable media (drying mode) in spaceflight conditions. *XIII Conference Space Biology and Aerospace Medicine*, Moscow, Russia; June 13-16, 2006.

Grigoriev AI, Sychev VN. Creation of a cosmonaut life-support system based on Biosphere mechanisms. *Vestnik RAN*. 2004;74(8):675-681.

Podolsky IG, Norokh AA, Bingham GE. Assessment of error in the thermal pulse method of measuring moisture content of root habitable media for space greenhouses. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2002;36(1):55-60.

Podolsky IG, Sychev VN, Levinskikh MA, Kozarinov VI, Planes OM, Bingham GE. Technology research of higher plant cultivation in space greenhouses FRETS on the International Space Station. The problems of habitability in the pressurized environment. *Materials Research Conference*. June 4-8, 2001:156-157.

This investigation is complete and all results are published.

Molecular and Plant Physiological Analyses of the Microgravity Effects on Multigeneration Studies of Arabidopsis thaliana (Multigen)

Research Area: Plant Biology
Expedition(s): 15 and 16
Principal Investigator(s):
- Tor-Henning Iversen PhD, Norwegian University of Science and Technology, Trondheim, Norway

Research Objectives

Molecular and Plant Physiological Analyses of the Microgravity Effects on Multigeneration Studies of Arabidopsis thaliana (Multigen) will grow *Arabidopsis thaliana*, a small flowering plant related to cabbage and mustard, in orbit for 3 generations. The results of this investigation will support future plans to grow plants on the long-duration transit to Mars.

In-orbit image from first part of Multigen experiment shows the flower stalk (stem) with 2-3 flower bulbs on top and a few stem leaves below. ESA image.

Results

In August 2007, seeds were cultivated in experiment containers on 2 separate rotors in the European Modular Cultivation System (EMCS), with images taken every 5 minutes. During the 73 day long experiment, 85% of the seeds germinated, despite interruptions caused by too high air flow on day 7 and unforeseen power outages.

The gravitropic response to 1 g applied force was greater for the microgravity grown plants than the 1 g grown plants, with the leaves curving upwards 30 minutes after the start of the rotor. At an early growth stage, rosette leaf movements usually bent down when exposed to light, bent upwards when exposed to darkness, and included oscillative (swinging) movements. In light periods, rhythmic leaf movements were present at 45 and 80 minutes. In darkness only 120 minutes rhythms could be found, but image quality was lower and could have missed detecting faster rhythms (Solheim et al. 2009).

Side stems showed small movements in microgravity and darkness, as well as pronounced circumnutations in 0.8 g force (in darkness and light), followed by no movement once the centrifuge stopped. Although power outages affected the quantity of observations collected, there was enough data to show the main stem demonstrated small movements in microgravity and amplified movements under applied acceleration (Johnsson et al. 2009).

Publication(s)

Johnsson A, Solheim BB, Iversen T. Gravity amplifies and microgravity decreases circumnutations in Arabidopsis Thaliana stems: Results from a spaceexperiment. *New Phytologist*. 2009;182:621-629. doi: 10.1111/j.1469-8137.2009.02777.x.

Solheim BB, Johnsson A, Iversen T. Ultradian rhythms in Arabidopsis Thaliana leaves in microgravity. *New Phytologist*. 2009;183:1043-1052. doi: 10.1111/j.1469-8137.2009.02896.x.

Solheim BB. 3D information from 2D images recorded in the European Modular Cultivation System on the ISS. *Advances in Space Research*. December 15, 2009;44(12):1382-1391. doi: 10.1016/j.asr.2009.07.008.

Kittang A, Kvaloy B, Winge P, Iversen T. Ground testing of Arabidopsis preservation protocol for the microarray analysis to be used in the ISS EMCS Multigen-2 experiment. *Advances in Space Research*. 2010;46:1249-1256. doi: 10.1016/j.asr.2010.06.021.

These investigations are complete and all results are published.

NanoRacks-Terpene Extraction in Microgravity (NanoRacks-Terpene)

Research Area: Plant Biology
Expedition(s): 29 and 30
Principal Investigator(s):
- Bill Lumsden, PhD, Ardbeg, Scotland, United Kingdom

Research Objectives

NanoRacks-Terpene Extraction in Microgravity (NanoRacks-Terpene) is an investigation sponsored by a commercial organization with the hope of finding new chemical building blocks for their products through microgravity extraction of the terpenes from wood samples.

NanoRacks-Terpene Extraction in Microgravity MixStix contain a dry wood sample and a 50/50 mixture of water and ethanol. Image courtesy of NanoRacks, LLC.

Earth Benefits

The company undertaking the research belongs to a multi-billion dollar consumer company that produces dozens of new products that contain terpenes and other compounds each year. These include beverages, perfumes, and cosmetics. Synthetic variations of terpenes and terpenoids also greatly expand the variety of flavors used in food additives. Another application is that the ingredients of terpenes have been shown to serve as natural agricultural pesticides. Hence, the understanding of terpenes extracted without gravity may well produce new understandings of a wide range of new products and processes. This is expected to be the first of several phases of research, all sponsored by the company.

Space Benefits

One of the key questions for space station utilization remains a) whether the unique environment of space can capture the interest of mainstream consumer companies; and b) whether by fostering greater understanding of complex molecules, researchers can shed light on the impact of gravity on basic materials.

Results

Results are pending further analysis.

This investigation is complete; however additional results are pending publication.

The Optimization of Root Zone Substrates for reduced Gravity Experiments Program (ORZS)

Research Area: Plant Biology
Expedition(s): 14-16 and 18
Principal Investigator(s):
- Gail E. Bingham, PhD, Utah State University, North Logan, Utah

Research Objectives

ORZS was developed to provide direct measurements and models for plant rooting media that cab be used in future Advanced Life Support (ALS) plant growth experiments. The goal of this investigation is to develop and optimize hardware and procedures to allow optimal plant growth to occur in microgravity.

ISS016E027955 – Astronaut Peggy Whitson, Expedition 16 commander, checks the progress of plants growing in the Russian Lada greenhouse in the Zvezda Service Module of the International Space Station.

Earth Benefits

As less fertile land becomes available to grow food, alternative agricultural systems that efficiently produce greater quantities of high-quality crops are increasingly important. Data from the operation of the ORZS can advance greenhouse and controlled-environment agricultural systems and help farmers produce better, healthier crops in a small space using the optimum amount of nutrients.

Space Benefits

The experiment develops and optimizes hardware and procedures to allow optimal plant growth to occur in microgravity to support long-term spaceflight life-support scenarios assuming the use of regenerating green plants to provide food supplies for crewmembers, as well as to recycle waste products.

Results

The present use of particulate plant growth media lags far behind the technological ability to engineer a porous medium for specific applications in a microgravity environment. Each gravity environment presents slightly different challenges with respect to water control and designing particular aspects of an optimal porous medium for plant growth. Capillarity, the ability of a liquid to flow through a narrow passage, is countered by the gravitational force (drainage), which prescribe the water retention property of the porous medium. A well-defined matrix can improve and stabilize plant rooting environmental conditions by optimizing and controlling fluxes and content of critical plant resources. The objectives of ORZS were to develop a modeling approach for optimizing liquid and gas fluxes to plant roots under extreme volume constraints and reduced gravity conditions. Secondly, this study aimed to extend this approach to design engineered porous media to satisfy plant root metabolic requirements in reduced gravity. Media properties in terms of hydraulic and structural constraints were combined with physiological information (optimal oxygen concentration or water content) and used to express gas and liquid fluxes to plant roots. Further efforts to engineer optimal porous medium properties should strike a balance between the biological needs of the plants, practical limitations regarding material properties (cost, weight, etc) and providing the desired transport properties (Jones 2005).

PUBLICATION(S)

Heinse R, Jones SB, Tuller M, Bingham GE, Podolsky IG, Or D. Providing optimal root-zone fluid fluxes: Effects of hysteresis on capillary-dominated water distributions in reduced gravity. *SAE Technical Paper*. July 12, 2009;2009-01-2360:10. doi: 10.4271/2009-01-2360.

Jones SB, Or D, Heinse R, Bingham GE. Modeling and design of optimal growth media from plant-based gas and liquid fluxes. *SAE Technical Paper*. July 2005; 2005-01-2949. doi: 10.4271/2005-01-2949.

This investigation is complete; however additional results are pending publication.

Photosynthesis Experiment and System Testing and Operation (PESTO)

Research Area: Plant Biology
Expedition(s): 4
Principal Investigator(s):
- Gary W. Stutte, PhD, Dynamic Corporation, Cape Canaveral, Florida

Research Objectives

Photosynthesis Experiment and System Testing and Operation (PESTO) studies the photosynthetic response of plant tissues grown in microgravity. Results can lead to the development of regenerative life support systems on future missions to the moon or Mars.

Earth Benefits

As less fertile land becomes available to grow food, alternative agricultural systems that efficiently produce greater quantities of high-quality crops are increasingly important. Data from the operation of the PESTO can advance greenhouse and controlled-environment agricultural systems and help farmers produce better, healthier crops in a small space using the optimum amount of nutrients.

ISS004E10138 – Close-up view of Apogee Wheat Plants with a scale as backdrop to exhibit the growth of the plants grown as part of the Photosynthesis Experiment and System Testing and Operation on ISS Expedition 4.

Space Benefits

The amount of food necessary to sustain a crew during a long-duration mission to Mars would prohibitively increase the mass of spacecraft and the overall cost of the mission. A possibility to alleviate this problem could be the use of plant systems as food sources or for regenerative life support systems. The biomass production systems may also be used as a filtration system for water and atmospheric gases.

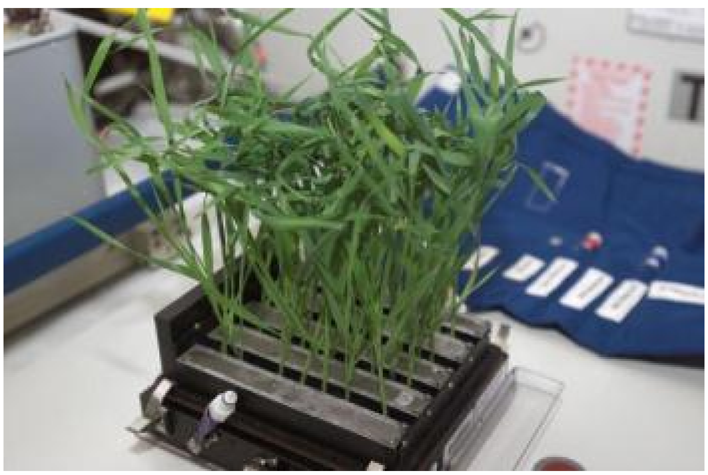
Results

During International Space Station (ISS) Expedition 4, PESTO grew 32 plants for 73 days inside the plant growth chambers of the Biomass Production System (BPS). Following return to Earth, these plants were compared to ground controls that were grown in BPS plant growth chambers on Earth.

The PESTO investigation had 3 dimensions that resulted in a more complete picture of microgravity influences on photosynthesis: gas exchange, partitioning, and metabolism. Carbon dioxide and light response curves allowed researchers to establish whether canopy photosynthetic responses were affected by space conditions. This is noteworthy since plants can be used to regenerate the atmosphere in space conditions through removal of carbon dioxide and production of oxygen. In addition, the tests that evaluated movement of water via transpiration are important since they are indicative of the stomatal responses that regulate photosynthesis. Further, the impact of microgravity on transpiration was significant since plants can be used to purify water under spaceflight conditions. These studies involving gas exchange at elevated carbon dioxide concentrations increased our understanding of the biological impacts of increasing levels of atmospheric carbon dioxide on Earth-based ecosystems. Furthermore, an understanding of plant responses under a range of carbon dioxide and light conditions has potential benefits to commercial, controlled environment, agriculture industries.

The growth and development of the dwarf wheat plants on the ISS was similar to the growth and development of plants on Earth. Analysis of the plants indicated that the microgravity-grown plants were 10% taller than plants grown on Earth, although the growth rate of dwarf wheat leaves was very similar to the plants grown on Earth. The near-real-time video data provided by BPS allowed for validation of the growth data in microgravity when compared to the controls. Design applications can be made to the BPS to allow for successful plant production on the ISS and future long-duration missions to the moon and Mars (Stutte 2003).

To effectively farm in space, multiple redundant plant growth chambers are needed to acquire the maximum yield of food, oxygen, and water. PESTO evaluated the transpiration (water) and photosynthesis (oxygen) processes of the dwarf wheat plant in microgravity and found that microgravity did not affect either the transpiration or the photosynthesis processes of the plants (Monje 2005).



ISS004E10128 – Close-up view of Apogee Wheat Plants grown as part of the Photosynthesis Experiment and System Testing and Operation investigation during International Space Station Expedition 4.

When environmental controls such as temperature, relative humidity, carbon dioxide, and water are effectively maintained, microgravity does not affect canopy growth of dwarf wheat plants. Slight differences in photosystem I (photosynthesis in which light of up to 700 nm is absorbed and reduced to create energy) and photosystem II (photosynthesis in which light of up to 680 nm is absorbed and its energy is used to split water molecules, giving rise to oxygen) were noted and are being evaluated further (Stutte 2005).

When conducting biological studies, it is important to maintain the integrity of the samples. The standard method to preserve samples is quick freezing at low temperatures (-80°C (-112°F) and below), but strict temperature control of samples on station is not always uniform or possible. Therefore, a preservative is needed that will maintain the integrity of biological samples before cooling. RNAlater™ was used to preserve some of the PESTO samples on station. The viability of the samples preserved with RNAlater™ was greater than that of the samples preserved using formalin. To carry out long-term studies aboard ISS, a fixative such as RNAlater™ is needed to maintain the integrity of samples at the varying temperatures that are experienced on ISS (Paul 2005).

The objective of PESTO was to determine what effects microgravity have on chloroplast development, carbohydrate metabolism, and gene expression in the leaves of the plants grown on the ISS. PESTO data indicated that microgravity alters leaf development, cell structure, and chloroplast morphology but does not compromise the overall physical function of the plant (Stutte 2006).

PUBLICATION(S)

Stutte GW, Monje O, Hatfield RD, Paul A, Ferl RJ, Simone CG. Microgravity effects on leaf morphology, cell structure, carbon metabolism, and mRNA expression of dwarf wheat. *Planta*. 2006;224(5):1038-1049. doi: 10.1007/s00425-006-0290-4.

Monje O, Stutte GW, Chapman DK. Microgravity does not alter plant stand gas exchange of wheat at moderate light levels and saturating CO2 concentration. *Planta*. 2005;222(2):336-345. doi: 10.1007/s00425-005-1529-1.

Paul A, Levine HG, McLamb W, et al. Plant molecular biology in the space station era: Utilization of KSC fixation tubes with RNAlater. *Acta Astronautica*. 2005;56:623-628.

Stutte GW, Monje O, Goins GD, Tripathy BC. Microgravity effects on thylakoid, single leaf, and whole canopy photosynthesis on dwarf wheat. *Planta*. 2005:1-11. doi: 10.1007/s00425-005-0066-2.

Frazier CM, Simpson JB, Roberts MS, et al. Bacterial and fungal communities in BPS chambers and root modules. *SAE Technical Paper*. 2003;2003-01-2528. doi: 10.4271/2003-01-2528.

Stutte GW, Monje O, Anderson S. Wheat (Triticum Aesativum L. cv. USU Apogee) growth onboard the International Space Station (ISS): Germination and early development. *Plant Growth Regulation Society of America*, Miami Beach, FL; 2003 64-69.

Stutte GW, Monje O, Porterfield DM, Goins GD, Bingham GE. Farming in space: Environmental and biochemical concerns. *Advances in Space Research*. 2003;31: 151-167.

This investigation is complete and all results are published.

PLANT GENERIC BIOPROCESSING APPARATUS (PGBA)

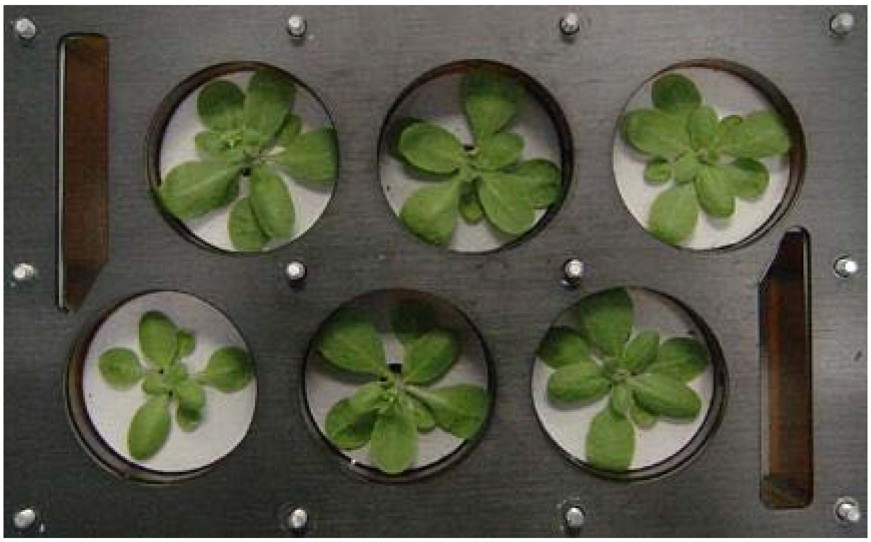
Research Area: Plant Biology
Expedition(s): 5
Principal Investigator(s):
- Anthony Gerard Heyenga, PhD, BioServe Space Technologies, Boulder, Colorado

RESEARCH OBJECTIVES

Plant Generic Bioprocessing Apparatus (PGBA) monitors and maintains light, temperature, humidity, and oxygen levels to study lignin production changes in *Arabidopsis thaliana* (a fast growing plant) grown in microgravity on the International Space Station (ISS).

EARTH BENEFITS

One interest to scientists and industry is the structural compound called lignin, which is produced by plants. Lignin is one of the molecules plants use to make stiff, woody cell walls. Plants grown in space produce less lignin, because in the absence of gravity they don't need such a woody structure. Genetic information gained from plants grown in the PGBA could enable scientists on Earth to control the amount of lignin a plant produces. Growing trees with less lignin could dramatically reduce the economic and environmental cost of paper production, allowing faster tree growth, more paper production, and less chemical use during milling. Other plants could gain added protection from the elements if lignin production was increased.



Arabidopsis thaliana (Brassica family) plants grown under controlled conditions in a plant cultivation module in the BioServe Laboratories. BioServe Laboratories image.

SPACE BENEFITS

The ability to grow plants in space has an enormous impact on the success of future interplanetary space exploration. Any long-term human presence on the moon or Mars requires sustainable plant growth, which can provide a renewable food supply for explorers and assist with the maintenance of breathable air.

RESULTS

The returned plant material did not develop in a normal manner, and the primary scientific objectives were not met. The study did, however, help identify the need for greater regulation of air quality within a plant growth chamber to ensure uniform plant growth. Although there will be no results published from this International Space Station activity, the lessons learned from this study are being applied to the development of subsequent plant growth investigations and improved spaceflight plant chamber design (Heyenga 2005).

PUBLICATION(S)

Heyenga AG, Kliss M, Blackford C. The performance of a miniature plant cultivation system designed for spaceflight application. *35th International Conference on Environmental Systems*, Rome, Italy; July 2005 [New designs influenced by lessons learned].

Heyenga AG, Stodieck LS, Hoehn A, Kliss M, Blackford C. Approaches in the design of a space plant cultivation facility for Arabidopsis thaliana. *34th International Conference On Environmental Systems,* Colorado Springs, CO; 2004 [New designs influenced by lessons learned].

This investigation is complete and all results are published.

Plant Signaling (Plant Signaling)

Research Area: Plant Biology
Expedition(s): 27 and 28
Principal Investigator(s):
- Imara Y. Perera, PhD, North Carolina State University, Raleigh, North Carolina

Research Objectives

Expedition 14 Commander Michael Lopez-Alegria performs the European Modular Cultivation System - Experiment Container replace activity in the Destiny Laboratory Module.

The Plant Signaling experiment studies the effects of microgravity on the growth of plants. The experiment is performed aboard the International Space Station (ISS) in collaboration with the European Space Agency (ESA). Images of the plants are captured and down-linked to Earth. Samples of the plants are harvested and returned to Earth for scientific analysis. The results of this experiment can lead to information that aids in food production during future long-duration space missions, as well as data to enhance crop production on Earth.

Earth Benefits

Further understanding of how plants grow and develop at a molecular level can lead to significant advancements in agricultural production on Earth. Understanding mechanisms of plant development supports improved agricultural production and leads to higher crop yields on Earth.

Space Benefits

During long-duration space missions, it is necessary to provide crew members with regenerative sources of food as well as supplemental methods to recycle carbon dioxide into breathable oxygen. As new information about how plants grow in microgravity emerges, sustainable plant-based life support systems may be developed.

RESULTS

PI received actual samples returned from ISS in April 2013. Molecular analysis is taking place on samples and results are forthcoming.

This investigation is complete; however additional results are pending publication.

EFFECT OF WEIGHTLESSNESS ON THE DISTRIBUTION OF CALCIUM IN THE STATOCYTES OF RAPESEED ROOTS, BRASSICA NAPUS (POLCA)

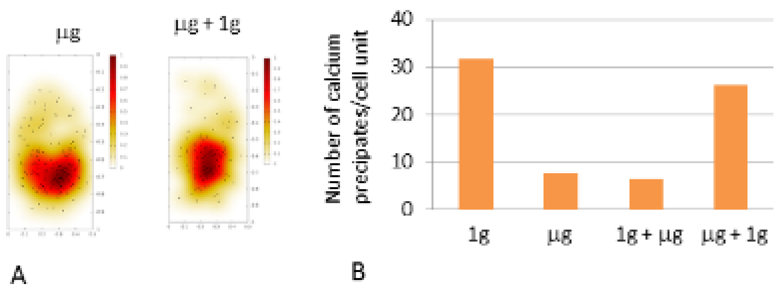
Research Area: Plant Biology
Expedition(s): 18
Principal Investigator(s):
- Valerie Legué, Clermont Université, Université Blaise-Pascal, Aubiere, France

RESEARCH OBJECTIVES

The objective of the Effect of weightlessness on the distribution of calcium in the statocytes of Rapeseed roots, Brassica napus (Polca) experiment is to analyze the effect of change in amyloplasts-ER interactions on calcium dependent pathways.

RESULTS

The Polca experiment was conducted using *Brassica napus* seedlings, which submitted 4 different conditions: continuously on 1 g centrifuge or continuously in microgravity conditions. Some seedlings that germinated on centrifuge for 28 hours were transferred for 10 minutes into microgravity conditions, leading to a loss of amyloplast-ER interactions through amyloplasts displacement. Others seedlings that germinated in microgravity conditions for 28 hours were transferred to a centrifuge for 10 minutes.



Amyloplasts distribution (A) and number of calcium precipitates (B) in statocytes of seedling roots grown in microgravity condition (mg), on 1-g centrifuge in space (1 g, space control), in microgravity for 28 hours and then transferred during 10 minutes on the centrifuge (mg + 1 g), or on 1 g centrifuge for 28 hours and transferred to microgravity condition for 10 minutes (1 g + mg). The relative distribution of amyloplasts is indicated by a color scale from yellow to red. ESA image.

One hundred percent of seed germination was obtained in all conditions. The analysis of amyloplast positioning (ESA Figure 1) showed clearly (1) a relocalization of amyloplast in statocytes of seedlings grown microgravity conditions compared to those grown on 1 g centrifuge; (2) a slight amyloplast displacement after 10 minutes of transfer. Surprisingly, despite the slight amyloplast displacement, a change in the number of calcium precipitation is revealed after each transfer. These results suggested that the calcium signaling seemed to be affected by a slight amyloplast displacement. The presence of a gravi-receptor near the amyloplast was then hypothesized.

This investigation is complete; however additional results are pending publication.

Role of Microtubule-Membrane-Cell Wall Continuum in Gravity Resistance in Plants (Resist Wall)

Research Area: Plant Biology
Expedition(s): 16 and 17
Principle Investigator(s):
- Takayuki Hoson, PhD, Osaka City University, Osaka, Japan

Research Objectives

The Role of Microtubule-Membrane-Cell Wall Continuum in Gravity Resistance in Plants (Resist Wall) investigation was conducted to determine the importance of the structural connections between microtubules, plasma membrane, and the cell wall as the mechanism of gravity resistance. The results of this investigation support future plans to cultivate plants on long-duration exploration missions.

Astronaut Garrett Reisman during a training session at NASA's Johnson Space Center with the Resist Wall investigation inside the MSG. JAXA image.

Earth Benefits

Data gathered from the Resist Wall study aims to further the understanding of how plant growth and development at a molecular level can lead to significant advancements in agricultural production on Earth.

Space Benefits

The Resist Wall experiment aims to explore the molecular mechanism by which the cell-wall construction of supporting tissues in land plants is regulated via gravity signal, which can benefit space explorers.

Results

Under microgravity conditions, seeds of the tua6 mutant were shown to germinate and grow normally until they reached the seedling stage. The seedlings were naturally air-dried in European Modular Cultivation System (EMCS) due to a failure in the water supply system. The cell wall mechanical properties of rehydrated hypocotyls exhibited typical stress-strains and stress-relaxation curves, which is normally seen in fixed or frozen materials. There were no prominent differences between space-grown hypocotyls and the ground controls.

During the final steps in gravity resistance, plants increase their cell wall rigidity by modifying their cell wall metabolism and cell wall environment. Under hypergravity conditions, the orientation of cortical microtubules was modified, suggesting that they play an important role in gravity resistance. The Resist Wall Experiment aims to clarify whether the gravity resistance of plants in 1*G*, specifically the function of microtubules, is the same as the resistance in hypergravity. In 2008, this experiment was carried out on the Plant Cultivation Chamber (PCC) in the EMCS on the International Space Station (ISS).

The mechanism of gravity resistance has often been confused with that of gravitropism. Future experiments will take place to further define this mechanism under microgravity conditions.

Results from this investigation can help scientists to support the growth of plants on long-duration space exploration missions, as well as improve agricultural methods on Earth.

PUBLICATION(S)

Hoson T, Matsumoto S, Soga K, et al. Growth and cell wall properties in hypocotyls of Arabidopsis tua6 mutant under microgravity conditions in space. *Biological Sciences in Space.* 2009;23(4):71-76. doi: 10.2187/bss.23.71.

Hoson T, Soga K, Wakabayashi K. Role of the cell wall-sustaining system in gravity resistance in plants. *Biological Sciences in Space.* 2009;23(3):131-136. doi: 10.2187/bss.23.131.

Kamada M, Omori K, Nishitani K, et al. Germination and growth test in four strains of *Arabidopsis thaliana* in the reference model of European Modular Cultivation System. *Japan Society of Microgravity Application.* 2009;26(3):249-254.

Kamada M, Omori K, Yokoyama R, et al. Preparation and outline of space-based studies on gravity responses and cell wall formation in plants. *Biological Sciences in Space.* 2009;23:115-120. doi: 10.2187/bss.21.56.

Wakabayashi K, Soga K, Hoson T. Modification of cell wall architecture in gramineous plants under altered gravity condition. *Biological Sciences in Space.* 2009;23(3):137-142. doi: 10.2187/bss.23.137.

Hoson T, Matsumoto S, Soga K, et al. The outline and significance of the resist wall experiment: Role of microtubule-membrane-cell wall continuum in gravity resistance in plants. *Biological Sciences in Space.* 2007;21(3):56-61. doi: 10.2187/bss.21.5610.2187/bss.21.56.

Kamada M, Omori K, Nishitani K, Hoson T, Shimazu T, Ishioka N. JAXA space plant research on the ISS with European Modular Cultivation System. *Biological Sciences in Space.* 2007;21(3):62-66.

This investigation is complete and all results are published.

Effects of the Space Environment on the Nuclear Structure and Function of Plant Root meristematic Cells Grown in Microgravity (Root)

Research Area: Plant Biology
Expedition(s): 7 and 8
Principal Investigator(s):
- Francisco-Javier Medina, Centro de Investigaciones Biologicas, Madrid, Spain

Research Objectives

The main scientific objectives of the Effects of the Space Environment on the Nuclear Structure and Function of Plant Root meristematic Cells Grown in Microgravity (Root) experiment is to study the modifications occurring in plant proliferating cells when they have been grown in a near weightless environment. For this experiment *Arabidopsis thaliana* has been used, the first plant species whose genome was totally sequenced.

Results

Conspicuous differences in length were found between seedlings grown at 1 g and the parallel samples grown under microgravity in that the latter were substantially longer. The causes of this differential growth were determined by examining the morphology of the root meristematic cells, with a focus on their nucleoli, in the 2 radial regions of the root meristem, namely the cortex and stele. While the stele showed longer cells with larger nucleoli in the longer roots of the flight samples compared with the ground controls, cortical cells from space-grown seedlings were shorter, more numerous and more densely packed compared to the ground control. However, nucleoli were smaller and less active in these fast proliferating cells of the flight sample than in the ground control sample. This lower level of ribosome synthesis per cell in the flight sample was probably due to an accelerated cell cycle, which resulted in shortened phases. An altered rate of cell proliferation may have been harmful for the plant and could be the reason of the reported reduced size of older seedlings grown in space. Furthermore, in order to explore a possible differential gene expression in proliferating cells caused by space conditions, 2-dimensional protein electrophoresis was performed on samples in which fixation was reversed by prolonged storage in buffer. The total proteomic profile of seedlings showed noticeable differences between the space sample and the ground control.

Immunocytochemical studies, which are currently in progress, will show differences in the levels as well as in the distribution of relevant nucleolar proteins, known to be regulated in their expression and in their mechanisms by factors affecting the cell proliferation rate and the cell cycle progression.

Publication(s)

Matia I, Gonzalez-Camacho F, Herranz R, et al. Plant cell proliferation and growth are altered by microgravity conditions in dpaceflight. *Journal of Plant Physiology*. 2010;167(3):184-193. doi: 10.1016/j.jplph.2009.08.012.

Medina F, Herranz R. Microgravity environment uncouples cell growth and cell proliferation in root meristematic cells: The mediator role of auxin. *Plant Signaling & Behavior*. February 1, 2010;5(2):176-179. doi: 10.4161/psb.5.2.10966.

Manzano AI, Matia I, Gonzalez-Camacho F, et al. Germination of *Arabidopsis* seed in space and in simulated microgravity: Alterations in root cell growth and proliferation. *Microgravity Science and Technology*. 2009;21(4):293-297.

Matia I, Gonzalez-Camacho F, Marco R, et al. The root experiment of the Cervantes Spanish Soyuz Mission: Cell proliferation and nucleolar activity alterations in *Arabidopsis* roots germinated in real or simulated microgravity. *Microgravity Science and Technology*. 2007;XIX(5/6):128-132. doi: 10.1007/BF02919467.

Matia I, Gonzalez-Camacho F, Marco R, Kiss JZ, Gasset G, Medina F. Nucleolar structure and proliferation activity of arabidopsis root cells from seedlings germinated on the International Space Station. *Advances in Space Research*. 2005;36(7):1244-1253. doi: 10.1016/j.asr.2005.01.068.

This investigation is complete and all results are published.

Life Cycle of Higher Plants under Microgravity Conditions (Space Seed)

Research Area: Plant Biology
Expedition(s): 19-22
Principle Investigator(s):
- Seiichiro Kamisaka, PhD, University of Toyama, Toyama, Japan

ISS021-E-006267 NASA astronaut Nicole Stott, Expedition 21 flight engineer, works with the Cell Biology Experiment Facility (CBEF) Space Seed experiment in the Kibo laboratory of the International Space Station. JAXA image.

Research Objectives

In Life Cycle of Higher Plants under Microgravity Conditions (Space Seed), *Arabidopsis thaliana* (a small flowering plant) are cultivated in microgravity to determine the role of gravity in regulating the seed-to-seed life cycle of higher plants.

Earth Benefits

The plant experimental unit (PEU) was developed in collaboration with JAXA. It is a small plant subsystem that is able to control the cultivation environment automatically. The PEU can be a basis of design for large-scale plant factories, which are more efficient on the ground.

Space Benefits

Plants are vital to long-duration space exploration. Green plants are valuable not only for food production but also for providing oxygen. The Space Seed experiment may provide fundamental data covering plant growth in space.

Results

Downlinked images from the Kibo laboratory demonstrated that seeds started to germinate 3 days after initial watering, followed by the development of rosette leaves, flower stalks, flowers, and siliques. Fruit formation was also observed regardless of the magnitude of gravity. The rosette leaves under microgravity remained dark green for longer as compared to plants grown in the 1*G* centrifuge, indicating that leaf senescence is delayed under microgravity. Microarray analysis of genes involved in supporting flower stalks revealed that under microgravity conditions, one gene was downregulated, while four genes were upregulated, indicating that microgravity conditions modify the pattern of gene expression involved in secondary cell formation.

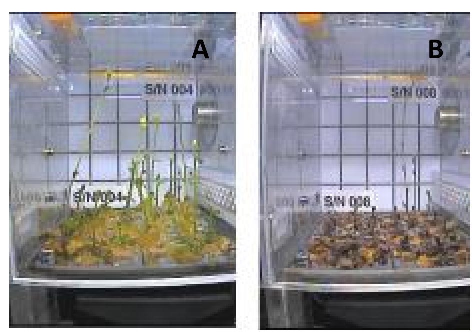


Photo A and B; Bolting of inflorescences in Arabidopsis plants grown for 28 days in Kibo. A, plants grown under microgravity; B, plants grown under artificial gravity (1.1 *G*) on a centrifuge. Note that the aging of rosette leaves is delayed under microgravity, as compared with 1.1 *G*. JAXA image.

This investigation is complete; however additional results are pending publication.

TRANSGENIC *ARABISOPSIS* GENE EXPRESSION SYSTEM (TAGES)

Research Area: Plant Biology

Expedition(s): 21, 21, 23 and 24

Principal Investigator(s):
- Anna-Lisa Paul, PhD, University of Florida, Gainesville, Florida
- Robert J. Ferl, PhD, University of Florida, Gainesville, Florida

RESEARCH OBJECTIVES

Transgenic *Arabidopsis* Gene Expression System (TAGES) investigation is one in a pair of investigations that use the Advanced Biological Research System (ABRS) facility. TAGES uses *Arabidopsis thaliana*, thale cress, with sensor promoter-reporter gene constructs that render the plants as biomonitors, or an organism used to determine the quality of the surrounding environment, using real-time nondestructive Green Fluorescent Protein imagery and traditional postflight analyses.

EARTH BENEFITS

The miniaturization of the Green Fluorescent Protein (GFP) imaging apparatus as a requirement for this spaceflight investigation has produced a device that is easily transportable and may be used as a means for conducting in situ analysis of appropriately genetically prepared biomonitors.

ISS021E030891 - Expedition 21 Flight Engineer 4 Robert Thirsk poses for a photo with Transgenic Arabidopsis Gene Expression System experiment hardware.

SPACE BENEFITS

TAGES along with the ABRS hardware demonstrates the capabilities of providing the correct environment for plant growth aboard spacecraft. For future long-duration exploration, crews need to be able to grow plants for a variety of applications.

RESULTS

TAGES analyzes root morphology of *Arabidopsis* grown on Petri plates while aboard the International Space Station (ISS). Imaging hardware delivered plant images from the ISS providing science without returned samples. These images revealed that in the absence of gravity with the presence of directional light, roots continued to grow away from the light source and shoot growth. This phenomenon was previously thought to be gravity dependent, however the TAGES experiment proved this incorrect. Root skewing also took place while in microgravity, identifying this process as gravity independent as well. Overall growth patterns in microgravity mimic those from simultaneous ground studies, with slightly less uniformity. Microgravity was also found to retard the rate of early *Arabidopsis* growth (Paul 2012).

PUBLICATION(S)

Ferl RJ, Koh J, Denison FD, Paul A. Spaceflight induces specific alterations in the *Proteomes of Arabidopsis*. *Astrobiology*. 2015;15. doi: 10.1089/ast.2014.1210.

Parsons-Wingerter P, Vickerman MB, Paul A, Ferl RJ. Mapping by VESGEN of leaf venation patterning in *Arabidopsis* with bioinformatic dimensions of gene expression. *Gravitational and Space Research*. August 2014;2:68-81.

Schultz ER, Kelley KL, Paul A, Ferl RJ. A method for preparing spaceflight RNAlater-fixed *Arabidopsis thaliana (Brassicaceae)* tissue for scanning electron microscopy. *Applications in Plant Sciences*. August 2013; 1:1300034. doi: 10.3732/apps.1300034.

Paul AL, Amalfitano CE, Ferl RJ. Plant growth strategies are remodeled by spaceflight. *BMC Plant Biology*. 2012; 12(232). doi:10.1186/1471-2229-12-232.

This investigation is complete; however additional results are pending publication.

ISS022E074348 - View of Run 3A Plants of the Transgenic Arabidopsis Gene Expression System experiment. Regular service was performed on the science payload Advanced Plant Experiments on Orbit-Cambium. 70 millimeter (mm) per crew wave file. Photo was taken during Expedition 22.

Analysis of a Novel Sensory Mechanism in Root Phototropism (Tropi)

Research Area: Plant Biology
Expedition(s): 21, 22, 23, 24, 27 and 28
Principal Investigator(s):
- John Z. Kiss, PhD, Miami University, Oxford, Ohio

Research Objectives

Analysis of a Novel Sensory Mechanism in Root Phototrpism (Tropi) studies *Arabidopsis thaliana* plants sprouting from seeds to gain insights into sustainable agriculture for future long-duration space missions.

Earth Benefits

Further understanding of how plants grow and develop at a molecular level can lead to significant advancements in agricultural production on Earth.

Space Benefits

During long-term space exploration, it is necessary to provide crew members with regenerative sources of food, as well as supplemental methods to recycle carbon dioxide into breathable oxygen. As new information about how plants grow in microgravity emerges, sustainable plant-based life support systems may be developed.

ISS022E087465 - NASA astronaut Jeffrey Williams, Expedition 22 commander, services the Tropism in Plants (TROPI2) experiment in the Columbus Laboratory of the International Space Station.

Results

Tropi was a multi-part experiment aimed to gain a better understanding of how microgravity affects phototropism, directed growth of a plant in response to a light stimulus, and gravitropism, directed growth in response to gravity, in *Arabidopsis thaliana*. An in space experiment was necessary because the microgravity conditions of space provide the opportunity to study phototropism in the absence of gravity (Correll 2005).

Tropi was initially performed during Increment 14 on the International Space Station (ISS). These experiments were returned to Earth on 3 space shuttle missions. Several important lessons were gained from this initial run. The first issue arose while using analog video tapes. Although quality images were taken, there was an inefficient use of resources in the time it took for image processing and analysis procedures to be performed. Another issue arose during

European Modular Cultivation System (EMCS) Tropi experiment unique equipment (EUE) shown stimulating Arabidopsis seedlings with blue light (left). EMCS Tropi EUE shown stimulating Arabidopsis seedlings with red light (right). Ames Research Center, Moffett Field, California image.

the seedling hydration procedure. The initial command did not take place and without video downlinks, the entire experiment would not have been completed. An additional issue arose in seed germination. The seeds were stored from 6 to 8 months prior to hydration and resulted in only 58% germination in the first run with progressive deterioration in the following 2 runs. The last major issue to arise was found in the transfer of the frozen materials from the shuttle to NASA cooler bags. Because the samples were allowed time to "warm up" during transfer, the RNA from the STS-116 samples degraded. This issue was mediated by implementing a "3-minute rule" in the following runs (Kiss 2009).

Although several issues did arise during the first part of Tropi, invaluable information was gained from this experiment. A novel positive phototrophic response to red light was observed in hypocotyls of seedlings that developed in microgravity. It is hypothesized that *A. thaliana* exhibits red-light phototropism in microgravity, while on Earth, it is suppressed by normal gravity. A greater phototrophic response was also observed in blue-light-based trials. A more prominent curvature was detected when shoots were briefly exposed to red light followed by blue light (Millar 2010).

Investigators had the opportunity to confirm and extend the results of Tropi in a follow-up experiment during Increment 22 on the ISS. Major modifications between part 1 and part 2 of Tropi took place to ensure optimal experimental conditions. Instead of using analog videos to capture images, part 2 used direct downlinks from the ISS. This allowed for much quicker processing of experiment images and results. Due to modifications in the storage time of the seedlings, the second part of Tropi demonstrated better seed germination (approx. 90%) and improved seedling growth compared to part 1. The last major modification in part 2 of Tropi involved a switch to use powered GLACIER freezers for the transfer of the frozen samples from the ISS to the space shuttle then to Earth. These freezers helped to maintain the low temperatures required to keep RNA intact (Kiss 2011).

Previous experiments have dealt with the effects normal gravity and microgravity on plant biology, however Tropi tested the effects fractional gravity has on plant development. More specifically, the effect fractional gravity has on hypocotyl and root development. Tropi part 2 confirmed red-light-based positive phototropism found in hypocotyls under microgravity. When gravity levels began to elevate, a decreased response was noted. Under microgravity conditions, roots displayed a positive phototropic response to red light. This response was only observed under microgravity because when 0.1g was induced, the red-light response was attenuated. Tropi was also utilized to determine the relationship between red-light pretreatments prior to blue-light exposure in hypocotyls and roots. Hypocotyls displayed a decreased response in phototropism while roots exhibited an increase response in phototropism when exposed to a red-light pretreatment. In response to these findings, investigators wanted to determine if there was a direct or indirect relationship between the red-light pretreatments in the hypocotyls and roots. In regards to the hypocotyls, these space studies support the concept that red-light is indirectly involved in blue-light-based phototropism through the attenuation of gravitropism. These results support the hypothesis that red-light enhancement of blue-light root phototropism is direct. Taking Tropi as a whole, these observations show that the microgravity conditions found in laboratories aboard the ISS can provide a unique research tool to gain insights into fundamental mechanisms in plant biology (Kiss 2012).

PUBLICATION(S)

Sindelar TJ, Millar KD, Kiss JZ. Red light effects on blue light–based phototropism in roots of *Arabidopsis thaliana*. *International Journal of Plant Sciences*. July 2014;175:731-740. doi: 10.1086/676303.

Kiss JZ, Millar KD, Edelmann RE. Phototropism of Arabidopsis thaliana in microgravity and fractional gravity on the International Space Station. *Planta*. 2012;236(2):635-645. doi: 10.1007/s00425-012-1633-y.

Kiss JZ, Millar KD, Kumar P, Edelmann RE, Correll MJ. Improvements in the re-flight of spaceflight experiments on plant tropisms. *Advances in Space Research*. 2011;47(3):545-552. doi: 10.1016/j.asr.2010.09.024.

Millar KD, Kumar P, Correll MJ, et al. A novel phototropic response to red light is revealed in microgravity. *New Phytologist*. 2010;186(3):648-656. doi: 10.1111/j.1469-8137.2010.03211.x.

Kiss JZ, Kumar P, Millar KD, Edelmann RE, Correll MJ. Operations of a spaceflight experiment to investigate plant tropisms. *Advances in Space Research*. 2009;44(8):879-886. doi: 10.1016/l.asr.2009.06.007.

Correll MJ, Edelmann RE, Hangarter RP, Mullen JL, Kiss JZ. Ground-based studies of tropisms in hardware developed for the European Modular Cultivation System (EMCS). *Advances in Space Research*. 2005;36:1203-1210. doi: 10.1016/j.asr.2004.11.003.

This investigation is complete and all results are published.

Influence of Gravity on the Cytoskeleton and the Determination of the Division Plane in Plants (Tubul/Tubul-2), Two Investigations

Research Area: Plant Biology

Expedition(s): 8, 9 and 13

Principal Investigator(s):
- Annie Emons, Wageningen University, Wageningen, Netherlands

Research Objectives

The main scientific objective of the Influence of Gravity on the Cytoskeleton and the Determination of the Division Plane in Plants (Tubul/Tubul-2), Two Investigations experiment is to study the effect of weightlessness over time on the microtubule cytoskeleton of individual walled plant cells (Tobacco Bright Yellow-2 cells). The team aimed to compare the microtubule cytoskeleton of plant cells exposed to weightlessness for a shorter period with the microtubule cytoskeleton of plant cells, which have been exposed to weightlessness for a longer period.

Results

It was found that at near weightlessness during an 8-day space experiment aboard the International Space Station (ISS), tobacco BY-2 suspension culture cells divided and grew as the control cells in the on-board 1-g centrifuge and the 1-g ground setup. Their interphase cytoarchitecture and their cortical microtubule and cellulose micro fibril ordering were also indistinguishable. Not only did near weightlessness not alter these characteristics, the whole environment, including radiation and vibrations, also did not affect the processes that are crucial for plant cell growth and proliferation. These are important and positive results if, in the future, plants have to be propagated from (frozen) cell culture stocks during long-term space missions. In general, the results agree with several studies using whole plants (Halstead and Dutcher 1987; Musgrave et al. 1997; Levine et al. 2001), but contrast with the findings of Sato and coworkers (1999), who reported, based on electron microscopic observations, that *Nicotiana tabacum* stem explants grown in space had reduced microtubule quantities. It was concluded that plant cells do not need to be organized in a tissue to grow, divide, and organize their microtubules and cellulose microfibrils in space.

Publication(s)

Sieberer BJ, Kieft H, Franssen-Verheijen T, Emons AC, Vos JW. Cell proliferation, cell shape, and microtubule and cellulose microfibril organization of tobacco BY-2 cells are not altered by exposure to near weightlessness in space. *Planta*. September 16, 2009;230(6):1129-1140. doi: 10.1007/s00425-009-1010-7.

Sieberer BJ, Emons AC, Vos JW. Culturing immobilized plant cells for the TUBUL space experiments on the DELTA and 12S Missions. *Microgravity Science and Technology*. September 2007; 19(5-6):191-194. doi: 10.1007/BF02919480.

These investigations are complete and all results are published.

VINE IN NEAR ORBIT (VINO)

Research Area: Plant Biology
Expedition(s): 10 and 11
Principal Investigator(s): ● Valfredo Zolesi, PhD, Kayser Italia, Srl, Livorno, Italy

RESEARCH OBJECTIVES

The aim of the Vine in Near Orbit (VINO) experiment is to test the survival and growth in space of tendril grafts from vines coming from Sassicaia vineyards in Tuscany, Italy. This scientific area has also received more attention with the perspectives of very long-duration orbital flights, in particular, future human exploration of Mars.

Vine in Near Orbit experiment container. ESA image.

RESULTS

The vine grafts were launched into orbit on Soyuz TMA-6 in a pressure/vacuum proof sealed metallic container to avoid any environment contamination.

Once back on the Earth, at the end of the short-duration ENEIDE mission in 2005 (Soyuz 10S/Soyuz 9S exchange) tendrils were planted, to test their growth. These were compared to equivalent plants that were treated in a similar fashion in parallel on the ground for reference purposes. This showed no comparable difference in growth.

This investigation is complete; however additional results are pending publication.

WAVING AND COILING OF ARABIDOPSIS ROOTS AT DIFFERENT G-LEVELS (WAICO AND WAICO-2), TWO INVESTIGATIONS

Research Area: Plant Biology
Expedition(s): 16
Principal Investigator(s):
- Günter Scherer, PhD, Leibniz Universitat Hannover, Hannover, Germany

RESEARCH OBJECTIVES

ISS016E031809 - View of *Arabidopsis thaliana* (commonly known as thale cress) plants growing as part of the WAICO experiment in the BioLab facility of the European Columbus Laboratory during Expedition 16.

Waving and Coiling of Arabidopsis Roots at Different g-levels (WAICO) has been studying the interaction of circumnutation (the successive bowing or bending in different directions of the growing tip of the stems and roots) and gravitropism (a tendency to grow toward or away from gravity) in microgravity and 1 g of *Arabidopsis thaliana* (commonly known as thale cress). One aim specifically is to verify that circumnutation of Arabidoposis roots is driven by an endogenous mechanism that is independent of gravity as a cue.

RESULTS

Postflight analysis is complete, and publication of results is imminent.

This investigation is complete; however additional results are pending publication.

Optimizing Heterologous Expression in Saccharomyces Yeast in Microgravity Based on the Example of Hepatitis B Surface Antigen Synthesis (Antigen)

Research Area: Vaccine Development
Expedition(s): 13-18
Principal Investigator(s):
- Grigoriy Y. Scherbakov, MD, Biopreparat, Moscow, Russia

Research Objectives

The Optimizing Heterologous Expression in Saccharomyces Yeast in Microgravity based on the Example of Hepatitis B Surface Antigen Synthesis (Antigen) investigation comparatively studies the specifics of the heterologous expression of the HBsAg gene of the Hepatitis B virus in the yeast *Saccharomyces cerevisiae* in microgravity and Earth. This investigation establishes methods for optimizing synthesis in order to obtain high-quality strains of producer yeasts of the HBs antigen to create an effective vaccine for Hepatitis B.

Earth Benefits

Studying the specifics and factors of HBs-antigen gene expression stability in yeast cells is relevant to optimize the large-scale production of a yeast recombinant vaccine for Hepatitis B.

Antigen experiment Bioekologiya kit aboard the International Space Station. Roscosmos image.

Space Benefits

The results obtained demonstrate the possibility of the suitable existence of microorganisms aboard spacecraft as a part of biotechnological factories that in the future will accompany extended interplanetary flights. The space investigations demonstrated that microorganism cultures with the needed properties can be selected both on Earth and in space.

Results

An analysis of the data obtained confirmed the feasibility of applying new methods to line breeding, super-producers of the HBs-antigen. Based on the data obtained, the following conclusions can be drawn: the stability of HBs-antigen characteristics does not depend on storage time on Earth or in space conditions, and it is mainly determined by strain properties and experiment design conditions.

This investigation is complete; however additional results are pending publication.

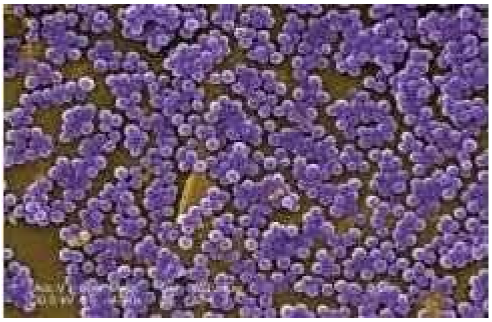
National Laboratory Pathfinder-Vaccine (NLP-Vaccine), Three Investigations

Research Area: Vaccine Development
Expedition(s): 16-28
Principal Investigator(s):
- Timothy G. Hammond, MBBS, Durham Veterans Affairs Medical Center, Durham, North Carolina

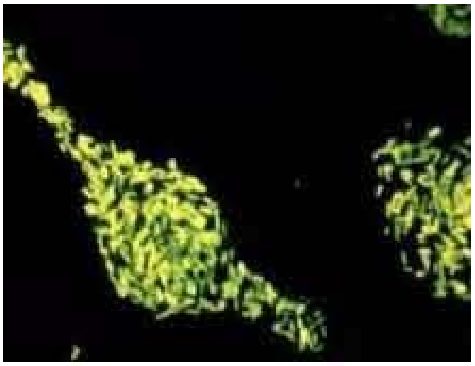
Research Objectives

NLP-Vaccine-MRSA

National Laboratory Pathfinder - Vaccine - Methicillin-resistant *Staphylococcus aureus* (NLP-Vaccine-MRSA) investigation uses microgravity to examine, Methicillin-resistant *Staphylococcus aureus*, a pathogenic (disease-causing) organism resistant to most common antibiotics, to develop a potential vaccine for the prevention of infection on Earth and in microgravity.



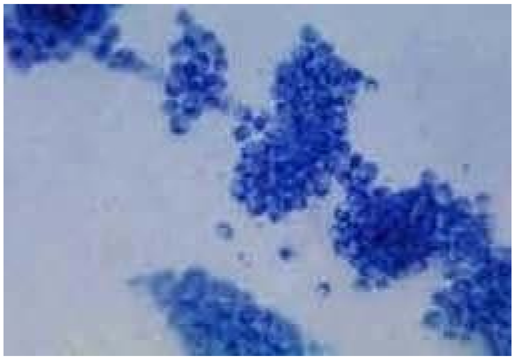
Colorized scanning electron micrograph depicts numerous clumps of methicillin-resistant Staphylococcus aureus bacteria. Centers for Disease Control and Prevention image.



Salmonella bacteria that have been cultured in a tetrathionate-enrichment broth, and stained using the direct fluorescent-antibody technique. Centers for Disease Control and Prevention image.

NLP-Vaccine-Salmonella

National Laboratory Pathfinder - Vaccine - *Salmonella* (NLP-Vaccine-Salmonella) investigation uses microgravity to examine Salmonella, a pathogenic (disease-causing) organism, to develop a potential vaccine for the prevention of infection on Earth and in microgravity.



Photomicrograph of the fungus *Candida albicans*.Centers for Disease Control and Prevention image.

NLP-Vaccine-Survey

National Laboratory Pathfinder - Vaccine - Survey (NLP-Vaccine-Survey) investigation uses microgravity to examine several pathogenic (disease causing) microorganisms to assist in the development of potential vaccines for the prevention of infections on Earth and in microgravity.

Earth Benefits

There is currently no vaccine available for the strains of organisms being examined by the NLP-Vaccine series of investigations. This research may help develop vaccines against these life threatening organisms.

Space Benefits

Results from this experiment may help scientists more clearly understand measures that should be taken to reduce the risk of infection and contraction of disease while in space.

Results

Results are pending publication.

Patent(s)

Hammond, Allen PL, inventors; Vaccine development strategy using microgravity conditions. United States Patent and Trademark Office. 2009.

These investigations are complete; however additional results are pending publication.

RECOMBINANT ATTENUATED SALMONELLA VACCINE (RASV)

Research Area: Vaccine Development
Expedition(s): 27 and 28
Principal Investigator(s):
- Cheryl A. Nickerson, PhD, Arizona State University, Tempe, Arizona

Cheryl Nickerson of the Biodesign Institute at Arizona State University. Image courtesy of Nick Meek.

RESEARCH OBJECTIVES

Recombinant attenuated Salmonella vaccine (RASV) evaluates the ability of the spaceflight platform to accelerate recombinant attenuated Salmonella vaccine development against pneumococcal pneumonia, which causes life-threatening diseases (pneumonia, meningitis, bacteremia) that kill over 10 million people annually, particularly children and elderly who are less responsive to current anti-pneumococcal vaccines. The overall goal of the RASV experiment is to use spaceflight as an innovative platform to facilitate the design and development of next generation vaccines with improved efficacy and protective immune responses while minimizing unwanted side effects by 1) providing novel gene targets for vaccine improvement and development, and 2) re-formulating existing vaccines. The experiment is a joint collaboration between Arizona State University researchers, Dr. Cheryl Nickerson and Dr. Roy Curtiss III.

EARTH BENEFITS

The research results from RASV could lead to the development of new and effective vaccines to combat pneumonia and related infections on Earth. Further, these vaccines could have fewer side effects and provide a template for the development of vaccines to combat other infectious diseases.

SPACE BENEFITS

Our previous spaceflight studies demonstrated a significant increase in virulence and/or virulence characteristics in bacterial pathogens when cultured during flight, thus increasing the uncertainty of the infection risk to the crew during a spaceflight mission. Our current spaceflight experiment provides additional key information that can advance our understanding of alterations that occur in microbial virulence during spaceflight and may lead to better countermeasures against infection in future human exploration missions.

This investigation is complete; however additional results are pending publication.

EARTH AND SPACE SCIENCE

The tradition of Earth observations from orbit was born in 1962 when Project Mercury astronaut John Glenn packed an Ansco Autoset 35 mm camera, which was bought at a local drug store, to take photographs of the Earth during the first NASA orbital mission. These images changed our view of ourselves and our relationship to the Earth. Even with the many satellites now orbiting in space, ISS continues to provide unique views of our planet and galaxy.

EUROPEAN TECHNOLOGY EXPOSURE FACILITY - EXPOSURE EXPERIMENT - ADAPT (EUTEF-EXPOSE-ADAPT)

Research Area: Astrobiology
Expedition(s): 16-20
Principal Investigator(s):
- Petra Rettberg, PhD, German Aerospace Centre, Cologne, Germany

RESEARCH OBJECTIVES

The European Technology Exposure Facility - Exposure Experiment exposes several investigations outside of the International Space Station (ISS) for 18 months on the external surface of the European Columbus Laboratory. The EuTEF-Expose-Adapt investigation examines the capability of highly resistant microorganisms to adapt themselves to being exposed to different levels of ultraviolet (UV) radiation. It looks at whether long exposure to UV radiation of different, harmful levels could result in highly resistant microbes to extreme environments in space or on other planets.

Expose allows long exposures to space conditions and solar UV-radiation on the International Space Station. Several trays filled with organisms were installed on the outside of the European Columbus laboratory as one of the 9 payloads of the European Technology Exposure Facility (EuTEF). ESA image.

RESULTS

From the 5 space factors (UV, vacuum, ionizing radiation, temperature variations, microgravity), solar extraterrestrial UV radiation, as well as the Martian UV spectrum, was the most harmful factor applied. In some samples only a few survivors were recovered from *Bacillus subtilis* MW01 spores exposed in monolayers. However, if shielded from solar irradiation, about 8% of MW01 spores survived in low-Earth orbit conditions, and 100% survived in simulated Martian conditions, compared to the laboratory controls. The results demonstrated the effect of shielding against the high sterilizing potential of extraterrestrial solar UV radiation, which limits the chances of survival of even the highly UV-resistant strain of *Bacillus subtilis* MW01 in the harsh environments of outer space and the Martian surface.

PUBLICATION(S)

Berger T, Hajek M, Bilski P, Körner C, Vanhavere F, Reitz G. Cosmic radiation exposure of biological test systems during the EXPOSE-E Mission. *Astrobiology.* 2012;12(5):387-392. doi: 10.1089/ast.2011.0777.

Rabbow E, Rettberg P, Barczyk S, et al. EXPOSE-E: An ESA astrobiology mission 1.5 years in space. *Astrobiology.* May 2012;12(5):374-386. doi: 10.1089/ast.2011.0760.

Wassmann M, Moeller R, Rabbow E, et al. Survival of spores of the UV-resistant *Bacillus subtilis* strain MW01 after exposure to low-Earth orbit and simulated Martian conditions: Data from the space experiment ADAPT on EXPOSE-E. *Astrobiology.* 2012;12(5):498-507. doi: 10.1089/ast.2011.0772.

Cockell CS, Rettberg P, Rabbow E, Olsson-Francis K. Exposure of phototrophs to 548 days in low-Earth orbit: Microbial selection pressures in outer space and on early Earth. *International Society for Microbial Ecology.* May 19, 2011;5:1671-1682. doi: 10.1038/ismej.2011.46.

Rabbow E, Horneck G, Rettberg P, et al. EXPOSE, an astrobiological exposure facility on the International Space Station - from proposal to flight. Origins of life and evolution of the biosphere. *The Journal of the International Society for the Study of the Origin of Life*. 2009;39(6):581-598. doi: 10.1007/s11084-009-9173-6.

Sample extraction of ADAPT experiment. ESA image.

This investigation is complete and all results are published.

European Technology Exposure Facility - Exposure Experiment - Life (EuTEF-Expose-Life)

Research Area: Astrobiology
Expedition(s): 16-20
Principal Investigator(s):
- Silvano Onofri, Università degli Studi della Tuscia, Viterbo, Italy

Research Objectives

The European Technology Exposure Facility - Exposure Experiment exposes several investigations outside of the International Space Station (ISS) for 18 months on the external surface of the European Columbus Laboratory. Lithic fungi and lichens from extreme environments are the best adapted eukaryotes (cells with a nucleus and internal specialized structures like our own cells) to dryness and radiations. The EuTEF-Expose-Life investigation aims to test selected representatives of these organisms to evaluate their survival in space conditions.

Expose allows long exposures to space conditions and solar UV-radiation on the International Space Station. Several trays filled with organisms were installed on the outside of the European Columbus laboratory as one of the nine payloads of the European Technology Exposure Facility (EuTEF). ESA image.

Results

Photosynthetic activities, growth tests, DNA tests, and vital staining tests have been performed and analyzed, while electron microscopy is still in progress. The experiment was considered successful with interesting results as space and Mars-like conditions resistance was observed for all eukaryotes tested for a long period. Samples resisted full solar irradiation (1 lichen with a PSII activity, ie, Photosystem II [or water-plastoquinone oxidoreductase, of 45% and one black fungus with 80% of DNA]). The dark samples, shielded from UV light, survived with different levels (from almost 100% to 2.5%). One sandstone sample contained interestingly a very high fraction of intact fungal cells though exposed to the full solar spectrum.

Publication(s)

Brandt A, de Vera J, Onofri S, Ott S. Viability of the lichen *Xanthoria elegans* and its symbionts after 18 months of space exposure and simulated Mars conditions on the ISS. *International Journal of Astrobiology*. July 2015;14(3):411-425. doi: 10.1017/S1473550414000214.

Berger T, Hajek M, Bilski P, Körner C, Vanhavere F, Reitz G. Cosmic radiation exposure of biological test systems during the EXPOSE-E Mission. *Astrobiology.* 2012;12(5):387-392. doi: 10.1089/ast.2011.0777.

de Vera J. Lichens as survivors in space and on Mars. *Fungal Ecology*. 2012;5(4):472-479. doi: 10.1016/j.funeco.2012.01.008.

Rabbow E, Rettberg P, Barczyk S, et al. EXPOSE-E: An ESA astrobiology mission 1.5 years in space. *Astrobiology.* May 2012;12(5):374-386. doi: 10.1089/ast.2011.0760.

Onofri S, de la Torre R, de Vera J, et al. Survival of rock-colonizing organisms after 1.5 years in outer space. *Astrobiology.* 2012;12(5):508-516. doi: 10.1089/ast.2011.0736.

Recovery of samples of LIFE experiment. ESA image.

Rabbow E, Rettberg P, Barczyk S, et al. EXPOSE-E: An ESA astrobiology mission 1.5 years in space. *Astrobiology*. May 2012;12(5):374-386. doi: 10.1089/ast.2011.0760.

Scalzi G, Selbmann L, Zucconi L, et al. LIFE experiment: Isolation of Cryptoendolithic organisms from Antarctic colonized sandstone exposed to space and simulated Mars conditions on the International Space Station. *Origins of life and evolution of the biosphere: The Journal of the International Society for the Study of the Origin of Life.* June 12, 2012;42:253-262. doi: 10.1007/s11084-012-9282-5.

Rabbow E, Horneck G, Rettberg P, et al. EXPOSE, an astrobiological exposure facility on the International Space Station - from proposal to flight. *Origins of life and evolution of the biosphere: The Journal of the International Society for the Study of the Origin of Life.* 2009;39(6):581-598. doi: 10.1007/s11084-009-9173-6.

This investigation is complete and all results are published.

European Technology Exposure Facility - Exposure Experiment - Process (EuTEF-Expose-Process)

Research Area: Astrobiology
Expedition(s): 16-20
Principal Investigator(s):
- Hervé Cottin, Universite Paris Diderot, Paris, France

Research Objectives

The European Technology Exposure Facility - Exposure Experiment exposes several investigations outside of the International Space Station (ISS) for 18 months on the external surface of the European Columbus Laboratory. EuTEF-Expose-Process improves our knowledge about the chemical nature and evolution of organic molecules in various space environments. Organic samples are exposed to space conditions to simulate their evolution on extreme places such as asteroids, comets, and the surface of Mars.

Expose allows long exposures to space conditions and solar UV-radiation on the International Space Station. Several trays filled with organisms were installed on the outside of the European Columbus laboratory as one of the 9 payloads of the European Technology Exposure Facility (EuTEF). ESA image.

Results

A selection of the results from the EuTEF-Expose-PROCESS experiment showed that resistance to radiation depends on the chemical nature of the exposed molecules and the wavelengths of the UV light. The experiment also demonstrated the protective effect of meteorite powder. The most altered compounds are the dipeptide, aspartic acid, and aminobutyric acid. The most resistant are alanine, valine, glycine, and aminoisobutyric acid. All molecules, with or without meteorite powder, were affected when exposed to solar radiation. Aspartic acid, an amino acid with a diacid group, is more sensitive to UV radiation than amino acids with alkyl chains. The dipeptide with an amide bond degraded almost completely when not associated with a mineral surface. In contrast, the amino acids with a substituted chain, such as valine, are more stable than those with a linear chain, as in the case of aminobutyric acid.

Aboard the ISS, the amino acids exposed in the free form degrade by more than 40%. The quantity of the leucine dipeptide (Leu2) in the samples is too low to be quantified, but intact molecules are present. More than 80% of the compounds associated with meteorite powder are preserved, except for the aspartic and amino butyric acids and Leu2. The protective effect of the meteorite powder is important, in particular for those compounds that showed the most degradation when exposed in the free form. In these 2 forms, free or embedded in meteorite powder, the most resistant compounds were the amino acids alanine, glycine, aminoisobutyric acid, and valine; the most degraded were the dipeptides and the aspartic and aminobutyric acids.

PUBLICATION(S)

Berger T, Hajek M, Bilski P, Körner C, Vanhavere F, Reitz G. Cosmic radiation exposure of biological test systems during the EXPOSE-E Mission. *Astrobiology.* 2012;12(5):387-392. doi: 10.1089/ast.2011.0777.

Bertrand M, Chabin A, Brack A, Cottin H, Chaput D, Westall F. The PROCESS Experiment: Exposure of amino acids in the EXPOSE-E Experiment on the International Space Station and in laboratory simulations. *Astrobiology.* 2012;12(5):426-435. doi: 10.1089/ast.2011.0755.

Cottin H, Guan YY, Noblet A, et al. The PROCESS Experiment: An astrochemistry laboratory for solid and gaseous organic samples in low-Earth orbit. *Astrobiology.* 2012;12(5):412-425. doi: 10.1089/ast.2011.0773.

Noblet A, Stalport F, Guan YY, et al. The PROCESS Experiment: Amino and carboxylic acids under Mars-like surface UV radiation conditions in low-Earth orbit. *Astrobiology.* 2012;12(5):436-444. doi: 10.1089/ast.2011.0756.

Rabbow E, Rettberg P, Barczyk S, et al. EXPOSE-E: An ESA astrobiology mission 1.5 years in space. *Astrobiology*. May 2012;12(5):374-386. doi: 10.1089/ast.2011.0760.

Rabbow E, Horneck G, Rettberg P, et al. EXPOSE, an astrobiological exposure facility on the International Space Station - from proposal to flight. *Origins of life and evolution of the biosphere: The Journal of the International Society for the Study of the Origin of Life*. 2009;39(6):581-598. doi: 10.1007/s11084-009-9173-6.

This investigation is complete and all results are published.

European Technology Exposure Facility - Exposure Experiment - Protect (EuTEF-Expose-Protect)

Research Area: Astrobiology
Expedition(s): 16-20
Principal Investigator(s):
- Gerda Horneck, German Aerospace Centre, Cologne, Germany

Research Objectives

The European Technology Exposure Facility - Exposure Experiment exposes several investigations outside of the International Space Station (ISS) for 18 months on the external surface of the European Columbus Laboratory. The EuTEF-Expose-Protect investigation is designed to assess the survivability of spacecraft contaminants on a landed mission to Mars. During the mission, bacterial endospores, attached to spacecraft qualified aluminum coupons, are subjected either to a simulated Earth-to-Mars trajectory or to simulated Martian surface conditions.

Expose allows long exposures to space conditions and solar UV-radiation on the International Space Station. Several trays filled with organisms were installed on the outside of the European Columbus laboratory as one of the 9 payloads of the European Technology Exposure Facility (EuTEF). ESA image.

Results

This study confirmed the high resistance of spores of 2 Bacillus species to the most adverse conditions encountered during a planetary mission, such as space vacuum, cosmic radiation, temperature fluctuations, long storage, and Martian atmospheric pressure and composition. The high sterilizing efficiency of solar UV radiation experienced on an Earth to Mars trip as well as on the surface of Mars was also confirmed. Spores could only escape the deadly radiation attack by hiding in cracks or pits of the spacecraft surface, protecting the inner layers in spore clumps, or shielding via the spacecraft itself. Because a landing probe would most likely be encased in an entry shield or bioshield, possible spore hitchhikers attached to a lander may well escape this irradiation during an Earth to Mars mission.

Publication(s)

Berger T, Hajek M, Bilski P, Körner C, Vanhavere F, Reitz G. Cosmic radiation exposure of biological test systems during the EXPOSE-E Mission. *Astrobiology.* 2012;12(5):387-392. doi: 10.1089/ast.2011.0777.

Horneck G, Moeller R, Cadet J, et al. Resistance of bacterial endospores to outer space for planetary protection purposes-Experiment PROTECT of the EXPOSE-E Mission. *Astrobiology*. 2012;12(5):445-456. doi: 10.1089/ast.2011.0737.

Moeller R, Reitz G, Nicholson WL, Horneck G. Mutagenesis in bacterial spores exposed to space and simulated Martian conditions: Data from the EXPOSE-E spaceflight experiment PROTECT. *Astrobiology*. 2012;12(5):457-468. doi: 10.1089/ast.2011.0739.

Nicholson WL, Moeller R, Horneck G. Transcriptomic responses of germinating *Bacillus subtilis* spores exposed to 1.5 years of space and simulated Martian conditions on the EXPOSE-E Experiment PROTECT. *Astrobiology*. 2012;12(5):469-486. doi: 10.1089/ast.2011.0748.

Rabbow E, Rettberg P, Barczyk S, et al. EXPOSE-E: An ESA astrobiology mission 1.5 years in space. *Astrobiology.* May 2012;12(5):374-386. doi: 10.1089/ast.2011.0760.

Flight sample carrier of experiments ADAPT and PROTECT after de-integration. DLR image.

Vaishampayan PA, Rabbow E, Horneck G, Venkateswaran K. Survival of *Bacillus pumilus* spores for a prolonged period of time in real space conditions. *Astrobiology*. 2012;12(5):487-497. doi: 10.1089/ast.2011.0738.

Rabbow E, Horneck G, Rettberg P, et al. EXPOSE, an astrobiological exposure facility on the International Space Station - from proposal to flight. *Origins of life and evolution of the biosphere: The Journal of the International Society for the Study of the Origin of Life*. 2009;39(6):581-598. doi: 10.1007/s11084-009-9173-6.

This investigation is complete and all results are published.

European Technology Exposure Facility - Exposure Experiment – Seeds (EuTEF-Expose-Seeds)

Research Area: Astrobiology
Expedition(s): 16-20
Principal Investigator(s):
- David Tepfer, Institute National de la Recherche Agronomique, Versailles, France

Research Objectives

The European Technology Exposure Facility - Exposure Experiment exposes several investigations outside of the International Space Station (ISS) for 18 months on the external surface of the European Columbus Laboratory. Plant seeds have evolved to conserve the species and its genome under extreme stress conditions (cold, drought, heat). EuTEF-Expose-Seeds determines the resistance of plant seeds when exposed to the open space environment. Plant seeds have in fact frequently been tested in space, mostly as part of microgravity and radiation studies, but never with full exposure to solar UV-C on a long-duration flight.

Expose allows long exposures to space conditions and solar UV-radiation on the International Space Station. Several trays filled with organisms were installed on the outside of the European Columbus laboratory as one of the 9 payloads of the European Technology Exposure Facility (EuTEF). ESA image.

Results

Of the 2 100 wild-type *Arabidopsis thaliana* (cress plant) and *Nicotiana tabacum* (tobacco) seeds, 23% produced suitable plants after exposure for 1.5 years to full space conditions including solar UV. The highest survival occurred in tobacco (44%). These results indicated that a seed-like entity could survive exposure to solar UV radiation unprotected during transport between Mars and Earth.

Full survival is attained in seeds shielded from solar light, demonstrating that a longer space travel would be possible for seeds embedded in an opaque matrix. Survival is lower in the *Arabidopsis wassilewskija* ecotype and in mutants lacking UV screens.

Chemical samples of seed flavonoid UV screens were degraded by UV, but their overall capacity to absorb UV was retained. Nucleic acids (large biological molecules essential for life) were also degraded by UV. However, a fragment was detected and the gene survived in space when protected from UV. This showed that even if seeds do not survive, components (eg, their DNA) might survive transfer over cosmic distances.

PUBLICATION(S)

Rabbow E, Rettberg P, Barczyk S, et al. EXPOSE-E: An ESA astrobiology mission 1.5 years in space. *Astrobiology.* May 2012;12(5):374-386. doi: 10.1089/ast.2011.0760.

Seeds samples postflight. ESA image.

Tepfer D, Zalar A, Leach S. Survival of plant seeds, their UV screens, and nptII DNA for 18 months outside the International Space Station. *Astrobiology.* 2012;12(5):517-528. doi: 10.1089/ast.2011.0744.

Rabbow E, Horneck G, Rettberg P, et al. EXPOSE, an astrobiological exposure facility on the International Space Station - From proposal to flight. *Origins of life and evolution of the biosphere: The Journal of the International Society for the Study of the Origin of Life.* 2009;39(6):581-598. doi: 10.1007/s11084-009-9173-6.

This investigation is complete and all results are published.

EXPOSE – R PHOTOCHEMICAL PROCESSING OF AMINO ACIDS IN EARTH ORBIT (EXPOSE-R-AMINO)

Research Area: Astrobiology
Expedition(s): 18-26
Principal Investigator(s):
- Hervé Cottin, Universite Paris Diderot, Paris, France

RESEARCH OBJECTIVES

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. Expose-R-Amino studies the evolution of organic molecules subjected to solar UV radiation. The exposed compounds belong to various chemical families (including amino acids, polymers, RNA) in the solid state and also as gas mixtures simulating planetary atmospheres. The molecules selected are relevant to the study of the organic chemistry at the surface or in the atmosphere of solar system bodies.

ISS018E039266 – View of Expose-R as it is being set up with Earth in the background.

RESULTS

Results from Expose-R-Amino, are pending completion of analysis and data evaluation before conclusive results are prepared and published.

This investigation is complete; however additional results are pending publication.

Expose – R Screening of Ultra-Violet Radiation in Endothilic and Microalgal Communities from Antartica (Expose-R-Endo)

Research Area: Astrobiology
Expedition(s): 18-26
Principal Investigator(s):
- Charles S. Cockell, University of Edinburgh, Edinburgh, Scotland

Research Objectives

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. Expose-R-Endo investigates the effects of space conditions on photosynthetic organisms. The experiment examines isolated cells of *Chroococcidiopsis*, a UV and desiccation resistant microorganism. Expose-R-Endo also examines a community of photosynthetic organisms within sections of porous rock to investigate the protection provided by rock habitats against extreme environmental conditions.

Sample containers are opened after they are returned to Earth for analysis. ESA image.

Results

Results from Expose-R-Endo are pending completion of analysis and data evaluation before conclusive results are prepared and published.

This investigation is complete; however additional results are pending publication.

EXPOSE – R EVOLUTION OF ORGANIC MATTER IN SPACE (EXPOSE-R-ORGANIC)

Research Area: Astrobiology
Expedition(s): 18-26
Principal Investigator(s):
- Pascale Ehrenfreund, PhD, The George Washington University, Washington, DC

RESEARCH OBJECTIVES

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. Expose-R- Organic monitors survival, destruction, and chemical changes of polycyclic aromatic hydrocarbons (PAHs) and fullerenes in space environment. Monitoring the behavior of these molecules upon space exposure will allow researchers to determine constraints on the photochemistry of these compounds in the interstellar medium.

ISS018E039266 – View of Expose-R as it is being set up with Earth in the background.

RESULTS

Results from Expose-R-Organic are pending completion of analysis and data evaluation before conclusive results are prepared and published.

This investigation is complete; however additional results are pending publication.

EXPOSE – R EXPOSURE OF OSMOPHILIC MICROBES TO SPACE ENVIRONMENT EXPOSE-R-OSMO)

Research Area: Astrobiology

Expedition(s): 18-26

Principal Investigator(s):
- Rocco Mancinelli, Carl Sagan Center, Mountain View, California

RESEARCH OBJECTIVES

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. Expose-R-Osmo focuses on unicellular organisms that survive in salty environments of high osmotic pressure, in this case *Synechococcus* and *Halorubrum chaoviatoris*. The experiment tests to see whether these salt-rich environments, as well as the high intracellular potassium concentration of the microorganisms, play a role in protecting their DNA from vacuum desiccation and UV radiation in space.

Sample containers are opened after they are returned to Earth for analysis. ESA image.

RESULTS

Results from Expose-R-Osmo are pending completion of analysis and data evaluation before conclusive results are prepared and published.

This investigation is complete; however additional results are pending publication.

EXPOSE – R PHOTO DNA PHOTODAMAGE: MEASUREMENTS OF VACUUM SOLAR RADIATION-INDUCED DNA DAMAGES WITHIN SPORES (EXPOSE-R-PHOTO)

Research Area: Astrobiology
Expedition(s): 18-26
Principal Investigator(s):
- Jean Cadet, French Alternative Energies and Atomic Energy Commission, Grenoble, France


ISS018E039266 – View of Expose-R as it is being set up with Earth in the background.

RESEARCH OBJECTIVES

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. This experiment is studying the effect of exposure of bacterial spores and samples of their DNA to solar UV radiation. The objective is to assess the quantity and chemistry of chemical products produced. The samples are either completely exposed or protected by artificial meteorite materials, clays, and salt crystals.

RESULTS

Results from Expose-R-Photo are pending completion of analysis and data evaluation before conclusive results are prepared and published.

This investigation is complete; however additional results are pending publication.

Expose – R Responses of Phage T7, Phage DNA and Polycrystalline Uracil to the Space Environment (Expose-R PUR)

Research Area: Astrobiology
Expedition(s): 18-26
Principal Investigator(s):
- Gy Rontó, Hungary Academy of Sciences, Budapest, Hungary

Research Objectives

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. This experiment studies the effect of solar UV radiation on a type of virus (Phage T7) and an RNA compound (uracil) to determine their effectiveness as biological dosimeters for measuring UV dose in the space environment.

Sample containers are opened after they are returned to Earth for analysis. ESA image.

Results

During the whole flight, the surface of PUR experiment was exposed to the solar radiation for 2 687 hours, which corresponds to a total UV (ultraviolet) dose of 1 100 MJ/m^2. The effect of the solar UV was evaluated by spectrophotometry in the specific UV range: 200-400 nm. The so-called dark samples (not exposed to the solar radiation) in the EXPOSE-R under the exposed ones did not change in the flight (ie, the measured absorption spectra did not change under the influence of space conditions). On the top of the exposed uracil and bacteriophage samples, magnesium fluoride filters of various (4 orders of magnitude) transparency were applied, which aimed to approximate dose effect relations for both targets. Based on the slope of the curves, higher sensitivity of the uracil samples was found. The resulting curves indicated that both bacteriophage T7 and uracil in thin layer form are suitable for the assessment of the biological risk due to extraterrestrial solar radiation (Berces 2013).

Publication(s)

Bérces A, Egyeki M, Fekete A, Kovacs G, Ronto G. Biological ultraviolet dosimetry in low-Earth's Orbit. *Astrobiology & Outreach.* 2013;1:104. doi: 10.4172/2332-2519.1000104.

This investigation is complete; however additional results are pending publication.

EXPOSE – R RADIATION RISKS RAIOMETER-DOSIMETER (EXPOSE-R R3DR)

Research Area: Astrobiology
Expedition(s): 18-26
Principal Investigator(s):
- Tsvetan Dachev, Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria

ISS018E039266 – View of Expose-R as it is being set up with Earth in the background.

RESEARCH OBJECTIVES

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. This investigation records with time resolution, the dose of solar light over 4 wavelength ranges as well as the flux of heavy cosmic particles. Relativistic Electron Precipitations (REP) have been observed for many years. Electrons with energies of a few MeV can penetrate the spacecraft shielding and can cause damage to sensitive electronic preamplifiers and whole systems of the spacecraft. The total dose of an astronaut on a 6-hour spacewalk inside the REP, has also been estimated to exceed the astronaut's short-term limits for both skin and eyes. The main idea of the analysis of daily fluences on the International Space Station (ISS) is to underline that REP events are common on ISS.

RESULTS

Comparison between the relativistic electron dose rate data measured by the R3D instrument on ESA's EuTEF facility (R3DE) and R3DR showed that during periods of simultaneous operation the R3DR dose rates were higher than for R3DE because the R3DR instrument was in a less shielded surrounding. The conclusion was that astronauts on EVA collect highly variable dose rates during REP in dependence of their position around the station. Only active personal dosimeters were able to accurately measure these large variations.

The most interesting period was between April and August 2010. The R3DR and GOES-11 daily relativistic electron fluences greatly increased on of April 6 and 7. Solar activity was at very low levels with isolated low-level B-class flares, and a halo coronal mass ejection was observed on April 3. The main conclusion of the research was that REP events were common on the ISS and require additional comprehensive investigations (Dachev 2012).

PUBLICATION(S)

Dachev TsP, Tomov BT, Matviichuk YN, et al. Relativistic electron fluxes and dose rate variations during April–May 2010 geomagnetic disturbances in the R3DR data on ISS. *Advances in Space Research.* July 2012;50(2):282-292. doi: 10.1016/j.asr.2012.03.028.

This investigation is complete; however additional results are pending publication.

EXPOSE – R SPORES IN ARTIFICIAL METEORITES (EXPOSE-R SPORES)

Research Area: Astrobiology
Expedition(s): 18-26
Principal Investigator(s):
- Gerda Horneck, German Aerospace Centre, Cologne, Germany

RESEARCH OBJECTIVES

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. This experiment studies the survival of spores of bacteria (*Bacillus subtilis*), fungi (*Trichoderma koningii*), and ferns (*Athyrium filix-femina*, *Dryopteris filix-mas*) on a simulated space journey via meteorites. This includes the study of their resistance against space conditions, ie, solar UV, vacuum, and cosmic radiation, as well as the degree of protection by meteorite material.

Sample containers are opened after they are returned to Earth for analysis. ESA image.

RESULTS

Results from Expose-R-Spores are pending completion of analysis and data evaluation before conclusive results are prepared and published.

This investigation is complete; however additional results are pending publication.

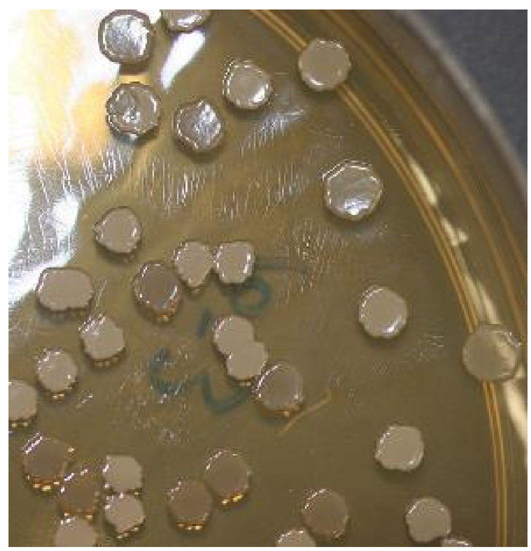
EXPOSE – R MUTATIONAL SPECTRA OF *BACILLUS SUBTILIS* SPORES AND PLASMID DNA EXPOSED TO HIGH VACUUM AND SOLAR UV RADIATION IN THE SPACE ENVIRONMENT (EXPOSE-R SUBTIL)

Research Area: Astrobiology
Expedition(s): 18-26
Principal Investigator(s):
- Nobuo Munakata, University of Tokyo, Tokyo, Japan

Sample containers are opened after they are returned to Earth for analysis. ESA image.

RESEARCH OBJECTIVES

The Expose-R facility hosts a suite of astrobiology experiments, some of which could help understand how life originated on Earth. This suite of experiments are accommodated in 3 special sample trays, which are loaded with a variety of biological samples and exposed to the harsh environment of open space for almost 2 years from March 2009-January 2011. This experiment determines the mutagenicity of the spores of the bacterium *Bacillus subtilis* induced by exposure to space vacuum and/or solar UV radiation. The experiment will use 2 different strains of the bacteria, 1 of which is deficient in repairing UV-induced photoproducts. The frequencies of rifampicin-resistant mutations and sequence changes in the induced mutants (mutagenic spectra) will be determined and compared with those obtained by the vacuum and solar-UV exposure on the ground.



Colonies of Bacillus subtilis grown on a culture dish in a molecular biology laboratory. (Wikimedia Commons)

RESULTS

Results from Expose-R-Subtil are pending completion of analysis and data evaluation before conclusive results are prepared and published.

This investigation is complete; however additional results are pending publication.

Alpha Magnetic Spectrometer - 02 (AMS-02)

Research Area: Astrophysics

Expedition(s): 27-ongoing

Principle Investigator(s):

- Samuel Ting, PhD, Massachusetts Institute of Technology, Cambridge, Massachusets
- Manuel Aguilar-Benitez, Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, Madrid, Spain
- Silvie Rosie, PhD, Insitut National de Physique Nucleaire et de Physique des Particules, Annecy-Le-Vieux, France
- Roberto Battiston, University of Perugia, Perugia, Italy Shih-Chang Lee, Academia Sinica, Taipei, Taiwan
- Stefan Schael, Rheinisch-Westfalische Technische Hochschule, Aachen, Germany Martin Pohl, Université de Genève, Geneva, Switzerland

Research Objectives

S134E007193, ISS028E016135 - Alpha Magnetic Spectrometer mounted on the S3 truss.

The Alpha Magnetic Spectrometer-02 (AMS-02) is a state-of-the-art particle physics detector constructed, tested, and operated by an international team. The AMS-02 uses the unique environment of space to advance knowledge of the universe and leads to an understanding of the universe's origin by searching for antimatter, dark matter, and measuring cosmic rays.

Earth Benefits

This investigation seeks to understand fundamental issues shared by physics, astrophysics, and cosmology on the origin and structure of the universe. Results from AMS-02 will be used to advance knowledge of the universe and lead to the understanding of the universe's origin by searching for antimatter, dark matter, and measuring cosmic rays.

Space Benefits

AMS-02 will provide a plethora of cosmic ray data that will help to advance and perhaps redefine much of what we know about the low-Earth orbit space radiation environment.

RESULTS

AMS-02 was installed on the International Space Station (ISS) on May 19, 2011. In the first 18 months of operations, AMS-02 recorded 6.8 million positron (an antimatter particle with the mass of an electron but a positive charge) and electron events produced from cosmic ray collisions with the interstellar medium in the energy range between 0.5 giga-electron volt (GeV) and 350 GeV. These events were used to determine the positron fraction (ratio of positrons to the total number of electrons and positrons). Below 10 GeV, the positron fraction decreased with increasing energy, as expected. However, the positron fraction increased steadily from 10 GeV to 250 GeV. This increase, seen previously though less precisely by instruments such as the Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics (PAMELA) and the Fermi Gamma-ray Space Telescope, conflicts with the predicted decrease of the positron fraction and indicates the existence of a currently unidentified source of positrons, such as pulsars or the annihilation of dark matter particles. Furthermore, researchers observed an unexpected decrease in slope from 20 GeV to 250 GeV. The measured positron to electron ratio is isotropic, the same in all directions. Above 250 GeV, more data is required to determine the positron fraction behavior.

Alpha Magnetic Spectrometer-02 is an international collaboration of 600 physicists from 56 institutes in 16 countries led by Nobel Laureate Dr. Samuel Ting of MIT.

PUBLICATION(S)

Aguilar-Benitez M, Aisa D, Alpat B, Alvino A, Ambrosi G, Andeen K. Precision measurement of the (e++e-) flux in primary cosmic rays from 0.5 GeV to 1 TeV with the Alpha Magnetic Spectrometer on the International Space Station. *Physical Review Letters*. November 28, 2014;113:221102. doi: 10.1103/PhysRevLett.113.221102.

Accardo L, Aguilar-Benitez M, Aisa D, et al. High statistics measurement of the positron fraction in primary cosmic rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station. *Physical Review Letters*. September 18, 2014;113:121101. doi: 10.1103/PhysRevLett.113.121101.

Aguilar-Benitez M, Aisa D, Alvino A, Ambrosi G, Andeen K, Arruda MF. Electron and positron fluxes in primary cosmic rays measured with the Alpha Magnetic Spectrometer on the International Space Station. *Physical Review Letters*. September 18, 2014;113:121102. doi: 10.1103/PhysRevLett.113.121102.

Bergstrom L, Bringmann T, Cholis I, Hooper D, Weniger C. New limits on dark matter annihilation from Alpha Magnetic Spectrometer cosmic ray positron data. *Physical Review Letters*. October 25, 2013;111:171101. doi: 10.1103/PhysRevLett.111.171101.

Aguilar M, Alberti G, Alpat B, et al. First result from the Alpha Magnetic Spectrometer on the International Space Station: Precision measurement of the positron fraction in primary cosmic rays of 0.5–350 GeV. *Physical Review Letters*. April 3, 2013;110(14):141102-1-141102-10. doi: 10.1103/PhysRevLett.110.141102.

This investigation is ongoing and additional results are pending publication.

STUDY OF THE FLUXES OF FAST AND THERMAL NEUTRONS (BTN-NEYTRON), SIX INVESTIGATIONS

Research Area: Astrophysics
Expeditions(s): 14-ongoing
Principal Investigator(s):
- Igor G. Mitrofanov, PhD, Institute of Space Research of the Russian Academy of Sciences, Moscow, Russia

Installation of the БТН-М1 on the exterior of the Service Module, 2006. Roscosmos image.

RESEARCH OBJECTIVES

The Study of the Fluxes of Fast and Thermal Neutrons (BTN-Neytron), focuses on the spatial and temporal distribution of neutron fluxes and spectra in near-Earth space, including during solar flares. These investigations help researchers to improve current in-orbit radiation models and examine the complete radiation dose the International Space Station (ISS) crew members receive during EVAs.

EARTH BENEFITS

Scintillators studied for their radiation-resistance during the BTN-Neytron experiment are currently in use in scientific equipment being created by Institute of Space Research of the Russian Academy of Sciences.

SPACE BENEFITS

The results may be used to create models of the neutron radiation situation in near-Earth and interplanetary manned space complexes.

RESULTS

BTN-Neytron-Database

The BTN-Neytron space experiment data accumulated between February 2007 through November 2011, the spectra of neutron fluxes outside the ISS were experimentally assessed for energies from the cadmium threshold of 0.4 eV to 10 MeV, which correlated well with the results of other space experiments.

BTN-Neytron-Design

A map was created of the distribution of neutron fluxes for various energies on ISS orbit, which indicated that the neutron fluxes on the station vary significantly depending on its geographic position, which is particularly evident during flight over the South Atlantic magnetic anomaly (SAA).

BTN-Neytron-Radiation ISS

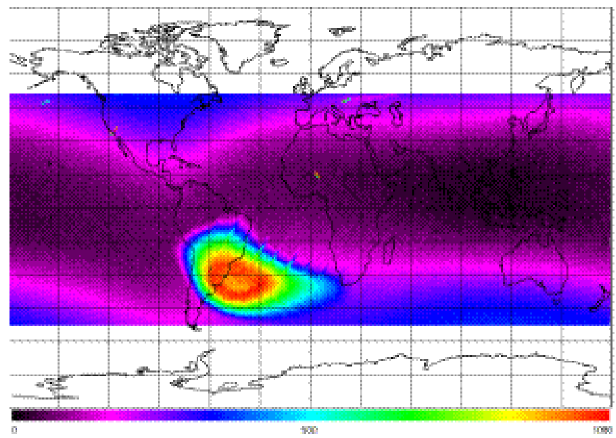
Assessments were made of the dose accumulation rate outside the ISS pressurized compartments from neutrons with energies from the cadmium threshold of 0.4 eV to 10 MeV, which, depending on the geographic position of the ISS, vary from 0.2 mSv/hour (in the equatorial zone) to 5 mSv/hour (in the vicinity of the South Atlantic Magnetic Anomaly [SAMA]). These data were compared to data from the Japan Aerospace Exploration Agency investigation Bonner Ball Neutron Detector (BBND) and demonstrated close correspondence, taking into account the differing levels of solar activity in these experiments.

BTN-Neytron-Ground Segment

Studies were performed on the degradation of crystals of prospective gamma scintillators, and it was shown that lanthanum bromide ($LaBr_3$[Ce]) and $LaCl_3$(Ce) crystals are suitable for use in future space applications, due to their low induced activity and minor degradation of spectrometric properties.

BTN-Neytron-Earth and Mars

Experiments confirmed the effect of increased neutron flux caused by increased galactic cosmic ray fluxes in a period of declining solar activity. The result obtained correlates well with the results of measuring neutron fluxes in Mars orbit and the network of neutron monitors on Earth.



Map of neutron flux distributions in the energy range from 0.4 eV to 100 keV. The color scale shows the neutron count rate. Roscosmos image.

BTN-Neytron-ISS

Recording of space gamma-ray bursts and other transient phenomena (for example, sources such as soft gamma repeaters) in the gamma range has started.

PUBLICATION(S)

Baranov DG, Gagarin YF, Dergachev VA, Nymmik RA, Panasyuk MI. Results of measuring the fluxes of solar energetic particles and methods of their interpretation. *Cosmic Research*. 2011;49(6):469-476. doi: 10.1134/S0010952511060013.

Tretyakov VI, Fedosov F, Kozyrev AS, Litvak ML, Lyagushin VI. Space experiment BTN-Neutron on Russian segment of International Space Station. *16th Workshops on Radiation Monitoring for the International Space Station*, Prague, Czech Republic; September 6-8, 2011.

Lyagushin VI, Kozyrev AS. Measurements of neutron environment inside and outside of ISS. *15th Workshop on Radiation Monitoring for the International Space Station*, Monte Porzio Catone, Italy; 2010.

Mitrofanov IG, Litvak ML, Tretyakov VI, Mokrousov MI, Malakhov AV, Vostrukhin AA. Neutron components of radiation environment in the near-Earth and near-Mars space. *Planetary and Space Science*. December 2009;57(14-15):193-195. doi: 10.1016/j.pss.2009.08.005.

Tretyakov VI, Kozyrev AS, Litvak ML, et al. Comparison of neutron environment and neutron component of radiation dose for space around Earth and Mars from data of instruments HEND/Mars Odyssey and BTN/ISS. *40th Lunar and Planetary Science Conference*, The Woodlands, TX. March 23-27, 2009.

This investigation is ongoing and additional results are pending publication.

Monitor of All-Sky X-Ray Image (MAXI)

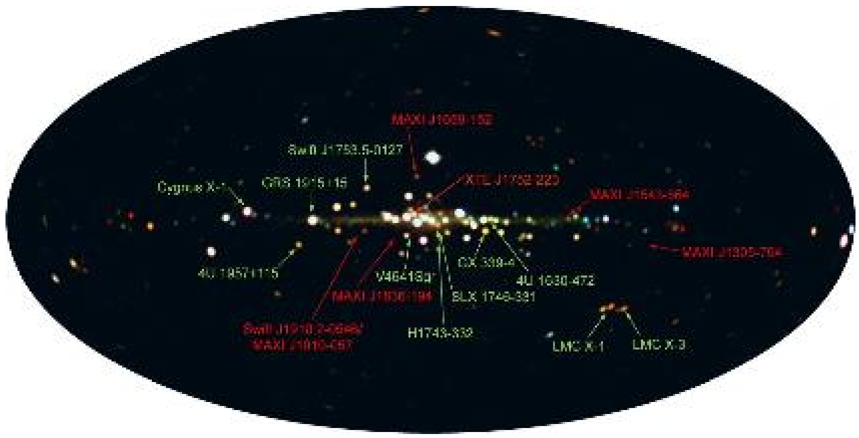
Research Area: Astrophysics

Expedition(s): 19-ongoing

Principal Investigator(s):
- Masaru Matsuoka, PhD, Institute of Physical and Chemical Research, Saitama, Japan

Research Objectives

Monitor of All-Sky X-Ray Image (MAXI) is an all-sky X-ray monitor located on the Japanese Experimental Module's Exposed Facility of the International Space Station (ISS). MAXI looks for galactic transient phenomena in the X-ray spectrum of the sky. When interesting phenomena are discovered, the information is made available to astronomers around the world.



All-sky image with Monitor of All-sky X-ray Image (MAXI) Gas Slit Camera (GSC). The 1.5 year data was used. The black hole candidates detected with MAXI are shown with the names. JAXA image.

Earth Benefit

The all-sky X-ray pictures obtained with MAXI are very useful in furthering science education. Images have already appeared in a planetarium program, a Japanese physics textbook, and a United States astronomy textbook.

Space Benefit

The X-ray charge-coupled device (CCD) camera technology developed for MAXI was used on the Hayabusa spacecraft that returned samples from a near Earth asteroid in 2010.

Results

Black Hole Candidates

MAXI has a distinctive capability of monitoring the outbursts of black hole binaries from beginning to end. MAXI is particularly useful in discovering and monitoring the very early phase of outbursts. MAXI discovered 5 new black hole candidates, named MAXI J1659−152 (Negoro 2010), MAXI J1543−564 (Negoro 2011a), MAXI J1836−194 (Negoro 2011b), MAXI J1305−704 (Sato 2012), and MAXI J1910−057 (Usui 2012). Since the activation of MAXI, half of all new black hole candidates have been discovered by MAXI.

Binary X-ray pulsars

The MAXI team reported more than 20 outbursts. MAXI detected an outburst of GX 304−1 for the first time in the last 30 years and another outburst 10 times bigger in 2010. The latter outburst was quickly followed by a coordinated Suzaku satellite observation, which detected a cyclotron resonance absorption line indicating the strongest magnetic field ever observed. The Swift Gamma-Ray Burst Satellite has also been conducting coordinated observations following the MAXI alerts. For example, Swift/XRT discovered X-ray pulsations in MAXI J1409−619 (Kennea 2010).

Stellar flare

The first unbiased survey of X-ray flares in stars and young stellar objects (YSO) is ongoing. MAXI detected 23 flares from 12 stars in the first 2 years, proving that large X-ray flaring is possible and providing a unified picture for star flaring.

Active Galactice Nucleus (AGN) and the tidal disruption of a star by a massive black hole

MAXI monitored 3 X-ray flares from the blazer (a class of AGN) Markarian 421, and provided a new insight on the origin of giant flares. MAXI and Swift also observed the instant that a massive black hole swallowed a star for the first time in the world.

MAXI catalog

The MAXI team released a GSC source catalog for high Galactic-latitude sky sources, which shows the member list of AGN in the X-ray sky drastically changed in the last 30 years (due to time variability). The catalog was used to make a reliable luminosity function of AGN in our local universe.

Hypernova Remnant

The MAXI Solid-state Slit Camera (MAX-SSC) revealed the existence of a hypernova remnant, estimated to be 3 million years old and is believed to be the first in our galaxy.

The size of the hypernova remnant discovered by Monitor of All-sky X-ray Image (MAXI) looks 20 times bigger than the full moon when viewed from the Earth. The right panel shows the all-sky X-ray image constructed from the 2.5 year data of the MAXI X-ray CCD Camera (or Solid-state Slit Camera, SSC). SSC is sensitive to "soft" X-rays, which is invisible to the other MAXI camera, GSC. Several extended regions are seen in the SSC image (right panel), but not in the GSC image, above. One of the extended regions (enclosed in the rectangle) is the newly discovered hypernova. JAXA image.

PUBLICATION(S)

Maselli A, Melandri A, Nava L, et al. GRB 130427A: A nearby ordinary monster. *Science*. November 21, 2013;343(6166):48-51. doi: 10.1126/science.1242279.

Morii M, Tomida H, Kimura M, et al. Extraordinary luminous soft X-ray transient MAXI J0158–744 as an ignition of a nova on a very massive O-Ne white dwarf. *The Astrophysical Journal*. December 20, 2013;779(2):118. doi: 10.1088/0004-637X/779/2/118.

Nakahira S, Koyama S, Ueda Y, et al. A spectral study of the black hole candidate XTE J1752-223 in the high/soft state with MAXI, Suzaku and Swift. *Publications of the Astronomical Society of Japan*. 2012;64(1).

Burrows DN, Kennea JA, Ghisellini G, et al. Relativistic jet activity from the tidal disruption of a star by a massive black hole. *Nature*. August 25, 2011;476(7361):421-424. doi: 10.1038/nature10374.

Hiroi K, Ueda Y, Isobe N, et al. The first MAXI/GSC catalog in the High Galactic-Latitude Sky. *Publications of the Astronomical Society of Japan*. 2011:14 pp.

Kennea JA, Romano P, Mangano V, et al. Swift follow-up observations of MAXI discovered galactic transients. Publications of the Astronomical Society of Japan. 2011:6 pp.

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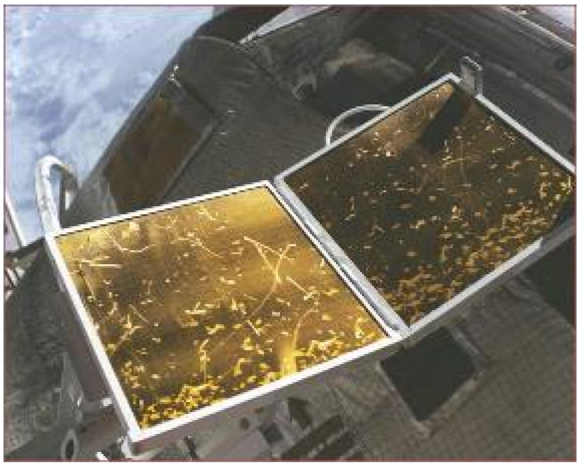
Yamamoto T, Sugizaki M, Mihara T, et al. Discovery of a cyclotron resonance feature in the X-ray spectrum of GX 304-1 with RXTE and Suzaku during outbursts detected by MAXI in 2010. *Publications of the Astronomical Society of Japan*.2010:7 pp.

This investigation is ongoing and additional results are pending publication.

SEARCHING FOR LOW-ENERGY HEAVY NUCLEI OF SOLAR AND GALACTIC ORIGIN USING THE PLASTIC TRACK ANALYZER (PLATAN), FIVE INVESTIGATIONS

Research Area: Astrophysics
Expedition(s): 4-9
Principal Investigator(s):

- Yuriy F. Gagarin, The Ioffe Institute for Research in Physics and Technology of the Russian Academy of Sciences, St. Petersburg, Russia



PLATAN-M chamber#1 during exposure on the surface of the International Space Station. The chamber is in its open, operating position. Roscosmos image.

RESEARCH OBJECTIVES

Searching for Low-Energy Heavy Nuclei of Solar and Galactic Origin using the PLAstic Track ANalyzer (PLATAN) measures streams of the heavy nuclei of cosmic rays in the Earth's magnetosphere. PLATAN consisted of 5 distinct investigations.

PLATAN-IRON

Study of the energy spectra of galactic cosmic ray iron nuclei in the energy range 30-160 MeV/nucleon at various phases of the solar activity cycle.

PLATAN-ARGON

Study of the anomalous component of cosmic rays (energy spectra of argon ions in the magnetosphere and assessing their charged state with increasing energy).

PLATAN-SUN

Study of the energy spectra of the iron ions of solar cosmic rays from the most powerful flares in the energy range 30-160 MeV/nucleon.

PLATAN-COSMIC RAYS

Determining the transmission function of particles from Earth's orbit into the magnetosphere and comparing it with simulation calculations.

PLATAN-ISS

Measuring microparticle streams in the environment surrounding the International Space Station (ISS) according to damage, in the form of through-and-through holes in heat shielding placed above a nuclei detector.

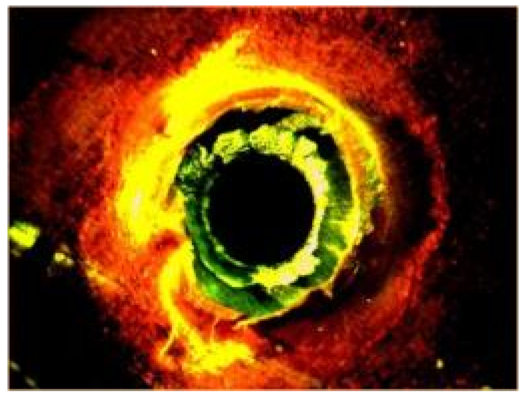
Earth Benefits

The results of the experiment will have great importance for answering a number of fundamental questions: the sources of low-energy cosmic ray nuclei, including anomalous component of cosmic ray, and the generation of energetic heavy particles in the sun.

Space Benefits

This investigation is applied to new knowledge and not specifically to advances in space exploration.

Results



A microparticle penetrating a steel frame 0.5 mm thick (PLATAN-M chamber #1). Roscosmos image.

The spectra of galactic cosmic ray iron nuclei and of the iron ions of solar cosmic rays from the most powerful flares in the range 30-160 MeV/nucleon were measured. The results obtained point to the broad capabilities of the PLATAN unit. This unit made it possible to measure the spectra of galactic cosmic ray iron nuclei and of iron ions of the most powerful solar cosmic ray flares reliably and with a high-energy resolution, which is extremely crucial to compare the results of measurements with theoretical models. The results of PLATAN together with those of a number of experiments on orbiting stations made it possible to discover the particular features of nuclei spectra and to identify the systematic methodological differences when measuring particle streams in space using different equipment. Microparticle streams in the environment surrounding the ISS, micrometeoroids, and orbital debris, caused damage to heat shielding placed above a nuclei detector. The total spectrum of the diameters of through-and-through holes caused by microparticle penetration in heat shielding film was measured. The spectrum measured was compared with simulation calculations. The majority of microparticles passing through the heat shielding film remained in the top layer of the detector (Lavsan). However, a unique event was noted: a microparticle punctured a steel frame of the chamber 0.5-mm thick. Such events pose a significant hazard for the crew and equipment of orbiting stations, therefore, assessing the probability of such cases is of great value.

Publication(s)

Platan-Iron

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Baranov DG, Gagarin YF, Dergachev VA, Nymmik RA, Yakubovsky EA. Low-velocity ferrum nuclei energetic spectra fluences of Galactic cosmic rays in solar activity extremes. *RAS Transactions Physics*. 2005;69(6):832.

Platan-Argon

Baranov DG, Gagarin YF, Dergachev VA, Nymmik RA. AKL argon multiply charged ions existence proof. *RAS Transactions Physics*. 2007;71(7):1011.

Platan-Cosmic Rays

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Baranov DG, Dergachev VA, Gagarin YF, et al. The high-energy heavy particle fluences in the orbits of manned space station. *Radiation Measurements*. 2002;35:423-431. doi: 10.1016/S1350-4487(02)00073-2.

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Baranov DG, Gagarin YF, Dergachev VA, Nymmik RA, Solovyev AV, Yakubovskii EA. Statute of the Platan experiments on the manned space stations. *RAS Transactions, Physics*. 2003;67(4):527-529.

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Platan-Sun

Baranov DG, Dergachev VA, Gagarin YF, Mottl DA, Nymmik RA. About the energy spectra of solar energertic particle events heavy ions. *27th International Cosmic Ray Conference*, Hamburg, Germany; August 7-15, 2001:3181.

This investigation is complete and all results are published.

Agricultural Camera – (AgCam) AgCam name used historically from 2005-2010, later version known as ISSAC

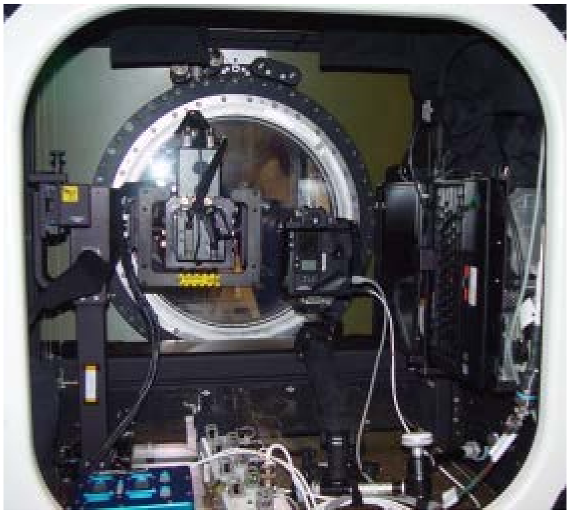
Research Area: Earth Remote Sensing

Expedition(s): 19-22

Principal Investigator(s):
- Bruce Smith, University of North Dakota, Grand Forks, North Dakota

Research Objectives

The Agricultural Camera (AgCam) takes frequent images, in visible and infrared light, of vegetated areas on Earth such as crops, rangeland, grasslands, forests, and wetlands in the northern Great Plains and Rocky Mountain regions of the United States. Requesting parties (eg, farmers, ranchers, foresters, natural resource managers, tribal officials, and educators) directly receive images within 2 days of requests, which helps them improve environmental stewardship. Students and faculty at the University of North Dakota, Grand Forks, North Dakota, chiefly built and operate the AgCam.



The Agricultural Camera is installed in the WORF Ground Test Rack. Shown with simultaneous installation of EarthKAM.

Earth Benefits

Anticipated benefits from AgCam data and information product imagery include nitrogen application maps for efficient fertilizer use, agriculture management zone decision support systems for nutrient and invasive species management, and rangeland management tools to improve livestock allocation and evaluation. The rapid responsiveness of AgCam imagery may also aid in disaster management applications, such as flood monitoring and wilderness fire mapping.

Space Benefits

AgCam is a space-related research project that provides direct benefits from space to the general public. Increasing the relevance of space-related research activities in the daily lives of the general public will benefit all ISS applications, whether for space or Earth applications. By using AgCam data in support of precision agriculture activities, the public will receive benefits synergistically from 3 different space systems: (1) Earth-observing from the ISS, (2) in-field navigation from the Global Positioning System (GPS), and (3) data delivery via satellite communications. With respect to the educational aspect of the AgCam project, using students to develop and operate AgCam helps train the next generation of scientists and engineers that will work on future space-based applications.

RESULTS

Agricultural Camera (AgCam name used historically from 2005 - 2010, later version known as ISSAC) was originally installed aboard the ISS over the US Lab Window in May 2009. On May 31, 2009, during the first execution of the AgCam TAKE_IMAGE command (which initiates image acquisition), an in-flight anomaly occurred. ISS crew re-secured a loose cable connection, however, the anomaly continued to occur. The anomaly manifested itself as an intermittently random failure to successfully take images. Over the next 5 months, an extensive troubleshooting and failure analysis effort was undertaken. This effort reached the conclusion that the intermittent random failure was isolated to an internal electronics hardware problem within one AgCam component, the Power/Data Controller (PDC). ISS crew deactivated and stowed the AgCam payload on November 13, 2009. An upgraded sensor was developed and installed that both eliminated the interface problem and significantly improved the science performance of the system by adding a third band to increase its spectral resolution. The remainder of the onboard and ground equipment functioned well and has been reused in the new investigation, which is known as the International Space Station Agricultural Camera (ISSAC).

Astronaut Michael Barratt, Expedition 19/20 flight engineer, performs Agricultural Camera setup and activation in the US Laboratory of the International Space Station.

This investigation is complete, and no results will be published.

COORDINATED AURORAL PHOTOGRAPHY FROM EARTH AND SPACE (AURORAMAX)

Research Area: Earth Remote Sensing
Expedition(s): 29 and 30
Principal Investigator(s):
- Ruth Ann Chicoine, Canadian Space Agency, St Hubert, Québec, Canada

RESEARCH OBJECTIVES

For Coordinated Aurora Photography from Earth and Space (AuroraMAX), crew members photograph the aurora borealis from the International Space Station (ISS). The photography may be timed with periods of increased solar activity to increase the chances of photographing auroras. This is a public outreach initiative designed to inspire the public to learn more about solar-terrestrial science and how solar activity affects Earth.

The Aurora Borealis as photographed from Earth. Canadian Space Agency image.

EARTH BENEFITS

The benefit is to enhance public awareness of the science of the aurora.

RESULTS

The AuroraMAX program promoted public interest in science and produced highly valuable science data. It was a public outreach and education initiative with the mission of bringing real-time auroral images to the public from a camera located outside Yellowknife, Canada. AuroraMAX used a digital All-Sky Imager (ASI) that collected full-color images of the night sky every 6 seconds and transmitted them via satellite Internet to the Canadian Space Agency (CSA) AuroraMAX Web server where they were made instantly available to the public. AuroraMAX was a highly successful outreach program with hundreds of thousands of distinct visitors to the website, thousands of followers on social media, and hundreds of newspaper, magazine, radio, and television spots.

AuroraMAX will eventually include real-time, high-resolution, single-lens reflex (SLR) auroral images taken from the ground as well as from the ISS where astronauts will take pictures of the aurora with a handheld SLR. AuroraMAX was one of nearly 40 All-Sky Imagers operating across

North America and integrated its data with the Canadian GeoSpace Monitoring (CGSM) ASI data, which was made available to the space science community through Web and FTP sites. Some of the data from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) and CGSM imagers will eventually be incorporated into the AuroraMAX system to maximize viewing opportunities.

Auroral photography from the International Space Station, like this image from the crew of Expedition 23, provides valuable information about the structure and profiling of auroras as well as captivating the public’s imagination. NASA image.

This investigation is complete and all results are published.

Crew Earth Observations (CEO)

Research Area: Earth Remote Sensing
Expedition(s): 1-ongoing
Principal Investigator(s):
- Susan Runco, Johnson Space Center, Houston, Texas

Research Objectives

In Crew Earth Observations (CEO), the crew on the International Space Station (ISS) photograph natural and human-made events on Earth. The photographs record the Earth's surface changes over time, along with dynamic events such as storms, floods, fires, and volcanic eruptions. These images provide researchers on Earth with key data to understand the planet from the perspective of the low-Earth Orbit.

Earth Benefits

Earth observations from human spaceflight serve as a unique record of environmental changes on Earth. These photographs provide valuable information that allows a better understanding of the planet from many perspectives. Short- and long-term events documented include hurricanes, floods, fires, volcanic eruptions, climate change, agricultural development, forest fires, urban sprawl, and pollution.

An Expedition 20 crew member photographed Sarychev Peak Volcano, in Russia's Kuril Islands, during the early stages of eruption on June 12, 2009. This detailed photograph is exciting to volcanologists because it captures several phenomena that occur during the earliest stages of an explosive volcanic eruption.

Space Benefits

The imagery captured by astronauts during long-duration missions provide insight for planetary surveys within our solar system and anomalies that occur in low-Earth orbit.

Results

ISS provides a unique opportunity to capture a variety of sites on Earth by providing repeated overflight passes of the Earth with different lighting and viewing angles. Through CEO, ISS crew members share their view of the Earth with the public and take pictures of some of the most dramatic examples of change on the Earth's surface. These sites have included major deltas in South and East Asia, coral reefs, cities, alpine glaciers, volcanoes, and features on Earth, such as impact craters, that are analogs to structures on other planets.

From Expedition 1 through March 2013, ISS crew members took more than 1 163 543 images of Earth, more than half of the total number of images taken from orbit by astronauts since the first Mercury missions. Scientists and the public around the world have access to CEO images captured by astronauts on ISS through the Gateway to Astronaut Photography of Earth website (http://eol.jsc.nasa.gov/). Between 400,000 and 1,000,000 digital photographs of Earth taken from the CEO collection are downloaded by the public each month. The website also features an Image of the Week and searchable access to all the photographs. Scientific analyses using CEO data have been published in scientific journals in a wide variety of disciplines.

ISS Expedition 6 science officer Don Pettit pioneered an approach using a homemade tracking system to track the ground as it moves relative to station; this allowed him to acquire long-exposure images under low-light conditions using very long exposures. This image shows the lights of Argentina's capital city, Buenos Aires.

Publication(s)

Jehl A, Farges T, Blanc E. Color pictures of sprites from non-dedicated observation on board the International Space Station. *Journal of Geophysical Research: Space Physics*. January 2013;118:454-461. doi: 10.1029/2012JA018144.

Wilkinson MJ, Allen CC, Oehler DZ, Salvotore MR. A new fluvial analog for the ridge-forming unit, Northern Sinus Meridiani/Southwest Arabia Terra Mars. *39th Lunar and Planetary Science Conference*. Houston, TX; 2008;1392-1393.

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Elvidge CD, Safran J, Sutton PC, et al. Potential for global mapping of development via Nightsat mission. *GeoJournal*. 2007;69(1-2):45-53. doi: 10.1007/s10708-007-9104-x.

Kohlmann B, Wilkinson MJ. The Tarcoles Line: Biogeographic effect of the Talamanca Range in lower Central America. *Giornale Italiano do Entomologia*. 2007;12:1-30 [Italian].

Gebelein J, Eppler DB. How Earth remote sensing from the International Space Station complements current satellite-based sensors. *International Journal of Remote Sensing*. 2006;27(13):2613-2629. doi: 10.1080/01431160600552250.

Wilkinson MJ, Marshall LG, Lundberg JG. River behavior on megafans and potential influences on diversification and distribution of aquatic organisms. *Journal of South American Earth Sciences*. 2006;21:151-172.

Andrefouet S, Gilbert A, Yan L, Remoissenet G, Payri C, Chancerelle Y. The remarkable population size of the endangered clam Tridacna maxima assessed in Fangatau Atoll using in situ remote sensing data*. ICES Journal of Marine Science*. 2005;62(6):1037-1048. doi: 10.1016/j.icesjms.2005;04.006.

Cembella AD, Ibarra DA, Diogene J, Dahl E. Harmful algal blooms and their assessment in fjords and coastal embayments. *Oceanography*. 2005;18(2):160-173.

Scambos T, Sergienko O, Sargent A, MacAyeal D, Fastook J. ICESat profiles of tabular iceberg margins and iceberg breakups at low altitudes. *Geophysical Research Letters*. 2005;32:L23S09. doi: 10.1029/2005GL023802.

Andrefouet S, Robinson JA, Hu C, et al. Influence of the spatial resolution of SeaWiFS, Landsat 7, SPOT, and International Space Station data on landscape parameters of Pacific Ocean atolls. *Canadian Journal of Remote Sensing*. 2003;29(2):210-218.

Lulla K. Two thousand three nighttime urban imagery from International Space Station: Potential applications for urban analyses and modeling. *Photogrammetric Engineering and Remote Sensing*. 2003;69:941-942.

Stefanov WL, Robinson JA, Spraggins SA. Vegetation measurements from digital astronaut photography. *International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences*. 2003;24:185-189.

Stumpf RP, Robinson JA, Holderied K, Feldman GC, Kuring N. Mapping water depths in clear water from space. *Proceedings of the 13th Biennial Coastal Zone Conference*, Baltimore, MD; 2003.

Quod J, Bigot L, Blanchot J, et al. Research and monitoring of the coral reefs of the French islands of the Indian Ocean. Assessment activities in 2002. Mission carried out in Glorieuses. *Réunion: IFRECOR (*Initiative Française pour les Récifs Coralliens). 2002;2 [French].

Robinson JA, Amsbury DL, Liddle DA, Evans CA. Astronaut-acquired orbital photographs as digital data for remote sensing: Spatial resolution. *International Journal of Remote Sensing*. 2002;23(20):4403-4438. doi: 10.1080/01431160110107798.

Robinson JA, Evans CA. Space station allows remote sensing of Earth to within six meters. *Eos, Transactions American Geophysical Union*. 2002;83:185-188.

PATENT(S)

Wilkinson MJ, inventor; Method for identifying sedimentary bodies from images and its application to mineral exploration. United States Patent and Trademark Office 6,985,606. January 10, 2006.

This investigation is ongoing and additional results are pending publication.

Crew Earth Observations - International Polar Year (CEO-IPY)

Research Area: Earth Remote Sensing

Expedition(s): 14-18

Principal Investigator:
- Donald Roy Pettit, PhD, Johnson Space Center, Houston, Texas

Research Objectives

Crew Earth Observations - International Polar Year (CEO-IPY) supports an international collaboration of scientists studying the Earth's Polar Regions from 2007 to 2009. International Space Station crew members photograph polar phenomena including icebergs, auroras, and mesospheric clouds in response to daily correspondence from the scientists on the ground.

Shows the regional view of Iceberg A22A, also known as 'Amigosberg', and a much more detailed image of ice breakup along the margin (white box and inset). The images were taken as part of the International Space Station support of the International Polar Year, initiated by astronaut Don Pettit, and implemented through the Crew Earth Observations payload.

Earth Benefits

Data collected by CEO-IPY will be used by an international collaboration of scientists to determine how the Polar Regions have changed over the past 125 years and might help to explain atmospheric phenomena such as Polar Mesospheric Clouds. The blueprint the data creates will be used to determine the changes in the Polar Regions in the future. The data gathered will also be used as an educational tool for teachers and students worldwide.

Layers of Earth's atmosphere, brightly colored as the sun rises over central Asia, and Polar Mesospheric Clouds are featured in this image photographed by an Expedition 17 crew member. The image was acquired in support of International Polar Year research.

Space Benefits

Observations that are made from Earth's orbit create the model for planetary exploration observations on future long-duration missions.

Results

ISS crew members successfully documented the break-up of large tabular icebergs that calved from the Antarctic ice shelves and drifted northward into the South Atlantic Ocean. Researchers from the National Snow and

Ice Data Center used the imagery from the ISS to examine surface features, including ice margins, cracks, and surface melt water ponds to better understand the mechanisms and timing of iceberg breakup. Large Tabular Icebergs can be used to model breakups of the Antarctic ice shelf. Several sequences of polar mesospheric clouds were observed and documented by the ISS crews, and imagery of auroras from the ISS and shuttle were collected simultaneously with data from ground stations and meteorological satellites. Some of the data were published and served to the public via NASA's Earth Observatory website (http://earthobservatory.nasa.gov).

PUBLICATION(S)

Scambos T, Ross R, Bauer R, et al. Calving and ice-shelf break-up processes investigated by proxy: Antarctic tabular iceberg evolution during northward drift. *Journal of Glaciology*. 2008;54(187):579-591.

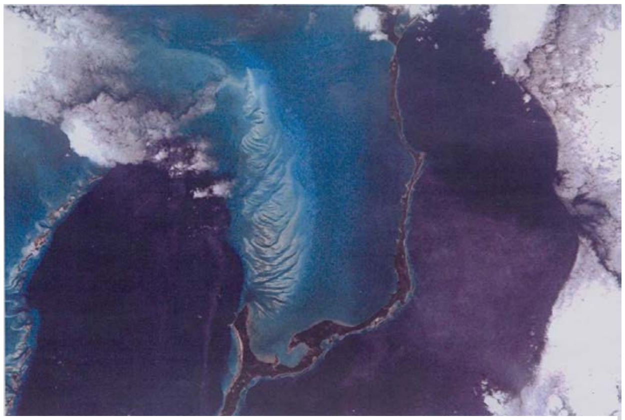
This investigation is complete; however additional results are pending publication.

STABILITY OF GEOGRAPHICAL POSITION AND CONFIGURATION OF BORDERS OF BIOPRODUCTIVE WATER ZONES OF THE WORLD'S OCEANS OBSERVED BY ORBITAL STATION CREWS (DIATOMEYA)

Research Area: Earth Remote Sensing
Expeditions(s): 2-18
Principal Investigator(s):
- Mikhail Ye. Vinogradov, P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

Stability of Geographical Position and Configuration of Borders of Bioproductive Water Zones of the World's Oceans Observed by Orbital Station Crews (Diatomeya) allows the International Space Station (ISS) crews to study and identify the patterns of the biologically productive waters of the world's oceans. This task is crucial with scientific and economic applications of global significance.



Tropical Atlantic. Color of the waters and structure of the bottom of the offshore waters of Eleuthera Island, Bahamas. Roscosmos image.

EARTH BENEFITS

Diatomeya creates scientific-technical and organizational foundations for obtaining trade-oceanologic information, which has commercial properties. This investigation documents data for real-time evaluation of the negative consequences of industry development of hydrocarbon deposits and other resources in areas of the continental shelf and distant areas of the open ocean.

SPACE BENEFITS

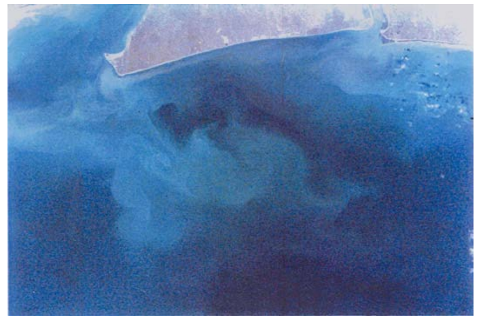
This investigation is applied to new knowledge and not specifically to advances in space exploration.

North Atlantic. Highly productive zone in the English Channel South. Roscosmos image.

RESULTS

A result of Diatomeya was that the scope and nature of the spatial-temporal variability were determined, which are important in trade relations of the bioproductive waters of the world's oceans, and namely the following were accomplished. This investigation also contributed to the data set of the influence of long-term spaceflight conditions on the quality of film and digital media carriers. For the Diatomeya investigation a new method was developed and implemented for azimuth fixing of photo images of the featureless waters (images were obtained using handheld cameras) and the conditions for manifestation of the contrast zones of the ocean in brightness fields were determined.

The Diatomeya data, along with the results of the vessel measurements and data from published sources, allowed the spatial-temporal variability of the highly productive waters of the North and South Atlantic, and the Black and Azov Seas, to be evaluated.



South Atlantic. Highly productive waters near the Magellan Channel and the island of Tierra del Fuego. Roscosmos image.

Publications(s)

Armand NA, Zavyalov PO, Yevgushchenko AN, Koprova LI, Tishchenko YG. Results of ocean observations from space under the "Diatomeya" space experiment program on the ISS RS. *Materials from the International Conference Fundamental Space Research; Latest Developments in the Field of Geoecological Monitoring of the Black Sea Region and Outlooks on Implementing Them*. September 22-27, 2008, Solnechnyy bereg, Bulgaria.

Vinogradov PV, Kaleri AY, Yevgushchenko AN, Koprova LI, Tishchenko YG. Scientific observations of the ocean from space onboard the International Space Station. *Kosmonavtika i raketostroyeniye*, 2007;4(49):85-90.

This investigation is complete and all results are published.

HICO and RAIDS Experiment Payload - Hyperspectral Imager for the Coastal Ocean (HREP-HICO)

Research Area: Earth Remote Sensing
Expedition(s): 19-ongoing
Principal Investigator(s):
- Mike Corson, Naval Research Laboratory, Washington, DC

Research Objectives

The HICO and RAIDS Experiment Payload - Hyperspectral Imager for the Coastal Ocean (HREP- HICO) uses a special camera that separates light into hundreds of wavelength channels, which reveals information about the composition of water and land along the coasts. Each scene covers an area of about 30 miles by 125 miles, which captures features like river outflow plumes or algae blooms, and lets scientists do environmental characterization of coastal regions.


A HICO image taken over the mouth of the Chesapeake Bay on October 7, 2009. NASA image.

Earth Benefits

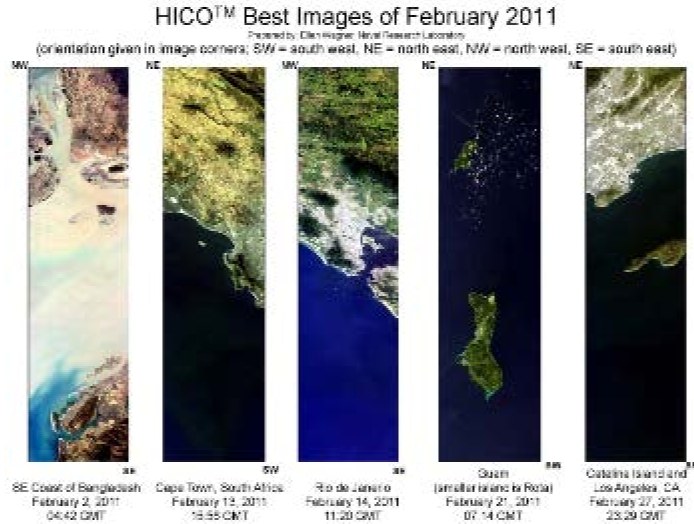
The HICO camera can study the ocean's depth, shallow sea floor, water visibility and chlorophyll content, which indicates the presence of microscopic species of plankton. Improved understanding of these ocean characteristics is important for the U.S. Navy and U.S. Marine Corps, which may need to move ships quickly in shallow or murky waters. HICO data can also be used to monitor water quality, which could help the Environmental Protection Agency and other civilian researchers studying coastal ecosystems.

Space Benefits

HICO is part of a larger experiment called HICO and RAIDS Experiment Payload (HREP) that combines HICO and the Remote Atmospheric and Ionospheric Detection System (RAIDS). Imagery captured during the experiment's long duration will provide new data about how sunlight, cloud cover, and different viewing angles can affect images taken in low-Earth orbit.

Results

HICO has been operating since September 25, 2009 aboard the ISS. Over 1 700 pictures were collected from HICO in the first year of operation. These images have been used to characterize a variety of optical conditions of ocean waters, such as chlorophyll concentrations, colored dissolved organic matter concentrations, suspended sediment concentrations, and water depth. Image targets have included the Yellow Sea near South Korea, to determine the depth of shallow mud flats and channels, and the Florida Keys, to demonstrate chlorophyll concentrations, dissolved organic matter and suspended sediment concentrations, water depth, and bottom information. In 2010, HICO images were used to observe chlorophyll-*a* concentrations in the Azov Sea, Russia. Model estimates of chlorophyll-*a* concentrations derived from HICO images were in close agreement with chlorophyll-*a* concentration measurements taken from actual samples. This verified HICO's ability to estimate chlorophyll-*a* concentrations in turbid waters in real-time. Data from HICO was also used to characterize the oil spill resulting from the Deepwater Horizon oil rig explosion on April 20, 2010. HICO collected data from targets around the explosion site and in the nearby marshlands of Louisiana and Mississippi. The results from HICO identified uncontaminated water and oil/water mixture, as well as strands of emulsified oil. Results from HICO will be used in the management of both inland and coastal aquatic ecosystems, for planning and executing operations from humanitarian relief to military actions, and for identification of oil spilled from ruptured oil pipes.



These images were taken in February, 2011, from the International Space Station experiment Hyperspectral Imager for the Coastal Ocean (HICO). Data from HICO is used to find bathymetry and water optical properties.

Publication(s)

Moses WJ, Gitelson AA, Berdnikov S, et al. HICO-based NIR-Red models for estimating chlorophyll-a concentration in productive coastal waters. *IEEE Geoscience and Remote Sensing Letters*. June 2014;11:1111-1115. doi: 10.1109/LGRS.2013.2287458.

Amin R, Lewis D, Gould, Jr RW, et al. Assessing the application of cloud-shadow atmospheric correction algorithm on HICO. *IEEE Transactions on Geoscience and Remote Sensing*. May 2014;52:2646-2653. doi: 10.1109/TGRS.2013.2264166.

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Davis CO, Tufillaro NB. Hyperspectral imaging of rivers and estuaries. *Proceedings of SPIE 8870, Imaging Spectrometry XVIII*, San Diego, CA; September 23, 2013;8870:88700K. doi: 10.1117/12.2023401.

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Wright R, Deloatch J, Osgood S, Yuan J. The spectral reflectance of ship wakes between 400 and 900 nanometers. *2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS),* Munich, Germany; July 22-27, 2012:4186-4189. doi: 10.1109/IGARSS.2012.6351746.

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Corson MR, Davis CO. A new view of coastal oceans from the space station. *Eos, Transactions American Geophysical Union*. May 10, 2011;92:161-162. doi: 10.1029/2011EO190001.

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Davis CO, Arnone RB, Gould Jr RW, Corson MR, Montes MJ. Data processing and first products from the Hyperspectral Imager for the Coastal Ocean (HICO) on the International Space Station. *Oceans from Space Symposium*, Venice, Italy; April 26-30, 2010; 73-74.

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Lucke RL, Corson MR, McGlothlin NR, Butcher SD, Wood DL. The Hyperspectral Imager for the Coastal Ocean (HICO): Fast build for the ISS. *Remote Sensing System Engineering III*, San Diego, CA; 2010;78130D.

Tufillaro NB, Davis CO, Jones KB. Indicators of plume constituents from HICO. *2010 Ocean Optics,* Anchorage, AL; 2010:8.

This investigation is ongoing and additional results are pending publication.

Observation of Environmental Phenomena (Imedias)

Research Area: Earth Remote Sensing
Expedition(s): 3
Principal Investigator(s):
- Jean-Pierre Lacaux, Centre National d'Etudes Spatiales, Toulouse, France

Research Objectives

Drawing on photos of remarkable phenomena, the Observation of Environmental Phenomena (Imedias) experiment aims to put together a collection of original images. Combined with satellite images, the collection provides scientists with crucial information in the field of Earth observation on clouds, desertification, deforestation, and much more.

Results

Unfortunately, the photo sessions in orbit did not manage to produce images of good enough quality to assist in the goals of the experiment.

This investigation is complete; however no publications are expected.

INTERNATIONAL SPACE STATION AGRICULTURAL CAMERA (ISSAC)

Research Area: Earth Remote Sensing
Expedition(s): 27-ongoing
Principal Investigator(s):
- Bruce Smith, University of North Dakota, Grand Forks, North Dakota

RESEARCH OBJECTIVES

The International Space Station Agricultural Camera (ISSAC) takes frequent images, in visible and infrared light, principally of vegetated areas (growing crops, grasslands, forests) in the northern Great Plains region of the United States. The sensor is also being used to study dynamic Earth processes around the world, such as melting glaciers, ecosystem responses to seasonal changes, and human impacts, including rapid-response monitoring of natural disasters. ISSAC was built and is being operated by students and faculty at the University of North Dakota, in Grand Forks, North Dakota.

EARTH BENEFITS

The combination of characteristics that ISSAC provides offers a unique data source that allows aspects of agricultural efficiency that are of particular importance to the northern Great Plains to be investigated and improved. More generally, these same capabilities of ISSAC can be applied to scientific study of any areas undergoing rapid ecosystem change, worldwide. Potential targets range from natural systems such as glacier melt and plant phenological transitions, to human impact such as deforestation and urbanization. The rapid responsiveness of ISSAC imagery may also aid in disaster monitoring applications worldwide.

ISS027E023647 - NASA astronaut Ron Garan, Expedition 27 flight engineer, works with International Space Station (ISS) Agricultural Camera hardware in the Destiny laboratory of the ISS.

SPACE BENEFITS

Using students to develop and operate ISSAC helps train the next generation of scientists and engineers who will work on future space-based applications.

RESULTS

ISSAC was installed into the Window Observational Research Facility (WORF) on May 13, 2011. Initial ISSAC images showed finer details when compared to Landsat 5 images. Additionally, radiance (measure of the radiation emitted from the Earth’s surface) and surface reflectance (fraction of the total radiation falling on a surface that is reflected by that surface) results from ISSAC images were compared with radiance and surface reflectance measurements taken on the ground and found to be in good agreement. In November 2011, ISSAC lost its pointing ability after experiencing a current spike caused by being physically obstructed by another payload, Earth Knowledge Acquired by Middle School Students (EarthKAM), which was mounted next to ISSAC. However, ISSAC continued to collect images even without the ability to target specific locations.

PUBLICATION(S)

Kim HJ, Olsen D, Laguette S. International Space Station Agricultural Camera (ISSAC) sensor onboard the International Space Station (ISS) and its potential use on the Earth observation. *American Society for Photogrammetry and Remote Sensing, Sacramento*, CA; March 19-23, 2012.

Florida west coastal region. UND UMAC image.

Olsen D, Kim HJ, Ranganathan J, Laguette S. Development of a low-cost student-built multi-spectral sensor for the International Space Station. *SPIE Optics and Photonics 2011*, San Diego, CA; 2011.

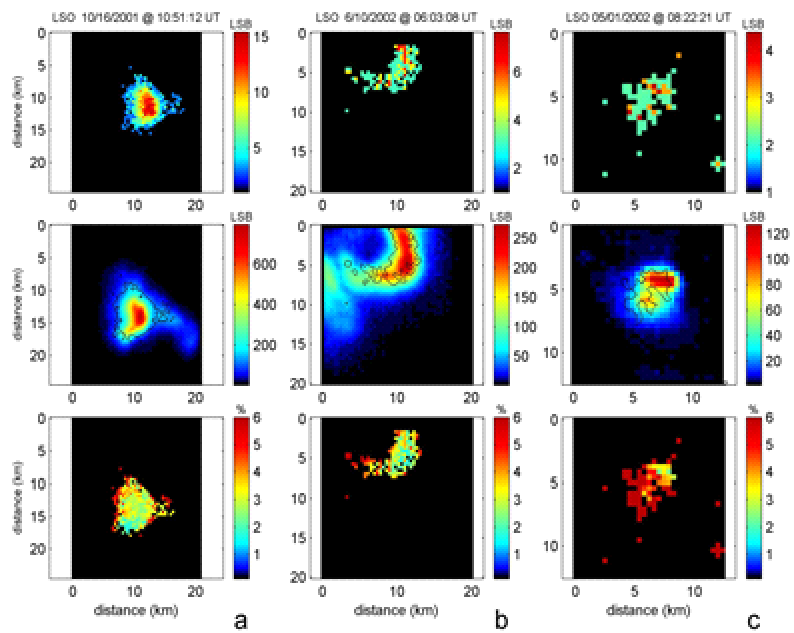
This investigation is ongoing and additional results are pending publication.

Lightning and Sprite Observations (LSO-B, LSO-F, LSO-H, LSO-S), Four Investigations

Research Area: Earth Remote Sensing
Expedition(s): 3, 5, 8, 9
Principal Investigator(s):
- Elisabeth Blanc, French Alternative Energies and Atomic Energy Commission, Bruyeres le Chatel, France

Research Objectives

The Lightning and Sprite Observations (LSO) investigation observes sprites during storms to determine the energy emitted and compare this to nightly emissions of lightning, as well as determining frequency of the phenomena. Sprites are a meteorological phenomenon, which have the appearance of a luminous glow above lightning storms between 50-90 km above the Earth's surface.



First observation of sprite from the nadir by Lightning and Sprite Observations. The color scale indicate the measured intensity 1) Top : filtered camera 2) Middle : camera in the visible and near IR, 3) Bottom : ratio of both camera intensities in percent. The event at the right is an intense lightning while both events on the left are sprites. They are differentiated by the ratio of the intensities measured by both cameras, most intense for sprites than for lightning. ESA image.

Results

During 19 hours of effective observations, 180 flashes were captured, and several possible sprites were identified, demonstrating the effectiveness of the differentiation method. In addition, during sunset and sunrise when the lower atmosphere is dark, LSO observed the airglow of the secondary ozone maximum at about 90 km modulated by gravity wave activity. At the end of the Odissea mission (2002), LSO observed 60 transitory events with the camera in the visible and near infrared and 13 events with both cameras. The ratio of the intensities received by both cameras was about 3 to 5%. The event is correlated to lightning activity measured at ground by the Japan Lightning Detection Network.

On the LSO data, 15 sprites were observed on a surface of 200x200 km within 19 hours of effective measurements over continents. During these 19 hours, about 1000 lightning occurred, according to LIS statistics. This corresponded to 1-3 sprites for 100 lightning flashes. This value was in agreement with the values generally given of 1 sprite for 100 to 500 lightning, even if the number of effective observation hours of LSO was still low for reliable statistics. It is necessary to obtain additional measurements to validate these first statistics.

*A*stronaut aboard the International Space Station captures red sprites, which happened to be passing over Myanmar during a large thunderstorm. ESA image.

The results obtained up to now are very encouraging. They allow validating the measurement concept, which will be used by the microsatellite TARANIS (Tool for the Analysis of RAdiation from lightNIng and Sprites) submitted to the Myriade microsatellite program of the CNES. Taranis is dedicated to the study of sprites and associated phenomena and to the global analysis of the coupling between the atmosphere, the ionosphere, and the magnetosphere in relation with these phenomena.

PUBLICATION(S)

Blanc E, Farges T, Brebion D, et al. Main results of LSO (Lightning and sprite observations) on board of the International Space Station. *Microgravity Science and Technology*. 2007;19(5-6):80-84. doi: 10.1007/BF02919458.

Blanc E, Farges T, Brebion D, Labarthe A, Melnikov V. Observations of sprites from space at the Nadir: The LSO (Lightning and Sprite Observations) Experiment on board of the International Space Station. *NATO Science Series*. 2006;225:151-166**.** doi: 10.1007/1-4020-4629-4_7.

Blanc E, Farges T, Roche R, et al. Nadir observations of sprites from the International Space Station. *Journal of Geophysical Research*. 2004; 109:A02306. doi:10.1029/2003JA009972.

This investigation is complete and all results are published.

Investigating Atmospheric Bursts of Gamma-Ray and Optical Emissions During Thunderstorm Activity (Molniya-Gamma)

Research Area: Earth Remote Sensing
Expeditions(s): 25-30
Principal Investigator(s):
- Vladimir D. Kuznetsov, PhD, NV Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences, Troitsk, Russia
- Alexander V. Gurevich, PN Lebedev Physical Institute, Moscow, Russia

Research Objectives

The Investigating Atmospheric Burst of Gamma-Ray and Optical Emissions During Thunderstorm Activity (Molniya-Gamma) investigation examines high-altitude lightning discharges, specifically the gamma-ray bursts and optical emissions in the Earth's atmosphere and ionosphere related to storm activity.

Earth Benefits

The results of the scientific processing of the gamma-ray flash data obtained in the Molniya-Gamma space experiment will be used for the purposes of fundamental geophysics research, such as analyzing the atmospheric gamma-ray burst generation mechanisms and verifying the existing theories of burst generation and correlation with high-altitude lightning discharges, as well as on a practical level, for mapping the gamma-ray emission background levels in the ISS orbit. This is important both for practical applications and for initiating and developing future experiments in this field.

Gamma sensor monitoring module and control and data acquisition module from the Foton-Gamma payload set up on one of the panels in the ISS RS Service module. Roscosmos image.

Space Benefits

Also of significance is that determining the physical nature, properties, rate of occurrence, and intensity of penetrating radiation could be of interest in terms of flight safety in the thunderstorm atmosphere.

RESULTS

The Molniya-Gamma investigation results should lead, in addition to explaining the physical nature of high-altitude sprite discharges, to detection in experiments of a new physical phenomenon, runaway electron breakdown. Based on current data, runaway electron breakdown should be an important factor in the entire system of atmospheric thunderstorm processes. Thus, the ISS-based investigation, in combination with a wide range of RF observations, including those using radio interferometers and radar, will facilitate significant advances in our knowledge of the processes occurring in the atmosphere during thunderstorms, as well as their correlation with events in the ionosphere.

This investigation is complete; however additional results are pending publication.

Study of the Electrodynamic Interaction Processes in the Earth's Atmosphere, Ionosphere, and Magnetosphere Using the BФC-3M Videophotometric System (Molniya-SM)

Research Area: Earth Remote Sensing
Expeditions(s): 3-10
Principal Investigator(s):
- Vladimir D. Kuznetsov, PhD, NV Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences , Troitsk, Russia

Research Objectives

The Study of the Electrodynamic Interaction Processes in the Earth's Atmosphere, ionosphere, and Magnetosphere Using the BФC-3M Videophotometric System (Molniya-SM) studies the optical emissions in the Earth's atmosphere and ionosphere associated with storm activity and seismic processes.


BФC-3M Videophotometric Camera installed on a window in the ISS RS Service Module. Roscosmos image.

Earth Benefits

The main emphasis while preparing and performing the Molniya-SM experiment was placed on studying the spatial and temporal characteristics of strong electrical discharges and their relation with the structure of thunderstorm cells to refine the physics of interactions with the electromagnetic radiation environment created by high-energy thunderstorm discharges. The assessment of the data obtained will be used for refining the transfer mechanism of energy and disturbances in a unified system consisting of lithosphere, atmosphere, ionosphere, and magnetosphere. This approach is necessary for developing a unified thermodynamic model of the geophysical environments in the near-Earth space.

Space Benefits

Also of significance is that determining the physical nature, properties, rate of occurrence, and intensity of penetrating radiation could be of interest in terms of flight safety in the thunderstorm atmosphere.

Results

The results of processing the data obtained during the Molniya-SM allow conclusions that advances future understanding of both the lightning discharge mechanisms and the entire array of processes relating to the upward discharge, including visible glow phenomena observed in the upper atmosphere. One of the main requirements for such experiments is high sensitivity of equipment, high temporal and spatial resolution, integration of optical and radio-physics methods, and the use of terrestrial, aircraft, balloon, and satellite-based measuring platforms. Based on the experiment results, the equipment as described here has been verified for future research of the processes associated with lightning discharge (Belyaev 2007, 2008).

Publications

Belyaev BI, Belyaev YV, Katkovsky LV, et al. Spectrophotometric system and method of measuring nighttime luminosity in the Earth's upper atmosphere from space. *Ukrainian National Conference*, Kiev, Ukraine; June 3-5, 2008; 51-53.

Belyaev BI, Katkovsky LV, Nesterovich EI, Sosenko VA, Sinelnikov VM, Khvaley SV. Equipment system and method for measuring nighttime atmospheric luminosity from space. *3rd Belorussian Space Congress*, Minsk, Belorus. October 23-25, 2007;57-61.

This investigation is complete; however additional results are pending publication.

SUPERCONDUCTING SUBMILLIMETER-WAVE LIMB-EMISSION SOUNDER (SMILES)

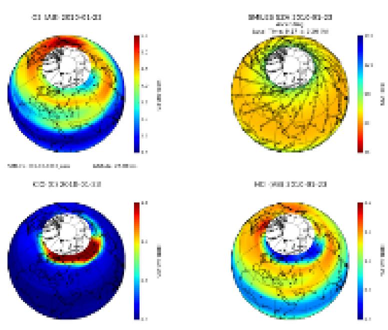
Research Area: Earth Remote Sensing
Expedition(s): 19-ongoing
Principal Investigator(s):
- Masato Shiotani, PhD, Kyoto University, Kyoto, Japan

RESEARCH OBJECTIVES

Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) is aimed at global mappings of stratospheric trace gases by means of a sensitive submillimeter receiver. From the International Space Station (ISS) altitude, the instrument detects a weak submillimeter electromagnetic wave that is emitted from atmospheric molecules as a "radiance spectrum." The spectra are analyzed with algorithms so that the amounts of several kinds of atmospheric molecules on various altitudes are calculated.

EARTH BENEFIT

The global distributions of ozone and related atmospheric constituents (eg, HCl, ClO and BrO) monitored from SMILES observation data with high resolution. The distribution of these species vary during the 24-hour day/night cycle on Earth, and SMILES can be observed, something previously not possible in such detail. The highly sensitive observations of SMILES will help to gain a better understanding of processes controlling the stratospheric ozone chemistry, and those related to climate change.



Sample of global distribution of ozone, HCl and ClO on certain altitude in stratosphere, which were measured with SMILES instrument. It measures electromagnetic wave emitted from atmospheric molecules on various altitude. Vertical distributions of such molecules are retrieved from the submillimeter spectra. JAXA image.

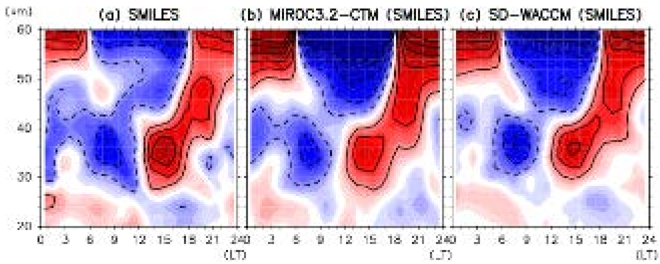
SPACE BENEFIT

The technologies of the cryogenic system used in SMILES to provide cooling for the scientific instruments will be used in future space science programs.

RESULTS

SMILES performed atmospheric observation of Earth for 6 months from October 12, 2009, to April 21, 2010. Due to a failure of the local oscillator component, the observation period was terminated. However, SMILES obtained sub-millimeter spectrum data with extremely low noise, and the instrument demonstrated its high potential for minor atmospheric constituent observations in the middle atmosphere.

For example, SMILES data revealed anomalous distribution of stratospheric ozone in tropic regions from autumn of 2009 to spring of 2010. In January of 2010, ozone depletion in the arctic (caused by the same mechanism as the antarctic ozone hole) was observed based upon SMILES data of ozone and chlorine compounds. Detailed comparisons with previous ground-based and spaceborne experiment data revealed that SMILES data quality is comparable or more high-precision than previous methods. This conclusion is also based upon comparisons with the multiple atmospheric numerical models. For example, diurnal variations of stratospheric ozone was revealed by SMILES data by analyzing increase and decrease ozone within a one-day cycle, which were in agreement with numerical models.



Ozone diurnal variation drawn with SMILES observation data and model calculation results of the same observation period. (Left SMILES, Center: Model calculation (NIES, Japan) and Right: Model calculation (NCAR, U.S.) JAXA image.

PUBLICATION(S)

Pawson S, Steinbrecht W, Charlton-Perez AJ, et al. Update on global ozone: Past, present, and future, Chapter 2 in Scientific Assessment of Ozone Depletion: 2014. *Global Ozone Research and Monitoring Project – Report No. 55, World Meteorological Organization*, Geneva, Switzerland, 2014.

Sakazaki T, Fujiwara M, Mitsuda C, et al. Diurnal ozone variations in the stratosphere revealed in observations from the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) on board the International Space Station (ISS). *Journal of Geophysical Research.* 2013;118. doi: 10.1002/jgrd.50220.

Mizobuchi S, Kikuchi K, Ochiai S, et al. In-orbit measurement of the AOS (Acousto-Optical Spectrometer) response using frequency comb signals. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. June 2012;5(3):977-983. doi: 10.1109/JSTARS.2012.2196413.

Suzuki M, Mitsuda C, Kikuchi K, et al. Overview of the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) and sensitivity to chlorine monoxide, ClO. *IEEJ Transactions on Fundamentals and Materials*. 2012;132(8):609-615. doi: 10.1541/ieejfms.132.609.

Ozeki H, Tamaki K, Mizobuchi S, et al. Response characteristics of radio spectrometers of the Superconducting Submillimeter-Wave Limb-Emission Sounder (JEM/SMILES). *2011 IEEE International Geoscience and Remote Sensing Symposium*, Vancouver, BC; July 24-29, 2011;2262-2265.

Suzuki M, Ochiai S, Mitsuda C, et al. Verification of pointing and antenna pattern knowledge of Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES). *2011 IEEE International Geoscience and Remote Sensing Symposium*, Vancouver, BC; July 24-29, 2011;3688-3691.

Takahashi C, Suzuki M, Mitsuda C, et al. Capability for ozone high-precision retrieval on JEM/SMILES observation. *Advances in Space Research*. 2011;48(6):1076-1085. doi: 10.1016/j.asr.2011.04.038.

Kikuchi K, Nishibori T, Ochiai S, et al. Overview and early results of the Superconducting Submilimeter-Wave Limb-Emission Sounder (SMILES). *Journal of Geophysical Research*. 2010;115. doi: 10.1029/2010JD014379.

Ochiai S, Irimajiri Y, Kikuchi K, et al. *Performance verification and calibration of Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES)*. July 25-30, 2010;4275-4277. doi: 10.1109/IGARSS.2010.5654162.

Ochiai S, Kikuchi K, Nishibori T, et al. Performance of JEM/SMILES in orbit. 21st International Symposium on Space Terahertz Technology, Oxford, UK; March 23-25, 2010;179-184.

This investigation is ongoing and additional results are pending publication.

OBSERVATION, IN THE NEAR-IR RANGE OF THE SPECTRUM, OF WAVE DISTURBANCES IN THE MIDDLE ATMOSPHERE (VOLNY)

Research Area: Earth Remote Sensing
Expedition(s): 11-13
Principal Investigator(s):
- Victor V. Alpatov, Fedorov Institute of Applied Geophysics, Moscow, Russia

RESEARCH OBJECTIVES

Observation, in the Near-IR Range of the Spectrum, of Wave Disturbances in the Middle Atmosphere (Volny) records and maps wave processes in the upper mesosphere and lower thermosphere of Earth's atmosphere. A component of the complex problem of climate change on Earth is the problem of mechanisms by which the various layers of the atmosphere interact.

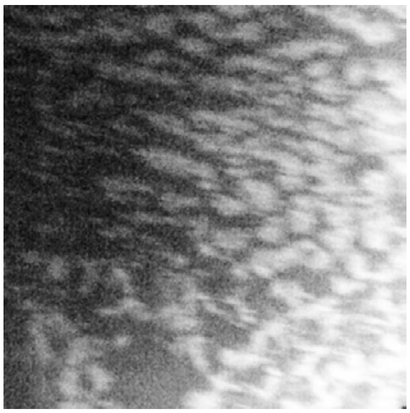


Image obtained during observation toward the nadir of the secondary ozone maximum in the range of waves of the atmospheric band (0,0) of oxygen (762±5nm). Roscosmos image.

EARTH BENEFITS

Volny studies the links between perturbations of density in the lower thermosphere and processes taking place beneath the surface of the Earth (earthquakes), on the Earth's surface (tsunamis, explosions, fires, launches of aerospace technology), and in the troposphere (storms, typhoons, tornados).

SPACE BENEFITS

This investigation is applied to new knowledge and not specifically to advances in space exploration.

RESULTS

Volny confirmed a previously stated hypothesis on the existence, at an altitude of about 90 km in the vicinity of the solar terminator, of a bright, emissive layer that emits in the atmospheric band (0,0) of molecular oxygen (762±5 nm). Mathematical processing of digital images of the emissive layer showed the possibility of obtaining the spectral characteristics of a group of atmospheric internal gravity waves passing through this emissive layer from the lower atmosphere to the upper atmosphere. Thus, the means of observing the atmospheric band (0,0) of molecular oxygen from the ISS that was developed and implemented in the Volny experiment holds promise for use in a system of global monitoring of climate changes.

PUBLICATION(S)

Belyaev AN, Alpatov VV. The possibilities of using the optical observations of O2 atmospheric band dayglow in the vicinity of the solar terminator for monitoring gravity wave activity. *36th Annual European Meeting on Atmospheric Studies by Optical Methods*, Kiruna, Sweden; 2009.

Armand NA, Smirnov MT, Tischenko YG. Hardware for scientific and applied studies in Earth resource remote sensing and environment monitoring from the International Space Station Russian Segment. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2007;(49):91-94.

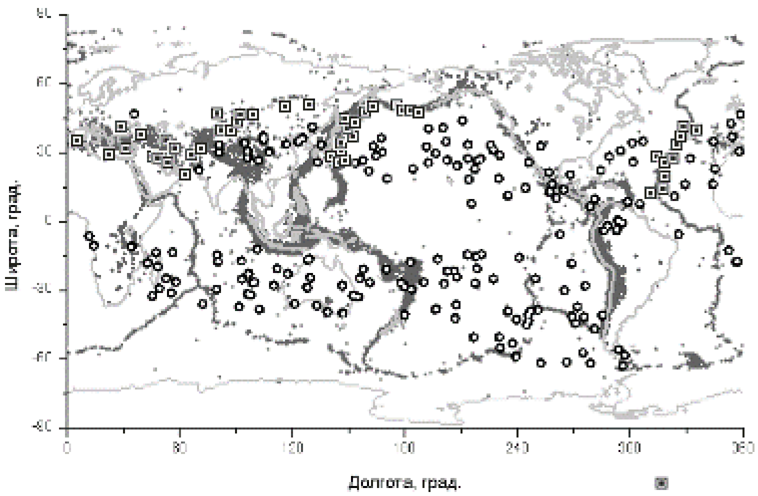
This investigation is complete and all results are published.

Monitoring Seismic Effects—Bursts of High-Energy Particles in Near-Earth Space (Vsplesk)

Research Area: Earth Remote Sensing
Expedition(s): 14, 17-34
Principal Investigator(s):
- Arkadiy M. Galper, National Nuclear Research University, Moscow, Russia

Research Objectives:

Monitoring Seismic Effects—Bursts of High-Energy Particles in Near-Earth Space (Vsplesk) studies seismo-magnetospheric phenomena that were discovered in recent years and are linked to a correlative dependence between the dynamics of fluxes of high-energy, charged particles in near-Earth space and seismic activity. One of the most significant directions for geophysical experiments today is the search for credible and sufficiently reliable signs of catastrophic seismic phenomena that will lead to a future method for predicting earthquakes and other emergency situations.



Geographic distribution of high-energy charged particle bursts (light circles and squares with a black dot in the center). Dark lines indicate tectonic faults. Squares with a black dot in the center indicate particle bursts found along fault lines. Roscosmos image.

Earth Benefits

Vsplesk will lead to developments in approaches to predicting seismic activity and individual powerful earthquakes using nuclear-physics methods and space technologies. It will also develop empirical models (both stationary and mobile) of the radiation situation in near-Earth space.

Space Benefits

Vsplesk will lead to developments in modern technologies to be used in the development and creation of scientific equipment that operates outside the pressurized volume and is designed to conduct long-term space experiments.

Results

Statistics on bursts of high-energy particles, collected from August 2008 through 2011 during the course of the Vsplesk experiment, together with data on particle bursts obtained from the Arina experiment on the Resurs-DK1 satellite, allowed the first detailed research on the geographic distribution of particle bursts. A detailed map of the geographic distribution of particle bursts is given in the figure above.

Correlative analysis for each of the particle bursts and seismic events was identified in the experiment. It considered the coincidence of L-coordinates of genetically linked particle bursts and earthquakes with a time shift of 1-5 hours in-between, identified 8 particle bursts that were potential candidates for harbingers of earthquakes with a magnitude of more than 4 on the Richter scale.

It was discovered that along with particle bursts observed at various longitudes of perturbed L-shells, there are particle bursts grouped along tectonic fault lines; that is, right in the zones of local perturbations of the Earth's radiation belt. The correlative analysis performed on the spatial and temporal characteristics of recorded particle bursts and on the data for seismic events showed in sufficient statistics that approximately 15% of particle bursts may be seismic in nature. They are localized in the L-shells of earthquakes and precede earthquakes with a magnitude greater than 4 by several hours.

Publication(s)

Aleksandrin SY, Bakaldin AV, Batischev AG, Bjeumikhova MA, Galper AM, et al. The origin of high energy charged particle bursts in the near-Earth space. *Annales Geophysicae*. 2011 [Aleksandrin SY, Bakaldin AV, Batischev AG, et al. High-energy charged particle flux dynamics in the near-Earth space caused by solar-magnetospheric and geophysical phenomena. *33rd International Cosmic Ray Conference 2013*, Rio de Janeiro, Brazil; 2013.]

Aleksandrin SY, Galper A, Koldashov SV. The study of local perturbations in the radiation belt in the Arina and Vsplesk satellite experiments. *31st All-Russian Conference on Cosmic Rays*, Moscow, Russia; 2010.

Aleksandrin SY, Koldashov SV. Monitoring local perturbations in the radiation belt using data from the Arina and Vsplesk experiments. *Scientific Session НИЯУ МИФИ-2010*, Moscow, Russia; 2010.

This investigation is complete and all results are published.

SUN MONITORING ON THE EXTERNAL PAYLOAD FACILITY OF COLUMBUS – SOLAR AUTO-CALIBRATING EUV/UV SPECTROPHOTOMETERS (SOLAR-SOLACES)

Research Area: Heliophysics
Expedition(s): 16-ongoing
Principle Investigator(s): ● Gerhard Schmidtke, Fraunhofer-IPM, Freiburg, Germany

RESEARCH OBJECTIVES

The Solar Auto-Calibrating EUV/UV Spectrophotometers (SOLACES) measures the extreme-ultraviolet/ultraviolet (EUV/UV) solar spectrum (17 nm to 220 nm) with moderate spectral resolution from the sun. The SOLACES instrument has been active since 2008, being located on the SOLAR facility on the external surface of the European Columbus Laboratory.

EARTH AND SPACE BENEFITS

The awareness of the environment of the Earth and of the sun radiation level and spectrum is of importance to both Earth-based and space-borne systems as well as to advanced studies on climate. Monitoring the sun radiation outside of the Earth atmosphere over a large electromagnetic spectrum and correlating with parallel observations with other space missions and on ground helps provide the accurate data required to support predictive models and anticipate on the influence of sun radiation on our environment.

Sun monitoring on the External Payload Facility of Columbus – SOLar Auto-Calibrating EUV/UV Spectrophotometers external facility mounted outside the Columbus module. ESA/NASA image.

RESULTS

The period of the solar Extreme-UV minimum between solar cycles 23 and 24 continued over an unexpected long period (roughly 2 years instead of 1 around 2008-2009 timeframe) with SOLACES showing a distinct minimum in August/November 2009. During the beginning of solar cycle 24 measurements were showing abnormally low characteristics of the EUV spectral irradiance. The maximum of the solar cycle was also predicted for late 2013. However, in SOLACES measurements up to now, the maximum of the Solar cycle appeared in late 2011. After that, the solar cycle subsided and is stagnating at a lower level, though measurements continue, which does not exclude another strong increase of solar activity within the near future.

Data from the SOLAR facility on the International Space Station together with data from the Solar EUV Experiment (SEE) aboard the NASA TIMED satellite (which measures Solar spectra in the wavelength range from 0.1 nm to about 200 nm) have helped to confirm the improvement in the EUV-TEC model. SOLACES has been measuring the short-wavelength solar EUV irradiance from 17 to 150 nm (Photo-ionisation occurs only at wavelengths up to 102 nm.) during the extended solar activity minimum.

PUBLICATION(S)

Thuillier MG, Bolsee D, Schmidtke G, et al. The solar irradiance spectrum at solar activity minimum between solar cycles 23 and 24. *Solar Physics*. June 2014;289(6):1931-1958. doi: 10.1007/s11207-013-0461-y.

Nikutowski B, Brunner R, Erhardt C, Knecht S, Schmidtke G. Distinct EUV minimum of the solar irradiance (16-40 nm) observed by SolACES spectrometers onboard the International Space Station (ISS) in August/September 2009. *Advances in Space Research*. 2011;48(5):899-903. doi: 10.1016/j.asr.2011.05.002.

This investigation is ongoing and additional results are pending publication.

Sun Monitoring on the External Payload Facility of Columbus –SOLar SPECtral Irradiance Measurements (SOLAR-SOLSPEC)

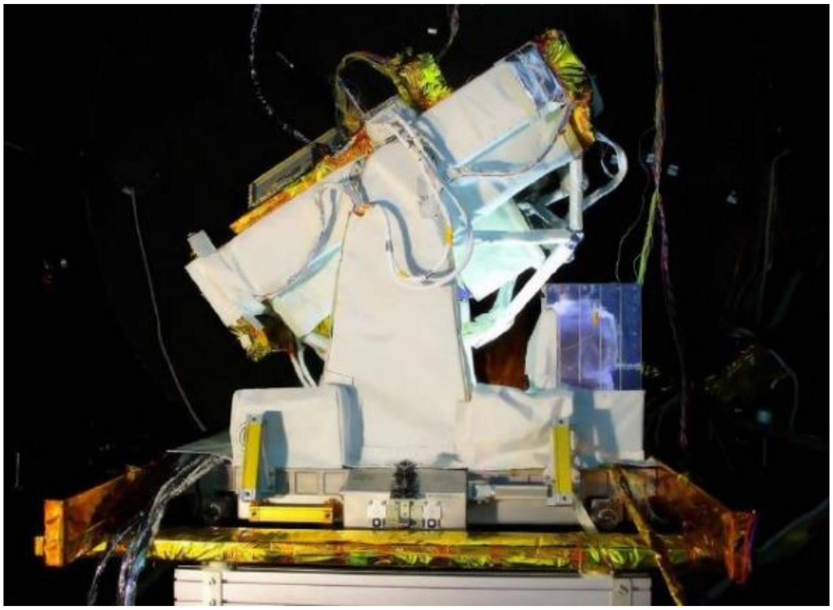
Research Area: Heliophysics
Expedition(s): 16-ongoing
Principle Investigator(s):
- Gerard Thuillier, CNRS, Verrieres le Buisson, France
- Thomas Foujols, CNRS, Verrieres le Buisson, France
- David Bolsée, Belgian Institute for Space Aeronomy, Belgium

Research Objectives

The SOLar SPECtral Irradiance Measurements (SOLSPEC) instrument operates at a high spectral resolution in the range of 180 to 3,000 nanometers (nm), with an accuracy of 2% in ultravaiolet (UV) and 1% in visible and infrared (IR) light for the purpose of measuring solar spectral irradiance (SSI) from the sun.

Results

SOLAR facility measurements were the first ones with in-orbit recalibration capability for the total spectral range of interest. In the extreme UV (EUV) spectral range, SolACES used ionization chambers that are considered a primary detector standard. Within SOLSPEC, several sources allowed checking instrument stability.



SOLAR consists of 3 complementary instruments: SOlar Variable and Irradiance Monitor (SOVIM) covers the near-ultraviolet, visible and thermal-infrared regions of the spectrum; SOLar Auto-Calibrating Extreme UV/UV Spectrophotometers (Sol-ACES) measures the extreme ultraviolet; and SOLar SPECtral Irradiance measurements (SOLSPEC) covers the 180– ,000 nm wavelength range. ESA image.

In August/September 2009 period, the EUV data showed a distinct minimum during the extended solar minimum period between solar cycles 23 (beginning in May 1996 and ending in January 2008) and 24 (from January 2008 until now, with several irregularities in terms of sun behavior), while at UV wavelengths this minimum appeared before. Using SolACES, SOLSPEC, and SOLSTICE SSI to fill the spectral gap between the 2 instruments, 2 spectra SOLAR 1 and SOLAR 2 have been developed, which differ between 1100 and 2400 nm by using ATLAS 3. In this range, SOLAR 2 showed a lower SSI reaching 10% at 1 700 nm. An exhaustive investigation has been carried to understand this difference (though currently no explanation has been found). An important aspect of SSI measurements was the validation/comparison with the theoretical approach. The numerical COde for Solar Irradiance (COSI model) has been used. Several comparisons between ATLAS 3, SOLAR, WHI, and COSI theoretical spectrum showed an overall agreement taking into account the uncertainties of these spectra. However, at some small wavelength domains, differences (expressed in terms of percentages) were above the mean. These cases were explained either by a low signal to noise ratio, instrument uncertainties, and limitation in lines list to simulate the solar spectrum. These spectra were used to derive the temperature of the solar atmosphere. Up to 1 100 nm, these temperatures were in agreement within 50 K. Above 1 100 K, measured spectra provided consistent temperature, however, greater than the COSI temperature and reaching 200 K. At the contrary, SOLAR 2 spectrum provided temperature smaller by 400 K than the temperature derived from the other experimental spectra.

PUBLICATION(S)

Thuillier MG, Bolsee D, Schmidtke G, et al. The solar irradiance spectrum at solar activity minimum between solar cycles 23 and 24. *Solar Physics*. June 2014;289(6):1931-1958. doi: 10.1007/s11207-013-0461-y.

Schmidtke G, Froelich C, Thuillier MG. ISS-SOLAR: Total (TSI) and spectral (SI) irradiance measurements. *Advances in Space Research*. January 2006;37(2):255-264. doi: 10.1016/j.asr.2005.01.009.

This investigation is ongoing and additional results are pending publication.

Sun Monitoring on the External Payload Facility of Columbus –SOlar Variable and Irradiance Monitor (Solar- SOVIM)

Research Area: Heliophysics
Expedition(s): 16, 17
Principle Investigator(s):
- Claus Fröhlich, Physikalisch-Meteorologisches Observatorium World Radiation Centre, Davos, Switzerland

Research Objectives

The SOlar Variable and Irradiance Monitor (SOVIM) measures solar spectral irradiance via filter-radiometers in the near-UV (402 nanometers), visible (500 nanometers) and near-IR (862 nanometers) regions together with the total solar irradiance (TSI), using 2 types of radiometers covering the range from 200 nanometers to 100 micrometers. SOVIM measures the total and spectral solar irradiance and calibration of TSI. The investigation studies the irradiance of the sun, with high precision and high stability.

Solar Facility on the International Space Station highlights the location of the different instruments. ESA image.

Results

The SOVIM package was composed of 3 PMO6 absolute radiometers, 2 sunphotometers, 1 pointing sensor (TASS), and 1 DIARAD radiometer. This summary came from the DIARAD/SOVIM TSI results (and their associated uncertainties). Concerning the acquired data, the TSI value from DIARAD/SOVIM for 3 days of measurements (June 13, 14 and 15 of 2008) was 1364.50 ± 1.38 W m^{-2} (watt per square meter) for the left channel and 1364.75 ± 1.38 W m^{-2} for the right channel. The uncertainty of ±1.38 W m^{-2} was obtained when the individual contributions of the instrument equation were added. If they were combined in quadrature, the uncertainty was around ±0.497 W m^{-2}. The difference between the independent left and right channel measurements as low as 0.25 W m^{-2}, which is within the absolute uncertainty limit of ±1.38 W m^{-2} (Total) and ±0.497 W m^{-2} (RSS). Although DIARAD/SOVIM TSI measurements were 1.2 W m^{-2} lower than DIARAD/ VIRGO TSI value, it was still 4 W m^{-2} higher than TIM/ SORCE TSI measurements.

Publication(s)

Mekaoui S, Dewitte S, Conscience C, Chevalier A. Total solar irradiance absolute level from DIARAD/SOVIM on the International Space Station. *Advances in Space Research.* 2010;45:1393–1406.

This investigation is complete; however additional results are pending publication.

Altering the Ionosphere by Pulsed Plasma Sources (Impuls Stage 1), Three Investigations

Research Area: Near-Earth Space Environment
Expedition(s): 18-26
Principal Investigator(s):
- Yuriy Ya. Ruzhin, PhD, NV Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences, Troitsk, Russia

Research Objectives

The Altering the Ionosphere by Pulsed Plasma Sources (Impuls Stage 1) investigation obtains data on the ionospheric disturbances and sources of low-frequency waves generated in the ionosphere upon injection of pulsed plasma streams from an orbital station, as well as data on the effect of artificially stimulated ionosphere heterogeneity regions and artificial plasma generations on the propagation of high- and low-frequency radio waves.

General View of the Pulsed Plasma Injector with Electro-physical Parameter Monitoring System Sensors on the ISS. Roscosmos image.

Disturbance

Studies the feasibility of using pulsed plasma injectors as sources of ionospheric disturbances and low-frequency electromagnetic waves.

Injector

Studies the space environment disturbances caused by artificial plasma streams from the ISS.

Generation of Artificial Plasma

Studies the impact of artificial plasma formations on the propagation of high- and low-frequency radio waves.

Earth Benefits

Impuls Stage 1 results will be used in the fields of applied geophysics, ecology, and radio communications.

Space Benefits

Supporting the background electro-physical parameters monitoring and investigation in the ISS near-surface areas under various station flight conditions and attitudes and in the ISS near-surface areas during various active experiments on the station.

Results

The experiment has produced the electro-physical parameters measurements obtained in the ISS RS SM near-surface areas on different days and in different orbits, including the period of flying from the equator point in one orbit to the equator point in the next orbit.

The electrical-field parameter measurements acquired in the ISS RS SM near-surface areas show significant strength variations in the direct and alternating components of the electrical field, depending on the station attitude relative to the orbital velocity vector and on the light/dark conditions. The increases (in absolute values) that were recorded in the electrical parameters in some sections of orbit and sometimes exceeded the telemetry range require special study in order to identify the sources of such variations.

The experiment has demonstrated that since the ISS operates in the ionosphere environment with continuously changing properties, the electro-physical parameters study determines the point in time and space when and where the electromagnetic background can be of the greatest impact on the operation of radio communication, navigation, and other systems of the station (Ruzhin 2009).

PUBLICATION(S)

Ruzhin YY, Ivanov KG, Kuznetsov VD, Petrov VG. Controlled injection of high-power radio pulses into the ionosphere-magnetosphere system and appearance of microsubstorms on October 2, 2007. Geomagnetizm I Aeronomiya (Geomagnetism and Aeronomy). June 2009;49(3):324-334. doi: 10.1134/S0016793209030062. [Original Russian Text ©. Ruzhin YY, Ivanov KG, Kuznetsov VD, Petrov VG. *Geomagnetizm i Aeronomiya*. 2009;49(3):342–352.]

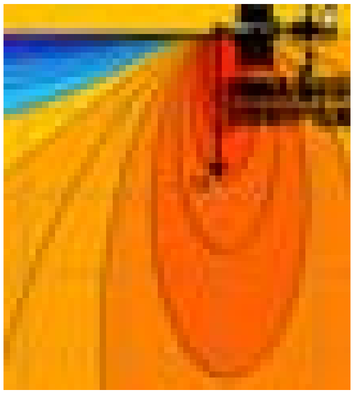
This investigation is complete; however additional results are pending publication.

Observation of the Reflective Characteristics of the Spacecraft Plasma Environment during Engine Firing in Space Using Ground-Based Instruments (Plazma-Progress)

Research Area: Near-Earth Space Environment
Expedition(s): 15-22
Principal Investigator(s):
- Ekaterina M. Tverdokhlebova, PhD, Central Research Institute for Machine Building , Korolev, Russia

Research Objectives

Observation of the Reflective Characteristics of the Spacecraft Plasma Environment during Engine Firing in Space Using Ground-Based Instruments (Plazma-Progress) studies the plumes of liquid-propellant engines as they are ionized by the effect of solar radiation and atomic oxygen. As a result, a large-scale and comparatively dense plasma environment occurs around the International Space Station (ISS). This plasma environment changes the radiophysical properties of the environment and its dimensions correspond to the ISS dimensions.



Liquid-propellant engine plume direction. Roscosmos image.

Earth Benefits

The results of Plazma-Progress answers contemporary questions about space research, including the physics of near-Earth space, the ionosphere and atmosphere, the study of solar-terrestrial links, the development of research methods, and equipment in the field of geophysics.

Space Benefits

Data on small-scale irregularities that form in the near-spacecraft area when liquid-propellant engines are fired will be used in studies of the ISS plasma environment and the electrical discharge situation on the station's exterior surface.

Results

During the Plazma-Progress space experiment, using the only incoherent scatter radar in Russia measurements were taken of the parameters of the ionospheric plasma environment and the reflective characteristics of the Progress cargo transport vehicle when engines were and were not firing. Computer and theoretical analysis was performed of the data obtained to determine the parameters of the large-scale plasma formations that formed during Progress cargo transport vehicle liquid-propellant engine firing. Another comparative analysis was performed of the ISS and Progress cargo transport vehicle's reflective characteristics when the liquid-propellant engines were and were not firing. Finally, comparative analysis was performed of the ionospheric parameters, taken on a digital ionospheric recorder, in areas the Progress cargo transport vehicle flew through while engines were and were not firing. Analysis of the collected data is ongoing by ground research teams.

PUBLICATION(S)

Borisov BS, Garkusha VI, Korsun AG, Sizov AA, Khomin TM, Tverdokhlebova EM. Experimental modeling in a vacuum chamber of the electro-physical processes occurring during the electric discharge between the high voltage solar arrays and the hull of the International Space Station. *Scientific Readings Dedicated to the 90th Birthday of Yuri Aleksandrovich Mozzhorin*, Korolev, Russia; 2010.

Borisov BS, Garkusha VI, Korsun AG, Sizov AA, Khomin TM, Tverdokhlebova EM. Study of the characteristics of electric discharges occurring on the metal-dielectric surfaces of the ISS. *VI International Conference Information Technology in Science, Engineering, and Education*, Pitsunda, Abkhaziya; 2010.

Korsun AG. Electric discharge processes in the ISS plasma environment generated by the high voltage solar arrays. *VI International Conference Information Technology in Science, Engineering, and Education,* Pitsunda, Abkhaziya; 2010.

Korsun AG, Gabdullin FF, Kurshakov MY, et al. Study of the reflective characteristics of the liquid-propellant engine plumes in the Plazma-Progress space experiment. *VI International Conference Information Technology in Science, Engineering, and Education*, Pitsunda, Abkhaziya; September 2010.

Korsun AG. Prediction of liquid propulsion impact on electric-discharge processes near the surface of the International Space Station. *International Space Propulsion*, San-Sebastian, Spain; 2010.

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Sizov AA, Orlov RV, Korsun AG, Tverdokhlebova EM. Experimental modeling of the electromagnetic emissions caused by electric discharge processes on ISS surfaces. *6th International Aerospace Congress*, Moscow, Russia; 2009.

Gabdullin FF, Korsun AG, Tverdokhlebova EM, et al. Study of the characteristics of the plasma environment of low-orbit spacecraft using radio sounding methods. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2008;50(1).

Lebedev VP, Kushnarev DS, Medvedev AV, et al. The first results of the series of radar observations of the Progress cargo transport vehicle with engines firing. *XXII All-Russian Science Conference Radiowave Propagation*, Rostov-on-Don, Russia; September 18-22, 2008.

Shpynev VG, Khakhinov VV, Medvedev AV, et al. Ionospheric perturbation associated with the “Plasma-Progress” experiment at irkutsk. *XXIXth URSI General Assembly*, Chicago, IL; August 7-16, 2008.

Korsun AG, Tverdokhlebova EM, Gabdullin FF, Manzhaley AI, Khakhinov VV, Lebedev VP. Study of the characteristics of the plasma environment of low-orbit spacecraft using radio sounding methods. *Science and Technical Conference on the Primary Results of Applied Science Research on the ISS RS*, Korolev, Russia; February 2007.

Tverdokhlebova EM, Korsun AG, Gabdullin FF. Dynamics of artificial plasma formations in space. *Moscow: A Model of Space. Vol. II. Actions of the space environment on spacecraft materials and equipment*; 2007.

This investigation is complete and all results are published.

PROCESSES OF RELAXATION IN THE ULTRAVIOLET BAND SPECTRUM BY HIGH-VELOCITY INTERACTION OF EXHAUST PRODUCTS ON ISS (RELAKSATSIYA), FIVE INVESTIGATIONS

Research Area: Near-Earth Space Environment
Expedition(s): 4-6, 8-13, and 15-ongoing
Principal Investigator(s):
- Yuri A. Plastinin, PhD, Central Research Institute for Machine Building , Korolev, Russia

RESEARCH OBJECTIVES

Processes of Relaxation in the Ultraviolet Band Specrum by High-Velocity Interaction of Exhaust Products on ISS (Relaksatsiya) comprises 5 distinct investigations to make UV spectrometer observation of chemiluminescent chemical reactions and atmospheric optical phenomena occurring during high-speed interaction between jet engine exhausts and the Earth's upper atmosphere, atmospheric optical phenomena during re-entry of bodies into rarified upper atmosphere and its optical properties in the UV range.

The *Fialka-MV-Kosmos* Multispectral system aboard the ISS RS. Roscosmos image

Relaksatsiya-Vykhlop (Relaxation - Exhaust)

Study on interaction between spacecraft's rocket engines exhaust and the ionosphere and the own International Space Station (ISS) external atmosphere.

Relaksatsiya-UF-Vkhod (Relaxation - UV-Entry)

Study on spatio-temporal structure of gas-flame formations during spacecraft entry into the Earth atmosphere and their fragmentation.

Relaksatsiya -Stend (Relaxation - Stand)

Study on modification of the Earth atmosphere and ionosphere under impact of powerful radiofrequency emission from the Earth.

Relaksatsiya-Groza (Relaxation – Thunderstorm)

Study on global electromagnetic processes in the Earth's upper atmosphere (thunderstorms, sprites, etc) in the UV portion of the spectrum.

Relaksatsiya-Spektr (Relaxation – Spectrum)

Hyperspectral monitoring of the Earth's atmosphere and the "atmosphere-surface of the Earth" system in the ultraviolet, visible, and infrared portions of the spectrum.

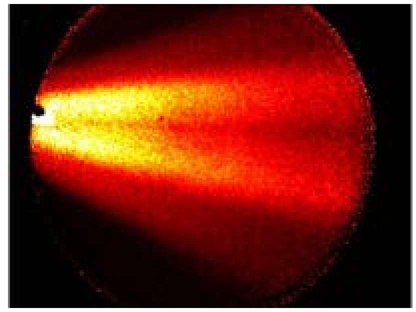
EARTH BENEFITS

The results of system and exploratory studies on natural and anthropogenous global phenomena in the Earth's atmosphere and ionosphere can be used for: development of future Earth remote-sensing spacecraft; development of new approaches to forecasting of earthquakes and other catastrophic phenomena; development of advanced methods for Earth hyperspectral monitoring; collection data about weather and gas composition of the atmosphere and ionosphere; and collection data concerning impacts of space activities on the Earth's atmosphere and ionosphere (interaction of space vehicles with the atmosphere and ionosphere).

RESULTS

Relaksatsya-Vykhlop

Global areas of interaction between rocket engine exhausts (installed on *Progress* and *Soyuz-TMA* spacecraft) and the upper rarefied atmosphere of the Earth (H ~ 350 to 400 km) were disclosed and studied; through analysis of brightness fields, fundamental constants of hypervelocity oxygen atoms interaction with components of engine exhausts were revealed.



Processed video frame of exhaust jets from docking and orientation engine, 2010. Roscosmos image.

It was found that during onboard engine units operations one can observe bright UV glow of the own ISS atmosphere in OH molecular bands related to decay and photolysis of the water vapor contained in engine exhaust gas**.**

Relaksatsya-UF-Vkhod

Unique *in situ* UV experimental data about spatial structure and intensity of the emission spectrum from spacecraft plasma formations and transport vehicle fragments during hypersonic reentry into the atmosphere throughout the entire descent trajectory, which includes entering and fragmentation of a *Soyuz-TMA* and a European cargo vehicle ATV Jules Verne were obtained.

Relaksatsya-Stend

A global glow of the Earth upper atmosphere at altitudes of about 100 to 140 km in the southern and northern hemispheres was discovered under impact of powerful radiofrequency emission from the Earth to the Earth's ionosphere and atmosphere—a probable mechanism of modification of the atmosphere is actuation of Alfven oscillations in the ionosphere.

Relaksatsya-Groza

For the first time in the UV spectrum, an investigation researched spatio-temporal and power budget of global thunderstorm phenomena in upper Earth's atmosphere (elves, sprites, jets, etc), as well as new, previously unknown data about their origin and development were received over the equatorial Africa.

Relaksatsya-Spektr

According to systematic UV-spectrum measurements of brightness in the upper atmosphere, it was revealed the phenomenon of bifurcation of the high-altitude limb at altitudes of about 100 km and, respectively, concentration of atomic oxygen layer over the seismically active area where tectonic plates converge in the region of the Arabian underwater mountain crest in the Indian Ocean.

Images of plasma units at the moment of re-entry into the Earth's upper atmosphere and fragmentation of ATV-1 in different spectral ranges: a) in UV-range, b) in visible range. Roscosmos image.

It developed a methodology and obtained data through hyperspectral monitoring of the atmosphere from the ISS in the UV, visible, and near-infrared portions of the spectrum along the ISS ground trace with different geo- and heliophysical viewing conditions (spectral resolution: 1.5 nm; swath: not less than 200 km; spatial resolution: from 1.5 km to 15 km).

Thus, the Relaxation series of space experiments conducted aboard the ISS from 2002-2010 demonstrated high effectiveness of UV spectral portion application to monitoring of global physical phenome of natural and man-made origin, geophysical conditions in the Earth's atmosphere, and near-Earth space.

PUBLICATION(S)

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Karabadzhak GF, Krasotkin VS, Manzhaley AI, Plastinin YA, Khmelinin BA. ISS-based observation of a European ATV cargo vehicle entering the Earth's atmosphere with the Fialka–MV-Kosmo multispectral system. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2010;59(2).

Karabadzhak GF, Komrakov GP, Kuznetsov VD, et al. ISS-based study of global spatiotemporal glowing of the Earth's upper atmosphere and ionosphere under radiofrequency emission impact on them. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2009;57(4):88-94.

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Karabadzhak GF, Plastinin YA, Rodionov AV, Szhenov EY, Sipachev GF, Khmelinin BA. Spectrosegmental studies in superlow natural and man-made emissions in the Earth's upper atmosphere and ionosphere. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2007;49(4):26-32.

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Karabadzhak GF. Revelation of the effective cross-section of the O + H2O = OH (A) + OH (X) reaction during hypervelocity collisions of components by measuring the intensity of hydroxyl glow in the course of space experiments. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering*). 2004;36(3):123-130.

This investigation is complete; however additional results are pending publication.

SPACE ENVIRONMENT DATA ACQUISITION EQUIPMENT - ATTACHED PAYLOAD (SEDA-AP), SEVEN INVESTIGATIONS

Research Area: Near-Earth Space Environment
Expedition(s): 19-ongoing
Principal Investigator(s):
- Kiyokazu Koga, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

The Space Environment Data Acquisition Equipment - Attached Payload (SEDA-AP) investigation consists of 7 small instruments designed to measure the space environment around the International Space Station (ISS). SEDA-AP instruments include 5 radiation and particle monitors, an electronic device performance monitor, a micro-particles capturer, and a space environment exposure device. Characterizing and understanding the environment around space vehicles through this unique combination of instruments allows researchers to develop and design more robust, safe, and protective spacecrafts in the future.

EARTH BENEFIT

It is possible to contribute to safety operation of broadcasting, communication, and the car navigation system satellite by using the space environment data measured by SEDA-AP. Additionally SEDA-AP provides support for space weather forecasting and other fields in atmospheric physics.

S127E008244 – Close-up view of Kibo arm moving Space Environment Data Acquisition Attached Payload. Solar arrays are visible in the background. JAXA image.

SPACE BENEFIT

The space environment is used to troubleshoot the satellite anomalies caused by radiation and the radiation dose control of the crews aboard the ISS.

RESULTS

SEDA-AP gathered valuable data of the space environment at an altitude of 400 km over a course of 3 years. This data will improve models used for the estimation of radiation hardiness of satellite exterior design and minimize the radiation dose during a solar flare. The space environment data is also useful for the trouble shooting of satellite anomalies caused by radiation as well as determining dose control of astronauts in the space station.

New findings from SEDA-AP are obtained by analysis of neutron measurements, such as understating the acceleration mechanisms of the solar flare particle and the evaluation of neutron leakage from the terrestrial atmosphere which is called CRAND (Cosmic Ray Arbedo Neutron Decay). Analysis of this data is ongoing. In this solar cycle 24, the solar activity is very low, however, solar activity has been increasing in recent years, and is expected to increase during the solar maximum phase in 2013. SEDA-AP will continue to investigate the effect of the space environment around ISS.

Publication(s)

Kimoto Y, Ishizawa J, Shimamura H. Passive space environment effect measurement on JEM/MPAC&SEED. Berlin: *Protection of Materials and Structures From the Space Environment*; 2013.

Miyazaki E, Kimoto Y, Yokota R. Flight experiment results of the polysiloxane-block-polyimide BSF-30 on the JEM/MPAC&SEED mission on the ISS. Berlin: *Protection of Materials and Structures From the Space Environment*; 2013.

Muraki Y, Koga K, Goka T, et al. Measurement by FIB on the ISS: Two emissions of solar neutrons detected? *Advances in Astronomy*. 2012;2012:14 pp. doi: 10.1155/2012/379304.

Obara T. Space environment data acquisition with Kibo exposed facility on the International Space Station (ISS). *Electronics and Communications in Japan*. 2012;95(9):10-16. doi: 10.1002/ecj.11418.

Koga K, Goka T, Matsumoto H, Obara T, Muraki Y, Yamamoto T. Measurement of high-energy neutrons at ISS by SEDA-AP. *Astrophysics and Space Science Transactions*. 2011;7: 411-416. doi: 10.5194/astra-7-411-2011.

Obara T, Matsumoto H, Koga K. Space environment measurements by JAXA satellites and ISS/JEM. *Acta Astronautica*. 2012;71:1-10. doi: 10.1016/j.actaastro.2011.08.009.

Obara T, Koga K, Kimoto Y, et al. Space environment data acquisition with the Kibo exposed facility on the International Space Station (ISS). *Data Science Journal*. March 4, 2010;8:IGY76-IGY84. doi: 10.2481/dsj.SS_IGY-007.

This investigation is ongoing and additional results are pending publication.

Service Module/Micro-Particles Capturer and Space Environment Exposure Device (SM/MPAC and SEED), Two Investigations

Research Area: Near-Earth Space Environment

Expedition(s): 3-11

Principal Investigator(s):
- Yugo Kimoto, PhD, Japan Aerospace Exploration Agency, Tokyo, Japan

Research Objectives

The space environment can have very severe and complex effects on materials depending on the orbit into which the spacecraft is placed. In low-Earth orbit, interaction with both high-energy particles in space and the dominant neutral gas, atomic oxygen, causes performance problems. The SM/MPAC and SEED experiment involves exposing materials to the space environment, and returning them to Earth for analysis, in order to provide an understanding of the effects of the space environment on materials.

Three identical Service Module/Micro-Particles Capturer and Space Environment Exposure Device (SM/MPAC and SEED) components were installed on the Russian Service Module (SM), Zvezda in October 2001. On August 26, 2002, the first unit of SM/MPAC and SEED, MPAC and SEED #1, was retrieved by EVA after 315 days of in-orbit exposure. Subsequently, MPAC and SEED #2 was retrieved on February 26, 2004, (after 865 days) and MPAC and SEED #3 on August 18, 2005 (after 1,403 days). JAXA image.

Earth Benefit

The MPAC investigation captures objects to determine the existence of original extraterrestrial objects with unknown mineralogical character. It can offer clues to help understand what happened in the early stages of the birth of the solar system.

The SEED investigation tests new materials to determine survivability in the space environment.

Space Benefit

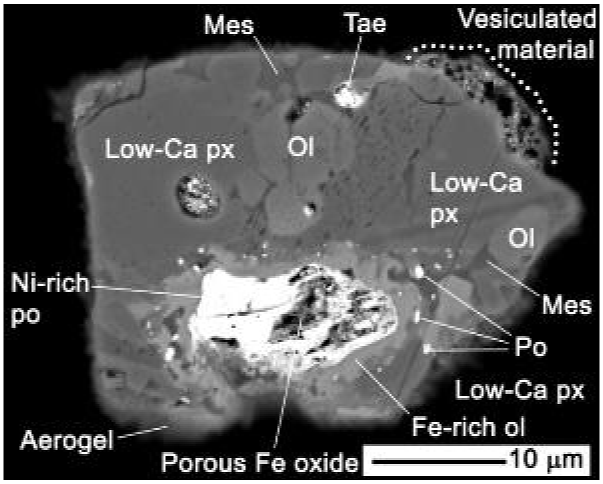
The MPAC investigation collects micro particle data, which includes flux, size, energy, and components.

The SEED investigation examines the actual degradation data for space material (polymeric materials, paint, adhesives, bearings, compound material, etc.) from space radiation, atomic oxygen, and from where UV is obtained. A considerable improvement in developing space material protection technology is expected.

Results

SM/MPAC and SEED revealed the space environment and its effects after periods of 1, 2, and 4 years of space exposure in the same position.

In addition, SM/MPAC and SEED discovered new extraterrestrial objects with a mineralogical characteristic, which was named "Hoshi," meaning "star" in Japanese. The object consists of a micro-particle, the origin of which relates to interplanetary dust and micrometeorites. It is also characterized by an unprecedented formation and mineral composition and represents a world-first discovery of this object.



Transmission electron microscope image (cross-section) of Hoshi. JAXA image.

SEED consists of 28 samples, in which the actual degradation data of these materials were acquired. In addition, analysis of AO fluence samples indicated that substantial contamination had occurred. The contaminant was sufficiently extensive to protect the surface of the AO fluence monitor sample from erosion, while the wake samples and holders were found to be uniformly covered with molecular contamination and had numerous colored spots. Surface analysis (X-ray Photoelectron Spectroscopy [XPS] depth profiles) showed the contaminant thicknesses depended on exposure duration.

PUBLICATION(S)

Kimoto Y, Ishizawa J, Shimamura H. Passive space environment effect measurement on JEM/MPAC&SEED. *Berlin: Protection of Materials and Structures From the Space Environment*; 2013.

Miyazaki E, Kimoto Y, Yokota R. Flight experiment results of the polysiloxane-block-polyimide BSF-30 on the JEM/MPAC&SEED mission on the ISS. *Berlin: Protection of Materials and Structures From the Space Environment*; 2013.

Noguchi T, Nakamura T, Ushikubo T, et al. A chondrule-like object captured by space-exposed aerogel on the international space station. *Earth and Planetary Science Letters*. 2011;309:198-206. doi: 10.1016/j.epsl.2011.06.032.

Edwards DL, Tighe AP, Van Eesbeck M, Kimoto Y, de Groh KK. Overview of the natural space environment and ESA, JAXA, and NASA materials flight experiments. *MRS Bulletin*. January 31, 2010;35(1):25-34. doi: 10.1557/mrs2010.613.

Shimamura H, Nakamura T. Investigation of degradation mechanisms in mechanical properties of polyimide films exposed to a low earth orbit environment. *Polymer Degradation and Stability*. January 2010;95(1):21-33. doi: 10.1016/j.polymdegradstab.2009.10.017.
Kimoto Y, Ichikawa S, Miyazaki E, et al. Space environment effects on materials at different positions and operational periods of ISS. *Proceedings of the 9th International Conference:*

Protection of Materials and Structures From Space Environment, Toronto, Canada; 2009 207-211.

Kimoto Y, Yano K, Ishizawa J, Miyazaki E, Yamagata I. Passive space-environment-effect measurement on the International Space Station. *Journal of Spacecraft and Rockets*. January 2009;46(1):22-27. doi: 10.2514/1.31851.

These investigations are complete; however additional results are pending publication.

Educational Activities and Outreach

ISS provides a unique platform for inspiring students to excel in science, technology, engineering and mathematics. Station educational activities have had a positive impact on thousands of students by involving them in station research, and by using the station to teach them the science and engineering that are behind space exploration.

AGROSPACE EXPERIMENTS SUITE (AES), TWO INVESTIGATIONS

Research Area: Classroom Versions of ISS Investigations
Expedition(s): 10 and 11
Principal Investigator:
- Guiseppe Colla, Universita della Tuscia, Viterbo, Italy
- Marco Casucci, Azimuth, Rome, Italy

RESEARCH OBJECTIVES

Agrospace Experiments Suite (AES) consists of 2 separate investigations: Seedlings and Space Beans for Students. Seedlings evaluates the feasibility of producing vegetable (rocket seeds) sprouts in space for food purposes and to study the influence of weightlessness on germination, growth, and the nutritional quality of sprouts. Space Beans for Students allows students in classrooms on Earth to germinate beans at the same time as being germinated by astronauts aboard the International Space Station (ISS).

Space Beans for Students experiment. Plastic bag contains paper towel, seeds, and the water container. ESA image.

RESULTS

On return to Earth, the plastic bags and seedlings were sent for quality analysis (eg, vitamin C, carbohydrates, nitrates, antioxidants). Producing sprouts directly during space missions may represent an interesting opportunity to offer high-quality fresh ready-to-eat food to the astronauts. The goal of this work was to compare, in terms of growth and nutritional quality, rocket (*Eruca sativa Mill*) seedlings grown in the International Space Station during the ENEIDE mission (Soyuz 10S/9S exchange) with those grown in a ground-based experiment (in presence and absence of clinorotation). The rocket seedlings obtained from the space-experiment were thinner and more elongated than those obtained in the ground-based experiment. Cotyledons were often closed in the seedlings grown in the space experiment. Quantitative (germination, fresh, and dry weight) and qualitative (glucose, fructose, sucrose, and starch) traits of rocket seedlings were negatively affected by microgravity, especially those recorded on seedlings grown under real microgravity conditions. The total chlorophyll and carotenoids of seedlings obtained in the space experiment were strongly reduced in comparison to those obtained in the ground-based experiment (presence and absence of clinorotation). The results showed that it is possible to produce rocket seedlings in the ISS; however, further studies are needed to define the optimal environmental conditions for producing rocket seedlings with high nutritional value.

PUBLICATION(S)

Colla G, Battistelli A, Proietti S, et al. Rocket seedling production on the International Space Station: Growth and nutritional properties. *Microgravity Science and Technology*. 2007;XIX(5/6):118-121. doi: 10.1007/BF02919465.

These investigations are complete; however no publications are expected.

Commercial Generic Bioprocessing Apparatus Science Insert-01: C. *elegans* and Seed Germination (CSI-01), Two Investigations

Research Area: Classroom Versions of ISS Investigations
Expedition(s): 14-15
Principal Investigator(s):
- Louis S. Stodieck, PhD, University of Colorado, BioServe Space Technologies, Boulder, Colorado

ISS014E20211 - Astronaut Sunita L. Williams, Expeditions 14 and 15 flight engineer, seen here with 2 G-Habs as part of the CSI-01 investigation. The G-Habs are placed in the Commercial Generic Bioprocessing Apparatus where their germination will be studied.

Research Objectives

Commercial Generic Bioprocessing Apparatus Science Insert - 01 (CSI-01) is comprised of 2 educational experiments utilized by middle school students in the Unites States and Malaysia. One experiment examines seed germination in microgravity including gravitropism (plant growth towards gravity) and phototropism (plant growth towards light). The second experiment examines how microgravity affects the model organism, *Caenorhabditis elegans*, a small nematode worm. Thousands of students began participating in the experiments in February 2007.

Earth Benefits

CSI-01 provides a unique educational opportunity to encourage and inspire students to pursue careers in the scientific and technical fields by participating in near real-time research activities on the ISS.

ISS014E20219 - A close-up view of astronaut Sunita L. Williams, Expeditions 14 and 15 flight engineer, activating the alfalfa seed in the G-Hab for the CSI-01 investigation.

Space Benefits

Influences children to continue their education in the science, technology, engineering, and math areas (STEM) and pursue related careers. This type of experiment promotes the next generation of scientists, engineers, and crew members for the space program. In addition, scientific research with the CHab and GHab experiments is expected to provide a greater understanding of the effects of spaceflight on biological organisms.

RESULTS

CSI-01 was the first in a series of experiments targeting students with an interactive approach to increase Science, Technology, Engineering, and Mathematics (STEM) interest. More than 5,000 students participated in the CSI-01 experiments by observing differences detected between *C. elegans* grown in classrooms and in-flight. Students also observed the alterations in seed germination rates along with the seed's ability to orient itself in space and ground samples (Hoehn 2007). The first experiment associated with CSI-01 examined the long term growth of *C. elegans* in space by observing biological changes in response to radiation and by comparing gene expression over multiple generations grown in space. Results showed *C. elegans* exhibit normal development and movements when fed with *C. elegans* Maintenance Medium (CeMM). CeMM was previously proven to be a sufficient food source aboard STS-107 (Szewczyk 2005). Although in both humans and *C. elegans* decreased production of myosin is observed while in space, *C. elegans* displayed normal movements when sufficiently fed. This finding suggests the decrease in muscular function is adaptive to microgravity, possibly relating this to human cardiac, skeletal, and vascular muscles. Because movement decline was not detected throughout the entire 12 generations observed, this also suggests there may be a muscular decline plateau (Oczypok 2012).

PUBLICATION(S)

Oczypok EA, Etheridge T, Freeman J, et al. Remote automated multigenerational growth and observation of an animal in low Earth orbit. *Journal of the Royal Society Interface.* March 2012; 9(68):596-599. doi: 10.1098/rsif.2011.0716.

Hoehn A, Countryman S, Freeman J, et al. Science research and rducation modules for the CGBA spaceflight incubator. *SAE International Journal of Aerospace.* 2007; 2007-01-3188. doi: 10.4271/2007-01-3188.

Szewczyk NJ, Mancinelli RL, McLamb W, Reed DW, Blumberg BS, Conley CA. *Caenorhabditis Elegans* survives atmospheric breakup of STS-107, Space Shuttle Columbia*. Astrobiology*. 2005;5(6):690-705. doi: 10.1089/ast.2005.5.690.

This investigation is complete and all results are published.

Commercial Generic Bioprocessing Apparatus Science Insert-02: Silicate Garden, Seed Germination, Plant Cell Culture and Yeast (CSI-02), Four Investigations

Research Area: Classroom Versions of ISS Investigations
Expedition(s): 15-18
Principal Investigator(s):
- Louis S. Stodieck, PhD, University of Colorado, BioServe Space Technologies, Boulder, Colorado

Research Objectives

Commercial Generic Bioprocessing Apparatus Science Insert - 02 (CSI-02) is an educational payload designed to interest middle school students in science, technology, engineering, and math (STEM) by participating in near real-time research conducted aboard the ISS. Students observe 4 experiments through data and imagery downlinked and distributed directly into the classroom via the Internet. The first experiment examines seed germination and plant development in microgravity. The second experiment examines yeast cells adaptation to the space environment. The third experiment examines plant cell cultures and the fourth is a silicate garden. The experiments conducted for CSI-02 are designed primarily to meet education objectives; however, to the maximum extent possible, meaningful scientific research is conducted to generate new knowledge into gravity-dependent biological processes and to support future plans for human space exploration. CSI-02 has the potential to impact over 15,000 middle school and high school students.

The above image shows the nickel sulfate silicate garden grown duriThe above image shows the nickel sulfate silicate garden grown during Expedition 17. BioServe Space Technologies image, University of Colorado, Boulder, Colorado.

Earth Benefits

CSI-02 provides a unique educational opportunity to encourage students to pursue careers in the scientific and technical fields. Approximately 15,000 students conduct ground controls and observe these experiments while aboard the ISS, influencing these students to further their education in STEM fields.

Space Benefits

This influences children to continue their education in STEM areas and pursue related careers. It promotes education of the next generation of scientists, engineers, and crew members for the space program. In addition, scientific research with the experiments is expected to provide a greater understanding of the effects of spaceflight on different biological systems, which could support future plans for the human exploration of the solar system.

Results

CSI-02 consisted of 4 unique experiments, including the “Silicate Garden.” Osmotic silicate gardens grow when a solid of a metal-ion salt is placed into a sodium silicate solution. As the salt begins to dissolve into the silicate, it develops a colloidal semi-permeable membrane of metal silicate. This investigation examined the growth of several types of silicate gardens when gravity forces were removed. Four sodium silicates—calcium chloride ($CaCl_2$), magnesium chloride ($MnCl_2$), cobalt chloride ($CoCl_2$), and nickel sulfate (NiSO4)—were mixed at various concentrations for study aboard ISS and compared to those grown on Earth using identical sets of reaction chambers. The reaction chambers were positioned in the Commercial Generic Bioprocessing Apparatus (CGBA) to capture still and video images of the experiment for downlink to the control center. In the ground samples, the tubes grew upward regardless of the location of the semi-permeable membrane’s initial burst, whereas flight experiments exhibited tubes that grew randomly in all directions (Cartwright 2011). This investigation reached 500 elementary, 3 500 secondary, 5 undergraduate, and 5 graduate students including 30 schools and 40 teachers.

Publication(s)

Cartwright JHE, Escribano B, Sainz-Diaz C, Stodieck LS. Chemical-garden formation, morphology, and composition. II. Chemical gardens in microgravity. *Langmuir*. 2011;27(7):3294-3300. doi: 10.1021/la104193q.

These investigations are complete and all results are published.

Commercial Generic Bioprocessing Apparatus Science Insert-03: Spiders and Butterflies (CSI-03), Two Investigations

Research Area: Classroom Versions of ISS Investigations

Expedition(s): 18, 21, and 22

Principal Investigator(s):

- Chip Taylor, Monarch Watch, University of Kansas, Lawrence, Kansas
- Ken Werner, Gulf Coast Butterflies, Naples, Florida
- Louis S. Stodieck, PhD, University of Colorado, BioServe Space Technologies, Boulder, Colorado
- Mark Stowe, Gainesville, Florida
- Mary Ann Hamilton, Butterfly Pavilion, Westminster, Colorado
- Nancy P. Moreno, PhD, Baylor College of Medicine, Houston, Texas
- Paula Cushing, PhD, Denver Museum of Nature and Science, Denver, Colorado

Research Objectives

Commercial Generic Bioprocessing Apparatus Science Insert - 03 (CSI-03) is one investigation in the CSI program series. The CSI program provides the K-12 community opportunities to utilize the unique microgravity environment of the ISS as part of the regular classroom to encourage learning and interest in science, technology, engineering, and math (STEM). CSI-03 examines the complete life cycle of the painted lady butterfly; how they eat, grow, and undergo metamorphosis in space.

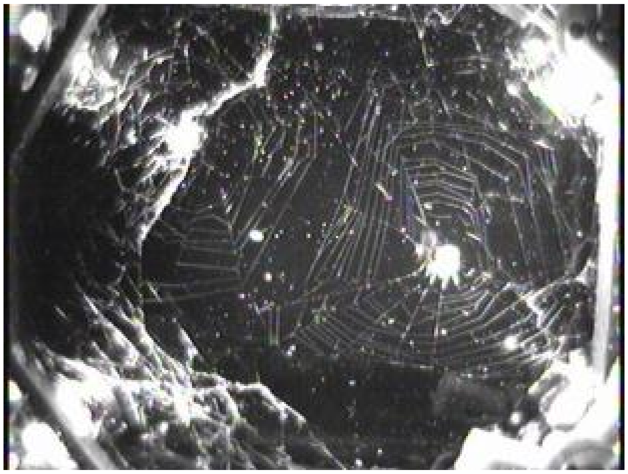
ISS021E028973 - Canadian Space Agency astronaut Robert Thirsk, Expedition 21 flight engineer, works with the new Commercial Generic Bioprocessing Apparatus Science Insert 03 (CSI-03) assembly in the Kibo Laboratory of the International Space Station.

Earth Benefits

CSI-03 provides a unique educational opportunity to encourage and inspire students to pursue careers in the scientific and technical fields by participating in near real-time research activities on the ISS. This promotes education of the next generation of scientists, engineers, and crew members for the space program.

Space Benefits

Results from CSI-03 might help scientists more clearly understand how different organisms are affected by the microgravity environment. CSI-03 influences children to continue their education in STEM areas and pursue related careers.



Orb weaving spider with web in CSI-03 habitat onboard the International Space Station (ISS) during ISS Expedition 18. Image courtesy of BioServe Space Technologies image, Boulder, Colorado.

Results

CSI-03 investigated the growth and behavior of spiders and butterflies aboard the ISS during expeditions 18 and 21/22. The experiments were designed to engage students in authentic science investigations and increase their interest in Science, Technology, Engineering, and Mathematics (STEM) academic areas. During expedition 18, the butterflies did not successfully pupate into adults due to food problems. The orb-weaver spiders, however, thrived in this environment. Students were able to track their web building and feeding activities throughout the expedition. This experiment was successful and laid the groundwork for future similar experiments to engage students. Teachers reported 80% of students expressed interest in science careers following completion of the investigation. On expedition 21/22, CSI-03 allowed students to track morphological, behavioral, and developmental differences from their own in-class butterflies to those aboard the ISS real-time. This experiment was highly publicized by several different media sources including social media sites such as Twitter, Facebook, and YouTube. During this expedition, approximately 180,000 students from all 50 states and 23 countries were able to observe 4 *Vanessa cardui* (painted lady) butterflies aboard ISS. CSI-03 showed that engaging students with hands-on scientific experiments is effective in increasing conceptual understandings and enthusiasm for science (Moreno 2012).

Publication(s)

Moreno NP, Vogt GL, Denk JP, Countryman S, Stodieck LS, Thomson WA. Butterflies and spiders in space: Space life science investigations for the classroom. *Gravitational and Space Biology*. 2012;26(1):77-87.

These investigations are complete and all results are published.

Commercial Generic Bioprocessing Apparatus Science Insert-05: Spiders, Fruit Flies, and Directional Plant Growth (CSI-05), Three Investigations

Research Area: Classroom Versions of ISS Investigations

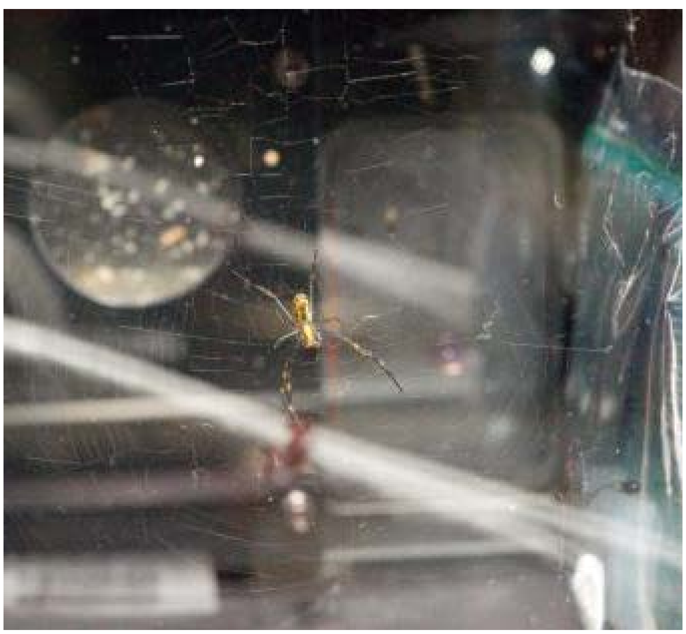
Expedition(s): 27-30

Principal Investigator(s):

- Heike Winter-Sederoff, Ph., North Carolina State University, Raleigh, North Carolina
- Louis S. Stodieck, PhD, University of Colorado, BioServe Space Technologies, Boulder, Colorado
- Mark Stowe, Gainesville, Florida
- Mary Ann Hamilton, Butterfly Pavilion, Westminster, Colorado
- Paula Cushing, PhD, Denver Museum of Nature and Science, Denver, Colorado
- Samuel Zschokke, PhD, University of Basel, Basel, Switzerland
- Sharmila Bhattacharya, PhD, NASA's Ames Research Center, Moffett Field, California
- Stefanie Countryman, University of Colorado, BioServe Space Technologies, Boulder, Colorado

Research Objectives

Commercial Generic Bioprocessing Apparatus Science Insert - 05: Spiders, Fruit Flies, and Directional Plant Growth (CSI-05) examines the long-duration orb-weaving characteristics of a *Nephila clavipes* (golden orb-web spiders), the movement behavior of fruit flies, and the thigmatropic (directional plant growth in response to a stimulus of direct contact), and phototropic (directional plant growth in response to a light source) responses that occur during seed germination in microgravity. CSI-05 utilizes the unique microgravity environment of the International Space Station (ISS) as part of the K-12 classroom to encourage learning and interest in science, technology, engineering, and math (STEM).



Nephila clavipes (golden orb spider) inside the Commercial Generic Bioprocessing Apparatus Science Insert – 05 (CSI-05) spider habitat aboard the International Space Station. NASA image.

Earth Benefits

CSI-05 influences children to continue their education in STEM areas, which can ultimately lead to related careers. This promotes education of the next generation of scientists, engineers, and crew members for the future's space program.

Space Benefits

Results from CSI-05 might help scientists more clearly understand how different organisms are affected by the microgravity environment. CSI-05 provides a unique educational opportunity to encourage and inspire students to pursue careers in the scientific and technical fields by participating in near real-time research activities aboard the ISS.

Results

This investigation impacted more than 119,000 students and 2,000 teachers and schools worldwide have participated in this classroom version of the ISS experiments. The list below breaks down participation:

- Number of K-8 Students (elementary): 106,416
- Number of 9-12 Students (secondary): 13,009
- Number of Undergraduate Students (college, postsecondary): 8
- Number of Graduate Students (master's, PhD, MD): 8
- Number of Schools: 1,989
- Number of Teachers: >2,000

These investigations are complete; however additional results are pending publication.

SPACE EXPOSED EXPERIMENT DEVELOPED FOR STUDENTS (EDUCATION- SEEDS)

Research Area: Classroom Versions of ISS Investigations
Expedition(s): 1
Principal Investigator(s):
- Howard G. Levine, PhD, NASA's Kennedy Space Center, Cape Canaveral, Florida

RESEARCH OBJECTIVES

On-orbit videotape and photographic images are taken of plant germination and early growth. Imagery is converted to educational videos for the purpose of exciting and engaging students in science and technology and for motivating and providing professional development for educators.

EARTH BENEFITS

Studies such as these could lead to a better understanding of how seeds germinate and grow on Earth.

ISS01E5191 - Bill Shepherd tends to a seed pouch during Increment 1. Additional pouches hang off the International Space Station wall above the "Astronauts at Work" sign.

SPACE BENEFITS

The goal of Education-SEEDS is to evaluate the growth of space-exposed seeds compared to earth-grown seeds. Another goal is the demonstration of plant growth in space. Food producing plants is necessary when it is impossible to carry enough freeze dried food to last the entire voyage. Another goal of Education-SEEDS is to increase student interest in science and space exploration; ie, stimulating enthusiasm in students and teachers for space related education.

RESULTS

The Education-SEEDS investigation, which was part of the Jason XI mission, was the first plant experiment to be performed on station. This experiment studied the effects of microgravity and light on the germination of corn and soybean seeds.

The corn seedlings that were exposed to light appeared to show phototropism (or growth towards light). The shoots grew toward the light and were green, demonstrating chlorophyll synthesis (the creation of the green pigment that is used in photosynthesis). The corn seedlings that were not exposed to light did not turn green and did not grow towards the light. The soybean seedlings grown in the light were slightly greener than the seedlings grown in the dark. The phototropic effect was more evident in the corn seedlings than in the soybean seedlings. On Earth, gravity influences the roots of plants to grow in a downward direction (gravitropism). While in orbit the seedlings grew in a microgravity environment. Whether grown in light or dark, the corn roots grew in random directions. The roots of the soybean seeds also grew in random directions (Levine 2001).

Examination of the seeds after their stay on ISS revealed that the nutritional and epidermal layers of the space exposed seeds were more porous than those of the ground-based control seeds. This might allow nutrients to disperse through the seeds more quickly and explain the faster germination and growth rates observed in the space-exposed seeds.

A total of 750,000 students across the United States participated in the experiments, growing corn and soybean seeds in their classrooms to compare their results with the results from the station and participating in live broadcasts.

PUBLICATION(S)

Levine HG, Norwood KL, Tynes GK, Levine HL. Soybean and corn seed germination in space: The first plant study conducted on Space Station Alpha. *38th Space Congress,* Cape Canaveral, FL; April 30-May 4, 2001; 181-187.

This investigation is complete and all results are published.

EUROPEAN SPACE AGENCY – EDUCATION PAYLOAD OPERATIONS – FOAM-S (ESA-EPO-FOAM-S)

Research Area: Classroom Versions of ISS Investigations
Expeditions: 29-ongoing
Principal Investigator(s):
- Dominique Langevin, Université Paris-Sud, Orsay, France
- HSO Promotion Office, ESA/ESTEC, Noordwijk, The Netherlands

RESEARCH OBJECTIVES


ESA astronaut Andre Kuipers with the European Space Agency – Education Payload Operations – Foam-S investigation. ESA image.

The European Space Agency – Education Payload Operations – Foam-S (ESA-EPO-Foam-S) investigation introduces foams to European students ages 10-18. School children operate identical experiments on the ground as were undertaken on the International Space Station (ISS) in order to witness how foams differ under the influence of gravity compared to Station's weightless environment. This project intends to stimulate the students' curiosity and motivate them towards science, technology, engineering, and mathematics (STEM) subjects as well as to bring awareness to the younger generation of the importance of the ISS as a testing bed for future exploration activities in space.

RESULTS

As an education activity the experiment was a success with all activities, including the live link, being accomplished. ESA-EPO-Foam-S distributes large numbers of kits to schools in order for students to undertake the same activity in the classroom as undertaken by the astronaut in orbit, and a multi-site live-link event to the ISS in order to present the conclusions of the experiment on the Station to the participating school children and the general public. Recordings were also made available online in order for children/students performing their investigations at a later time to that performed on-board ISS. The investigation observations are supported using footage and observations of terrestrial events.

This investigation is complete; however no publications are expected.

Demonstrating the Effect of Restoring the Form of Billets Made of Cellular Polymer Materials (MATI-75)

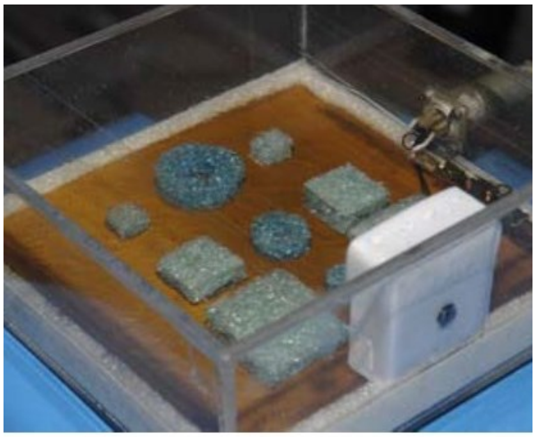
Research Area: Classroom Versions of ISS Investigations

Expedition(s): 16-18 and 33/34

Principal Investigator(s):
- Pyotr G. Babayevskiy, PhD, Tsiolkovsky Russian State University of Technology, Moscow, Russia

Research Objectives

Demonstrating the Effect of Restoring the Form of Billets Made of Cellular Polymer Materials (MATI-75) demonstrates the ability of polyurethane foam to restore and lock their shapes, sizes, and the pore structure during heating and cooling in microgravity.



Before shape restoration (top), after shape restoration (bottom). Roscosmos image.

Earth Benefits

Graduate students were involved in the creation of the procedures for the MATI-75 investigation.

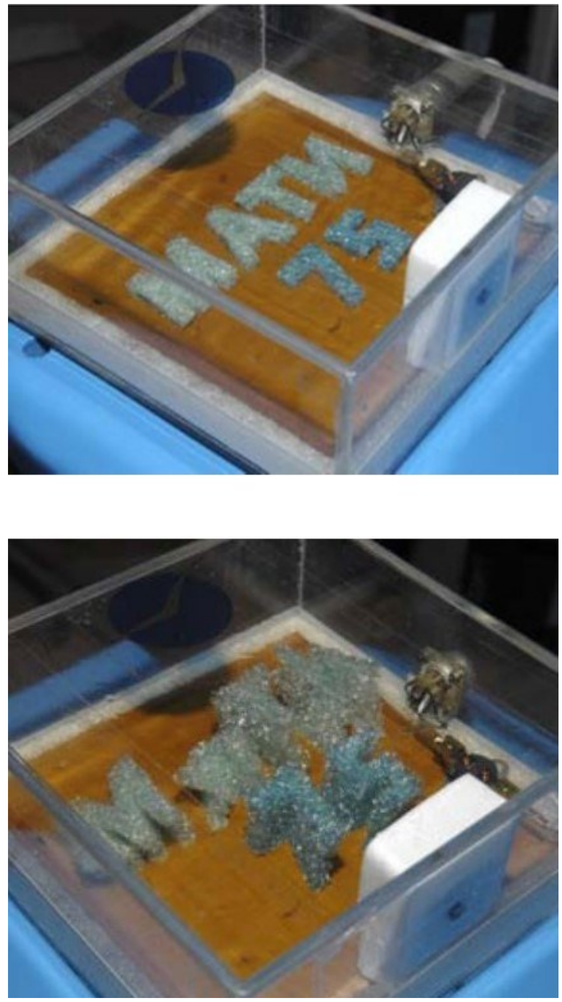
Space Benefits

MATI-75 focuses on 2 areas: character and kinetics of restoring the sizes and shapes of foam samples in microgravity as well as the results of the subsequent studies of their structure and properties on the ground in comparison with the results of a similar ground investigations. The data gained during the investigation can be used during the development of intelligent composite materials that have shape memory for transforming large-scale space structures.

Results

MATI-75 demonstrated the memory of the shape and sizes of a cellular polymer material made of polyurethane foam with a specified type of open porous structure and porosity value in microgravity conditions. An analysis of photographs showed that shape restoration occurred practically the same aboard the International Space Station (ISS) and in ground conditions.

A distortion of the shape of samples was observed both aboard the ISS and in ground conditions due in large measure to a twist appearing in samples with a small cross-section (cylinders with a diameter of 10 mm). The twist of the main axis of samples was $45 \pm 5°$. The twist of the shape was explained, most likely, by the uneven heating of the samples, caused by the fact that the samples were heated using heating elements, located on the bottom of the case. The convective air thermal currents that occurred were unevenly distributed around the case volume and heat was unevenly transferred to the samples. In connection with this, the development of a method for evenly heating the foam in the case of their practical use to create transforming structures will be necessary. The degree of restoration of the sizes of the flight samples was slightly less in comparison with the ground samples, which may be explained by the lack of or minimal intensity of the convective currents during heating of the samples in microgravity conditions. The constituent porosities (opened and closed) of the samples vary in considerably large ranges and depend on both the height and the depth of the layer being used for the studies.



Before shape restoration (top), after shape restoration (bottom). Roscosmos image

PUBLICATION(S)

Devicheva OV. The influence of nature and the quantity of carbon filler on the properties of polyurethane foam with shape memory. *Scientific Works of the International Youth Science Conference*; 2010.

Devicheva OV, Kozlov NA. The influence of the concentration of catalyzer on the manifestation of shape memory in polyurethane foam. *Materials of the All-Russian Scientific-Technical Conference: New Materials and Technologies MTM-2010*, Moscow, Russia; November 16-18, 2010.

Baryshnikov AM, Agapov IG. The influence of filler orientation in carbon-fiber with a polyurethane matrix on shape memory. *Materials of the All-Russian Scientific-Technical Conference: New Materials and Technologies MTM-2010*, Moscow, Russia; November 16-18, 2010.

This investigation is complete and all results are published.

OIL EMULSIONS EXPERIMENT (OEE)

Research Area: Classroom version of ISS Investigations
Expedition(s): 13
Principal Investigator:
- Hartmut Ripken, PhD, German Aerospace Center (DLR), Cologne, Germany

RESEARCH OBJECTIVES

Oil Emulsion is an experiment that is used to teach students basic principles of fluid physics. Identical experiments are performed on the International Space Station (ISS) and in the classroom to compare mixing oil and water in microgravity to mixing them on Earth.

The container with the oil and water mixture that is used in the Oil Emulsion investigation. DLR image.

RESULTS

Students (11-14 years old) carried out this experiment on Earth, and Thomas Reiter did the same in orbit during his long-duration Astrolab mission aboard the ISS. The space section of Oil Emulsion was filmed and downlinked. This experiment aimed to highlight how an oil and water emulsion behaves differently in weightlessness and under gravity conditions. A sealed container holding 2 non-combining fluids, clear oil and ink colored water, was shaken until the 2 fluids were slightly mixed.

The fluids' behavior in space was filmed within defined time slots during a 2-week period. The data was downlinked and the results were shown in a special children's program on German public television. The different kinds of segregation that occurred during the experiment, in space, and on Earth, could be observed and then explained by the teacher. This experiment can form the basis of further physics lessons (concerning weightlessness, density, and other fluid parameters) and maybe even lessons in other scientific areas. The Oil Emulsion experiment was introduced by DLR and is a co-operation between DLR and the European Space Agency.

This investigation is complete; however no publications are expected.

Seeds in Space (Seeds)

Research Area: Classroom version of ISS Investigations
Expedition(s): 9
Principal Investigator:
- Jack van Loon, Free University Amsterdam, Netherlands

Start of the Seeds in Space experiment in April 2004. Via an International Space Station inflight call, Dutch ESA astronaut André Kuipers (top right on screen) joins a class of Dutch children and Dutch Minister for Education, Culture, and Science, Maria van der Hoeven (left). Over 70,000 schoolchildren simultaneously started the experiment. ESA image.

Research Objectives

Seeds in Space demonstrates the influence of gravity on the germination and growth of plants to young people by engaging them in the comparison of an on-ground experiment. This allows students to experience that science is fun and that the weightless environment of space opens new possibilities.

Results

Within the Netherlands, some 80,000 students participated, representing 15% of the population in the age group of 10-14 years old. In addition, another 80,000 German pupils, a few local schools in the Moscow-Koroljov area and some in the Dutch Antilles also participated.

Considering these numbers, it can be concluded that Seeds in Space was a very successful educational project and might be considered for future spaceflight missions. The Dutch schoolchildren simultaneously started the Seeds in Space experiment on April 22, 2004 by planting their seeds in a rocket-shaped kit. After 4 days, they compared the growth of their seeds with those of Dutch ESA astronaut André Kuipers' aboard the International Space Station. Kuipers opened his "growing rocket" during a live video downlink from the International Space Station. The plants in the dark chamber had grown in all directions. In space, the seedlings in the light chamber had grown larger and were greener, and they had all grown towards the same direction—towards the light. The children who participated made conclusions about the experiment.

A young student prepares her Seeds folding rocket kit. ESA image.

The conclusion of Seeds: light or gravity help plants to know in which direction to grow. In the absence of both, the plants get confused. The result of the Seeds experiment showed school children how scientific research is undertaken, and contributes to space travel in the future. If astronauts are to go on longer space missions in the future, say to the moon, or even to Mars, they will know the best way to grow their food.

Publication(s)

Tepfer D, Zalar A, Leach S. Survival of plant seeds, their UV screens, and nptII DNA for 18 months outside the International Space Station. *Astrobiology*. 2012;12(5):517-528. doi: 10.1089/ast.2011.0744.

Colla G, Battistelli A, Proietti S, et al. Rocket seedling production on the International Space Station: Growth and nutritional properties. *Microgravity Science and Technology*. 2007;XIX(5/6):118-121. doi: 10.1007/BF02919465.

Weterings KA, Wamsteker JA, van Loon JJ. Seeds-in-space education experiment during the Dutch soyuz mission DELTA. *Microgravity Science and Technology*. September 2007;19(5-6):244-248. doi: 10.1007/BF02919491.

Kimoto Y, Yamagata I, Ishizawa J, Miyazaki E, Baba N, Kato M. Japanese space materials exposure experiment utilizing International Space Station. *57th International Astronautical Congress*, Valencia, Spain; 2006.

van Loon JJ, Wamsteker JA, Weterings KA. Seeds-in-Space education experiment during the Dutch Soyuz mission, DELTA. *Journal of Gravitational Physiology*. 2005;12(1):213-2124.

This investigation is complete and all results are published.

Taste in Space

Research Area: Classroom version of ISS Investigations
Expeditions: 23 and 24
Principle Investigator(s):
- Shamim Hartevelt, European Space Agency HSO Promotion Office, Noordwijk, Netherlands

Research Objectives

Taste in Space attempts to show if the sense of taste is affected in microgravity conditions. Taste is part of the curriculum of school children around Europe. By recording a tasting session aboard the International Space Station (ISS), ESA's Human Spaceflight and Operations Promotion Office aims to develop an online lesson that educators could use in their classroom. This activity targets pupils aged 10 to 12 years old.

Results

ISS Flight Engineer and NASA astronaut Shannon Walker supported the Taste in Space education activity, which took place in the Russian Service Module on November 2, 2010, with the support of NASA astronaut Doug Wheelock. The activity demonstrated to primary school students the differences in the way in which the sense of taste is affected under weightless conditions and on Earth by comparing the results of a blind tasting of 6 different food items on the ground and in space. Video files of the demonstration accounting for almost an hour of material were downlinked to ground. The material was used to produce ESA educational Web-based material for upper primary school teachers and their students aged 10-12 years old.

The lesson covered topics such as:

- Different environmental conditions on the ISS (concept of weightlessness) compared to Earth.
- Eating and drinking on the ISS is done differently, taking into account weightlessness.
- Food and drink on the ISS need to be prepared differently to conserve/preserve and save on weight.
- Is our sense of taste affected by any other of our senses, such as smell?
- Has microgravity conditions had any effect on the food's flavors as compared to when tasted on Earth?
- Eating is an important part of astronauts living aboard the ISS, therefore, food taste is important (not just for nutrition but psychologically).

A range of food and drinking products were selected in order to have products with similar consistencies. In addition, only standard available products were chosen in order to avoid specific upload for this activity. All items are part of the crew's standard menu except the coffee, which is a freely available drink stored separately.

This investigation is complete; however no publications are expected.

EUROPEAN SPACE AGENCY – EDUCATION PAYLOAD OPERATIONS – FUJI 3D (ESA-EPO-FUJI 3D)

Research Area: Technology Demonstration, Education/Outreach
Expeditions: 26, 27, 30 and 31
Principal Investigator(s):
- Massimo Sabbatini, European Space Research and Technology Research Centre, Noordwijk

RESEARCH OBJECTIVES

The European Space Agency – Educational Payload Operations – Fuji 3D (ESA-EPO-Fuji 3D) investigations makes 3D imagery and movies aboard the International Space Station (ISS) and the visiting vehicles during the ESA long-duration missions. Images and movies taken are related to ESA aboard payloads or views of the ISS for educational purposes and illustration of 3D imaging technology.

The Fujifilm Finepix Real 3D W1 camera. ESA image.

RESULTS

Footage from the Fuji 3D camera proved valuable for use in public outreach activities, and have been the first 3D images that ESA has received from EVA activities, mainly from cosmonauts conducting spacewalks. The small size of the camera also provided good flexibility of use. These photos were integrated into various 3D productions on ESA's YouTube channel. This included (http://www.youtube.com/watch?v=bOSHE4fXbCA) a 3D virtual spacewalk outside the International Space Station, which mixed the 3D photos with video footage from ESA's ISS virtual reality simulator that had received over 15,000 hits. It also included Space walks in 3D and other recent imagery from the ISS, which mixed the 3D photos with 3D video footage and had over 18,000 hits (http://www.youtube.com/watch?v=_gfEF8xkjrQ&list=PL41C087F0054D0454&index=4).

This investigation is complete; however no publications are expected.

Creating, Preparing, and Launching Small Spacecraft during Extravehicular Activity (RadioSkaf)

Research Area: Cultural Activities
Expedition(s): 12, 25-28-ongoing
Investigator(s):
- Alexander P. Alexandrov, PhD, S.P. Korolev Rocket and Space Corporation Energia, Korolev, Russia

Research Objectives

Creating, Preparing, and Launching Small Spacecraft during Extravehicular Activity (RadioSkaf) uses a decommissioned Orlan spacesuit equipped with a ham radio transmitter and a compact disk containing messages and images from students around the world. After being released during extravehicular activities, the suit will transmit a ham radio signal and then re-enter the Earth's atmosphere and burn up. Students and hobbyists from around the world can tune in to the signal to identify the transmitted words and image. This investigation will not only inspire the next generation of explorers but can help bridge the cultural gap of people around the globe.

RadioSkaf created using a decommissioned Russian Orlan spacesuit that is outfitted with transmission hardware was released during an extravehicular activity. Roscosmos image.

Earth Benefits

The results obtained during the experiment sessions proved the capacity for student-created space objects with various target applications using recycled components and not requiring large material expenditure. During the experiment, sessions were conducted to receive information from the satellite at ham radio stations on the ground, thus confirming the capability to receive data from the International Space Station (ISS) by all ham radio communication stations on the ground located in the area of radio coverage of the microsatellite.

Space Benefits

During the experiment, a microsatellite was successfully launched from aboard the ISS during extravehicular activity; microsatellite equipment was also tested experimentally in autonomous flight. Viewing and listening to the data received made it possible to confirm the stability of satellite signal reception on Earth from the ISS.

ISS012E16899 – RadioSkaf/Suitsat-1 in orbit after release from the International Space Station during Expedition 12.

Results

During the RadioSkaf experiment, data was obtained for the development of future projects to launch similar satellites as a part of youth education programs. A procedure was developed for assembling and launching satellites such as RadioSkaf from the ISS during extravehicular activity. Verification of technical solutions on receiving radio signals from a chaotically tumbling object, the operating lives of spacesuit batteries, temperature changes in the spacesuit without the operation of a temperature control system, and other parameters, were completed.

The Kedr amateur microsatellite was a new stage of the RadioSkaf experiment, which began in 2006. This experiment was carried out within the framework of the UNESCO student program on space education for the youth around the world. Audio satellite recognition signals and photographs of the Earth were received by ham radio stations on the ground in various countries.

Publication(s)

Lamzin VA, Odelevskiy VK, Firsiuk SO, Khokhulin VS. Space exploration and education and modern satellite technologies. IV International Conference Aviation and Space Exploration. 2005.

This investigation is ongoing; however, additional results are pending publication.

Space Seeds for Asian Future (SSAF)

Research Area: Cultural Activities
Expedition(s): 27 and 28
Principal Investigator(s):
- Kibo-ABC Initiative

Research Objectives

The Space Seeds for Asian Future (SSAF) program is one of the activities under the “Kibo-ABC” Initiative of the Asia-Pacific Regional Space Agency Forum (APRSAF), intended to provide a better understanding of the utilization taking place in the Kibo laboratory. This program also aims to provide children and students in the Asia-Pacific region with opportunities to learn about space experiments and the space environment, including orbital microgravity.

Earth Benefits

Students from across Asia are inspired to seek careers in the field of aerospace and science by experimenting with actual seeds flown aboard the International Space Station (ISS).

Space Benefits

The future of space exploration is dependent on the generations of students yet to come. This program aims to spark interest in space activities and scientific research among young people in the Asia-Pacific region by allowing them to actually hold the seeds from space in their hands. The seeds themselves have little scientific importance; however, the impact of this experiment lays the foundation for scientific curiosity among today’s young people.

Results

Well over 1000 students from 4 Asian countries (Indonesia, Malaysia, Thailand, and Vietnam) participated in this program (Space Seeds for Asian Future 2010-2011), allowing them an opportunity to grow "space seeds" retuned from the Kibo laboratory. Various domestic programs were conducted by the local agencies including: Bandung Institute of Technology (ITB, Indonesia); National Institute of Aeronautics and Space (LAPAN, Indonesia); National Space Agency (ANGKASA, Malaysia); Malaysian Agricultural Research and Development Institute (MARDI, Malaysia); Ministry of Education (MOE, Malaysia); Department of Agriculture (DOA, Malaysia); National Science and Technology Development Agency (NSTDA, Thailand); and Tay Nguyen Institute of Biology and Space Technology Institute of the Vietnam Academy of Science and Technology (TNIoB/VAST and STI/VAST, Vietnam).

Indonesia received 2 kinds of space seeds, tomato and garden balsam. The tomato seeds were distributed to students during a science competition at Space Science Festival in 2011, and the garden balsam seeds were distributed to students during 2012 L’Oreal Girls Science Camp and 2012 Kalbe Junior Science Award.

Malaysia sent its original strain of chili (MC-11) seeds to space. ANGKASA established a local committee to conduct this program. The committee consists of MARDI, MOE, and DOA and ran both education and research programs. As an education program, the Malaysia Space Seed

Program Competition was open to all secondary students in Malaysia. Schools are only allowed to send in 1 team, which comprises a maximum of 20 students supervised by 4 teachers.

In Thailand, 17 schools received the chili seeds from the hands of the Minister of the Ministry of Science and Technology at the Siam City Hotel in Bangkok. The event was held by NSTDA and there were many dignitaries including JAXA representative in Thailand and newspersons attended. Both the Minister and the NSTDA director wore the astronaut jumpsuits specially designed for this event. About 100 people were in attendance, and the event generated interest from more than 20 news publications.

Students in Indonesia (left), Malaysia (center), and Thailand (right) that participated in SSAF. JAXA image.

STI/VAST participates in this program as a condition and sees it as good luck for such a young institute to pioneer the field of space technology in Vietnam. The seed program was launched in Vietnam in June 2010 organized by STI and TNIoB. Vietnam has sent 3 different kinds of flower seeds: garden balsam, snapdragon, tropical sage.

SSAF is a serial program which continues to evolve. Successor missions with growing number of participating institutions and increasing sophistication are under development.

PUBLICATION(S)

Takaoki M, Yano S, Mathers N, et al. Space seeds for Asian future. *Transactions of JSASS Aerospace Technology.* 2014;12(29):Tp_1-Tp_5.

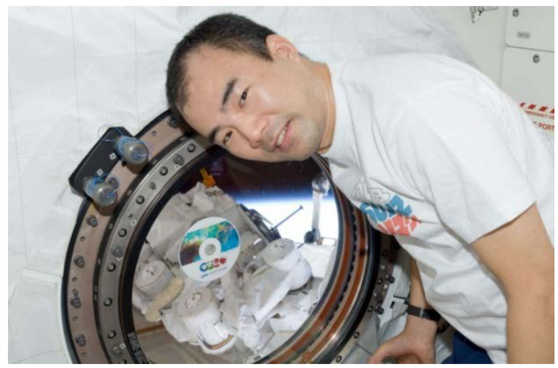
This investigation is complete and all results are published.

Ucyu Renshi: Connecting Global People with Words (Space Poem Chain)

Research Area: Cultural Activities
Expedition(s): 18 and 22
Principal Investigator(s):
- Japan Aerospace Exploration Agency, Tsukuba, Japan

Research Objectives

Ucyu Renshi: Connecting Global People with Words (Space Poem Chain) is a form of poetry developed from traditional Japanese linked verse (renga and renku) and practiced worldwide. Space Poem Chain is an attempt to create a collaborative place through linked verse by thinking together about the universe, Earth, and life itself, unfettered by barriers of nation, culture, generation, profession, and position or rank. Space Poem Chain was compiled from entries contributed over the Internet by the general public combined with contributions from poets and other cultural figures.



Space Poem Chain Volume 3, DVD and astronaut Soichi Noguchi in front of JEM window. JAXA image.

Earth Benefits

Space Poem Chain began to connect people, including crew members in space, and allowed them to feel more involved with space activities. Even those not interested in space sciences and technologies can participate and enjoy Space Poem Chain.

Space Benefits

As scientific progress continues to unravel the world's mysteries one by one, space continues to inspire a limitless curiosity in us. At the same time, it makes us aware of the infinite. Thinking about space, and collaborating with other participants, are essential to creating Space Poem Chain and building bonds amongst people.

Results

Four Space Poem Chains were composed when it began in 2006. Each Space Poem Chain consisted of approximately 24 short poems. Half were written by the public and the rest featured contributions by famous poets. The first poem of each Space Poem Chain was read by an astronaut in space.

After the Space Poem Chain completed, it was loaded onto the International Space Station (ISS). All participants can imagine their poems on the ISS, a shining star in space, when they see it from Earth. The Space Poem Chain symposiums introduced the project to the public. Space Poem Chain is also being applied to Japanese language classes in elementary schools. Students compile Space Poem Chains in class with famous poets while learning the importance of cooperation within the class.

This investigation is complete and all results are published.

KIDS IN MICRO-GRAVITY (KIDS IN MICRO-G), TWO INVESTIGATIONS

Research Area: Educational Competitions
Expedition(s): 23-28
Principal Investigator(s):
- Trinesha Dixon, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Kids In Micro-gravity provides students in grades 5-8 a hands-on opportunity to design an experiment or simple demonstration that could be performed both in the classroom and aboard the International Space Station (ISS).

NASA astronauts Catherine (Cady) Coleman and Ronald (Ron) Garan perform the Attracting Water Drops experiment from Chabad Hebrew Academy. NASA image.

EARTH BENEFITS

Kids In Micro-g is part of NASA's continuing effort to use space as a unique educational tool for students. Science is given a new twist by combining the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

SPACE BENEFITS

Kids in Micro-g is designed to encourage students to pursue studies and careers in science, technology, engineering, and mathematics (STEM).

Results

Kids in Micro-g List of Winners			
Investigations	**School**	**Grade**	**City, State**
Water Absorption/Capillary: This experiment determines the water absorption rates of 2 different materials.	Brownell Middle School	8	Grosse Pointe Farms, Michigan
Bottle Blowing in Space: This experiment determines if blowing across the tops of bottles filled with different amounts of water create the same tones in space as on Earth.	Vaughan Elementary	5	Powder Springs, Georgia
Speed: This experiment determines if the radius (of the circle of revolution) affects the speed at which an outer object travels around a central object, and whether microgravity changes the results in this experiment.	Hamlin School	7	San Francisco, California
Water and Hot Sauce: This experiment determines if adding water to hot sauce in a microgravity environment affects its surface tension.	Brownell Middle School	8	Grosse Pointe Farms, Michigan
Newton's Space Office: This experiment tests Newton's Laws of Motion using a bag of paper clips.	East Hartford-Glastonbury Elementary Magnet School	5	East Hartford, Connecticut
Motion of Projectiles: This experiment investigates the effects gravity has on the motion of slingshot projectiles. Speed, distance traveled, and path of projectile specifically are studied.	Carl Sandburg Middle School	6	Old Bridge, New Jersey
Low Gravity Artist: This experiment studies human adaptability, focusing on the role that gravity plays in a human's ability to draw a picture.	Henry E. Lackey High School	8	Orlando, Florida
Liquids in Microgravity: This experiment determines if liquid moves from its original position inside a bottle while in microgravity.	Virginia Academy	8	Ashburn, Virginia
Water Absorption: This experiment tests the water absorption capabilities	Vaughan Elementary	5	Powder Springs, Georgia

of various materials in a microgravity environment.			

Kids in Micro-g-2 List of Winners			
Investigations	**School**	**Grade**	**City, State**
Attracting Water Drops: This experiment determines if a free-floating water drop is attracted to a static charged rubber exercise tube.	Chabad Hebrew Academy	5	San Diego, California
Flight of Paper Rockets Launched by Air Cannon: This experiment determines the direction and distance traveled by a paper air rocket launched in microgravity.	Neighborhood After School Science Association	5-8	Ava, New York
Pondering the Pendulum: This experiment examines the effects of microgravity on a pendulum.	Key Peninsula Middle School	8	Lakebay, Washington
Pepper Oil Surprise: This experiment investigated the interaction of liquid pepper/oil and water in a plastic bag in microgravity.	Potlatch Elementary	6	Potlatch, Idaho
Buoyancy in Space: This experiment determines if the buoyancy of an object is affected in a microgravity environment.	Gate of Heaven School	8	Dallas, Pennsylvania
Dispersion of Liquid: This experiment compares the dispersal of liquid pepper in microgravity to its dispersal in Earth's gravity.	Will James Middle School in Billings	6-7	Billings, Montana

These investigations are complete and all results are published.

Synchronized Position Hold, Engage, Reorient, Experimental Satellites-Zero-Robotics (SPHERES-Zero-Robotics)

Research Area: Educational Competitions

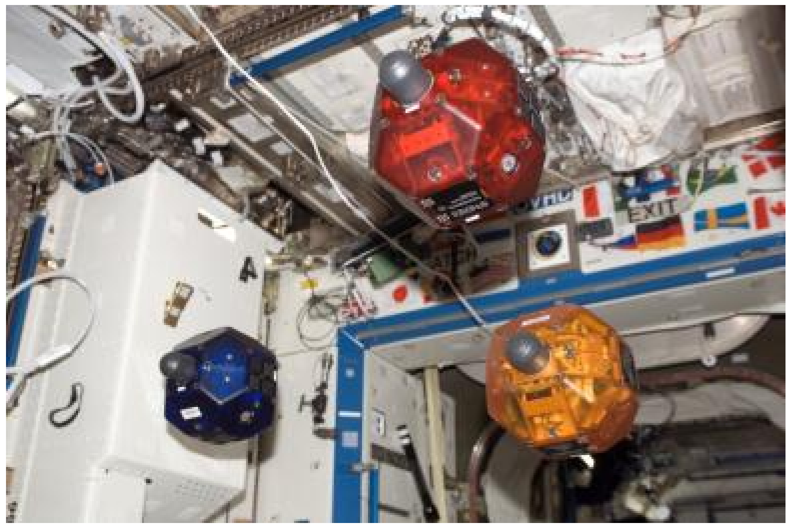
Expedition(s): 21-26, 29/30

Principal Investigator(s):

- Alvar Saenz-Otero, PhD, Massachusetts Institute of Technology, Cambridge, Massachusetts
- Jeffrey A. Hoffman, PhD, Massachusetts Institute of Technology, Cambridge, Massachusetts

Research Objectives

The Synchronized Position Hold, Engage, Reorient, Experimental Satellites - Zero - Robotics (SPHERES-Zero-Robotics) investigation establishes an opportunity for high school students to design research for the International Space Station (ISS). As part of a competition, students write algorithms for the SPHERES satellites to accomplish tasks relevant to future space missions. The algorithms are tested by the SPHERES team and the best designs are selected for the competition to operate the SPHERES satellites aboard the ISS.



Three satellites fly in formation as part of the Synchronized Position Hold, Engage, Reorient, Experimental Satellites investigation.

Earth Benefits

SPHERES-Zero-Robotics provides a unique and valuable opportunity to maintain students interested in science, technology, engineering, and mathematics (STEM) careers; even those who do not wish to pursue space careers see their lives affected by knowing their work can have an impact beyond the classroom. The ability of the students to participate in real engineering activities, beginning in high school, potentially encourages them to remain interested in those fields. SPHERES-Zero-Robotics also builds critical engineering skills for students such as problem solving, design thought process, operations training, teamwork, and presentation skills.

Space Benefits

The NASA “International Space Station Education Concept Development Report” calls out 3 levels of interaction for students involved with NASA activities: exposure, engage, and educate. SPHERES-Zero-Robotics provides a unique and valuable opportunity to go far beyond exposure. The students are truly engaged in space research; the need for them to create their own programs takes it to the point where they are being educated. In this way, SPHERES-Zero-Robotics inspires future scientists and engineers to work within the space program. Starting at the high school age group, students view working in space as “normal,” with the expectation that they become inspired to push the limits of space exploration, engineering, and development.

RESULTS

2009: SPHERES-Zero-Robotics Pilot Program

In the fall of 2009, the pilot competition for SPHERES-Zero-Robotics included 2 teams from Idaho. Bonners Ferry High School and Coeur d'Alene School district competed in simulation ground and ISS testing. Neither team was eliminated at any point. The first SPHERES-Zero-Robotics competition aboard the ISS took place on December 9, 2009 (Saenz- 2011).

2010: HelioPHERES

SPHERES-Zero-Robotics 2010 Challenge: HelioSPHERES saw 24 teams selected from a pool of 48 applicants to participate in the inaugural competition. The finals took place on December 16, 2010, with the LCA team ZeroBotX from Lexington Christian Academy, Massachusetts, winning the tournament. Team Delta Falmouth from Falmouth High School, Maine, received special mention for being the only team to demonstrate station docking during the finals. Team Ganymede from Friendswood High School in Texas also received special recognition for leading the competition until the finals and setting the path for exemplary strategies. The final standings were as follows:

- **1st**- LCA Team ZeroBotX, Lexington Christian Academy, Massachusetts
- **2nd**- Delta Falmouth, Falmouth High School, Maine
- **3rd**- SuperNOVA, Prince William County School System, Virginia
- **4th**- A-Team, Cyprus High School, Utah
- **5th**- Ganymede, Friendswood High School, Texas
- **5th**- Glenbrook North, Glenbrook North High School, Illinois
- **5th**- USC SCALE, Upper St. Clair School District, Pennsylvania
- **5th**- Stuy-Naught, Stuyvesant High School, New York
- **9th**- BACON, Charlottesville High School, Virginia
- **9th**- Team Vector, Naples High School, Florida

The impact of crowdsourcing, the process of outsourcing a task to an outside group of people, was also investigated in conjunction with the SPHERES-Zero-Robotics Challenge 2010. Crowdsourcing was used to develop the spacecraft software framework used by the students during the challenge (Nag 2012). Results showed that crowdsourcing increased the quality of solutions for the software framework (Nag 2012 thesis).

2011: AstroSPHERES

SPHERES-Zero-Robotics 2011 Challenge: AstroSPHERES finals took place on January 23, 2012. Over 100 teams began the competition. After the 3-D simulation competition they formed alliances of 3 teams each. The top 9 alliances reached the finals aboard the ISS (a total of 27 teams). A special award was announced for Team y0b0tics! from Montclair High School in New Jersey for spearheading the leading protocol and setting the pace in the tournament. The competition winners were:

- **1st-** Alliance Rocket, Riverhill High School, Maryland
- **1st-** Storming Robots, New Jersey
- **1st-** The Pink Team, Rockledge High School, Florida

2012: RetroSPHERES

SPHERES-Zero-Robotics 2012 Challenge: RetroSPHERES was held on January 11, 2013, involving over 200 High School students from around the world. This competition was the first SPHERES-Zero-Robotics tournament involving European students through participation hosted by the European Space Agency (ESA). The ISS finalist winners were:

United States Champions:

- **1st**- Mira Loma Matadors, Mira Loma High School, California
- **1st**- y0b0tics!, Montclair High School, New Jersey
- **1st**- Green Wrenches, Evergreen School District, Washington

European Champions:

- **1st**- Kathe in Space, Kaethe Kollwitz Oberschule, Germany
- **1st**- Sunday Programmers, Liceo SS E. Fermi, Italy
- **1st**- Herder-Berlin, Herder Gymnasium Berlin, Germany

Publication(s)

Liu J, Feenstra W, Saenz-Otero A, Magrane K. STEM education students touch space through free robotics programming competition. *6th International Conference on Computer Supported Education*, Barcelona, Spain; April 1-3, 2014: 5.

Nag S, Katz JG, Saenz-Otero A. Collaborative gaming and competition for CS-STEM education using SPHERES Zero Robotics. *Acta Astronautica*. February 2013;83:145-174. doi: 10.1016/j.actaastro.2012.09.006. [Also presented during 62nd IAC in Cape Town.]

Nag S, Heffan I, Saenz-Otero A, Lydon M. SPHERES Zero Robotics software development: Lessons on crowdsourcing and collaborative competition. *2012 IEEE Aerospace Conference,* Big Sky, MT*;* 2012:1-17.

Nag S, Hoffman JA, de Weck O. SPHERES Zero Robotics software development: Lessons on crowdsourcing and collaborative competition and STEM education using SPHERES Zero Robotics. *Massachusetts Institute of Technology*. 2012.

Saenz-Otero A, Katz J, Mwijuka AT. The Zero Robotics SPHERES Challenge 2010. *IEEE Aerospace and Electronic Systems Magazine*. 2011;26(7):4-17. doi: 10.1109/MAES.2011.5958758.

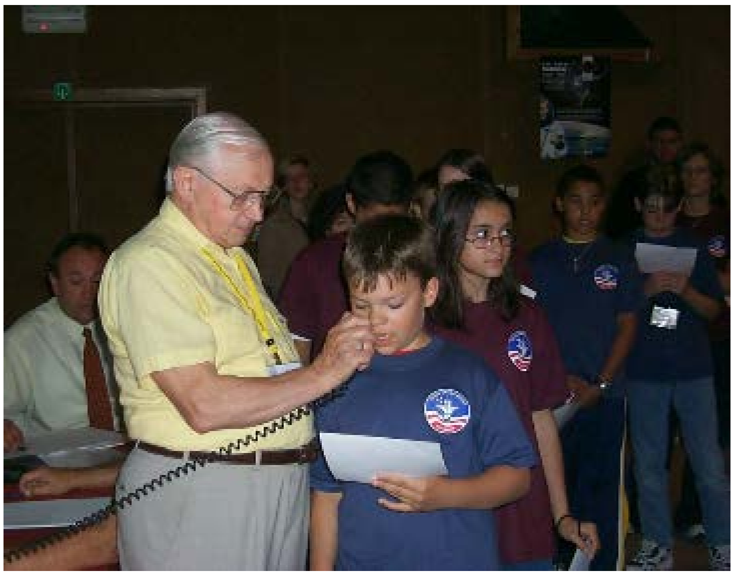
This investigation is ongoing and additional results are pending publication.

AMATEUR RADIO ON THE INTERNATIONAL SPACE STATION-EUROPEAN SPACE AGENCY (ARISS-ESA)

Research Area: Educational Demonstrations
Expedition(s): 5 -11 and 14
Principal Investigator:
- Gaston Bertels, ARISS-Europe, Brussels, Belgium

RESEARCH OBJECTIVES

Amateur Radio on the International Space Station-European Space Agency (ARISS-ESA) has the task of conducting amateur radio contacts for schools, which allows students to ask questions of astronauts aboard the International Space Station and receive their answer direct from space. Candidate schools perform a science, technology, engineering, and mathematics (STEM)-oriented educational project as part of their event activities.



Students attend Space Camp at the Euro Space Center in Belgium are gathered in an auditorium to speak with astronaut Ed Lu, aboard the International Space Station. ARISS image.

RESULTS

Since 2000, 859 successful educational radio contacts were performed by the ARISS organization, allowing thousands of students to put questions to astronauts aboard the International Space Station and receive their answer directly from space in real time. The educational STEM projects developed by schools, needed for gaining the privilege of a “space talk,” constitute an excellent tool for teachers and a powerful incentive for students to investigate space related topics. Detailed statistics are available at Zoho Reports: https://reports.zoho.com/ZDBPublicDBView.cc?DBID=4122180000000020415.

This investigation is complete; however no publications are expected.

DREAMTiME (DREAMTiME)

Research Area: Educational Demonstrations
Expedition(s): 3
Principal Investigator(s):
- Ben Mason, Dreamtime Holdings Inc, Moffett Field, California

Research Objectives

DREAMTiME supplies high definition television video cameras and obtains high-quality video footage of activities on the International Space Station (ISS) for commercial, historical, training, educational, and public-interest use.

Earth Benefits

Ownership of the imagery collected during flight is divided between NASA and DREAMTiME. As for the success of the mission, all HDTV hardware performed as expected, and the crew collected historical footage that is far beyond the initial imagery expectations. The footage includes imagery of Human Life Sciences, life on ISS, ISS structures, Earth views, and STS docking, and is irreplaceable in its enhancement to the NASA archives.

ISS003E5826 — Cosmonaut Vladimir N. Dezhurov, Expedition 3 flight engineer, works with camera equipment in the *Zvezda* service module.

Space Benefits

This new video recording technology can document future long-duration exploration missions. HDTV can provide improved imagery for spacecraft surveys while inflight.

Results

In developing the original public-private partnership, NASA had hoped that DREAMTiME would play a role in developing commercial products based on the historic activities on ISS. Lacking commercial direction from DREAMTiME, yet recognizing the historical significance of activities on the station, NASA took the initiative and developed scenarios and created storyboards for the flight crew to record ISS documentary footage of outstanding quality during the mission. The result of this effort returned over 500 minutes of HDTV footage, suitable for commercial purposes, and far exceeding the expected imagery return. The private company that originally sponsored DREAMTiME was short-lived, and no results were generated. The Bioastronautics Research Program has created the video Secrets of Science in Outer Space using some of the DREAMTiME footage.

This investigation is complete and all results are published.

E-LEARNING

Research Area: Educational Demonstrations
Expedition(s): 14
Principal Investigator:

- Sylvie Ijsselstein, European Space Agency, Education Office, Noordwijk

RESEARCH OBJECTIVES

E-Learning involved an interactive, real-time lecture involving ESA astronaut Thomas Reiter from the International Space Station (ISS) and universities across Europe. The main aim was to inspire the next generation of space explorers.

A student participates in an in-flight call to ESA astronaut Thomas Reiter. ESA image.

RESULTS

Professor Dr Gregor Morfill of the Max-Planck-Institute in Garching, Germany presented a lecture to European university students following the EuMAS Masters Program in Aeronautics and Space. The lecture was on plasma crystals and complex plasmas, with reference to the Plasma Crystal Research on the ISS (ie, the PK-3+ experiment of which professor Dr Morfill is one of the science team).

During the live link-up with the ISS, Thomas Reiter demonstrated the PK-3+ hardware, and the students submitted questions to Thomas Reiter in real time and received feedback.

Image taken at the Columbus Control Center, in Oberpfaffenhofen, Germany on October 17, 2006. DLR image.

This investigation is complete; however no publications are expected.

Educational Payload Operations (EPO)

Research Area: Educational Demonstrations
Expedition(s): 4-5, 7-9
Principal Investigator(s):
- Jonathan Neubauer, NASA's Johnson Space Center, Houston, Texas

Research Objectives

Education Payload Operations (EPO) includes curriculum-based educational activities that demonstrate basic principles of science, mathematics, technology, engineering, and geography. These activities are videotaped and then used in classroom lectures. EPO is designed to support the NASA mission to inspire the next generation of explorers.

Earth Benefits

EPO is part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items, such as toys and tools, are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

Space Benefits

EPO introduces the next generation of explorers to the environment of space.

Images of education demonstrations conducted by crewmembers on board the International Space Station. NASA images.

Results

EPO has been a successful education program on the International Space Station (ISS). By using simple objects and the microgravity environment, NASA is able to produce videos that demonstrate physical properties, such as force, motion, and energy that might be obscured by gravity on Earth. To date, over 500 videos, DVDs, and video clips have been produced and distributed to science teachers and schools throughout the United States. About 1 500 teachers each year are trained to use the materials in their classrooms. An additional 30.9 million students have had the opportunity to participate in live downlink events where their classmates pose questions of ISS crews in orbit.

This investigation is complete and all results are published.

EDUCATIONAL PAYLOAD OPERATIONS-CLOUD OBSERVATION-DEMONSTRATIONS (EPO-CLOUD OBSERVATION-DEMOS)

Research Area: Educational Demonstrations
Expedition(s): 23/24
Principal Investigator(s):
- Matthew Keil, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Education Payload Operations-Cloud Observation-Demonstrations (EPO-Cloud Observation-Demos) record video education demonstrations performed by crew members on the International Space Station (ISS) using hardware already aboard and provides students in grades 5-8 and educators with a better understanding of the Cloud Observations available from the ISS. EPO-Cloud Observation-Demos enhance existing NASA education resources and programs for educators and students in grades K-12. EPO-Cloud Observation-Demos support the NASA mission to inspire the next generation of explorers.

EARTH BENEFITS

EPO-Demos are part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

On January 4 a large presence of stratocumulus clouds was the central focus of camera lenses, which remained aimed at the clouds. NASA image.

SPACE BENEFITS

These investigations and related activities have strong ties to NASA's Vision for Space Exploration and are designed to encourage students to pursue studies and careers in science, technology, engineering, and mathematics (STEM).

This investigation is complete and all results are published.

EDUCATIONAL PAYLOAD OPERATIONS-DEMONSTRATIONS (EPO-DEMOS)

Research Area: Educational Demonstrations
Expedition(s): 7-ongoing
Principal Investigator(s):
- Trinesha Dixon, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Education Payload Operation - Demonstrations (EPO-Demos) records video education demonstrations performed on the International Space Station (ISS) by crew members using hardware already aboard the International Space Station (ISS). EPO-Demos enhance existing NASA education resources and programs for educators and students in grades K-12. EPO-Demos support the NASA mission to inspire the next generation of explorers.

Teaching From Space Office team members in NASA's Johnson Space Center TeleScience Center supporting an EPO-Demo conducted by astronaut Suni Williams. NASA image.

EARTH BENEFITS

EPO is part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items, such as toys and tools, are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

SPACE BENEFITS

EPO introduces the next generation of explorers to the environment of space.

RESULTS

EPO-Demos have been a successful education program on ISS. By using simple objects and the microgravity environment, NASA is able to produce physical properties, such as force, motion, and energy that might be obscured by gravity on Earth. Several specific videos demonstrating basic science principles have been created and are available via the NASA Education Project and Central Operations of Resources for Educators.

This investigation is ongoing, and results are pending.

Educational Payload Operations-Educator (EPO- Educator)

Research Area: Educational Demonstrations
Expedition(s): 15
Principal Investigator(s):
- Jonathan Neubauer, NASA's Johnson Space Center, Houston, Texas

Research Objectives

Education Payload Operations - Educator (EPO - Educator) uses video and still photography to capture data of experiment activities in orbit. Students also design and complete ground-based investigations developed by the NASA Education Office, focusing on grades K-12. The activities support the educator crew member in their mission in orbit. An educator crew member is a full-time astronaut who has experience teaching in K-12 classrooms.

Earth Benefits

Using a new approach in the classroom on spaceflight, science, and mathematics captures the imagination of students. Allowing students to participate in activities that directly involve NASA inspires them to pursue careers in science and engineering.

Space Benefits

The participation of the students in the design processes for the EPO-Educator activities is preparing the next generation of scientists and engineers.

Results

Through the EPO-Educator investigation, nearly 1 million students in grades K-12 have participated in the NASA Engineering Design Challenge Lunar Plant Growth Chamber. This engineering design challenge asks students to design, build and evaluate a plant growth chamber for future missions to the moon. Students learn about the engineering design process and how to conduct a scientific experiment. In conjunction with the engineering design challenge, approximately 10 million cinnamon basil seeds were flown in space. As part of a comprehensive suite of education activities, the seeds are being delivered to students and educators across the country. To get involved in this activity and to see video captured during EPO-Educator visit www.nasa.gov/education/plantchallenge.

Educator astronaut Barbara Morgan speaks with students during Space Center Houston's "Meet an Astronaut Day" on January 19, 2007. NASA image.

This investigation is complete and all results are published.

EDUCATIONAL PAYLOAD OPERATIONS-INTERNATIONAL TOYS IN SPACE (EPO-INTERNATIONAL TOYS IN SPACE)

Research Area: Educational Demonstrations
Expedition(s): 5
Principal Investigator(s):
- Jonathan Neubauer NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Education Payload Operations-International Toys in Space (EPO-International Toys in Space) includes curriculum-based educational activities that demonstrate basic principles physics by studying how common everyday items (toys and games) act in a microgravity environment. These activities are videotaped and then used in classroom lectures. EPO-International Toys in Space is designed to support the NASA mission to inspire the next generation of explorers.

Astronauts tested toys in space to help students learn about the laws of science. NASA image.

EARTH BENEFITS

EPO-International Toys in Space is part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items, such as toys, are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

SPACE BENEFITS

EPO-International Toys in Space introduces the next generation of explorers to the environment of space.

RESULTS

EPO-International Toys in Space is a successful education program on the International Space Station (ISS). By using simple objects and the microgravity environment, NASA is able to produce videos that demonstrate physical properties, such as force, motion, and energy, which might be obscured by gravity on Earth. To date, over 500 videos, DVDs, and video clips have been produced and distributed to science teachers and schools throughout the United States. About 1 500 teachers each year are trained to use the materials in their classrooms. An additional 30.9 million students have had the opportunity to participate in live downlink events where their classmates pose questions of ISS crews in orbit.

PUBLICATION(S)

International Toys in Space - Science on the Station. *National Aeronautics and Space Administration Educational Product*. 2004;ED-2004-06-001-JSC.

International Toys in Space - Science on the Station [DVD]. 2004.

This investigation is complete and all results are published.

Education Payload Operations - Kit C: Plant Growth Chambers (EPO-Kit C)

Research Area: Educational Demonstrations

Expedition(s): 15

Principal Investigator(s):
- Jonathan Neubauer, NASA's Johnson Space Center, Houston, Texas

Research Objectives

Education Payload Operations - Kit C Plant Growth Chambers (EPO-Kit C) is an in-orbit plant growth investigation using basil seeds. The still and video imagery acquired is used as part of a national engineering design challenge for students in grades K-12. Students grow basil seeds (control and flown seeds) to conduct their own science experiments on plant growth using growth chambers created by the students on the ground.

Earth Benefits

Using a new approach in the classroom on spaceflight, science, and mathematics captures the imagination of students. Allowing students to participate in activities that directly involve NASA inspires them to pursue careers in science and engineering.

Basil plants grown from seeds on Earth in a simple plant growth chamber (opened). NASA's Johnson Space Center image.

Space Benefits

Student participation in the design processes for the EPO-Kit C activities prepares the next generation of scientists and engineers.

Results

The EPO-Kit C, 20-day in-orbit plant growth investigation was successful. The cinnamon basil seeds germinated in the microgravity environment and had some growth during the short investigation. Toward the end of the experiment, the plants appeared to have received more water than needed, causing them to slowly deteriorate. When the 20 days were up, the growth chambers were collapsed and prepared for their trip home on STS-120.

Through the EPO-Kit C investigation, nearly 1 million students in grades K-12 participated in the NASA Engineering Design Challenge Lunar Plant Growth Chamber. This engineering design challenge asked students to design, build, and evaluate a plant growth chamber for future missions to the moon. Students learned about the engineering design process and how to conduct a scientific experiment. To get involved in this activity and to see video captured during EPO-Kit C and EPO-Educator visit www.nasa.gov/education/plantchallenge.

This investigation is complete and all results are published.

Education Payload Operations - Kit D (EPO-Kit D)

Research Area: Educational Demonstrations
Expedition(s): 19/20
Principal Investigator(s):
- Matthew Keil, NASA's Johnson Space Center, Houston, Texas

Education Payload Operations - Kit D items including Earth, moon, and Mars scale models, gyroscopes, string, and a ruler. Feng (Michael) Li image.

Research Objectives

Education Payload Operation - Kit D (EPO-Kit D) includes educational items that are used to support the live International Space Station (ISS) education downlinks and Education Payload Operation-Demonstrations (EPO-Demos) aboard the ISS. The main objective of EPO-Kit D supports the NASA goal of attracting students to study and seek careers in science, technology, engineering, and mathematics.

Earth Benefits

EPO-Kit D is part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items, such as toys and tools, are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

Space Benefits

EPO-Kit D introduces the next generation of space explorers to the environment of space. This investigation encourages students to pursue studies and careers in science, technology, engineering, and mathematics.

Results

EPO-Kit D engaged students by allowing them to understand how everyday items are used to support the ISS by viewing downlinks directly from the station. This investigation aimed to pique student interest in STEM areas.

This investigation is complete and all results are published.

EDUCATION PAYLOAD OPERATIONS–LEWIS AND CLARK-DEMONSTRATIONS (EPO-LEWIS AND CLARK DEMO)

Research Area: Educational Demonstrations
Expedition(s): 7
Principal Investigator(s):
- Matthew Keil, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Education Payload Operations-Lewis and Clark-Demonstrations (EPO-Lewis and Clark-Demos) records video education demonstrations performed on the International Space Station (ISS) by crew members using hardware already aboard the International Space Station (ISS). EPO-Lewis and Clark-Demos enhance existing NASA education resources and programs for educators and students in grades K-12. EPO-Lewis and Clark-Demos support the NASA mission to inspire the next generation of explorers.

This close up photo shows water droplets in microgravity. Science Kids image.

EARTH BENEFITS

EPO-Lewis and Clark-Demos is part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

SPACE BENEFITS

These investigations and related activities have strong ties to NASA's Vision for Space Exploration and are designed to encourage students to pursue studies and careers in science, technology, engineering, and mathematics (STEM).

RESULTS

EPO-Demos have been a successful education program on ISS. By using simple objects and the microgravity environment, NASA is able to produce physical properties, such as force, motion, and energy that might be obscured by gravity on Earth. Several specific videos demonstrating basic science principles have been created and are available via the NASA Education Project and Central Operations of Resources for Educators (CORE).

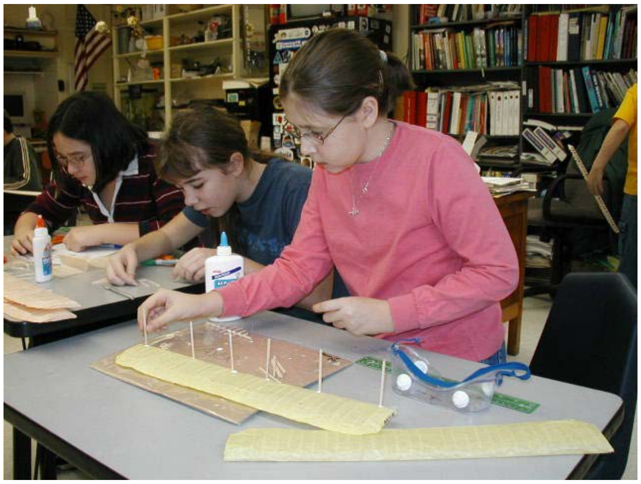
This investigation is complete and all results are published.

EDUCATION PAYLOAD OPERATIONS–MUSEUM AEROSPACE EDUCATION ALLIANCE (EPO-MAEA)

Research Area: Educational Demonstrations
Expedition(s): 7-9
Principal Investigator(s):
- Jonathan Neubauer NASA's Johnson Space Center, Houston, Texas
- Matthew Keil, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Education Payload Operations-Museum Aerospace Education Alliance (EPO-MAEA) includes 5 participating museums that develop educational activities for diverse applications in exhibits and other informal educational activities. EPO-MAEA is designed to support the NASA mission to inspire the next generation of explorers.


Students working on their balsa wood scale models of the Wright Flyer. NASA image.

EARTH BENEFITS

EPO-MAEA is part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items, such as toys and tools, are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

SPACE BENEFITS

EPO-MAEA introduces the next generation of explorers to the environment of space.

RESULTS

EPO-MAEA is a successful education program on ISS. By using simple objects and the microgravity environment, NASA is able to produce videos that demonstrate physical properties, such as force, motion, and energy, which might be obscured by gravity on Earth. To date, over 500 videos, DVDs, and video clips have been produced and distributed to science teachers and schools throughout the United States. About 1 500 teachers each year are trained to use the materials in their classrooms. An additional 30.9 million students have had the opportunity to participate in live downlink events where their classmates pose questions to ISS crews in orbit.

This investigation is complete and all results are published.

EDUCATION PAYLOAD OPERATIONS–ROBOTICS (EPO-ROBO)

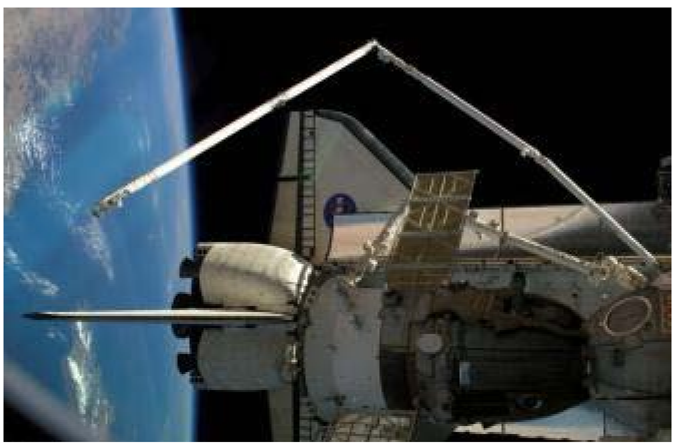
Research Area: Educational Demonstrations
Expedition(s): 23/24
Principal Investigator(s):
- Matthew Keil, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Education Payload Operations - Robotics (EPO-Robo) creates an in-orbit video demonstration explaining robotic arm operations on the Space Shuttle and the International Space Station (ISS).

EARTH BENEFITS

EPO-Robo is part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.



ISS011E11520 - SSA line of thunderstorms form the backdrop for this view of the extended Space Shuttle Discovery's remote manipulator system robotic arm while docked to the International Space Station during the STS-114 mission.

SPACE BENEFITS

EPO-Robo introduces the next generation of explorers to the environment of space.

RESULTS

EPO-Robo allowed students to have a once in a lifetime opportunity to learn about the robotic arm operations associated with the ISS.

This investigation is complete and all results are published.

EDUCATION PAYLOAD OPERATIONS–SESAME STREET DEMONSTRATION (EPO-SESAME STREET-DEMOS)

Research Area: Educational Demonstrations
Expedition(s): 21-28
Principal Investigator(s):
- Matthew Keil, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Education Payload Operations-Sesame Street-Demonstrations (EPO-Sesame Street-Demos) records video education segments performed on the International Space Station (ISS) by crew members for episodes to air on Sesame Street. EPO-Sesame Street-Demos aims to promote science, technology, engineering, and mathematics (STEM) interest.

Soichi Noguchi floats the letter F on the International Space Station.

EARTH BENEFITS

EPO-Sesame Street-Demos is part of NASA's continuing effort to use space as a unique educational tool for K-12 students. Everyday items are given a new twist by combining them with the allure of spaceflight and the unusual weightless environment to produce educational materials that inspire interest in science and technology and encourage curiosity and creativity.

SPACE BENEFITS

These investigations and related activities have strong ties to NASA's Vision for Space Exploration and are designed to encourage students to pursue studies and careers in STEM.

RESULTS

Space station astronaut Soichi Noguchi completed 4 educational videos for "Sesame Street" during his stay on the International Space Station from December 2009 to June 2010. The 4 videos aired on Sesame Street throughout the fall 2010 season. On the episode "F is for Float" (show number 4214) Noguchi held up the letter "F" to represent the word "float" while he floated around the space station to demonstrate the word.

"Word on the Street" (show number 4222) featured Noguchi explaining to the character "Murray" what the word "float" means, using similar demonstrations with a lemon, socks, and a ball.

On the episode "A is for Astronaut" (show number 4225) Noguchi held up the letter "A" to represent the word “astronaut.” Noguchi sounded out the letter and the word for children.

On the “Countdown to Space” episode (show number 4234) Noguchi counted down from 10 to 1. Noguchi counted down and said “blast-off!” while floating from the floor to ceiling.

This investigation is complete and all results are published.

European Space Agency – Education Payload Operations – Greenhouse (ESA-EPO-Greenhouse)

Research Area: Education

Expeditions: 25 and 26

Principal Investigator(s):
- Shamim Hartevelt, HSO Promotion Office, ESA/ESTEC, Noordwijk, Netherlands

Research Objectives

The European Space Agency – Education Payload Operations – Greenhouse (ESA-EPO-Greenhouse) introduces the idea that space explorers might need to be able to produce fresh food and become partially self-reliant to survive long-duration space missions. This idea targeted European children ages 12-14 years old and links this concept to the biology and science curriculum. By demonstrating the idea that greenhouses can be specially developed to support plant growth for food and following the life cycle of a flowering plant on the International Space Station (ISS), school children are able to follow with their own similar control experiment on the ground to see how plants can be grown and used in space.

Students involved in constructing greenhouses and planting seeds. ESA images.

Results

This investigation began February 17, 2011; following 3 weeks of steady growth in space under the watchful eye of ISS crew member Paolo Nespoli, the *Arabidopsis* plants (small flowering plants related to cabbage and mustard) found a new and unexpected travelling companion: fungus. The ISS ecosystem is a particularly delicate one. Whereas some fungi does not cause much harm to earthly plants or humans, the balance of the closed systems in the station could be compromised.

It is known that spaceflight reduces the crew's immune systems, their ability to fight off infections; once safety experts had confirmed that a fungus was growing in the greenhouse, by mid-March 2011, the unavoidable decision was made to carefully remove the greenhouse from the ISS, thus avoiding any probability of causing any harm to the astronauts.

Paolo Nespoli was the first one to remark that simple procedures on Earth are extremely complex and possibly dangerous in weightlessness. "Part of the experiment was indeed a success: we were able to grow the plants and observe them." Even though the in-orbit experiment experienced this problem, the experiment did produce some very stimulating activities for the participating students, especially as they could continue their individual growth experiments along with the participants of the Mars 500 isolation study that were also taking part in the project.

This investigation is complete; however no publications are expected.

European Space Agency – Education Payload Operations – Mission-X (ESA-EPO Mission-X)

Research Area: Educational Demonstrations
Expeditions: 29-ongoing
Principal Investigator(s):
- Elisabeth Celton, ESTEC HSO-K, Noordwijk, Netherlands

Paolo Nespoli on the International Space Station kicked off the 'Mission X - Training like an Astronaut' program in January 2011. ESA/NASA image.

Research Objectives

Education Payload Operations Mission-X (ESA-EPO-Mission-X) is a worldwide educational initiative to encourage healthy and active lifestyles among children. Teams of primary school students (8-12 years old) learn principles of healthy eating and exercise, competing for points by finishing training modules, and getting excited about the world's future in space and the educational possibilities for their own future.

Results

As an education objective, this activity was a success. It has a growing number of students taking part in successful live link activities with astronauts on the International Space Station, and a global audience of children participated. To date, 3 ESA astronauts have taken part in the Mission X program (Paolo Nespoli in 2011, André in 2012 and Luca Parmitano in 2013).

At the time of compilation the most recent ESA mission to include Mission X was the mission of ESA astronaut Luca Parmitano. ESA and NASA anticipated as many as 15,000 students would join in the competition—3 times more than the first time Mission X was undertaken.

This investigation is ongoing and additional results are pending publication.

Scientific and Educational Demonstration of Physical Laws and Phenomena in Microgravity (Fizika-Obrazovaniye), Three Investigations

Research Area: Educational Demonstrations

Expedition(s): 18-22 and 31/32

Principle Investigator(s):

- Nikolay L. Shoshunov, PhD, S.P. Korolev Rocket and Space Corporation Energia, Korolev, Russia

Research Objectives

Scientific and Educational Demonstration of Physical Laws and Phenomena in Microgravity (Fizika-Obrazovaniye) studies and demonstrates various physical processes in microgravity for educational purposes in physics. This program is geared toward high school students in elective courses involving the in-depth study of physics, mathematics, and information technology. Fizika-Obrazovaniye is composed of 3 distinct studies.

Fizika-LT

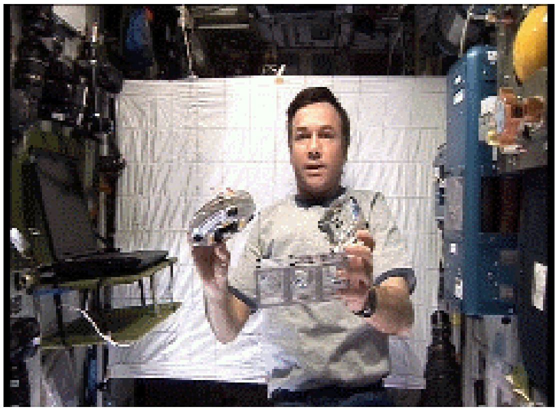
Demonstrates the effects of the physical laws of motion with a spinning geometrically symmetrical body (much like a flying saucer), in microgravity.

Fizika-Faza

Studies the complete gas-liquid phase separation of a fine dispersion system in microgravity with the effects of diffusion and the surface tension of liquid.

Fizika-Otolit

Demonstrates the simulation processes for the transfer of motion and the effects on the human vestibular system in microgravity.



Video screen shot of a Fizika-Obrazovaniye session from aboard the International Space Station. Roscosmos image.

Students at Mission Control Center-Moscow. Roscosmos image.

Earth Benefits

The results of the comprehensive Fizika-Obrazovaniye investigations are used in education as graphic demonstration tools, and to develop educational scientific teaching materials for high schools.

Space Benefits

The results of the experiment can be used to verify the appropriateness of the mechanical modeling of the human vestibular system in microgravity and, if possible, to model several of the negative effects microgravity has on this system.

RESULTS

Video of sessions were recorded and downlinked with commentary by a crew member during space-to-ground communications. Video footage was used for initial analysis and demonstrations of the laws of motion to students. A radio conference between students and the International Space Station commander was also held at the Mission Control Center-Moscow (MCC-M).

Forward motion of the flying saucer according to Bernoulli's law, (top). Flying saucer while flying, unstable state (middle). Flying saucer while spinning, stable state (bottom). Roscosmos image.

When the laboratory processing of video footage and a comprehensive analysis of Fizika-Obrazovaniye space experiment results are complete, scientific educational presentation materials are planned to be released on compact disks on the following topics: "demonstration of the effects of reactive and gyroscopic forces in microgravity and the impact of internal and external forces on the pattern of motion of spinning bodies" and "demonstration of the phenomenon of the clustering of gas bubbles during gas-liquid phase separation in a fine-dispersion system in microgravity occurring with the effects of diffusion processes and liquid surface tension forces." Fizika-Obrazovaniye experiment materials were included in the film "Urok iz kosmosa" (Lesson from Space) created by the Roscosmos film studio.

FIZIKA-LT

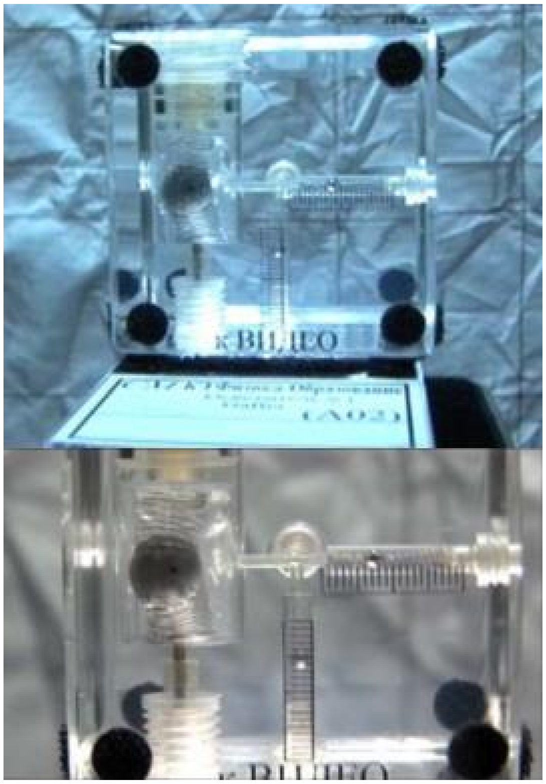
During the Fizika-LT study, the rates of forward motion and rotation of a flying saucer and the motion of a spinning ellipsoid according to the Bernoulli's law were demonstrated and compared with theoretical calculations. In the experiment, behavior that is of interest for demonstrational purposes was noted: stabilized rotation of a body with simultaneous displacement (sideways "drift") of its axis of rotation. The unstable and stable behavior of a body in weightlessness, the initial stage of precession, and motion with eccentricity of the spatial position of the axis of rotation was demonstrated.

FIZIKA-FAZA

During the Fizika-Faza study, it was demonstrated that in microgravity the process of gas and liquid phase separation has significant differences:

- Complete phase separation takes noticeably longer, and the clustering of gas bubbles has different patterns than under conditions of the Earth's gravitation.

- The pattern of the gas bubble clustering process in the very earliest stage is of an accelerated nature.



Otolit device on the mass meter platform, initial state (top). Otolit device under a g-load as of approximately 0.3 g (X axis) at the extreme positions of the mass meter oscillation platform. Test mass displacement amplitude: 2 mm (bottom).

FIZIKA-OTOLIT

During the Fizika-Otolit study, the modeling of the transfer of motion processes of 2.5-g and 0.2-g test masses that were exposed to small (approximately 0.3 g) oscillating accelerations was demonstrated, during which the amplitude of test mass displacement was approximately 2 mm. A comparative assessment of the results of the experiment with theoretical calculations and the amplitude-frequency characteristics of the process in weightlessness can be obtained after processing and analyzing the experiment data.

This investigation is complete; however additional results are pending publication.

POPULARIZING ACHIEVEMENTS IN RUSSIAN MANNED SPACE EXPLORATION (GREAT START)

Research Area: Educational Demonstrations
Expeditions: 27-ongoing
Principal Investigator(s):
- Mikhail Y. Belyaev, PhD, S.P. Korolev Rocket and Space Corporation Energia, Korolev, Russia

RESEARCH OBJECTIVES

The Popularizing Achievements in Russian Manned Space Exploration (Great Start) investigation popularizes achievements of the Russian manned space exploration and presents the results of research applying them in universities and business activity using educational and Internet technologies. Methodological materials on popularizing achievements in space exploration, scientific and educational video footage from on board the International Space Station, and the use of the results of space research and investigation for educational and business purposes were developed and tested using Internet technologies.

Planeta Koroleva website for the Great Start investigation. Roscosmos image.

EARTH BENEFITS

Using Internet technologies and the ISS functioning on orbit, new educational technologies are tested to popularize achievements in Russian manned space exploration and to use the results of space investigations for educational and business purposes. One interesting methodological result of the space investigations was obtained regarding proposals to use the results of imagery taken on the ISS for educational purposes, such as in geography classes (Uragan investigation materials). Interesting methodological materials were also obtained on approaches to popularizing achievements in Russian science using Internet technologies and using the results of space activities in the domestic economy.

SPACE BENEFITS

The main result of this investigation was educational and pedagogical, with the achievements of Russian space exploration being accumulated during its implementation. An important result of the investigation is providing opportunities to use space activities to many experts in various fields, which subsequently, provides opportunities to obtain new ideas for the development of space exploration and the use of spaceflight results based on questionnaires.

RESULTS

To disseminate the achievements of Russian manned space exploration and popularize the results achieved, a bilingual (Russian/English) Internet portal "Planeta Koroleva" was created (http://gagarin.energia.ru, Figure 1). Planeta Koroleva is a social informational/education project facilitating the development of scientific ideas in the field of space technologies and broadening the scope of their application in the socio-economic life of society.


Video screen shot of ISS Expedition 27 crew announcing Great Start winners. Roscosmos image.

The project was timed to coincide with the celebration of the 50th anniversary of the first manned flight to space. On this site, any user can fill out the Great Start questionnaire and become a participant in the investigation. Answers to the Great Start educational investigation questionnaire collected on the Planeta Koroleva portal from various universities, organizations, and individuals are periodically sent to the ISS RS. While preparing for a questionnaire analysis session, crewmembers review questionnaire answers and select the most interesting ones for each question.

Statistics on Planeta Koroleva portal views during the Great Start investigations:

- 22,130 views of the portal
- 6,432 individual visitors of the portal
- 139 views per day
- 1,937 visitors who viewed the portal more than once

85 completed questionnaires able to be used for the processing

During the video session, the most interesting answers and the names and addresses of investigations participants were announced. The video footage with crewmember participation was placed on the Planeta Koroleva Internet portal. This portal also presents some results of space investigation and considers possibilities for using them. A method of an educational process in the field of manned space exploration was developed, making it possible to use technologies to apply the results of space activities in the domestic economy and education. Participants were awarded personally or by email diplomas confirming their participation on the ISS in the events dedicated to the 50th anniversary of the first manned flight to space.

This investigation is ongoing; however additional results are pending publication.

Production of Japan Aerospace Exploration Agency - Astronaut Report (JAXA-AstroReport)

Research Area: Human Behavior and Performance
Expedition(s): 23 and 24

Research Objectives

Japan Aerospace Exploration Agency - Astronaut Report (JAXA-AstroReport) allows crew members to document their living and working life aboard the International Space Station (ISS).

Japan Aerospace Exploration Agency (JAXA) astronaut Soichi Noguchi, Expedition 22 flight engineer. JAXA image.

Earth Benefits

JAXA-AstroReport gives the Japanese population an insight into the everyday life of a crew member aboard the ISS.

Space Benefits

The next generation of explorers can be inspired by gaining insight into what crew members do on a daily basis.

Results

The report was created by Astronaut Soichi Noguchi. He wrote about his tasks and life aboard the ISS. His reports reached the Japanese population through newspapers and magazines with articles that motivated people to understand and learn more about ISS and space.

This investigation is complete and all results are published.

JAPAN AEROSPACE EXPLORATION AGENCY EDUCATION PAYLOAD OBSERVATION (JAXA EPO), SIXTEEN INVESTIGATIONS

Research Area: Cultural Activities

Expeditions: 17-24, 26, 27, 29 and 30

Principal Investigator(s):

- Takao Fujiwara, Kyoto City University of Arts, Kyoto, Japan
- Takuro Osaka, University of Tsukuba, Tsukuba, Japan
- Yuichi Yonebayashi, Tokyo University of the Arts, Tokyo, Japan
- Hitoshi Nomura, Kyoto City University of Arts, Kyoto, Japan
- Michiyo Miyanaga, Tokyo University of the Arts, Tokyo, Japan
- Setsuko Ishiguro, Ochanomizu University, Tokyo, Japan
- Shiro Matsui, Kyoto City University of Arts, Kyoto, Japan
- Yoichiro Kawaguchi, The University of Tokyo, Tokyo, Japan
- Ayako Ono, Tohoku University, Sendai, Japan
- Yuzo Murayama, Doshisha University, Kyoto, Japan
- Noriyasu Fukushima, Kyoto City University of Arts, Kyoto, Japan

RESEARCH OBJECTIVES

Japan Aerospace Exploration Agency Educational Payload Observation (JAXA EPO) is a suite of activities demonstrating educational events and artistic and cultural activities aboard the International Space Station (ISS) Japanese Experiment Module (JEM), Kibo, to enlighten the general public about microgravity research and human spaceflight.

Artistic Experiments Using a Water Sphere. JAXA image.

ARTISTIC EXPERIMENTS USING A WATER SPHERE (FUJIWARA, EXPEDITION 17)

The Artistic Experiments Using a Water Sphere investigation determines how water spheres change shape with oscillation from 2 points in microgravity.

International Space Station crew members participating in "Chuon" The Space Voice of the Open Mind. JAXA image.

"CHUON" THE SPACE VOICE OF THE OPEN MIND (FUKUSHIMA, EXPEDITION 30)

The Space Voice of the Open Mind (Chuon) surveys the effects of the space environment on the feelings, opinions, and minds of International Space Station astronauts. Chuon focuses on the sense of hearing; a crewmember will listen to emitted sounds and document the sensations they experience.

Dewey's Forest (Matsui, Expedition 22)

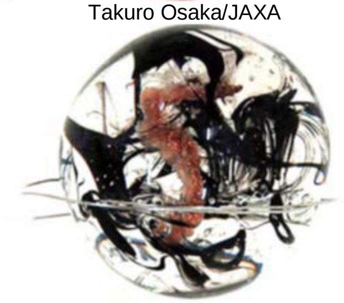
Dewey's Forest shows how gravity controls the laws of nature and influences our ways of thinking. The project is a catalyst to rediscover our relationship with plants on the ground and the age old history of our gardens.

International Space Station crew member participating in Hiten. JAXA image.

Hiten (Ishiguro, Expedition 19)

Hiten records crewmembers performing some postures of ancient East Asian Flying Deities in microgravity.

Takuro Osaka/JAXA



Takuro Osaka/JAXA

Marbling painting on a water ball (Ink Ball). JAXA image.

Ink Ball (Osaka, Expedition 17)

Suminagashi is the marble painting process involving floating ink on water, the pattern of which is soaked onto washi, traditional Japanese paper.

Ink Ball-II (Osaka, Expedition 29)

Using spheres of seawater injected with ink, Ink Ball-II expresses the evolution of life on Earth using the familiar marbling technique.

Japanese Powdered Green Tea in Space (Kawaguchi, Expedition 29)

Japanese Powdered Green Tea in Space demonstrates the feasibility of mixing green leaf tea powder and water in microgravity.

Message in a Bottle (Matsui, Expedition 26)

Message in a Bottle creates a unique communication interface between space and Earth, as well as present and future humankind. During an extra vehicular activity (EVA), a small cylinder is filled with the essence of space. Once Message in a Bottle is returned to Earth and placed in people's hands, it becomes a conduit between humans and space, and between this world and the one beyond us.

Video screen shot of Modeling Clay in Space. JAXA image.

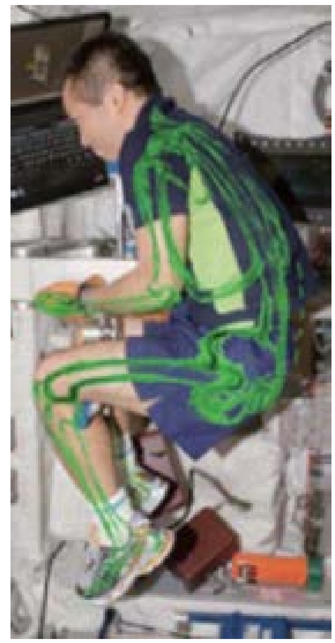
Modeling Clay in Space (Yonebayashi, Expedition 17)

Creating human-shaped figures is a centuries old practice. However, there have always been limitations placed upon imagination by constraints of gravity. For instance, if arms and legs are too long or too thin, they will snap due to their own weight. Modeling Clay in Space explores what figures can be created without the limitations of gravity.

Sample of Moon Score images. JAXA image. ©Hitoshi Nomura.

'MOON' SCORE: ISS ASTRONAUT (NOMURA, EXPEDITIONS 17-24)

Moon Score aims to compose a musical score using the pictures of the moon in diverse phases, which are photographed from a window of the Kibo module by ISS astronauts. Five circular lines are superimposed upon the pictures so that the photographed moon can be interpreted as a note on the 5 horizontal lines of a musical score.



International Space Station astronaut demonstrating the Space Clothes Experiment on board ISS. JAXA image. Green line indicating the skeletal structure traced by Dr. Miyanaga, image by Tatsuya Tayama, Mitsunari Kita.

SPACE CLOTHES EXPERIMENT (MIYANAGA, EXPEDITION 19)

Space Clothes investigates the body movement under microgravity and obtains basic data for future clothes.

SPACE MUSICAL INSTRUMENTS (ONO, EXPEDITION 30)

Space Musical Instruments looks for a new sound and playing style in microgravity using brass musical instruments, like maracas and handbells. The instruments are played in orbit, and the performance and sound are recorded by a HD camcorder.

SPACE SAKURA (MURAYAMA, EXPEDITION 30)

Gravity constraints have limited the design and scope of Japanese traditional crafts. Perhaps such constraints resulted in an immobilization of culture. However, by recreating landscapes of Japan under a zero gravity setting, new possibilities which never previously existed could open up. The theme 'a sakura petal flurry,' which is a phenomenon symbolic of Japanese spring, was chosen.

Spiral Top investigation on board the International Space Station. JAXA image.

SPARKLING NEURONS (NOMURA, EXPEDITION 17)

Sparkling Neurons obtains imagery with HDTV. Imagery will be returned to Earth for examination. The investigator will then create an intuitive image of the space environment.

SPIRAL TOP (OSAKA, EXPEDITION 19)

Spiral Top aims to record the motion of a luminous spinning top onboard the ISS.

Spiral Top – II Aurora Oval (Osaka, Expedition 27)

Spiral Top – II Aurora Oval aims to record the motion of a luminous spinning top onboard the ISS.

International Space Station (ISS) astronaut conducting the Japanese Powdered Green Tea in space investigation in the ISS Kibo module. JAXA image.

Earth Benefits

JAXA EPO is an interactive activity to enlighten the general public about microgravity utilization and human spaceflight. It also expands to the cultural and social science area.

Space Benefits

JAXA EPO attracts attention to Japanese manned spaceflight activities to gain the support of the Japanese community for future manned space exploration.

Results

Artistic Experiments Using a Water Sphere

The resulting spheres formed triangular and hexagonal shapes.

"Chuon" The Space Voice of the Open mind

While everything about the ISS is man-made, an attempt took place to explore the source and nature of sound which has nurtured human sensitivity by stimulating acoustic sense. It also attempted to seek what human senses are all about.

Chuon, a 3-dimensional sound-emitting object, was created with the intention of producing sounds which would move one's senses and touch one's heart. Scientists are working with astronauts to determine how the sound emitted by the object is heard and felt in space.

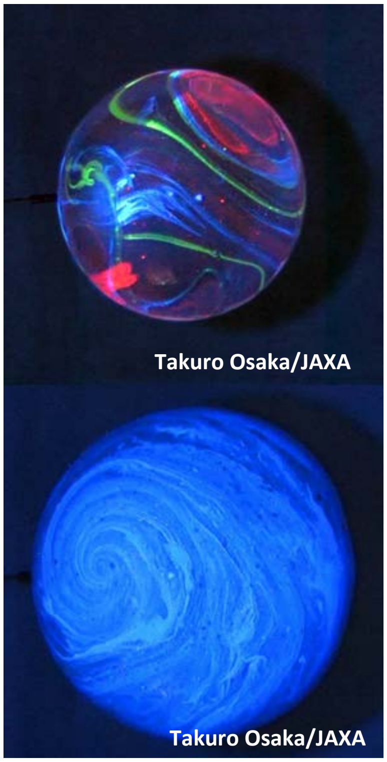
Marbling Painting on a Water Ball (Ink Ball)

As all the colors mixed thoroughly, the spheres eventually turned completely black. When the water was soaked onto washi, the colors printed on the washi showed rich and bright patterns. The result was a new form of expression in microgravity.

International Space Station crew members gathered in Kibo to observe the growth of Dewey's Forest. JAXA image.

Dewey's Forest

By creating a garden in Kibo, differences in gardens between space and Earth were explored. Furthermore, examinations were made of the feelings of astronauts of having a garden in space. The space garden was shaped like a round air ball. Seeds were planted in a cultivation kit. Astronauts watered it every 10 days or so, and cultivation took place over a period of approximately 2 months.



Ink Ball-II spheres created on board ISS. JAXA image.

Hiten

Hiten refers to flying deities, which were portrayed on the walls of ancient ruins along the Silk Road approximately 1600 years ago. In Japan the story of Hiten was described as those who send flowers from the sky, play music, and fly the high sky. While living and working on board the ISS, the basic movements and posture of dancing were performed to express the image of Hiten by an ISS astronaut, inside Kibo. The microgravity environment enables certain movements, eg, curvilinear pivoting around a point indicating a center of gravity. Further developments of these movements would enable certain movements which previously existed only in people's i maginations. Those findings can also be applied to physical artistic expressions on Earth.

Marbling Painting on a Water Ball (Ink Ball-II)

The first ball was made with salt water to symbolize Earth. Blue fluorescent ink and powder extracted from sea-fireflies, which are bioluminescent species, were injected into it. As for the second sphere, red, blue, and green fluorescent ink, representing the 3 primary colors of light were injected. After mixing them, an LED black light was turned on. In the first sphere a blue striped print emerged while the second sphere showed the fluorescent ink all the way through from the other side.

ISS astronaut collecting "space" for the Message in a Bottle investigation. JAXA image.

Japanese Powdered Green Tea in Space

Whisking green tea in outer space is a challenging task, as the powder and liquid would fly everywhere. We prepared a green tea powder capsule, a custom-made bamboo whisk, and a hermetically-sealed round container. The difference with tea on Earth was foam. Foam in outer space tea had a hard and metallic feel, and its surface reflected its surrounding environment like lenses. The foam did not burst, even when mixed. Once stirring ceased, the form stayed still. This attempt proved that it is possible to conduct outer space experiments which involve diffusion and scattering.

MESSAGE IN A BOTTLE

Message in a Bottle captured "space" in a glass bottle. The intention was to bring it back to Earth so people would feel closer to outer space. Unfortunately, "space" was not brought back to Earth because the bottle was broken on the first attempt. The second attempt was successfully conducted and "space" was brought back to Earth.

One of the bells utilized for the Space Musical Instruments investigation. JAXA image.

MODELING CLAY IN SPACE

This experiment was an attempt to create clay figurines in tebineri style (hand-pinching) in a micr ogravity environment. The findings show that a gravity-free environment enables creation of figurines of any shape.

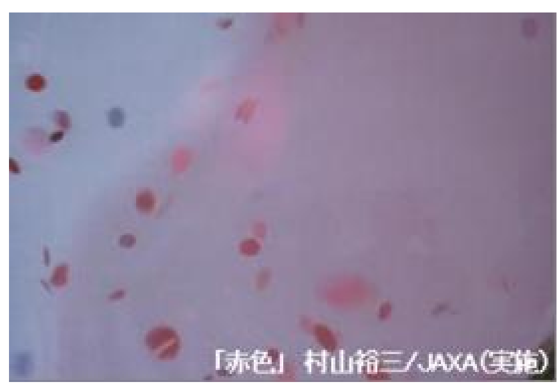
'MOON' SCORE: ISS ASTRONAUT

This score is unlike an ordinary music score consisting of vertical notes. Rather, it consists of 5 oval-shaped circular lines. Sounds were assigned such that craters are played by marimba and lunar mares by cembalo, whereupon this piece of music was performed.

SPACE CLOTHES EXPERIMENT

Fashion arises from functionality and then develops into mode. This experiment sought new fashion which would be suitable for long-term stays in space. An important factor for clothes is how efficiently one can move in a specific environment. To explore how to move one's body in a microgravity environment, an ISS astronaut, imitated the movement of fish, birds, and spiders to examine physical movements. In particular, the difference in the role played by lower body limbs in space and Earth was highlighted, providing insights into clothes which would be suitable for this environment.

SPACE MUSICAL INSTRUMENTS



Space Sakura investigation. JAXA image.

Space Musical Instruments demonstrated 2 bells. One was a fractal bell, which resembles different-sized leaves lined on top of each other. The other is an ellipsoid bell, which contains a natural fragrant ball made of Japanese cypress. The fractal bell showed movements which were more intricate than expected. The Ellipsoid Bell showed that the sound disappears upon rotation due to centrifugal force, but it produces sounds when its rotating movement ceases, unlike anything we hear on Earth. Furthermore, the beautiful sounds produced resonate much longer than they would on Earth. There was an exquisite balance of sounds; the wooden ball controlling the metallic sounds to some extent. Under weightlessness, sounds are created when instruments are pushed or jiggled; so a new method of playing, away from the accepted musical wisdom to date, will be necessary. These findings are expected to spark the discovery of new styles of music and the development of space musical instruments in the future.

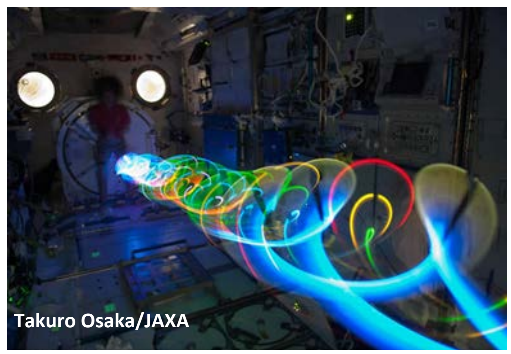
Space Sakura

One thousand sakura petals made from twelve colors of Yuzen-dyed silk fabric flurried from right to left and down to up. Movements which would be impossible on Earth were witnessed in a microgravity environment. This was filmed using a 3D video camera, and the image was sent to Earth to be applied to the development of new craft design.

Night view of Japan taken by a scratched International Space Station high definition TV camera. JAXA image.

Sparkling Neurons

As radiation hits the charged-coupled image sensor device of the TV camera on the ISS, it leaves scratches which show up as white spots on the screen. This is valuable material for art and it was used as an expression of humankind to progress in new environments. The images of space with white spots which were photographed from the window of Kibo and footage of Earth taken with the scratched high definition TV camera are now being edited to represent space environment and life.



Spiral Top – II Aurora Oval in operation onboard the International Space Station. JAXA image.

Spiral Top

There are many spirals in your body; spirals are deeply connected to life. The Spiral Top investigation paints spirals with floating light. When a figure with many LEDs is spun like a spinning top, the axis becomes inverted and beautiful phenomenon unique to space is revealed. During Spiral Top, Kibo became a beautiful canvas with an image of bright lights.

Spiral Top – II Aurora Oval

Dots become lines, and lines become planes. This is the basic principle of modern formative art. This experiment is the sequel to Spiral Top. In Spiral Top – Auroral Oval, a fiber optics light beam was added. Upon rotation, a line turns into a plane, creating an aurora like steric light beam.

This investigation is ongoing and additional results are pending publication.

KIBO KIDS TOUR

Research Area: Educational Demonstrations
Expedition(s): 19 and 20
Principle Investigator(s):
- Shiho Ogawa, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

Kibo Kids Tour introduces in-orbit Japanese utilization activities in the Kibo Module of the International Space Station (ISS) to the children of Japan.

Video screen shot from the Kibo Kids Tour. JAXA image.

EARTH BENEFITS

Kibo Kids Tour gives children the opportunity to enhance their knowledge of in-orbit Japanese utilization activities through video with a crew member aboard the ISS.

SPACE BENEFITS

Crew members are able to share their duties and knowledge by providing video tours of the Kibo laboratory to the inquiring minds of school-aged kids during spaceflight.

RESULTS

The footage was taken by Astronaut Koichi Wakata, and it goes on JAXA HP. People can learn more about the first Japanese manned space facility, Kibo. The video was used in developing education curriculum support materials for distribution to educators.

This investigation is complete and all results are published.

Study of the Dynamics of a System of Charged Particles in a Magnetic Field in Microgravity Conditions (Kulonovskiy Kristall)

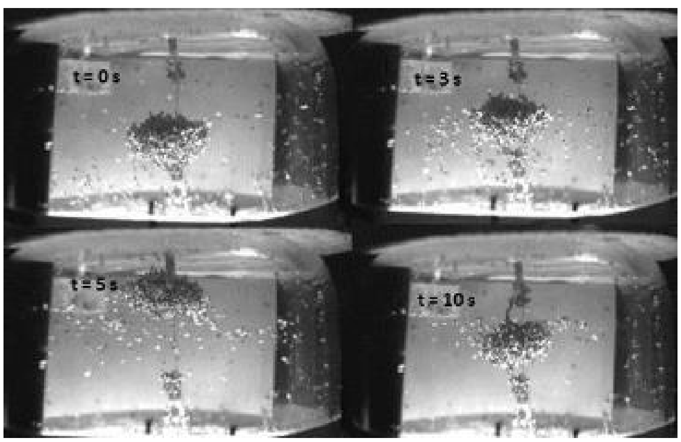
Research Area: Educational Demonstrations
Expedition(s): 23-ongoing
Principal Investigator(s):
- Vladimir E. Fortov, PhD, Institute of Thermal Physics of Extreme Conditions, Moscow, Russia

Research Objectives

Kulonovskiy Kristall studies the formation of a Coulomb ensemble of charged graphite particles located in a replaceable container when exposed to the dynamic impacts of a magnetic and electric field or mechanical agitation aboard the International Space Station (ISS).

Earth Benefits

The educational and demonstrational components of the experiment consist of attracting university-level and graduate students at higher educational institutions to the scientific processing of the information obtained. This investigation aims to attract creative youth to participating in space experiments.



Positions of the graphite particle cloud during one period of induced decaying oscillations. Particle diameter = 400 µm. Roscosmos image.

Space Benefits

The experiment's results may be applied when developing future sources of energy for spacecraft using photovoltaic cells. In these cells, fine-dispersed powder of solid radioisotopes forms a homogenous floating suspension in a gaseous medium. The gaseous medium, when exposed to ionizing charged particles, generates ultraviolet radiation, which in turn is converted into electrical current by high-efficiency, wide-bandgap semiconductors.

Results

Kulonovskiy Kristall created stable, spatially ordered structures consisting of charged, strongly interacting graphite particles. The particles' charge was evaluated, and the characteristic oscillation time of the dust cloud was determined.

Research was performed for the first time on strongly interacting Coulomb systems in an antiprobkotron magnetic field (B ~ 103 G, $|\nabla B|$ ~ 400 G/cm), consisting of a large number (~104) of charged diamagnetic graphite particles with dimensions of 100, 200, 300, and 400 µm in microgravity conditions. The period of induced oscillations of the particle cloud was determined to be T = 10 s and the oscillation damping decrement was determined to be δ = 0.07 s^{-1}.

PUBLICATION(S)

Borisenko AI, Kaleri AY, Markov AV, et al. Space Experiment Kulonovskiy Kristall on the ISS. *Space Forum 2011 Dedicated on 50th Anniversary for Yu. A. Gagarin Flight, Moscow, Russia*. October 18-21, 2011.

Savin SF, D'yachkov LG, Myasnikov MI, et al. Coulomb ensemble of charged diamagnetic particles in a heterogeneous magnetic field in microgravity conditions. *Letters to the Journal of Experimental and Theoretical Physics*. 2011;94(7):548-552.

Petrov OF, Savin SF. Project Coulomb Crystal: Demonstrative/ Educational and scientific experiments with electromagnet use onboard ISS-Russian segment. *Project Coulomb Crystal: Demonstrative/ Educational and Scientific Experiments with Electromagnet Use onboard ISS-Russian Segment*, 2003.

Cosmonaut A.Yu. Kaleri performs a session of the Kulonovskiy Kristall experiment. Roscosmos image.

Savin SF. Coulomb crystals formed by charged diamagnetic particles in non-uniform stationary magnetic field. *Seminar on Weightlessness Mechanics and Gravity Sensible Systems*, RSC Energia, Korolev Moscow Region; 2001.

This investigation is ongoing and additional results are pending publication.

LEGO® Bricks (LEGO Bricks)

Research Area: Educational Demonstrations
Expedition(s): 27-30
Principal Investigator(s):
- The Lego Group, Billund, Denmark

Research Objectives

The LEGO® Bricks payload is a series of toy LEGO kits that are assembled in orbit and used to demonstrate scientific concepts. Some of these models include satellites, a space shuttle orbiter, and a scale model of the International Space Station (ISS).

Earth Benefits

The LEGO® Group and LEGO® Education use the LEGO® Brick and LEGO® kits to teach fundamental Science, Technology, Engineering, and Mathematics concepts to a variety of students worldwide. These educational activities are geared for students ages 4-18 and offer a unique setting for students to investigate topics such as forces and motion, simple machines, renewable energy, and robotics. The release of new products, the website, and along with the supporting of future education, gives the space program a new boost and offers many possibilities for young students.

Students used LEGOs to 'Build the Future' at NASA's Kennedy Space Center in Cape Canaveral, Fla, on Wednesday, Nov. 3, 2010. The 'Build the Future' event was part of pre-launch activities for the STS-133 mission. These events occur throughout the NASA/Lego partnership. Bill Ingalis/NASA image.

Space Benefits

The LEGO® Brick is widely well-known throughout the world. NASA partnering with this company makes the U.S. space program highly visible to a new audience. The LEGO® Group has developed a new commercial line titled "LEGO® Space City" that premiers in the U.S. in early 2011. This new product features vehicles and models directly from NASA real-life vehicles. To accompany this, the Lego Group is launching a new LEGO® Space website that NASA can link to. The release of new products, the website, and the support of future education, gives the space program a new boost and offers many possibilities for young students.

Results

NASA has partnered with the LEGO Group to develop innovative educational materials and activities. This partnership, documented in a Space Act Agreement between the 2 organizations, is designed to support NASA's educational programs in exploration, technology, science, and aeronautics. This opportunity provides the unique learning environment of microgravity to promote student interest in STEM content and careers. To accomplish this task, LEGO kits are flown aboard the ISS.

Crew members perform tasks to demonstrate simple science concepts and show how LEGO bricks work differently in a microgravity environment.

This investigation is complete and all results are published.

LESSONS FROM SPACE-2 (LES-2)

Research Area: Educational Demonstrations
Expedition(s): 19-22
Principal Investigator:
- C. Olivotto ESA HSO Promotion Office, Noordwijk, Netherlands

ESA astronaut Frank De Winne demonstrates an experiment during the "Take your classroom into space" event. ESA image.

RESEARCH OBJECTIVES

Lessons from Space-2 seek to inspire students of all ages to follow science-based subjects using the unique environment of the International Space Station The Lesson-2 activity. This included a live link demonstration designed to give students an appreciation of the conditions of freefall through 2 simple, curriculum relevant experiments.

RESULTS

Hundreds of schoolchildren participated during a live link-up in September 2009 with ESA astronaut Frank De Winne inside the European Columbus laboratory on the International Space Station (ISS). During the 20-minute link-up, De Winne successfully conducted the "Do objects have weight in space?" experiment that was proposed by European teachers in response to a call for experiments that can be carried out on the International Space Station to demonstrate the effects of freefall. To support the activity, ESA distributed Education Kits in Dutch, French, German, Greek, Italian, and Spanish to participating schools containing the same hardware De Winne would use in orbit.

The demonstration involved calculating the mass of an object on the ISS by measuring the time it takes to oscillate whilst hooked onto a spring. The experiment helped to illustrate the difference between the concepts of weight and mass. The schoolchildren performed the experiment themselves at the same time as De Winne from the museums in Barcelona (Spain), Thessaloniki (Greece), Milan (Italy), and Mechelen (Belgium). An edited highlights video was made available afterward, and the recording of the demonstration apis was also used to produce ESA multimedia educational material.

This investigation is complete; however no publications are expected.

Lessons from Space-3 (LES-3)

Research Area: Educational Demonstrations
Expedition(s): 19-22
Principal Investigator:
- C. Olivotto, ESA HSO Promotion Office, Noordwijk, Netherlands

Research Objectives

The Lesson-3 educational activity includes a live link between primary school students with ESA astronaut Frank De Winne who gives a lesson about life on the International Space Station (ISS), which includes demonstrations of various water properties.

De Winne performs demonstration with water. ESA image.

Results

A live link activity took place between ESA astronaut Frank De Winne on the ISS and nearly 300 Belgian schoolchildren on October 6, 2009. The kits were distributed to many other schools. The children, aged 10-12 years old, gathered at the Free University in Brussels for a day of activities dedicated to learning about life on the ISS. The students asked De Winne questions directly such as “How do the astronauts wash themselves?”; “How do they brush their teeth”; “What and how do they eat?” and “How do they keep fit and healthy?”

Organized with the Belgian European Space Education Resource Office (ESERO), in collaboration with the Belgian Federal Science Policy Office, the ministries of education of the Flemish Region, the French-speaking and German-speaking communities in Belgium, UNICEF Belgium and ESA’s Directorate of Human Spaceflight, the emphasis of the ISS Day was water scarcity in space and on Earth. This theme tied in with De Winne's role as UNICEF ambassador and his support for their Water, Sanitation and Hygiene (WaSH) campaign.

Water is vital for the health of people on Earth and in space and the day's activities encouraged children to make the link between the problems of water management in space and the problems facing millions of people on Earth. The live link was the finale of the day, during which De Winne performed 3 simple demonstrations to show how water behaves in space before answering the children’s questions.

The recording of the demonstration was used to produce ESA multimedia educational material for upper primary school teachers and their students aged 10-12.

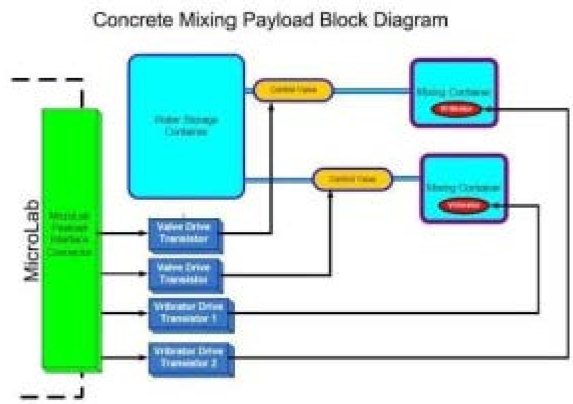
This investigation is complete; however, no publications are expected.

NanoRacks-Faith Christian Academy-Concrete Mixing Experiment (NanoRacks-FCA-Concrete Mixing)

Research Area: Educational Demonstrations
Expedition(s): 29 and 30
Principal Investigator(s):
- Faith Christian Academy, Coalinga, California

Research Objectives

NanoRacks-Faith Christian Academy-Concrete Mixing Experiment (NanoRacks-FCA-Concrete Mixing) is a NanoLab project to compare the strength and molecular structure of concrete mixed in microgravity compared with similar ground-mixed concrete. The comparison is made using an Atomic Force Microscope after the NanoLab is returned to Earth.



NanoRacks-Faith Christian Academy-Concrete Mixing Experiment Block Diagram. Faith Christian Academy image.

Earth Benefits

Utilizing the unique microgravity environment on the International Space Station (ISS) allows for determining the fundamental physical properties that occur when concrete is mixed and settles. By removing the force of gravity, it is hoped that the molecular structure of concrete and the properties that control its strength leads to developing a more robust form of concrete to be used on Earth.

Space Benefits

While concrete is not likely to be used in space, studying the structural and settling properties of this mixture might lead to a better understanding of the chemical and physical properties of similar mixtures. If it is found that mixing concrete in microgravity produces concrete of sufficient strength, then one could mix concrete and build concrete buildings on the moon or Mars that have smaller gravity fields.

Results

Students were responsible with creating and testing their individual experiments. This was an opportunity to increase STEM interest among high school students.

Publication(s)

Kirschhock CE, Kremer SP, Grobet P, Jacobs PA, Martens JA. New Evidence for precursor species in the formation of MFI Zeolite in the Tetrapropylammonium Hydroxide−Tetraethyl Orthosilicate−Water System. *Journal of Physical Chemistry B*. May 16, 2002;106:4897-4900. doi: 10.1021/jp015617x.

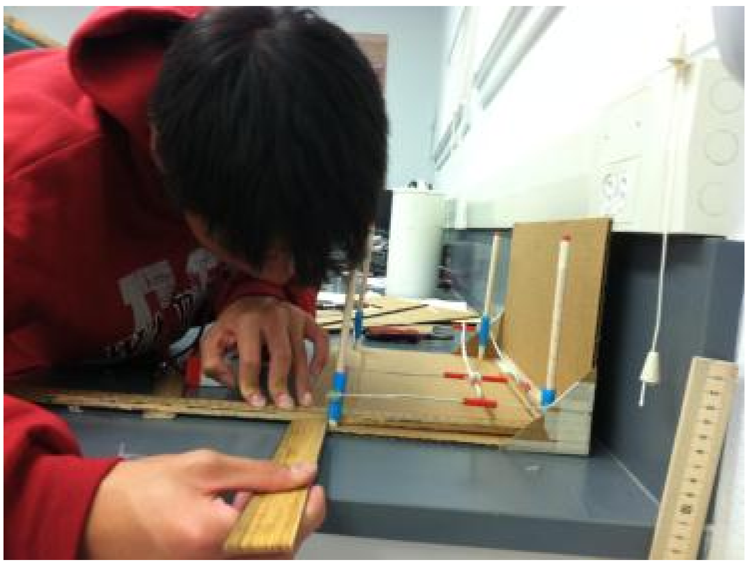
This investigation is complete and all results are published.

NanoRacks-Fremont Christian High School-Micro-Robot (NanoRacks-FCHS-Robot)

Research Area: Educational Demonstrations
Expedition(s): 29 and 30
Principal Investigator(s):
- Fremont Christian High School, Fremont, California

Research Objectives

NanoRacks-Fremont Christian High School-Micro-Robot (NanoRacks-FCHS-Robot) is a NanoLab project studying the effects of microgravity on remotely controlled robot control mechanisms and mechanical devices. The Fremont Christian School Micro-Robot is named principal investigator for Programmable Intelligence. The goal of the investigation is to determine the feasibility of using robots to complete tasks in a microgravity environment, where the only force to overcome is friction.



A conceptual drawing of the NanoRacks-Fremont Christian High School-Micro-Robot from a side view, drawn on an iPad. Fremont Christian School image.

Earth Benefits

The students of Fremont Christian School are gaining an invaluable educational experience by completing this investigation. Many of the advancements in robotics on Earth have come from technologies designed, tested, and flown in the space program.

Space Benefits

Determining how robots function remotely in microgravity is essential to advancing the space program beyond low-Earth orbit. Robots play a key role in the space program as they have the potential to complete tasks that would otherwise take up valuable crew time as well as withstand the harsh environment of space.

Results

Students were responsible for creating and testing their individual experiments. This was an opportunity to increase STEM interest among high school students.

This investigation is complete and all results are published.

PHOTOSYNTH™ THREE-DIMENSIONSAL MODELING OF ISS INTERIOR AND EXTERIOR (PHOTOSYNTH)

Research Area: Educational Demonstrations
Expedition(s): 18-20, 25-ongoing
Principal Investigator(s):
- Dylan Mathis, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Photosynth™ Three-Dimensional Modeling of ISS Interior and Exterior (Photosynth) synthesizes 3-D models of the International Space Station (ISS) from a series of overlapping still photographs mainly as a tool for education and public outreach. Photosynth is a collaboration between the NASA and the Microsoft Live Labs.

EARTH BENEFITS

The Photosynth models of the ISS provide educators a better way to view the ISS and teach about space and science. The interested public also benefits from having a better way to view the space station and its scope. Feedback can assist Microsoft with potential Photosynth™ product improvements for general consumer and commercial use.

View of the inside of U.S. Laboratory Destiny during Expedition 18. Taken for PhotoSynth Three-dimensional Modeling of ISS Interior and Exterior project.

SPACE BENEFITS

The Photosynth models are evaluated for possible use by the ISS Program in areas such as crew training, maintenance, and logistics.

RESULTS

During Expedition 18 ISS Increment Flight Engineer Sandy Magnus took approximately 900 images of the USOS. These images were downlinked and are currently being used to create the Photosynth™ models of the ISS interior.

This investigation is complete and all results are published.

Sally Ride Earth Knowlegde Acquired by Middle School Students (Sally Ride EarthKAM)

Research Area: Educational Demonstrations
Expedition(s): 2-ongoing
Principal Investigator(s):
- Sally Ride, PhD, University of California, San Diego, La Jolla, California

Research Objectives

Sally Ride Earth Knowledge Acquired by Middle School Students (Sally Ride EarthKAM) is a NASA education program that enables thousands of students to photograph and examine Earth from a space crew's perspective. Using the Internet, the students control a special digital camera mounted aboard the International Space Station (ISS). This enables them to photograph the Earth's coastlines, mountain ranges, and other geographic items of interest from the unique vantage point of space. The team at Sally Ride EarthKAM then posts these photographs on the Internet for the public and participating classrooms around the world to view.

Map of countries participating in the Sally Ride EarthKAM missions.

Earth Benefits

Sally Ride EarthKAM offers a powerful way for students to investigate Earth from the unique perspective of space. The image collection is posted on the Internet for both public use and participating classrooms around the world. In addition to the raw images, the Sally Ride EarthKAM Data-system contains selected images that have been annotated and even more images that can be displayed as overlays on various format maps. Learning guides and activities are available to support education in Earth science, space science, geography, social studies, mathematics, communications, and even art. The concepts in these projects support the National Science Education Standards, National Math Education Standards, National Geography Standards, and the National Science Education Teaching Standards.

SPACE BENEFITS

The students at UCSD are gaining experience as real-time flight controllers while working on the Sally Ride EarthKAM. This experience is inspiring the next generation of flight controllers for space programs.

Third graders from Sacaton, Arizona tracking the ISS for their Sally Ride EarthKam project.

RESULTS

Approximately 2,800 schools with 190,000 middle school students and 3,000 teachers in the United States and 48 other countries have participated in the Sally Ride EarthKAM. A total of 150 undergraduate students from the University of California at San Diego (UCSD), San Diego, California, also have participated in integrating and operating the experiment. No other NASA program gives students such direct control of an instrument flying on a spacecraft orbiting Earth, and as a result, students assume an unparalleled personal ownership in the study and analysis of their Earth photography.

PUBLICATION(S)

Hurwicz M. Case Study: Attack of the space data – Down to Earth data management at ISS EarthKAM. *New Architect.* 2002;38.

This investigation is ongoing and additional results are pending publication.

DEVELOPING A PROCEDURE FOR RADIOSOUNDING OF THE SATELLITE COVERAGE AREA USING A NETWORK OF GROUND RECEIVERS (TEN-MAYAK)

Research Area: Educational Demonstrations
Expedition(s): 4, 5, 7, 8, 9, 12-30, and 33-ongoing
Principal Investigator(s):
- Oleg M. Alifanov, PhD, Kosmos International Educational-Scientific Center, Moscow, Russia

RESEARCH OBJECTIVES

Developing a Procedure for Radiosounding of the Satellite Coverage Area using a Network of Ground Receivers (Ten-Mayak) studies very high frequency (VHF) radio reception and transmittal signal conditions from an onboard radio beacon located on the International Space Station (ISS) using the world radio amateur network and determine the characteristics of the radio signals broadcasting and retransmitting using an onboard transceiver.

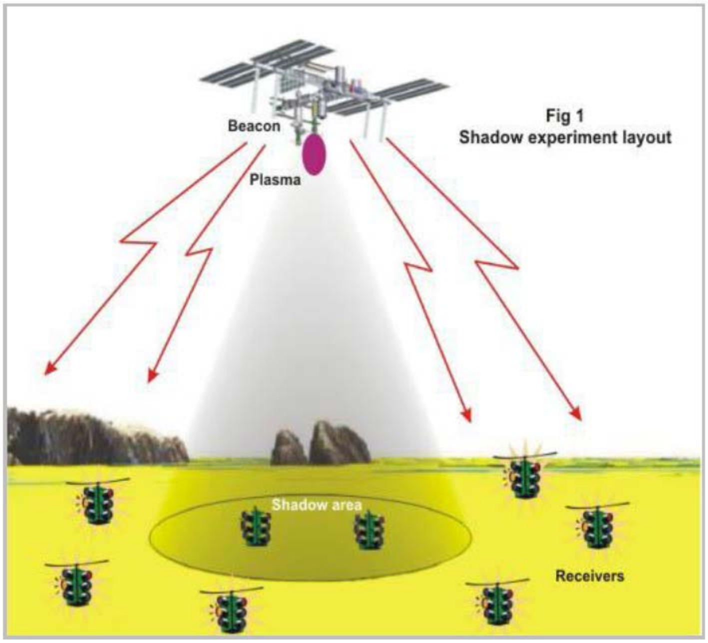


Diagram of the experiment Developing a Procedure for Radiosounding of the Satellite Coverage Area using a Network of Ground Receivers (Shadow-Beacon). Roscosmos image.

EARTH BENEFITS

Ten-Mayak is used in practical classes in schools, ie, for holding collective sounding signal receipt sessions, which can be applied particularly successfully and effectively in non-classroom activities in high schools.

SPACE BENEFITS

The sum total of the data and calculations obtained on the current reciprocal positions of a satellite and a ground receiver is a final product of the experiment, with which the main characteristics of the procedure for space-to-ground radio sounding can be determined using the ground radio amateur network to monitor plasma irregularities in the satellite coverage area. The initial results of the experiment confirmed the principle feasibility of using the multi-beam method of the satellite coverage area radio sounding.

RESULTS

During the experiment, sounding packets from the on-station radio beacon in the form of time tags were emitted and received by the ground reception network, which included amateur VHF receivers, and the measuring results were broadcast on the Internet. Numerous reports on the receipt of data from participants were sent to the information collection center. The data received was processed and classified. The effect of the non-uniform sensitivity of the ground reception network was evaluated for the accuracy of space and time measurements when applying this procedure of the satellite coverage area radio sounding. Maps of coverage areas for measurement orbits were compiled. In this series of Ten-Mayak experiments, a new tool was developed to increase the timeliness and effectiveness of ground measuring network management, specifically a special Ten-Mayak experiment site that is part of the Roscosmos scientific/technical coordination board's portal allowing the automatic registration of experiment participants and the real-time distribution of urgent notifications and news.

M.V. Tiurin during the Developing a Procedure for Radiosounding of the Satellite Coverage Area using a Network of Ground Receivers experiment. Roscosmos image.

This investigation is ongoing and additional results are pending publication.

EDUCATION PAYLOAD OPERATIONS-TOMATOSPHERE II (EPO-TOMATOSPHERE II)

Research Area: Educational Demonstrations

Expedition(s): 9-11

Principal Investigator(s):

- Jonathan Neubauer and Matthew Keil, NASA's Johnson Space Center, Houston, Texas

ISS009E15359 - Astronaut Mike Fincke holds a bag of tomato seeds for the Education Payload Operations Tomatosphere II project in the SM during Expedition 9.

RESEARCH OBJECTIVES

Education Payload Operations-Tomatosphere II (EPO-Tomatosphere II) includes curriculum-based educational activities that demonstrate basic principles of science, space, and agriculture. These activities are videotaped and then used in classroom lectures. EPO-Tomatosphere II is designed to support the NASA mission to inspire the next generation of explorers.

EARTH BENEFITS

EPO-Tomatosphere II is part of NASA's continuing effort to use space as a unique educational tool for K-12 students.

SPACE BENEFITS

EPO-Tomatosphere II introduces the next generation of explorers to the environment of space.

RESULTS

The 1.5 million Tomatosphere-II seeds from Expedition 9 were divided and distributed to 160,000 students in 6,000 classrooms across Canada.

This investigation is complete and all results are published.

During a previous Tomatosphere program, students studied the growth of tomato plants in Miss Smith's grade 3 class at Langley Fundamental Elementary, Vancouver, British Columbia, Canada. The students took their plants home to grow in their gardens over the summer. Tomatosphere image.

TOMATOSPHERE-III

Research Area Educational Demonstrations

Expeditions 19-20, 27-36

Principal investigator(s)

- Jason Clement, Canadian Space Agency, Saint Hubert, Quebec, Canada

RESEARCH OBJECTIVES

Tomatosphere-III aims to increase student interest in space science and horticultural technology in addition to increasing student familiarity and experience with research methodologies. Tomatosphere-III sends 600,000 tomato seeds to the International Space Station (ISS) for exposure to the space environment. The seeds are returned to Earth for use in over 13,000 classrooms throughout Canada as a learning resource. Students measure the germination rates, growth patterns, and vigor of growth of the seeds.

Canadian astronaut Chris Hadfield displays the seeds he will return to Earth for the Tomatosphere-III project. Canadian Space Agency/NASA image.

EARTH BENEFITS

This payload allows students to contribute to science at their level, thereby providing them with exposure to the scientific method and research methodologies, and serving to inspire them to pursue their studies and careers in science related fields in order to contribute as the next space generation.

SPACE BENEFITS

The goal of Tomatosphere-III is to evaluate the growth of space-exposed seeds compared to earth-grown seeds.

RESULTS

The project started in 2001 with 2,700 classrooms and has grown to more than 11,000 classes in 2009 (and 13,000 projected for 2010). In the 8-year period, the project has touched more than 1,530,000 students, mostly in Canada, but also in the United States and other countries. Participating teachers praised the program and indicated that it increased students' interest in science (98%), reinforced the scientific method (97%), met their classroom needs (92%), and matched their curriculum needs (96%). The registration process, teacher's guide, and website are all rated as excellent. The project has successfully integrated science promotion goals of the education sector with communication goals of the respective partners on the team (Agriculture and Agri-Food Canada, Canadian Space Agency, Ontario Centers of Excellence, H.J. Heinz of Canada, Stokes Seed Ltd, and the Space and Advanced Life Support Agriculture program of the University of Guelph).

PUBLICATION(S)

Morrow R, Rondeau V, Dixon M. Tomatosphere – Mission to Mars: An evaluation of a space science outreach program. *40th International Conference on Environmental Systems*; 2010.

Morrow R, Dixon M, Thirsk R, Steinberg M. Tomatosphere – To Mars and beyond: An educational outreach project for primary and secondary schools. *57th International Astronautical Congress;* 2006.

Vuk T, Dixon M, Morrow R. Tomatosphere – Mission to Mars: An educational outreach project for primary and secondary schools. *SAE Technical Paper*, 2004;1-2423.

Vuk T, Dixon M, Morrow R. Tomatosphere – Mission to Mars. An educational outreach project for primary and secondary schools. *SAE Transactions*, 2004;113:952-957.

Evans L, Patten L, Steinberg M, Clement J. Canadian Space Learning Network: Inspiring lifelong learning. *54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law*, 2003.

This investigation is complete and all results are published.

TRY ZERO-GRAVITY (TRY ZERO-G)

Research Area: Educational Demonstrations
Expedition(s): 18-20, 22, 23, 28 and 29
Principal Investigator:
- Naoko Matsuo, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

Try Zero-Gravity (TryZero-G) allows the public, specifically children, to vote for and suggest physical tasks for JAXA crew members in order to demonstrate the difference between 0*g* and 1*g* for educational purposes. Some of the tasks include putting in eye drops, performing push-ups on the ceiling, making soap bubbles, and creating string figures.

Astronaut Koichi Wakata conducting the “Water Pistol” activity as part of the Try Zero-G experiment. JAXA image.

EARTH BENEFITS

Try Zero-Gravity (Try Zero-G) allows children to interact with ISS crew members through various activities for educational purposes. These activities help to enlighten the general public about microgravity and human spaceflight and demonstrate that microgravity is useful not only for scientists and engineers, but also for writers, poets, teachers, and artists. The Try Zero-G activities are downlinked, edited, and used to support educational resources for educators throughout Japan.

SPACE BENEFITS

Try Zero-G introduces the next generation of explorers to the space environment.

RESULTS

The demonstrations are filmed and can be viewed at JAXA HP (http://iss.jaxa.jp/kiboresults/utilization/try_zero-g/index.html). Educational tools containing footage of the experiments have been distributed to teachers and are used in the classrooms throughout Japan.

This investigation is ongoing and additional results are pending publication.

European Space Agency – Mission DVD Series (Video-1, Video-2, Video-3, DVD-4)

Four Investigations

Research Area: Educational Demonstrations

Expedition(s): 8, 9, 11, 13, 14

Principal Investigator(s):

- Netherlands (Video-1)
- Manuel Paiva, PhD, Universite Libre de Bruxelles, Brussels, Beglium (Video-2)
- Sylvie Ijsselstein, European Space Agency, Education Office, Noordwijk,Netherlands (Video-3 and DVD-4)

Research Objectives

The DVD (previously known as Video) series of education activities focuses on demonstrating science, mathematics, engineering, technology, and geography principles in a microgravity environment. The activities involve video recording of the demonstrations to be used in classrooms across the ESA member states. The DVD series is aimed at secondary school students in levels 9-12.

Pedro Duque is filmed by Alexander Kaleri for the educational experiment that will demonstrate basic physical phenomena featured in Mission 1 DVD: Newton in Space. ESA image.

Results

During their missions, ESA astronauts Pedro Duque, André Kuipers, Roberto Vittori, and Thomas Reiter participated in this DVD series by performing experiments aboard the International Space Station. Assisted by students on the ground, all aspects of human spaceflight and space in general were touched upon in this series. Twenty thousand prints of each DVD (1-4) have been printed and distributed to European schools. The DVD series is also available on YouTube and has several thousand views months after publication. The DVD series is an ideal, modern, and fast-paced modular film series that can easily be used by teachers to suit their teaching needs. The DVDs cover topics of Newton's Laws, the effect of space on the body, chemistry of matter, and robotics.

The activities have involved more than 10,000 students, 500 teachers, and 500 schools from the following European countries: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Romania, Spain, Sweden, Switzerland, and United Kingdom.

PUBLICATION(S)

Ijsselstein S. Secondary level ESA education demonstrations per soyuz mission. *Microgravity Science and Technology*. September 2007;19(5-6):235-238. doi: 10.1007/BF02919489.

This investigation is complete and all results are published.

VIDEO LESSON EUROPEAN SPACE AGENCY - I (VLE-I)

Research Area: Educational Demonstrations

Expeditions: 18

Principle Investigator(s):
- C. Olivotto, ESA HSO Promotion Office, Noordwijk, Netherlands

RESEARCH OBJECTIVES

Video Lesson European Space Agency - I (VLE-I) focuses on demonstrating the life support and other (health and nutritional) equipment aboard the International Space Station (ISS). The activities involve video recording of the demonstrations to be used in classrooms across the ESA member states.

View of food preparation related to upcoming Video Lesson ESA-1 program. An Ordinary Meal in the Service Module during Expedition 18. Sandra Magnus in view. ESA image.

RESULTS

In January 2009, 2 recording sessions took place on the ISS with ISS Flight Engineer Sandy Magnus filming ISS Commander Mike Fincke during scheduled activities for the experiment on the ISS. This included a number of filmed, scripted scenes that presented “An ordinary meal.” The theme of the various scenes was “A Celebration Meal,” undertaken in the Service Module, Node 1, and the European-built Node-2. The scenes highlighted the importance of communal and celebratory eating, particularly in space where it provides a key opportunity for communication between crew members. It also described ISS food and the differences between American and Russian food.

The recorded footage was made available for use in an ESA Video Lesson about “life support systems” and “Health & Nutrition” fitting the basic European science curriculum of the target age group: 12-18 year olds. It was also made available for distribution to secondary school teachers across ESA Member States.

This investigation is complete; however no publications are expected.

YouTube Space Lab (YouTube Space Lab)

Research Area: Educational Demonstrations

Expedition(s): 29/30

Principal Investigator(s):

- Amr Mohamed, Alexandria, Egypt
- Dorothy Chen, Troy, Michigan
- Sara Ma, Troy, Michigan
- Zahaan Bharmal, Google, London, United Kingdom

View of Expedition 33 Commander Sunita Williams with the YouTube SpaceLab (YTSL) payload Spider Habitat to be packed for return on the Dragon commercial vehicle.

Research Objectives

YouTube and Lenovo, in cooperation with Space Adventures and space agencies, including NASA, ESA, and JAXA, launched the YouTube Space Lab contest, a global initiative that challenges 14 to 18 year old students to design a science experiment that can be performed in space. The winning team's experiment is conducted aboard the International Space Station (ISS), making it the universe's largest science lesson streamed live for the world to see via YouTube. Space Lab is part of a larger YouTube for Schools initiative aimed at highlighting and providing educators access to the wealth of educational content available on YouTube and is also part of Lenovo's focus on equipping students with 21st century skills via personal computer (PC) technology.

Earth Benefits

YouTube Space Lab increases awareness of and generates excitement for the Science, Technology, Engineering, and Mathematics (STEM) areas, space sciences and for the space program in general.

Space Benefits

YouTube Space Lab is a world-wide science contest that highlights the International Space Station (ISS), its uses, and potential.

Nefertiti was another spider sent to the International Space Station for students to observe.

Results

Of the 2,000 entries received from around the world, 60 finalists were selected. A prestigious panel of scientists, crew members, and teachers judge the entries with input from the YouTube community. Six regional finalists gathered in the United States in March 2012 to experience a zero-gravity flight, and those who were not finalists received other prizes. The 2

Cleopatra, one of the two spiders sent to the ISS, lives in the habitat designed for use in space.

global winners saw their experiments performed 250 miles into space and live streamed on YouTube. These experiments examined the predatory behavior of a jumping spider and the anti-fungal properties of *Bacillus subtilis*, a naturally occurring bacteria that is commonly used as an anti-fungal agent for agricultural crops. Also, the global winners choose a unique space experience as a prize: either a trip to Japan to watch their experiment blast off to space or a trip to Russia for an authentic space training experience at the facilities where Yuri Gagarin became a cosmonaut.

This investigation is complete and all results are published.

SPACECRAFT AND MODERN TECHNOLOGIES FOR PERSONAL COMMUNICATIONS (MAI-75)

Research Area: Engineering Education
Expedition(s): 11, 18-38
Principal Investigator(s):
- Oleg M. Alifanov, PhD, Kosmos International Educational-Scientific Center, Moscow, Russia

RESEARCH OBJECTIVES

The Spacecraft and Modern Technologies for Personal Communications (MAI-75) educational experiment is dedicated to developing and validating the structural principles, an information and telecommunications system that offers real-time video information from space to a broad circle of users within the framework of the educational community. MAI-75 creates science-based methods and specialized software and hardware supporting the interaction of various categories of users with the International Space Station (ISS) crew via specialized communication channels through the use of remote user terminals.

MAI Data Reception and Processing Center control room during communication session with the International Space Station. Roscosmos image.

Submitted by: Geoff Carmont, VK2HEF, Australia. Acquired: 05/14/2010, 16:28:00. Roscosmos image.

EARTH BENEFITS

Participants and students gain the opportunity to master methods of recognizing typical elements of the landscape, to perform georeferencing of the photos using maps and atlases, and to use the obtained images within the framework of interdisciplinary communications.

SPACE BENEFITS

The system makes it possible to implement step-by-step development of a satellite video-information system. During the experiment, work is performed to confirm the possibility of transmitting video information from space in real time to publicly accessible ground-based user terminals, including various users in the aerospace-education system.

RESULTS

During the course of the experiment, images in SSTV format were received in various regions of the world. The use of information from space for educational purposes makes it possible to increase the effectiveness of teaching disciplines in the natural-science curriculum, to attract the public's attention to the progress of the space program and the possibilities of obtaining direct, practical returns. The experience from the work performed within the framework of MAI-75 shows the great potential of the ISS RS as a platform for a broad array of educational experiments.

PUBLICATION(S)

Alifanov OM, Firsyuk SO, Odelevskiy VK. Use of the results of space activity in education. *Polyet*. 2011;(4):157-165.

Alifanov OM, Biryukova MV, Odelevskiy VK, et al. Main results and development prospects for the Space Educational Experiment MAI-75 on board the ISS Russian Segment. *Proceedings of the K.E. Tsiolkovskiy Memorial Scientific Lectures,* Kaluga; 2010.

Alifanov OM, Odelevskiy VK, Firsyuk SO, Khokhulin VS. The practice of using space information in the personnel-training system for rocket-space enterprises. *34th Academic Lectures on Cosmonautics.* 2010.

Alifanov OM, Firsyuk SO, Khokhulin VS, Odelevskiy VK, Samburov SN, Spirin AI. The MAI-75 Experiment Space Program basic results and prospects of its progress. *Kosmonavtika i Raketostroyeniye* (*Cosmonautics and Rocket-Building*). 2007;4(49):145-149.

Alifanov OM, Odelevskiy VK, Samburov SN, Spirin AI, Firsyuk SO, Khokhulin VS. SOVIK satellite educational video information complex and educational experiments on the ISS. *Proceedings of the 8th International Forum on High Technologies of the 21st Century*. Moscow Expocenter Central Exhibition Complex*;* April 23-26, 2007.

Alifanov OM, Lamzin VA, Odelevskiy VK, Firsyuk SO, Khokhulin VS. Space Experiment MAI-75. *4th International Conference on Aviation and Cosmonautics*. 2005.

This investigation is complete; however additional results are pending publication.

Analysis of Inertial Solid Properties (APIS)

Research Area: Student-Developed Investigations
Expedition(s): 8
Principal Investigator:
- Ana Laveron-Simavilla, Universidad Politecnica de Madrid, Spain

Research Objectives

Analysis of Inertial Solid Properties (APIS) demonstrates solid body rotation principles and prepares a video for later use in education. APIS focuses on the behavior of a rigid body rotating around its center of mass. The experiment was only concerned with torque-free rotational motion.

Analysis of Inertial Solid Properties experimental configuration. ESA image.

Results

The experiment showed the different types of motion that could appear depending on the mass distribution of the body and on the mechanical energy dissipation effect due to external or internal actions. An undesirable effect of internal energy dissipation is to change the axis of rotation. Similar changes of the spin axis may appear also by changes such as deployment of booms, solar panels, antennae, etc.

Several videos showing both stable and unstable configurations were recorded in the International Space Station during ESA's Cervantes (Soyuz 7S / 6S exchange) mission. Later, on ground, the videos were analyzed and reproduced with analytical and numerical models. The materials produced allow students to gain a global comprehension of the dynamics of solid body rotation and its dependence on the distribution of mass within the body.

Publication(s)

Laverón-Simavilla A, Lapuerta V, Esteban J, Lloret J, Costa M, Fernández JJ. Apis experiment during the Spanish Soyuz Mission Cervantes. *Microgravity Science and Technology*. 2007;19(5-6):253-259. doi: 10.1007/BF02919493.

This investigation is complete and all results are published.

BUG ENERGY- STUDY OF OUTPUT OF BACTERIAL FUEL CELLS IN WEIGHTLESSNESS (BUGNRG)

Research Area: Student-Developed Investigations
Expedition(s): 9
Principal Investigator:
- Sebastian de Vet, Technical University of Delft, Netherlands

RESEARCH OBJECTIVES

The Bug Energy-Study of Output of Bacterial Fuel Cells in Weightlessness (BugNRG) experiment studies the influences of weightlessness on the output of bacterial fuel cells, using the *Rhodoferax ferrireducens* strain. The aim of the set-up is to acquire precision data of the output during a total drain of a fuel cell in weightlessness. This is the first time that bacterial fuel cells have been tested in space. Currently foreseen applications are very promising for spaceflight and include waste disposal on human spaceflight missions.

Bacterial Fuel Cells. R. Rutgers, S.J. de Vet image.

RESULTS

Due to differences in magnitude of the output the data had to be normalized and cumulatively plotted. In all, it can be concluded that bacterial fuel cells showed similar phases in the output under different gravitational conditions. Hence it can be concluded from a biological point of view that bacterial fuel cells do operate in space.

PUBLICATION(S)

De Vet SJ, Rutgers R. From waste to energy: First experimental bacterial fuel cells onboard the International Space Station. *Microgravity Science and Technology*. 2007;19(5-6):225-229. doi: 10.1007/BF02919487.

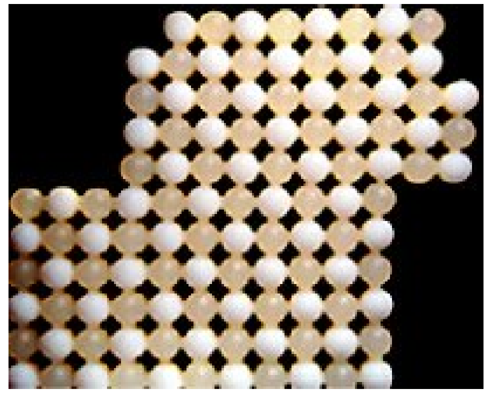
This investigation is complete and all results are published.

Electrostatic Self-assembly Demonstration (ESD)

Research Area: Student-Developed Investigations
Expedition(s): 10 and 11
Principal Investigator:
- W. Carey, ESA/ESTEC, Noordwijk, Netherlands

Research Objectives

The Electrostatic Self-assembly Demonstration (ESD) education experiment is aimed at demonstrating the electrostatic self-assembly of 2 different types of macroscopic spheres of identical dimensions to create different molecular structures in weightless conditions aboard the International Space Station by means of filming 3 demonstrations. Comparable on-ground experiments were performed and filmed in order to familiarize students with the differences between the Earth and space environments.



Electrostatically assembled square structure with 2 different types of spheres alternating within the lattice. ESA image.

Results

During the demonstration, organized structures of PMMA/PTFE spheres were formed, but instead of forming one large 3-D cluster in the center of the container as anticipated, numerous, smaller individual clusters were observed, the majority of which attached themselves to the inner surfaces of the container. However, a small number of 3-D structures were seen in the stills from the video sequences.

The contact electrification appeared to have charged the particles strongly such that they were attracted to the inner surface of the container—this behavior had been observed during an earlier parabolic flight test, but not to the extent visible during the ENEIDE Mission.

Footage of the "on-ground" and "in space" demonstrations were recorded, and the footage used to develop an International Space Station DVD lesson, fitting the basic European science and technology curriculum of the target age group: 12-18 year olds. The DVD was distributed in 12 languages to secondary school teachers in ESA Member States.

Publication(s)

AG Noordwijk. *Project: Zero Gravity, Mission 3: Space Matters* [DVD]. European Space Agency ISS Education Office, The Netherlands; 2006.

Grzybowski BA, Winkleman A, Wiles JA, Brumer Y, Whitesides GM. Electrostatic self-assembly of macroscopic crystals using contact electrification. *Nature Materials*. March 23, 2003;2(4):241-245. doi: 10.1038/nmat860.

This investigation is complete and all results are published.

NanoRacks-National Center for Earth and Space Science Education (NanoRacks-NCESSE-1 & NanoRacks-NCESSE-2), Two Investigations

Research Area: Student-Developed Investigations
Expedition(s): 27 and 28
Principal Investigator(s):
- Jeff Goldstein, PhD, National Center for Earth and Space Science Education, Capitol Heights, Maryland

Students manipulating robotics. NASA image.

Research Objectives

NanoRacks-NCESSE-1 and -2 are part of a commercial program that incorporates the science projects of schools from across the United States. Students design their own experiments using flight-approved fluids and materials that are flown on the Materials Diffusion Apparatus (MDA) or MixStix NanoLabs in a NanoRacks module. Students complete proposals for a flight opportunity, experience a science proposal review process, complete a flight safety review, and attend their own science conference. The goal of this program is to allow students to experience scientific exploration through their own involvement.

Earth Benefits

The long-term goal of this project is to enhance technological, industrial, and educational growth for the benefit of people on Earth.

Space Benefits

This investigation is a part of a series of investigations to be conducted aboard the International Space Station (ISS) to provide the foundation for use of the ISS as a National Laboratory following assembly complete.

Results

As a result of the NCESSE Student Spaceflight Experiments Program (SSEP) announcements of opportunity, 39 communities across the United States have joined the program, providing 71 900 students in grades 5 through 14 the opportunity to participate.

NanoRacks-NCESSE-1	School	Grade	City, State
Development of Prokaryotic Cell Walls in Microgravity	Shelton High School	12	Shelton, Connecticut
Apples in Space	Crystal Lake Middle School	8	Broward County, Florida

NanoRacks-NCESSE-1	School	Grade	City, State
The Effect of Microgravity on the Ability of Ethanol to Kill E. Coli	Maitland Middle School	8	Orange County, Florida
Efficiency of Microencapsulation in Microgravity as Compared to Gravity	Lincoln Hall Middle School	6	Lincolnwood, Illinois
The Effect of Microgravity on the Viability of *Lactobacillus GG*	The Academy @ Shawnee	9-11	Jefferson County, Kentucky
What is the Effect of Microgravity on the Growth Rate of Murine Myoblasts?	Copper Mill Elementary School	5	Zachary, Louisiana
Swimming Patterns and Development of Zebra Fish After Exposure to Microgravity	Esperanza Middle School	8	Saint Mary's County, Maryland
Honey as a Preservative on Long-Duration Spaceflights	Harry A. Burke High School	10	Omaha, Nebraska
Effects of Microgravity on Lysozyme's Antibacterial Properties	Omaha North High Magnet School	12	Omaha, Nebraska
Does the Radiation Exposure Effect Seed Germination Without the Protection of the Ozone Layer?	Tse' Bit' Ai Middle School	8	Shiprock, New Mexico
The Development of Minnow Fish Eggs in Space	Milton Terrace South Elementary School	5	Ballston Spa, New York

NanoRacks-NCESSE-2	School	Grade	City, State
Microgravity Yeast Experiment	Parkridge Elementary School	7	Peoria, Arizona
Microgravity's Effect on Tomato Growth	Annie Fisher STEM Magnet School	8	Hartford, Connecticut
Will Microgravity Effect the Development of Goldfish	Skinner West Classical, Fine Arts, and Technology School	5	Chicago, Illinois
All Mixed Up (Based on Gause's 1932 Experiment): The Effect of Microgravity on the Interaction of *Paramecium bursaria* and	Avicenna Academy and Life Learning Cooperative	4-6, 4-12	Crown Point, Indiana

NanoRacks-NCESSE-2	School	Grade	City, State
Paramecium caudatum in a Mixed Culture, Using Yeast and Bacteria as a Food Source			
How Does Microgravity Affect the Maximum Cell Size of Tardigrades?	Ridge View High School	9-11	Galva-Holstein, Iowa
Physiological Effects of Microgravity on Germination and Growth of *Arabidopsis thaliana*	Henry E. Lackey High School	9-12	Charles County, Maryland
The Growth Rate of *Lactobacillus acidophilus* in Microgravity	Montachusett Regional Vocational Technical High School	11	Fitchburg, Massachusetts
Effects of Microgravity on Goodstreak Wheat	Potter-Dix Schools	6-12	Potter and Dix, Nebraska
The Effects on Microgravity on Oil Production in Salt-Stressed *Chlamydomonas reinhardtii*	Lincoln Public Schools Science Focus Program	11-12	Lincoln, Nebraska
Effects of Microgravity on Osteoblast Specialization and Bone Growth	Bridgewater-Raritan High School	11-12	Bridgewater-Raritan, New Jersey
Deposition and Formation of Zinc Phosphate Crystals in Microgravity	Yeshiva Ketana of Long Island	6-7	Inwood, New York

This investigation is complete and all results are published.

NanoRacks-Valley Christian High School (NanoRacks-VCHS), Four Investigations

Research Area: Student-Developed Investigations
Expedition(s): 29 and 30
Principal Investigator(s):
- Valley Christian High School, San Jose, California

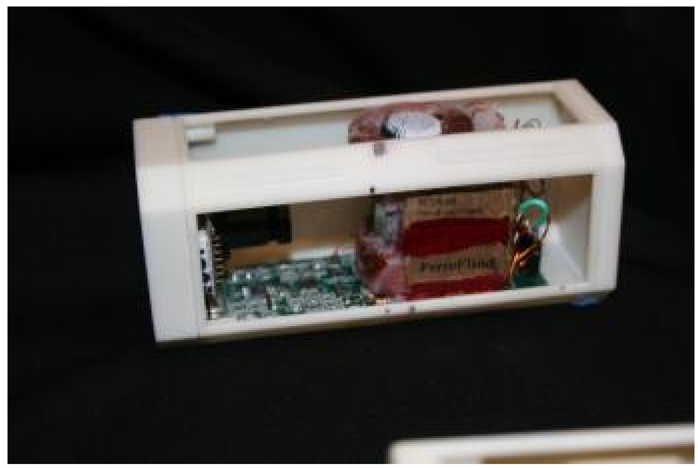
Research Objectives

Bacillus Subtilis Bacteria Growth

NanoRacks-Valley Christian High School-*Bacillus Subtilis* Bacteria Growth (NanoRacks-VCHS-*B. Subtilis*) studies the growth and growth rate of *Bacillus subtilis* bacteria in microgravity. Beef broth is added to the *Bacillus subtillis,* and the rate of growth is determined by measuring the amount of light shining through the bacteria-broth solution over time by using lumen sensors and analyzing the bacteria photos.

Electromagnetic Effects on Ferrofluid

NanoRacks-Valley Christian High School-Electromagnetic Effects on Ferrofluid (NanoRacks-VCHS-Electromagnetic Ferrofluid) studies the effects of a variable magnetic field on ferrofluids in microgravity. Three-D figures formed by the varying magnetic field are photographed and downlinked to the students daily to be analyzed and compared with those formed on the ground.



NanoRacks-Valley Christian High School-Electromagnetic Effects on Ferrofluid Ground Test Unit. Valley Christian High School image.

Electroplating

NanoRacks-Valley Christian High School-Electroplating (NanoRacks-VCHS-Electroplating) studies the effects of electroplating gold and bronze in microgravity aboard the station and compares the results of identical electroplating on Earth. Samples of electroplating in space and on the ground are analyzed with Valley Christian's atomic force microscope.

Plant Growth

NanoRacks-Valley Christian High School-Plant Growth (NanoRacks-VCHS-Plant Growth) examines the growth and growth rate of marigold and thyme seeds in microgravity. With the bank of light-emitting diodes to simulate the sun, 2 Wisconsin fast plants and 2 English thyme plants are watered at a predetermined rate and photographed to measure the rate of growth. The growth is compared with the growth of the same plants grown on the ground.

Earth Benefits

NanoRacks-VCHS allows students at Valley Christian High School to participate in an out of this world experiment to determine how microgravity affects several different research areas including bacterial growth, ferrofluids, electroplating, and plant growth. A better understanding of the fundamental properties benefits each discipline individually. The color photos from the ferrofluids experiment are beautiful and artistic and help bridge science and the arts. A better and more consistent method of electroplating could result in the start of a new commercial space plating industry that would result in more jobs and plating applications. A similar and larger automated plant growth design could be used to grow plants in any area of a home, including the basement and attic, reducing the amount of land required to provide food for the world's rapidly increasing human population.

NanoRacks-Valley Christian High School-Electroplating Experiment Ground Test Unit. Valley Christian High School image.

SPACE BENEFITS

In order to ensure crew health during spaceflight and long-duration missions, an understanding of how bacteria behave in microgravity leads to better prevention and treatment of infections. Understanding ferrofluids is also important because if they can be moved by the application of a magnetic field, they could be made part of a restartable space liquid propulsion system that would be moved toward the nozzle before ignition. This would eliminate the need to have heavy liquid containment screens within the propellant tanks. Electroplating is also of importance because if it is determined that electroplating in space produces more consistent plating than plating on the ground, this could result in the start of a new commercial space plating industry. Lastly, if crew members are going to travel to Mars, and they do not have sufficient room to take all the food required for the 3-year trip, they will have to grow some of their food aboard the space vehicle. Research is required to determine the best method to provide an automated plant growth system.

RESULTS

A total of 4 teams consisting of 38 Valley Christian High School Students were given a NanoLab to house its microgravity science experiment in. Each team was responsible for selecting, designing, building, programming, and testing its own investigation.

This investigation is complete and all results are published.

NanoRacks-Whittier Christian High School-E. Coli Bacteria and Kanamycin Antibiotic (NanoRacks-WCHS-E. Coli and Kanamycin)

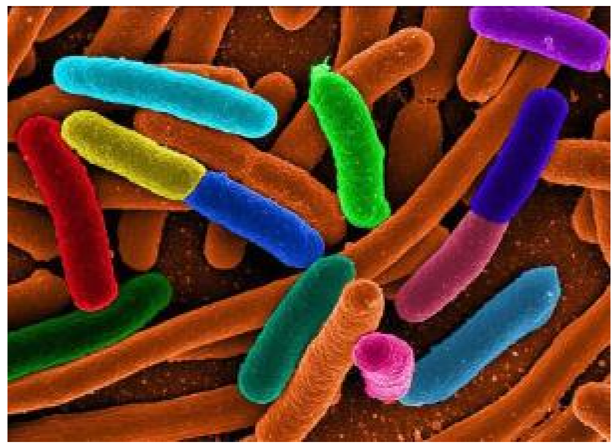
Research Area: Student-Developed Investigations
Expedition(s): 29 and 30
Principal Investigator(s):
- Whittier Christian High School, La Habra, California

Research Objectives

NanoRacks-Whittier Christian High School-E.Coli Bacteria and Kanamycin Antibiotic (NanoRacks-WCHS E. Coli and Kanamycin) is a NanoLab project studying the growth of Escherichia coli (E. coli) bacteria in microgravity and the E. coli bacteria's resistance to the antibiotic Kanamycin by varying the antibiotic dosage.

Earth Benefits

Escherichia coli (E. coli) bacteria cause major illnesses. The microgravity environment on the International Space Station (ISS) provides a means to determine the degree of antibiotic resistance and dosage level required to eliminate bacterial colonies. Removing gravity has proven to cause bacteria to grow differently and by determining dosage response in microgravity to ground controls, improved treatment methodologies might be developed.



This image shows a microscopic view of E. coli (Escherichia coli) bacteria that is enhanced with color. Science Kids image.

Space Benefits

Escherichia coli (E. coli) bacteria are found as normal flora in the human body. While most strains are harmless, some can cause major illness. It is important to determine the antibiotic resistance of *E. coli* in order to treat crew members who might potentially be infected by this bacteria.

Results

Students studied the growth of green fluorescent protein tagged *Escherichia coli* (*E. coli*) bacteria in microgravity and the *E. coli* bacteria's resistance to the antibiotic Kanamycin by varying the antibiotic dosage. Photos of the bacteria were taken to determine its growth as measured by the amount of fluorescence. The bacteria's resistance to antibiotics was determined by measuring the decrease in fluorescence.

This investigation is complete and all results are published.

Space Experiment Module (SEM)

Research Area: Student-Developed Investigations

Expedition(s): 10-11, 13 and 14

Principal Investigator(s):
- Ruthan Lewis, PhD, NASA's Goddard Space Flight Center, Greenbelt, Maryland

Research Objectives

The Space Experiment Module (SEM) introduces students to the concept of performing space-based research on the International Space Station (ISS). SEM provides students with the opportunity to conduct their own research on the effects of microgravity, radiation, and spaceflight on various materials.

Earth Benefits

Eleven schools are running experiments on the first Space Experiment Module (SEM) satchel flight. The experiments are contained in clear polycarbonate vials. These vials are also flown in passive (no power required) SEM experiment modules. Students create their own experiments, and consider such variables as space radiation, microgravity, and launch environment. SEM is educating and inspiring the next generation to take the journey.

View of Expedition 13 Space Experiment Module (SEM) Satchel number 3 open showing vials; Part Number (P/N) GE2067544-003, Barcode 00031809G. Photo taken in the U.S. Laboratory/Destiny on the International Space Station during Expedition 13.

Space Benefits

SEM introduces the concept of space-based scientific experiments to the next generation.

Results

Eleven schools and 3,300 students developed experiments for SEM Satchel 001. The satchel was launched during ISS Expedition 10 in December 2004 and returned to Earth on Space Shuttle *Discovery* (STS-114) in August 2005. The sample vials were returned to the students for analysis.

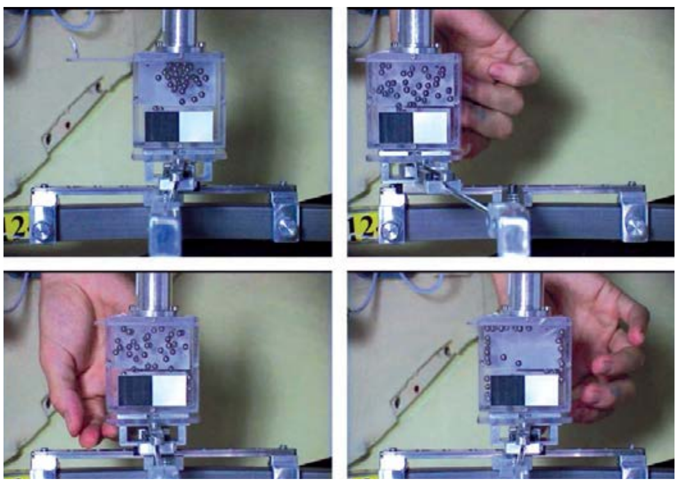
This investigation is complete and all results are published.

TEST OF THE BASIC PRINCIPLES OF MECHANICS IN SPACE (THEBAS)

Research Area: Student-Developed Investigations
Expedition(s): 7 and 8
Principal Investigator:
- Ana Laveron Simavilla, Universidad Politecnica de Madrid, Spain

RESEARCH OBJECTIVES

Test of the Basic Principles of Mechanics in Space (Thebas) prepares a video for educational use that would illustrate the principles of dynamics ranging from the classic mechanics of solid bodies to the continuous media mechanics. The experimental setup used to perform the experiment consisted of transparent closed containers (having the same size and total mass) filled with solid spheres of different sizes that were periodically oscillated in one dimension.



Sequence of experiment images showing spheres being accelerated. ESA image.

RESULTS

The figure (left) is a sequence of the experiment container with 48 spheres: (a) The spheres coming out of the small holder, (b) the container sliding to the end of the sliding guide, (c) the container in motion, and (d) the configuration after the stop of oscillation. There is a difference between spheres distribution in (c) and (d). The behavior of the spheres in (d) was due to electrostatic effects that affected the motion of the spheres inside the container in a way that was not expected, changing the dynamics of collisions between spheres and between the spheres and the container. This effect was more important for the containers with higher number of spheres.

Another problem was that the lubricant was too viscous and the guide did not slide properly, reducing oscillation displacement. For safety reasons all the sliding parts of the experiment had to be lubricated by a specific lubricant, but it was not possible to test the hardware with the lubricant in advance.

Several improvements could be made in the future. Proofs with different allowed lubricants should be performed in advance to achieve the desired slide. An important part of the experiment was the study of the container with the fluid; therefore, a triple level of containment container would need to be designed, to fulfil the safety specifications in the International Space Station. Finally, a study of the materials to be used would need to be done to avoid the electrostatic forces, irrelevant in the ground experiments but important in microgravity conditions.

Publication(s)

Lapuerta V, Laveron-Simavilla A, López EJ, Rodríguez J. Thebas experiment during the Spanish Soyuz Mission Cervantes . *Microgravity Science and Technology*. September 2007;19(5-6):249-252. doi: 10.1007/BF02919492.

This investigation is complete and all results are published.

UNIVERSITY RESEARCH CENTERS-MICROBIAL-1 (URC-MICROBIAL-1)

Research Area: Student-Developed Investigations
Expedition(s): 21 and 22
Principal Investigator(s):
- Olufisayo Jejelowo, PhD, Texas Southern University, Houston, Texas

Students in the Center for Bio-nanotechnology and Environmental Research at Texas Southern University prepare samples for the URC-Microbial-1 investigation. Texas Southern University image.

RESEARCH OBJECTIVES

University Research Centers-Microbial-1 (URC-Microbial-1) evaluates morphological and molecular changes in *Escheria coli* and *Bacillus subtilis* in microgravity. This investigation is a proof-of-concept model providing spaceflight experience to stimulate and excite University Research Center scientists and students at Texas Southern University. The experiment involves the study of morphological and molecular changes of *Escheria coli* and *Bacillus subtilis* microbes brought about by the spaceflight environment.

EARTH BENEFITS

URC-Microbial-1 identifies ways in which microorganisms impact human health and life and allow student from underrepresented minority university to explore research careers in space and space science.

SPACE BENEFITS

This investigation is a part of a series of investigations to be conducted aboard the ISS to provide the foundation for use of the ISS as a National Laboratory following assembly complete.

RESULTS

Each component of the experiment was designed to be reproduced easily in the classroom, providing hands-on experience to the students who were involved. Postflight repeat experiments were conducted in schools across the nation, and samples from this flight experiment were shared among principal investigators in other institutions. Texas Southern University developed courses incorporating the data into the microbiology curriculum.

This investigation is complete and all results are published.

UNDER THE BACKGROUND INFLUENCE (UTBI)

Research Area: Student-Developed Investigations
Expedition(s): 14
Principal Investigator:

- Nuria Escobar, Universidad de Valencia, Spain
- Candid Reig, Ph., Universidad de Valencia, Spain
- Ernesto Lopez-Baeza, PhD, Universidad de Valencia, Spain
- Javier Sanchis, Universidad de Valencia, Spain
- Nuria Escobar, Universidad de Valencia, Spain
- Maria Moreno, Universidad de Valencia, Spain
- Rafael Gisbert, Universidad de Valencia, Spain
- V. Reglero
- J. M. Rodrigo

RESEARCH OBJECTIVES

The main goal of Under the Background Influence (UTBI) is the measurement of the background radiation inside spacecraft. Measurements of the X-ray, gamma ray, and other particles (protons, neutrons, electrons) have a very important effect outside the Earth's geomagnetic field, which can help in the development of future space vehicles and other space technologies.

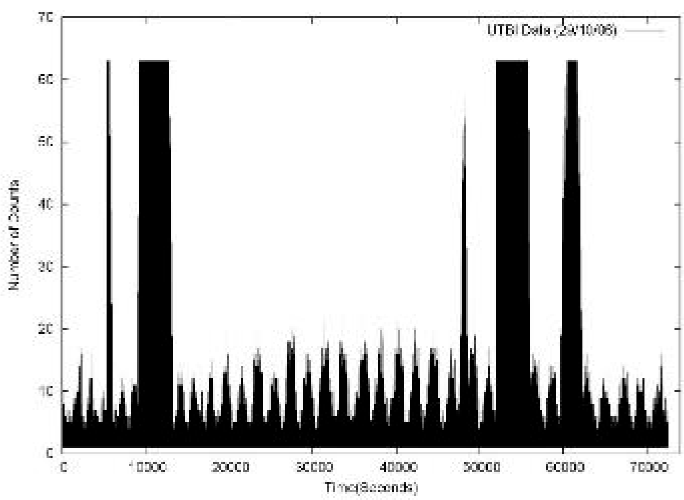


Image plot of Under the Background Influence image date over time. ESA image.

RESULTS

The radiation aboard the International Space Station has been measured. The fluctuation of the radiation along the orbit has been measured. The influence of the Earth Magnetic Field (L-Shell) and the South Atlantic Anomaly has been imaged (representative image to the left).

This investigation is complete; however no publications are expected.

HUMAN RESEARCH

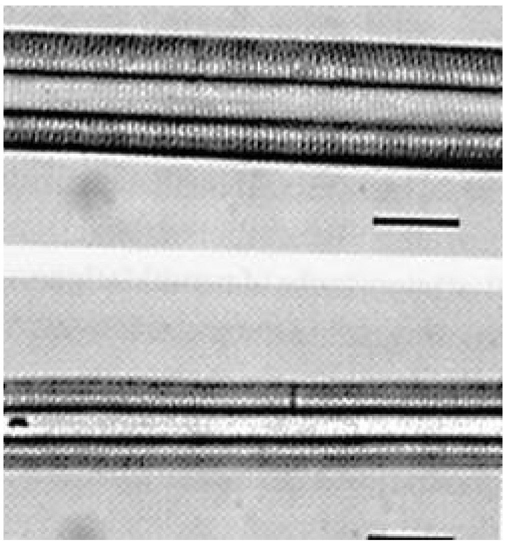
ISS is being used to study the risks to human health that are inherent in space exploration. Many research investigations address the mechanisms of the risks—the relationship to the microgravity and radiation environments—and other aspects of living in space, including nutrition, sleep, and interpersonal relationships. Other experiments are used to develop and test countermeasures to reduce these risks. Results from this body of research are critical enablers for missions to the lunar surface and future Mars exploration missions.

EFFECT OF PROLONGED SPACEFLIGHT ON HUMAN SKELETAL MUSCLE (BIOPSY)

Research Area: Bone and Muscle Physiology
Expeditions: 5-7 and 9-11
Principal Investigator(s):
- Robert H. Fitts, PhD, Marquette University, Milwaukee, Wisconsin

RESEARCH OBJECTIVES

Biopsy examines calf muscle samples of crew members before and after their stay aboard the International Space Station (ISS) to study muscle adaptation to weightlessness. This investigation helps to develop exercise program aimed at keeping muscles at their peak performance during long-duration space missions.



This photomicrograph shows normal skeletal muscle fibers (above) and atrophied skeletal muscle fibers (below). Note the marked decrease in size of the atrophied skeletal muscle below. NASA image.

EARTH BENEFITS

As people age on Earth, muscle tissue tends to lose elasticity. The results of this research provide a better understanding of muscle atrophy in the elderly population on Earth.

SPACE BENEFITS

It is well established that muscle mass and strength decrease during spaceflight. The atrophy of muscles in space affects not only the performance of crew members during missions, but can lead to severe muscle injuries upon return to Earth. Astronauts landing on Mars may be susceptible to muscle injury once they step onto the planet. The exact cellular and biochemical events that produce these losses of mass and strength are not as well understood. Biopsy is the first experiment to tackle the cellular question in long-term spaceflight. The data from this experiment are used to illustrate the structural and metabolic changes that occur within individual muscle fiber cells. This experiment also helps to create a model that illustrates to what degree muscles deteriorate in space over time, which can be used to predict risks for long-term flight. As the mechanisms of muscle deterioration during spaceflight become clearer, scientists can pursue new methods to protect muscles for long missions.

RESULTS

This study examined calf muscle physiology and performance of the astronauts who completed exercise routines on various exercise systems during their 6-month stay on the ISS. Specifically, calf muscle volume, calf muscle performance, and muscle fiber physiology and microanatomy were assessed before and after spaceflight. Data showed a reduction in calf muscle mass and performance along with a slow-to-fast fiber type transition in the calf muscles. The decrease in muscle performance, combined with muscle physiological and anatomical changes (transition of the slow fiber types into the fast fiber types, increased thin filament density, and decreased fiber diameter and overall muscle volume), show the exercise countermeasures did not provide the intensity needed to maintain calf muscle performance and structure (Trappe 2009 and Fitts 2010). Fast-twitch muscle fibers contract quickly but get tired quickly so a substantial microgravity-induced muscle fiber shift from the slow to fast type over long-duration spaceflight would be physiologically harmful and would increase the crew's risk of injury, impacting mission objectives. After several ISS missions and long-term bed rest experiments in the last decade, enough data now exists to warrant changes to the astronaut exercise regimen. Since completing this study, a second treadmill was added, the Combined Operational Load-Bearing External Resistance Treadmill (COLBERT) to ISS and an improved resistance exercise device, the Advanced Resistive Exercise Device (ARED). This allows for greater musculoskeletal loading during exercise. A new high-intensity, low-volume resistance and aerobic exercise program is also being implemented. The latest regimen alternates days of high-intensity interval training with continuous aerobic exercise (opposed to mostly continuous aerobic exercise) and 3 days/week of high-intensity resistance training (opposed to 3-6 days/week at lower intensity). Ongoing research is investigating the effectiveness of the new exercise program for protecting skeletal muscle health over long stays aboard the ISS (Bagley 2012).


ISS030E148397 – European Space Agency astronaut Andre Kuipers, Expedition 30 flight engineer, prepares to exercise in the Tranquility node of the International Space Station (ISS), using the Advanced Resistive Exercise Device (ARED).

PUBLICATION(S)

Fitts RH, Colloton PA, Trappe SW, Costill DL, Bain JL, Riley DA. Effects of prolonged spaceflight on human skeletal muscle enzyme and substrate profiles. *Journal of Applied Physiology*. September 1, 2013; 115(5):667-679. doi: 10.1152/japplphysiol.00489.2013.

Bagley JR, Murach KA, Trappe SW. Microgravity-induced fiber type shift in human skeletal muscle. *Gravitational and Space Biology.* 2012;26:34-40.

Fitts RH, Trappe SW, Costill DL, et al. Prolonged spaceflight-induced alterations in the structure and function of human skeletal muscle fibers. *Journal of Physiology.* 2010;588:3567-3592. doi: 10.1113/jphysiol.2010.188508.

Trappe SW, Costill DL, Gallagher PM, et al. Exercise in space: Human skeletal muscle after 6 months aboard the International Space Station. *Journal of Applied Physiology.* January 15, 2009; 106: 1159-1168. doi: 10.1152/japplphysiol.91578.2008.

This investigation is complete and all results are published.

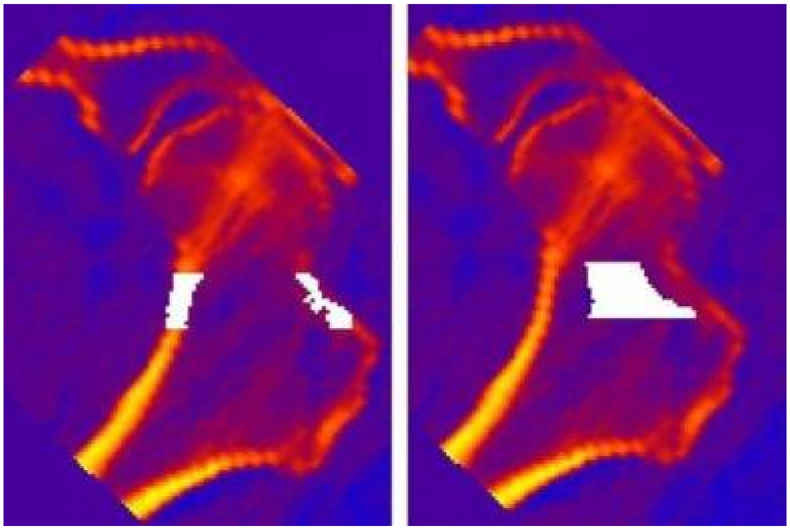
BISPHOSPHONATES AS A COUNTERMEASURE TO SPACEFLIGHT-INDUCED BONE LOSS (BISPHOSPHONATES)

Research Area: Bone and Muscle Physiology
Expeditions: 18-30
Principal Investigator(s):

- Adrian D. Leblanc, PhD, Universities Space Research Association, Houston, Texas
- Toshio Matsumoto, PhD, MD, University of Tokushima, Kuramoto, Japan

RESEARCH OBJECTIVES

The purpose of the Bisphosphonates study is to determine whether an antiresorptive agent, in conjunction with the routine in-flight exercise program, protects International Space Station (ISS) crew members from the regional decreases in bone mineral density documented on previous ISS missions.



Pictured is 1-mm-thick sections through the mid frontal plane of the hip, showing regions of evaluation in white superimposed on a false color image of the Quantitative Computed Tomography (QCT) data. The left-hand image shows the cortical region of the femoral neck, and the right-hand image shows the trabecular bone regions. NASA image.

EARTH BENEFITS

The benefits of this research are primarily for space travelers. However, knowledge gained from this investigation may generate useful information applicable to patients on Earth with accelerated bone loss because of disuse (eg, spinal cord injury patients or those with prolonged immobilization).

SPACE BENEFITS

If shown to be an effective countermeasure to spaceflight-induced bone loss, bisphosphonates could prevent or reduce several potential bone-related problems identified in NASA's Critical Path Roadmap. If bisphosphonates improve the efficiency of in-flight exercise to maintain bone mass, then more crew time could be made available for other purposes.

RESULTS

Seven ISS astronauts who spent a mean of 5.5 months on the ISS were given an oral dose of 70 mg of alendronate (a bisphosphonate drug used to treat the thinning of bone, ie, osteoporosis) weekly starting 3 weeks before flight and continuing throughout the mission to study the effectiveness of alendronate on reducing bone loss. All crew members had a treadmill, cycle ergometer, and a resistance exercise device available for exercise. Bone assessment included densitometry of multiple bone regions using X-ray absorptiometry (DXA) and quantitative computed tomography (QCT) and assays of biomarkers of bone metabolism. In addition to pre- and post-flight measurements, these results are compared to data from 18 astronauts who flew ISS missions and who exercised using an early model resistance exercise device called the interim resistance exercise device and 11 ISS astronauts who exercised using the newer Advanced Resistance Exercise Device (ARED). Findings indicate that the ARED provided significant lessening of bone loss compared with the older device, although some post-flight decreases in the femur neck and hip remained. The combination of ARED and bisphosphonate lessen the expected decline in essentially all indices of altered bone physiology during spaceflight. Losses in bone mineral density of the spine, hip, and pelvis, as well as measurements of fall and stance bone strength of the hip, bone resorption markers, and urinary calcium show that the combination of exercise plus an antiresoptive drug may be useful for protecting bone health during long-duration spaceflight.

Publication(s)

Leblanc AD, Matsumoto T, Jones JA, et al. Bisphosphonates as a supplement to exercise to protect bone during long-duration spaceflight. *Osteoporosis International.* July 2013;27(7):2105-2114. doi: 10.1007/s00198-012-2243-z.

This investigation is ongoing and additional results are pending publication.

CREWS HEALTH: INVESTIGATION ON REDUCED OPERABILITY (CHIRO)

Research Area: Bone and Muscle Physiology
Expedition(s): 4
Principal Investigator(s):
- Paolo Pastacaldi, Hospital Santa Chiara, Pisa, Italy
- Valfredo Zolesi, Kayser Italia, Livorno, Italy

RESEARCH OBJECTIVES

Experiments on the upper limbs are becoming more significant in human spaceflight; being the principal means of locomotion and fatigue can have a significant effect on the hand for ordinary work and in particular for spacewalks. Crew's Health: Investigation on Reduced Operability (CHIRO) provides early data within a wide range of research on human upper limb behavior and performances. The purpose of the experiment is to determine the influence of the microgravity on the control of the grip force exerted by the hand or by a group of fingers and the adaptive behavior of this control through long-term exposure to microgravity.

Astronaut Roberto Vittori uses the Hand Grip Dynamometer on the International Space Station in 2002. ESA image.

RESULTS

In general, a loss of motor control was observed in the blind period of contraction due to the absence of visual feedback; as soon as the visual feedback was restored (at the beginning of the final period), the test subject tried again to reach the fixed threshold, even if attempts were often nullified by the arising muscle fatigue. The weightlessness influenced the motor control and the capability of keeping muscle contraction constant was much stressed. So the Static Effort, after an early increase, recovered the initial values, whereas the Root Mean Square was often still increasing; this can lead to different hypothesis: a) the biomechanic system gain (amplification factor) increases due to the absence of gravity; even if the stimuli to keep the fixed force level are the same, the Root Mean Square of oscillations increases. b) the biomechanic system gain does not change, but the stimuli is higher. Finally, the collected data confirmed the increasing of Root Mean Square during the blind period of experiment independently of weightless effects.

PUBLICATION(S)

Pastacaldi P, Orsini P, Bracciaferri F, et al. Short term microgravity effect on isometric hand grip and precision pinch force with visual and proprioceptive feedback. *Advances in Space Research.* January 2004;33(8):1368-1374. doi: 10.1016/j.asr.2003.09.040.

This investigation is complete and all results are published.

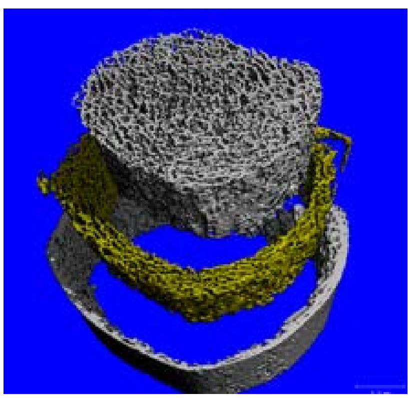
EARLY DETECTION OF OSTEOPROSIS IN SPACE (EDOS)

Research Area: Bone and Muscle Physiology
Expedition(s): 15-22, 29-ongoing
Principal Investigator(s):

- Christian Alexandre, MD, University of St-Etienne, St-Etienne, France
- L. Braak, University of St-Etienne, St-Etienne, France
- Laurence Vico, PhD, University of St-Etienne, St-Etienne, France
- Peter Ruegsegger, Swiss Federal Institute of Technology, Zürich, Switzerland
- Martina Heer, PhD, German Aerospace Center, Cologne, Germany

RESEARCH OBJECTIVES

The Early Detection of Osteoporosis in Space (EDOS) experiment is testing the skeletal adaptation to long-term space exposure by 3-dimensional peripheral quantitative computed tomography (3DpQCT) as a technique for detection of bone structure. Its goal is to provide a detailed evaluation of the bone loss and kinetics of recovery after flight.



Xtreme CT distal radius. Image provided courtesy of SCANCO Medical. ESA image.

EARTH BENEFITS

With crew members exhibiting bone loss similar to osteoporosis in space, ie, about 1% loss per month in space, this research should significantly contribute to the development of a reference technique to perform an early detection of osteoporosis on Earth. These improved diagnostics in the early stages of such a medical condition may prove extremely important in development of more effective countermeasures to the effects of osteoporosis. The 3DpQCT scanner used in EDOS, which the European Space Agency supported the development of for a non-invasive/in vivo technique for bone structure observation, has already been commercialized successfully.

SPACE BENEFITS

The EDOS project helps to assess the efficiency of countermeasures, developed through ESA research and research from other organizations, to the bone loss crew members experienced on long-duration space missions such as to the International Space Station. This will assist in the optimal planning of long-duration missions with respect to pharmacological, dietary, or exercise-based protocols in order to alleviate such adverse effects and hence improve/maintain the health and performance of crew members in orbit. This data could also feed into the development of numerical bone models for crew members that could assist in the optimal planning for future longer-duration human exploration missions.

This investigation is ongoing, and additional results are pending publication.

EUROPEAN SPACE AGECNY HAND POSTURE ANALYZER (ESA HPA)

Research Area: Bone and Muscle Physiology

Expedition(s): 7, 8, 11

Principal Investigator(s):
- Valfredo Zolesi, PhD, Kayser Italia, Livorno, Italy
- Aleandro Norfini, Kayser Italia, Livorno, Italy

RESEARCH OBJECTIVES

Upper limbs are the principal means of locomotion for astronauts and fatigue can have a significant effect on the hand during ordinary work, or in particular for extravehicular activities. Hand Posture Analyzer (HPA) examines the way hand and arm muscles are used differently during grasping and reaching tasks in weightlessness. Measurements are compared to those taken before and after flight to improve understanding of the effects of long-duration spaceflight on muscle fatigue.

RESULTS

The experiment was undertaken with 2 long-duration astronauts during Expeditions 7 and 8 aboard the International Space Station (ISS) and 1 astronaut during a short-duration Soyuz mission. The HPA hardware consisted of 2 dynamometers (Handgrip and Pinch Force Dynamometers - HGD/PFD) for measuring handgrip and pinch forces, together with an instrumented glove device.

ISS008E21614 – International Space Station Science Officer Mike Foale performs the Hand Poster Analyzer investigation during Expedition 8, using the hand grip dynamometer to test the muscle fatigue of the forearm.

With respect to power performance parameters, the Maximum Voluntary Contraction (greatest amount of tension a muscle can generate and hold) decreased by up to 45% in weightlessness for the handgrip measurements whereas the Static Effort (which investigates the subject’s muscle fatigue, measuring force/effort applied for a period of time) globally increased for both hand grip tests and pinch force tests. Muscular microfilaments performance could be reduced by the reduction of the concentration of the calcium ion Ca^{2+} or by other physiological factors correlated with the Ca^{2+} concentration. This process is without adaptation in long-term space missions as confirmed by Maximum Voluntary Contraction and Static Effort parameters.

With respect to muscle Contraction Speed (ability to change force intensity with the time) for long-duration astronauts, contraction speed decreased in the global time window by up to 45% across the mission for the hand grip tests but with no significant difference in the pinch force tests. This was probably correlated with the same factors involved in the Maximum Voluntary Contraction decrease for handgrip measurements.

In weightless conditions, the force level control and the maintenance of constant force level improved, however for higher target level (75% of Maximum Voluntary Contraction), the muscular fatigue effects were evident. This effect is predominant and more evident in weightlessness, probably dependent on the same physiological factors involved in the Maximum Voluntary Contraction decrease for handgrip measurements. Proprioceptive feedback seems to produce better results in weightless conditions.

PUBLICATION(S)

Pacelli F, Paoli A, Zolesi V, Norfini A, Donati A, Reggiani C. Implementation and ground validation of a facility for functional and structural analysis of proximal upper limb muscles in microgravity. *Basic Applied Myology*. 2009;19(2-3):77-86.

Zolesi V, Norfini A, Neri G. Hand Posture Analyzer: A facility for the study of the human upper limb on the ISS. *54th IAC Conference*. doi: 10.2514/6.IAC-03-G.P.15.

This investigation is complete and all results are published.

Foot Reaction Forces During Spaceflight (Foot)

Research Area: Bone and Muscle Physiology
Expeditions: 6, 8, 11 and 12
Principal Investigator(s):
- Peter R. Cavanagh, PhD, DSc, University of Washington, Seattle, Washington

Research Objectives

The Foot/Ground Reaction Forces During Spaceflight (Foot) experiment studies the load on the lower body and muscle activity in crew members while working on the International Space Station (ISS). This study will provide a better understanding of the bone and muscle loss in the lower extremities experienced by astronauts in microgravity.

Earth Benefits

The human body is designed to bear weight. Without the stimulation caused by placing weight on lower extremities, whether because of the microgravity environment or lack of use on Earth, bones lose mass, and muscles lose strength. The results of this experiment will help in future spaceflights as well as have significance for understanding, preventing, and treating osteoporosis on Earth.

ISS006E11018 – Expedition 6 Mission Commander Kenneth Bowersox, wearing a body harness, runs on the Treadmill Vibration Isolation System (TVIS) while conducting the Foot/Ground Reaction Forces During Spaceflight (Foot) experiment in the Zvezda/Service Module.

Space Benefits

The loss of bone mineral in the lower extremities is widely viewed as one of the critical factors that may limit long-term human habitation of space (upper extremity changes in bone mineral density [BMD] appear to be minimal or to increase). Deficiencies in lower extremity muscle function as a result of prolonged exposure to microgravity also have implications for performance and safety during space missions. The information derived from this study is expected to shed new light on possible solutions to bone mineral loss and drops in muscle function of the lower extremities. These results will lay an important foundation for the further development of countermeasures for lower extremity muscle and bone loss.

Results

The Foot investigation collected foot reaction forces data from four crew members during exercise with the Treadmill with Vibration Isolation and Stabilization (TVIS), Cycle Ergometer with Vibration and stabilization (CEVIS), and Interim Resistance Exercise Device (iRED) over their 6-month missions over the period from Increments 6-12 (November 2002 and April 2006) on the ISS. A ground-based study collected baseline data from crew members performing prescribed exercises and wearing the Lower Extremity Monitoring Suite (LEMS) system. Results show the LEMS is capable of providing valid and useful biomechanical information on long-term exercise activities aboard the ISS (Cavanaugh 2009). Normal daily activity ground-reaction forces on the feet are measured for each crew member for 4 days prior to going to space, and approximately 4-7 days' worth of data are recorded while the subject is performing daily activities on the ISS. Experimental data show that foot forces, based on direct in-shoe force measurements, are greatly reduced, upward to nearly half in some cases, for the same activity as on Earth. These mechanical loading reductions on weight-bearing bones are used to correlate the rate of bone loss of the most affected areas of the skeleton. The results demonstrate exercise countermeasures with TVIS, CEVIS, and iRED are not adequate in preventing significant bone degradation over long-duration spaceflights. It is concluded that the lighter amount of force applied to bones and muscles during exercise and daily activities aboard the ISS plays a crucial role in the reduction of Bone Mineral Density (BMD) (Cavanaugh 2010). Additional results showed that foot loads were reduced by at least two-thirds while performing resistive exercises on these equipment with the exception of the CEVIS at its highest setting. It is concluded that the TVIS, CEVIS, and iRED, as designed, were not generating enough resistive loads equal to that on Earth, and the need for greater loading should be addressed for upgrades and the next generation of exercise equipment for the ISS (Genc 2010). Precise measurement of the forces exerted by the muscles and bones in microgravity provides a means to quantify the relationship between force reduction and the rate of atrophy of the musculoskeletal system. Researchers are optimistic that the hypothesis of minimum-loading stimulus, in terms of exercise repetition and the amount of force being applied, can be confirmed and the threshold to maintain fitness can be accurately pinpointed. Already, the latest generation of exercise equipment with improved mechanical loading, individually tailored exercise programs, and crew-friendly setup and maintenance is being implemented on the ISS. The Combined Operational Load Bearing External Resistance Treadmill (COLBERT) and Advance Resistive Exercise Device (ARED) are actively collecting data while giving crew members the high-intensity workouts they need in order to remain healthy over the course of their mission.

ISS012E18576 – Astronaut William S. (Bill) McArthur, Expedition 12 commander and NASA space station science officer, uses the Cycle Ergometer with Vibration Isolation System (CEVIS) while participating in the Foot/Ground Reaction Forces During Spaceflight (Foot) experiment in the Destiny laboratory of the International Space Station (ISS). McArthur wore the specially instrumented Lower Extremity Monitoring Suit (LEMS), cycling tights outfitted with sensors, during the experiment.

Publication(s)

Cavanagh PR, Genc KO, Gopalakrishnan R, Kuklis MM, Maender CC, Rice AJ. Foot forces during typical days on the international space station. *Journal of Biomechanics.* 2010;43:2182-2188. doi: 10.1016/j.jbiomech.2010.03.044.

Genc KO, Gopalakrishnan R, Kuklis MM, et al. Foot forces during exercise on the International Space Station. *Journal of Biomechanic.* November 16, 2010; 43(15):3020-3027. doi: 10.1016/j.jbiomech.2010.06.028.

Gopalakrishnan R, Genc KO, Rice AJ, et al. Muscle volume, strength, endurance, and exercise loads during 6-month missions in space. *Aviation, Space, and Environmental Medicine.* 2010; 81(2): 1-102. doi: 10.3357/ASEM.2583.2010.

Cavanagh PR, Gopalakrishnan R, Rice AJ, et al. An ambulatory biomechanical data collection system for use in space: Design and validation. *Aviation, Space, and Environmental Medicine.* 2009;80(10):870-881. doi: 10.3357/ASEM.2266.2009.

Genc KO, Humphreys BT, Cavanagh PR. Enhanced daily load stimulus to bone in spaceflight and on Earth. *Aviation, Space, and Environmental Medicine.* 2009;80:919-926. doi: 10.3357/ASEM.2380.2009.

Pierre MC, Genc KO, Litow M, et al. Comparison of knee motion on Earth and in space: An observational study. *Journal of Neuroengineering and Rehabilitation.* 2006;3(8). doi: 10.1186/1743-0003-3-8.

This investigation is complete and all results are published.

HAND POSTURE ANALYZER (HPA)

Research Area: Bone and Muscle Physiology
Expeditions: 7, 8, 11, 16
Principal Investigator(s):
- Valfredo Zolesi, PhD, Kayser Italia Srl, Livorno, Italy

RESEARCH OBJECTIVES

Hand Posture Analyzer (HPA) examines the way hand and arm muscles are used differently during grasping and reaching tasks in weightlessness. Measurements are compared to those taken before and after flight to improve understanding of the effects of long-duration spaceflight on muscle fatigue.

EARTH BENEFITS

Data from the investigation contribute to the development of new methods, protocols, and instruments for the study and treatment of upper limb problems on Earth.

ISS008E21614 – ISS science officer Mike Foale is performing the HPA investigation during Expedition 8, using the hand grip dynamometer to test the muscle fatigue of the forearm.

SPACE BENEFITS

This investigation provides information on performance modification of the muscular system during long stays in microgravity and the characterization of motion strategies and postural behavior of the human body in weightlessness. Results may lead to the optimization of constructive criteria in the design of orbital modules, devices, and tools for use in space.

RESULTS

The absence of gravity causes many inconveniences, generically referred to as "space motion sickness," but collected data have shown crew members normally adapt to microgravity in about a week. The HPA was used extensively on the ISS during 2003 and 2004. The main objective of HPA is the assessment of upper limbs performance, specifically the holding or grasping movements, and muscular function since the upper limbs are the principal means of work and locomotion onboard the space station. Daily tasks and movements, as well as physically demanding extra-vehicular activities, can have a significant effect on the hand causing muscle fatigue. This degradation of muscular-skeletal performance can be easily recognized on the upper limb. Another aspect is the adjustment of the brain and motor control system to microgravity on the upper limb, affecting not only bio-mechanics but in general the psycho-physical conditions. Overall, tests show prompt recovery after short-term flight and loss of force up to 40% after 6 months in space. These results provide a quantitative evaluation of the performance of the upper limb and provide the base to develop countermeasures (eg, tools to facilitate adaptation and make working in space easier) against the impairments due to change in gravity. Also, the experience gained from these experiments can be applied for treatment of patients with local traumas or diseases of the central nervous system on Earth (Pastacaldi 2004).

PUBLICATION(S)

Pastacaldi P, Orsini P, Bracciaferri F, et al. Short-term microgravity effect on isometric hand grip and precision pinch force with visual and proprioceptive feedback. *Advances in Space Research*. January 2004;33(8):1368-1374. doi: 10.1016/j.asr.2003.09.040.

Zolesi V, Serafini L, Baldacci S, et al. New protocols for the analysis of the performance of the human upper limb on the International Space Station. *AIAA Space 2003 Conference and Exposition*, Long Beach, CA; September 23-25, 2003.

Neri G, Zolesi V. Biomedical research on the International Space Station postural and manipulation problems of the human upper limb in weightlessness. *AIP Conference Proceedings: Space Technology and Applications International Forum*, Albuquerque, New Mexico; January 30 - February 3, 2000 166-171.

This investigation is complete and all results are published.

Study of Low Back Pain in Crewmembers During Spaceflight (Muscle)

Research Area: Bone and Muscle Physiology

Expedition(s): 8, 9, 12, 14, 15, 16, 18, 19, 20

Principal Investigator(s):

- Chris Snijders, University Medical Center, Rotterdam, Netherlands
- Pool-Goudzwaard, University Medical Center, Rotterdam, Netherlands

Research Objectives

The main scientific objective of the experiment is to assess the (expected) development of low-back pain by means of a questionnaire in astronaut/cosmonauts. The type and intensity of pain recorded after every day is related to the data on the physiological process of muscle adaptation as obtained from the Berlin Bed Rest Study. This study aims to measure changes in morphology and muscle volumes by means of MRI in the lower back and pelvic region and the same questionnaire on low back pain is used. Strong evidence for atrophy of the multifidus muscle is found in the Berlin Bedrest Study related to pain on the site of the iliolumbar ligaments.

Results

The prevalence of Low Back Pain (LBP) in space (68%) is higher than on Earth. This is likely due to changes in the lumbar spine as adaptation to microgravity. Although these changes occur in response to microgravity, it is not clear when this will lead to the development of LBP in space. Data is lacking on both development and natural cause of LBP during microgravity.

Aim of the current study was to describe the development and natural cause of LBP in microgravity during short flight (15 days) and compare this with similar data collected during the 2 Berlin bed rest studies (n=12). Twenty astronauts participated in the study and filled in a questionnaire 7 days prior to flight, during each flight day, and 7 days after flight. Besides pain levels (NRS), location, neurological signs, provoking moments, and relieving countermeasures were also described. Results demonstrated that LBP, mostly experienced in the central area of the lower back spreading via the iliac crests, occured in 12 out of 20 astronauts with 2 astronauts who experienced 1 day, 6 experienced 2-4 days, and 4 more > 6 days pain with a mean pain level NRS of 3 (min 1, max 6). The pain was self-limiting. No LBP was reported by any astronaut during the last flight days. No pain was reported 7 days after flight. No neurological signs were present.

This investigation is complete; however additional results are pending publication.

Spinal Elongation and its Effects on Seated Height in a Microgravity Environment (Spinal Elongation)

Research Area: Bone and Muscle Physiology
Expeditions: 19-28
Principal Investigator(s):
- Sudhakar Rajulu, PhD, Johnson Space Center, Houston, Texas

Research Objectives

The Spinal Elongation and its Effects on Seated Height in a Microgravity Environment (Spinal Elongation) study provides quantitative data as to the amount of change that occurs in the seated height because of spinal elongation in microgravity.

Earth Benefits

This study provides data and insight on spinal elongation and compression for people who suffer from back pain on Earth.

Expedition 22 Commander Jeffrey Williams gets his seated height measured in the shuttle commander's seat using the Spinal Tracking Anthropometric Posture Assembly while STS-130 was docked to the International Space Station (ISS) on February 15, 2010. NASA image.

Space Benefits

This seated height data in microgravity is considered necessary to correctly identify the seated height projections of the crew in the Orion configuration. Correct projections of seated height should lead to proper positioning of the seats within the vehicle; adequate clearance for seat stroke in high acceleration impacts; providing proper fit in seats; proper placement of seats with respect to each other and the vehicle; and proper orientation to displays and controls. Additionally, data concerning the effects of spinal elongation on seated height would aid in the design of suit components, habitation requirements, and tool specifications.

Results

Data analysis is ongoing for the Spinal Elongation investigation before conclusive results are prepared.

This investigation is complete; however additional results are pending publication.

INTEGRATED RESISTANCE AND AEROBIC TRAINING STUDY (SPRINT)

Research Area: Bone and Muscle Physiology
Expeditions: 27-ongoing
Principal Investigator(s):
- Lori Ploutz-Snyder, PhD, Universities Space Research Association, Houston, Texas

RESEARCH OBJECTIVES

Integrated Resistance and Aerobic Training Study (Sprint) evaluates the use of high intensity, low volume exercise training to minimize loss of muscle, bone, and cardiovascular function in International Space Station (ISS) crew members during long-duration missions.

ISS029E036754 – NASA astronaut Mike Fossum, Expedition 29 commander, performs a SPRINT leg muscle self scan in the Columbus Laboratory of the International Space Station (ISS). Fossum powered on the Ultrasound 2 (USND-2) unit and Video Power Converter (VPC) hardware, and connected the VPC to Human Research Facility 1 (HRF-1) in order to perform this activity.

EARTH BENEFITS

Data gathered from the Sprint investigation help scientists develop/enhance aerobic training and resistance protocols that may be used on Earth to aid in muscle, bone, and cardiovascular health.

SPACE BENEFITS

Upon completion of this study, investigators expect to provide an integrated resistance and aerobic exercise training protocol capable of maintaining muscle, bone, and cardiovascular health while reducing total exercise time over 180 days of spaceflight. This evaluation provides valuable information in support of space exploration's long-term goal of insuring human fitness for even longer space exploration missions.

RESULTS

Data analysis is ongoing for the Sprint investigation before conclusive results are prepared.

This investigation is ongoing and additional results are pending publication.

Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Spaceflight (Subregional Bone)

Research Area: Bone and Muscle Physiology

Expeditions: 2-8

Principal Investigator(s):
- Thomas F. Lang, PhD, University of California, San Francisco, California

Research Objectives

Bone density scans are taken preflight, soon after landing, and again 1-year postflight to understand the effects of microgravity on bone loss because of long-duration spaceflight. This is a long-term study to understand the distribution of bone loss resulting from long-duration spaceflight; the recovery of bone mass postflight in the year after landing; and the extent to which these changes compare to the spread of bone mineral density measures in healthy Earth-bound individuals.

Earth Benefits

Additionally, comparison of bone mineral density in the hip and spine between space-flight crew members and healthy normal subjects improves understanding of the prevalence of osteoporosis between different race and gender sub-groups on Earth as well as in space crews.

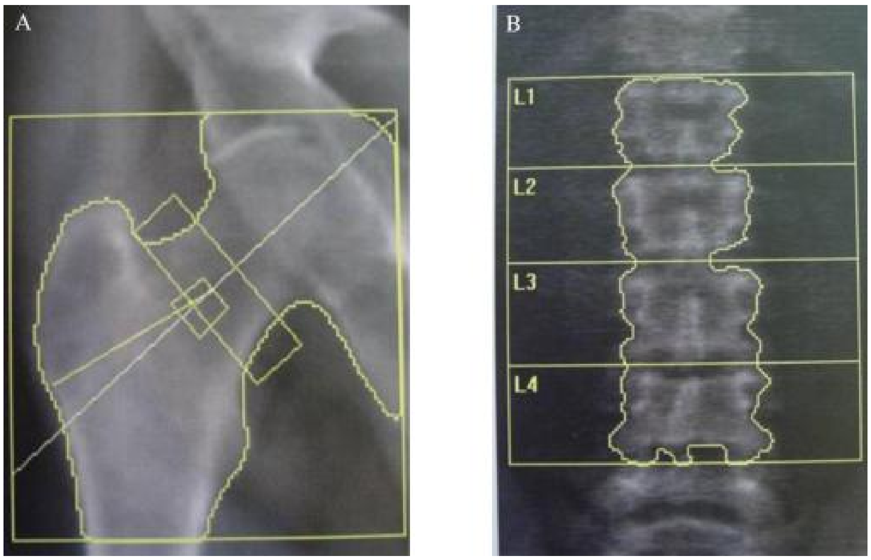
ISS009E17466 – Expedition 9 Commander Gennady Padalka performs an ultrasound bone scan on Flight Engineer and Science Officer Edward (Mike) Fincke's heel using the Advanced Diagnostic Ultrasound in Micro-G (ADUM) setup in the Destiny U.S. Laboratory Module. The ADUM keyboard, flat screen display, and front control panel are visible in the right field of view.

Space Benefits

Bone loss, which can increase the risk of fracture by weakening the skeleton, is an established medical risk in long-duration spaceflight. There is little information regarding which sub-regions of the most important skeletal sites, the spine and hip, are most affected. Moreover, there is little information about the extent to which the lost bone is recovered after spaceflight. This study provides the first information on spaceflight related compartmental bone loss (magnitude and distribution) in the axial skeleton and on the extent to which lost bone is recovered in the year following return. Furthermore, this study has implications for the frequency of assignment to long-duration missions and for the health of the astronauts in older age. It may also be of use in designing exercise or medicine countermeasures to prevent bone loss.

Results

This investigation used noninvasive quantitative computed tomography (QCT) scans and finite-element (FE) structural engineering modeling to compare the pre-flight and post-flight geometry and strength of the proximal (segment joining the hip) femur of 13 astronauts who had not taken any medical countermeasures to prevent bone loss during missions (this area of the femur typically experienced the highest rate of bone loss while in space). FE calculations determined up to a 2.6% per month decrease in proximal femoral strength while standing, and up to a 2.0% decrease against falling for crew members exposed to microgravity for 4 to 6 months aboard the ISS. Over long-duration missions, the cumulative effect represented a significant reduction in bone strength. The authors considered estimates of bone strength by this method would be more revealing since complex 3-D and nonlinear changes in Bone Mineral Density (BMD) were taken into account. Furthermore, QCT scans showed that while overall bone mass appeared recoverable after 1 year back on Earth, the regained bulk was from volumetric growth and the corticoid bone portion, but the reductions in trabecular bone mineral density (tBMD) and strength, did not necessarily follow suit, and these losses could potentially be permanent (Keyak 2009). An affiliated study augmented previous investigations by Lang (2007) with the first long-term volumetric measurements of human bone mineral status and bone geometry of the hip and spine of an 8-crew member subset for up to 4.5 years after long-duration spaceflights. Observed time points at landing, 1 year, and 2-4.5 years later showed bone recovery rate and characteristics for the spine and proximal femur in line with previous findings (Sibonga 2007) in that the intergral bone mineral density (iBMD) regained near preflight status over the following 2-4.5 years along with net gains in total volume and trabecular bone for the hip region. However, volumetric density measurements by QCT showed an overall trabecular bone density average decline to 88% of the preflight value over the same period, and there were no indications that this quantity of tBMD loss would eventually be recovered. Researchers also proposed that the persistent deficits in trabecular bone and bone strength coupled with natural aging osteoporosis may significantly elevate the risk for astronauts who underwent extended or repeat missions and predispose them to premature osteoporosis later in life (Carpenter 2010).



Dual-energy X-ray absorptiometry (DEXA) assessment of bone mineral density of the femoral neck (A) and the lumbar spine. Image courtesy of Dr Caroline Lebreton, Raymond Poincaré Hospital, Garches, France.

PUBLICATION(S)

Li W, Kezele I, Collins DL, et al. Voxel-based modeling and quantification of the proximal femur using inter-subject registration of quantitative CT images. *Bone*. November 2011; 41(5):888-895. doi: 10.1016/j.bone.2007.07.006.

Carpenter RD, Leblanc AD, Evans HJ, Sibonga J, Lang TF. Long-term changes in the density and structure of the human hip and spine after long-duration spaceflight. *Acta Astronautica*. July-August, 2010; 67(1-2):71-81. doi: 10.1016/j.actaastro.2010.01.022.

Zhao Q, Li W, Li CF, et al. A statistical method (cross-validation) for bone loss region detection after spaceflight. *Australasian Physical & Engineering Sciences in Medicine*. July 15, 2010; 33(2):163-169. doi: 10.1007/s13246-010-0024-6.

Keyak JH, Koyama AK, Leblanc AD, Lu Y, Lang TF. Reduction in proximal femoral strength due to long-duration spaceflight. *Bone*. 2009; 44(3):449-453. doi: 10.1016/j.bone.2008.11.014.

Sibonga JD, Cavanagh PR, Lang TF, et al. Adaptation of the skeletal system during long-duration spaceflight. *Clinical Reviews in Bone and Mineral Metabolism*. December 2007;5:249-261. doi: 10.1007/s12018-008-9012-8.

Sibonga J, Evans HJ, Spector ER, et al. Bone health during and after spaceflight. Cleveland, Ohio: Bone loss during spaceflight: Etiology, countermeasures, and implications for bone health on Earth; 2007.

Sibonga J, Evans HJ, Sung H, et al. Recovery of spaceflight-induced bone loss: Bone mineral density after long-duration mission as fitted with an exponential function. *Bone*. December 2007;41(6):973-978. doi: 10.1016/j.bone.2007.08.022.

Lang TF, Leblanc AD, Evans HJ, Lu Y. Adaptation of the proximal femur to skeletal reloading after long-duration spaceflight. *Journal of Bone and Mineral Research*. 2006;21(8):1224-1230. doi: 10.1359/JBMR.060509.

Lang TF, Leblanc AD, Evans HE, Lu Y, Genant HK, Yu A. Cortical and trabecular bone mineral loss from the spine and hip in long-duration spaceflight. *Journal of Bone and Mineral Research*. 2004;19(6):1006-1012. doi: 10.1359/JBMR.040307.

This investigation is complete and all results are published.

PHYSIOLOGICAL PARAMETERS THAT PREDICT ORTHOSTATIC INTOLERANCE AFTER SPACEFLIGHT (AORTA)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 7, 8
Principal Investigator(s):
- John M. Karemaker, University of Amsterdam, Netherlands

RESEARCH OBJECTIVES

Physiological Parameters That Predict Orthostatic Intolerance After Spaceflight (Aorta) plans to predict orthostatic intolerance due to microgravity before and after return from microgravity. This investigation categorizes the cardiovascular reaction pattern of a crew member and acts as a predictor for the outcome of the test.

Subjects lie on tilt tables and are being monitored for physiological changes simulating headward fluid shift in microgravity. ESA image.

RESULTS

Data indicated that blood pressure (BP) levels in space were not very different from preflight; the circadian BP rhythm appeared dampened. Only daytime diastolic pressures and nighttime heart rate (HR) were significantly lower in space. However, compared to the effect of a control tilt maneuver on the ground, even lower BP values might have been expected. Striking were the BP and HR surges during the working days in space, often related to stressful moments such as live appearances on public broadcast. Systemic vascular resistance (SVR) dropped during the night, unlike HDT. Thus, actual spaceflight refutes earlier findings in HDT, both for BP levels and for daytime to nighttime changes.

PUBLICATION(S)

Karemaker JM, Berecki-Gisolf J. Twenty-four hour blood pressure in space: The dark side of being an astronaut. *Respiratory Physiology and Neurobiology*. 2009;169:S55-S58. doi: 10.1016/j.resp.2009.05.006.

Berecki-Gisolf J, Immink RV, Van Lieshout JJ, Stok WJ, Karemaker JM. Orthostatic blood pressure control before and after spaceflight, determined by time-domain baroreflex method. *Journal of Applied Physiology*. May 2005;98(5):1682-1690. doi: 10.1152 /japplphysiol.01219.2004.

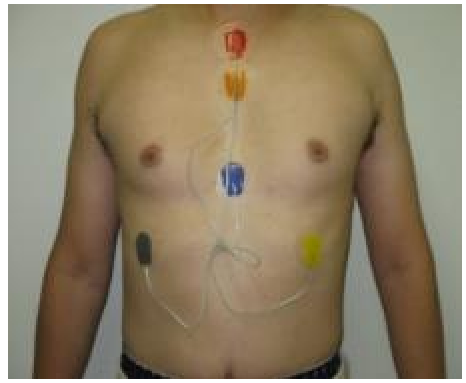
This investigation is complete and all results are published.

The Effect of Long-term Microgravity Exposure on Cardiac Autonomic Function by Analyzing 24-hours Electrocardiogram (Biological Rhythms)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 18-29
Principal Investigator(s):
- Chiaki Mukai, MD, PhD, Japan Aerospace Exploration Agency, Tsukuba, Japan

Research Objectives

The Effect of Long-term Microgravity Exposure on Cardiac Autonomic Function by Analyzing 24-hours Electrocardiogram (Biological Rhythms) examines the effect of long-term microgravity exposure on cardiac autonomic function by analyzing 24-hour electrocardiogram of long-duration International Space Station (ISS) crew members.



Ground test subject with Holter attached to collect ECG data. JAXA image.

Earth Benefits

The crew health care technology for the biological rhythm disruption during spaceflight provides the general public with useful hints to promote a healthy daily lifestyle.

Space Benefits

Monitoring cardio autonomic functions is important for improving crew health technology during long-duration spaceflight.

Results

Three Data collection periods of ECG readings using the Digital Holter ECG aboard the ISS were conducted to provide trends for long-duration, microgravity exposure. Over 24 hours, the average main (large heart pulse) RR interval periods were kept almost within circadian range. The circadian rhythm contained in RR intervals was significantly stronger in the latter period than in the early and middle periods. The study of circadian rhythm on RR intervals in a microgravity, long-duration environment will be analyzed to assist astronauts in the recovery of normal circadian rhythms in a prolonged space stay in the future.

Publication(s)

Yamamoto N, Otsuka K, Kubo Y, et al. Effects of long-term microgravity exposure in space on circadian rhythms of heart rate variability. *Chronobiology International*. November 13, 2014;1–14.

This investigation is complete; however additional results are pending publication.

LONG TERM MICROGRAVITY: A MODEL FOR INVESTIGATING MECHANISMS OF HEART DISEASE WITH NEW PORTABLE EQUIPMENT (CARD)

Research Area: Cardiovascular and Respiratory Systems

Expedition(s): 14, 19-22, 25-32

Principal Investigator(s):
- Peter Norsk, MD, University of Copenhagen, Denmark

RESEARCH OBJECTIVES

The Long Term Microgravity: A Model for Investigating Mechanisms of Heart Disease with New Portable Equipment (Card) experiment studies blood pressure decreases in the human body exposed to microgravity aboard the International Space Station. Card tests the hypothesis that cardiac output is increased and arterial resistance is lowered in microgravity. Blood vessel volume reduction causes higher sympathetic nervous activity and the sensitivity of the arterial resistance vessels to this increase is reduced by weightlessness. Another hypothesis is that high sympathetic nervous activity is a compensatory response to the increased cardiac output and blood flow in the upper parts of the body on the expense of the lower body parts and that this causes some degree of vasoconstriction in the arms and legs to maintain an adequate blood pressure.

JAXA astronaut Koichi Wakata, Expedition 19 flight engineer, during procedures for the Long Term Microgravity: A Model for Investigating Mechanisms of Heart Disease with New Portable Equipment experiment. ESA/NASA image.

RESULTS

The team observed in 8 astronauts a decrease in 24-hour ambulatory blood pressure of 10 mm Hg corresponding to a low-dose antihypertensive medication effect, a 30% increase in cardiac output and stroke volume, and a 30% decrease in peripheral systemic vascular resistance. Thus, the conclusion was that long-term spaceflight (3-6 months) has a vasodilatory, antihypertensive (lower blood pressure) effect, which purely from a cardiovascular point of view is healthy. At the same time, an unchanged level of efferent sympathetic nervous activity was found, which is surprising considering the vasodilatory effects, and which thus requires further investigation.

PUBLICATION(S)

Christensen NJ, Heer MA, Ivanova K, Norsk P. Sympathetic nervous activity decreases during head down bed rest but not during microgravity. *Microgravity Science and Technology*. September 2007;19(5-6):95-97. doi: 10.1007/BF02919460.

Gabrielsen A, Norsk P. Effect of spaceflight on the subcutaneous venoarteriolar reflex in the human lower leg. *Journal of Applied Physiology*. 2007;103(3):959-962. doi: 10.1152/japplphysiol.00899.2006.

Christensen NJ, Heer MA, Ivanova K, Norsk P. Sympathetic nervous activity decreases during head-down bed rest but not during microgravity. *Journal of Applied Physiology*. June 16, 2005;99(4):1552-1557. doi: 10.1152/japplphysiol.00017.2005.

This investigation is complete; however additional results are pending publication.

COGNITIVE CARDIOVASCULAR EXPERIMENT-1 (CARDIOCOG-1)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 5, 7-10
Principal Investigator(s):
- Andre Aubert, Katholieke Universiteit, Leuven, Belgium

RESEARCH OBJECTIVES

The Cognitive Cardiovascular Experiment -1 (Cardiocog-1) experiment studies the impacts of weightlessness on the cardiovascular system and the respiratory system. This investigation examines stress, and cognitive and physiological reactions of crew members during short-duration space missions.

RESULTS

In view of the limited data about autonomic cardiovascular control in relation to mental stress in space, a hypothesis that mental load may alter cardiovascular neural response in microgravity was tested on 5 crew members before, during, and after spaceflight over three 10- to 11-day European Space Agency missions (Odissea, Cervantes, and Delta) to the International Space Station. This investigation examined cardiovascular responses to mental arithmetic tasks and found no effect in space when compared to baseline testing results for heart rate, mean arterial pressure, and Heart Rate Variability (HRV) parameters.


ESA astronaut Pedro Duque during the Cardiocog experiment in 2003. NASA image.

Parallel studies on the same subjects for up to 25 postflight days found heart rate (HR) increased only with the standing position in early postflight, and researchers concluded this as typical response to upright stress after returning to gravity and full tolerance was reestablished after 4 days. Symptoms such as dizziness, loss of balance and/or vision, or consciousness from uncompensated fall in blood pressure disappeared rather quickly after flight, but it was unclear how long changes in dynamic HR control needed to recover. A simple paced-breathing method was used to study respiratory control on the autonomic heart rhythms and data collected 10 days prior to launch, then 1 and 25 days upon return to Earth showed that in spite of increased HR and associated reduction in the rhythmic fluctuation of heart rate with breathing (known as Respiratory Sinus Dysrhythmia or RSD), respiratory-mediated blood pressure dynamics were unchanged after short-duration spaceflight. Results suggested that a fundamental neural control deficit from microgravity deconditioning was less likely, and post-flight reductions in RSD and blood-pressure control of heart rate were actually appropriate autonomic adjustments that accounted for the altered blood flow regulation after spaceflight, which typically resolve within 25 days after landing.

PUBLICATION(S)

Verheyden B, d'Ydewalle C, Beckers F, Aubert AE, Van den Bergh O. Effects of mental stress on autonomic cardiac modulation during eeightlessness. *American Journal of Physiology Heart and Circulatory Physiology*. 2010; 298(H202-H209). doi: 10.1152/ajpheart.00865.2009.

Verheyden B, Liu J, Beckers F, Aubert AE. Adaptation of heart rate and blood pressure to short and long duration space missions. *Respiratory Physiology & Neurobiology*. October 2009; 169(S13-S16). doi: 10.1016/j.resp.2009.03.008.

Verheyden B, Liu J, Beckers F, Aubert AE. Cardiovascular autonomic control after short-duration spaceflights. *Acta Astronautica*. 2009;65(5-6):804-812. doi: 10.1016 /j.actaastro.2009.03.004.

Beckers F, Verheyden B, Couckuyt K, Aubert AE. Non-linear heart rate control in orthostatic tolerant cosmonauts after short-duration spaceflight. *Microgravity Science and Technology*. 2007;19(5-6):98-101. doi: 10.1007/BF02919461.

Verheyden B, Liu J, Beckers F, Couckuyt K, Aubert AE. Respiratory modulation of cardiovascular rhythms before and after short-duration human spaceflight. *Acta Physiologica*. 2007;191(4):297-308. doi: 10.1111/j.1748-1716.2007.01744.x.

This investigation is complete and all results are published.

Cognitive Cardiovascular Experiment-2 (Cardiocog-2)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 12-15
Principal Investigator(s):
- Andre Aubert, Katholieke Universiteit, Leuven, Belgium

Research Objectives

The Cognitive Cardiovascular Experiment (Cardiocog-2) experiment studies the impacts of weightlessness on the cardiovascular system and the respiratory system. This investigation examines stress and cognitive and physiological reactions of crew members during long-duration space missions on the International Space Station.

Cosmonaut Oleg Kotov, Expedition 15 flight engineer, collects medical data for the Cognitive Cardiovascular experiment in the Zvezda Service Module of the International Space Station. ESA image.

Results

Cardiocog-2 was a comprehensive in-flight study with 6 astronauts/cosmonauts who took part in 6 long-duration increments for up to 6 months. In this study, primary cardiovascular data were measured as a function of body position preflight and in weightlessness. The main findings were that heart rate and blood pressure in weightlessness did not change significantly compared to the supine (lying face upward) preflight values during these extended stays. However, long-term space missions seem to induce chronic relaxation of the circulation in humans, which was nicely demonstrated by one of the subjects having borderline high blood pressure before flight and subsequently showing normal blood pressure in space. One interesting (and unexpected) result was the blood pressure neural feedback linked to controlling heart rate appeared to slow significantly in space but the cause(s) was (were) unclear and needs further investigation.

No astronauts in the studies showed symptoms or signs of impending fainting the first days after landing, which strongly supported the involvement of effective exercise countermeasures in the adaptation process to prolonged space missions. It was suggested that individual performance on countermeasures should therefore be shared between scientists in the future to improve the depth, scientific outcome, and overall conclusion of these studies (Verheyden 2009, 2010).

Publication(s)

Verheyden B, Liu J, Beckers F, Aubert AE. Operational point of neural cardiovascular regulation in humans up to 6 months in space. *Journal of Applied Physiology*. 2010;108:646-654. doi: 10.1152/japplphysiol.00883.2009.

Beckers F, Verheyden B, Liu J, Aubert AE. Cardiovascular autonomic control after short-duration spaceflights. *Acta Astronautica.* 2009;65(5-6):804-812. doi: 10.1016/ j. actaastro.2009.03.004.

Aubert AE, Verheyden B, d'Ydewalle C, Beckers F, Van den Bergh O. Effects of mental stress on autonomic cardiac modulation during weightlessness. *American Journal of Physiology: Heart and Circulatory Physiology*. 2009;298:H202-H209. doi: 10.1152/ajpheart.00865.2009.

Verheyden B, Liu J, Beckers F, Aubert AE. Adaptation of heart rate and blood pressure to short and long duration space missions. *Respiratory Physiology and Neurobiology*. 2009;169:S13-S16. doi: 10.1016/j.resp.2009.03.008.

Verheyden B, Beckers F, Couckuyt K, Liu J, Aubert AE. Respiratory modulation of cardiovascular rhythms before and after short-duration human spaceflight. *Acta Physiologica*. 2007;191(4):297-308. doi: 10.1111/j.1748-1716.2007.01744.x.

Beckers F, Verheyden B, Aubert AE. Evolution of heart rate variabilty before, during, and after spaceflight. *Journal of Gravitational Physiology*. 2003;10:107-108.

This investigation is complete and all results are published.

Comprehensive Study of the Pattern of Main Indicators of Cardiac Activity and Blood Circulation (Cardio-ODNT/Cardio-ODNT Perfection), Two Investigations

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 1, 2, 4, 6, 7, 10, 12, 14-17
Principal Investigator(s):
- Valeriy V. Bogomolov, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Comprehensive Study of the Pattern of Main Indicators of Cardiac Activity and Blood Circulation (Cardio-ODNT/Cardio-ODNT Perfection) identifies the associations in regulation of human systemic and pulmonary circulation during the stages of individual adaptation to conditions of long-term microgravity using functional load testing along with the application of negative pressure to the lower part of the body (LBNP) in order to assess and predict orthostatic intolerance (dizziness upon standing up).

Earth Benefits

The scientific results of the Cardio-ODNT experiment are intended for doctors working mainly on the medical support of manned spaceflights. New knowledge is expected to be the major benefit of this investigation.

Cosmonaut Sergey Volkov performs the Cardio-ODNT experiment. Roscosmos image.

Space Benefits

The adaptation mechanisms of various levels of the human circulatory system in microgravity can be clarified from studying the functional capabilities of the human body in spaceflight. The scientific information obtained make it possible to analyze and evaluate the functional state of the cardiovascular system overall, and in particular the filling capacity and tone of blood vessels of various sizes in each region tested in accordance with criteria generally accepted in normal clinical practice, including determining functional state ranges (high, normal, and low blood pressure, high and low blood volume). Results from this study adds substantially to the knowledge of the impact of microgravity on the functional state of various parts of the cardiovascular system of crew members in long-term spaceflights.

Results

Objective information was obtained for the first time enabling the functional state of various regions of the systemic and the pulmonary circuit to be comprehensively evaluated with LBNP in microgravity. The feedback mechanisms of vessels in the systemic and pulmonary circuits were clarified. Results showed that the hemodynamic state of the body was significantly different before and during flight. The features of adaptation reactions for each region studied and their relationships upon simulating a vertical position using LBNP were identified, depending on the original hemodynamic state of the body. The regions that are the most impacted by long-term microgravity were determined. The data obtained highlighted the positive benefits of exposing the lower body to negative pressure during flight on the hemodynamic equilibrium in the body in general, and in particular on circulation in the pulmonary circuit, which is most affected by microgravity. Data confirmed the effectiveness of LBNP sessions on the circulatory system during crew member training for the return to Earth.

PUBLICATION(S)

Cardio-ODNT

Turchaninova VF, Alfyorova IV, Krivolapov VV. Several aspects of a comparative analysis of hemodynamic reactions to LBNP in crewmembers from various age groups. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2010;44(1):20-25.

Cardio-ODNT Perfection

Turchaninova VF, Alferova IV, Krivolapov VV, Liamin VR, Beliaev AP. Dependence of the circulation system functioning on cosmonaut age according to the results of physical loading tests on a veloergometer. *Human Physiology*. December 29, 2013;39(7):707-711. doi: 10.1134/S0362119713070189. [Original Russian Text © Turchaninova VF, Alferova IV, Krivolapov VV, Liamin VR, Beliaev AP. *Aviakosmicheskaya i Ekologicheskaya Meditsina*. 2010; 44(5):8-12.]

Turchaninova VF, Alfyorova IV, Golubchikova ZA, Lyamin VR, Krivolapov VV. The Kardio-ODNT experiment on board the ISS. 5th International Scientific and Applied Conference Manned Spaceflights, Star City, Moscow Region, Russian Federation; April 9-10, 2003.

Turchaninova VF, Alfyorova IV, Golubchikova ZA, Lyamin VR, Krivolapov VV. Initial results of the Kardio-ODNT experiment on board the ISS. *Space Biology and Aerospace Medicine*, Moscow, Russia; June 10-14, 2002;330-331.

PATENT(S)

Cardio-ODNT Perfection

Grigoriev AI, Yarov AS, Kriutchenko SG, Kleyev VV, inventors; Device for the redistribution of blood in the human body during arterial hypertension, and under conditions of weightlessness during spaceflight. Russian Federation. Patent Number 47643. September 10, 2005.

This investigation is complete and all results are published.

CARDIORESPIRATORY ADAPTATION TO THE SPACE ENVIRONMENT (CARDIORESPIR)

Research Area: Cardiovascular and Respiratory Systems

Expedition(s): 5

Principal Investigator(s):

- Manuel Paiva, PhD, Universite Libre de Bruxelles, Brussels, Belgium
- Pierre Migeotte, Universite Libre de Bruxelles, Brussels, Belgium
- Rui Carlos Sá, Universite Libre de Bruxelles, Brussels, Belgium
- Thomas Dominique, Universite Libre de Bruxelles, Brussels, Belgium
- G. Kim Prisk, PhD, University of California San Diego, La Jolla, California

RESEARCH OBJECTIVES

Cardiorespiratory Adaptation to the Space Environment (CardioRespir) examines the alterations of the preload conditions of the hearts of space explorers in microgravity. Results from previous space missions have shown that early in weightlessness cardiac filling and stroke volume increase, there is a decrease in resting heart rate. These changes are the onset of complex adaptation mechanisms in the cardiovascular and cardiopulmonary systems, which play a role on mechanisms of orthostatic intolerance, one of the most important physiological problems endured by astronauts after spaceflight and a potential hazard for longer spaceflight, especially for future exploration missions.

RESULTS

Measurements were performed on 3 crew members with preflight, inflight, and postflight sessions recording ECG and respiratory measurements with imposed and controlled breathing protocols. Analysis shows that the amplitude of the respiratory sinus arrhythmia (RSA) showed a linear relationship with the breathing period (T_{resp}). In flight, the slope of this relationship was slightly decreased, with a difference more pronounced for the (on-ground) standing than the supine posture. For the first days after return, a significant decrease of the slope was observed compared to both supine and standing preflight slopes. Between the 15th and 25th days after return, there was a progressive return to normal values of the RSA relationship with breathing period.

The results of decreased amplitude of RSA and decreased slope of the relationship between RSA and T_{resp} during and after exposure to weightlessness support the hypothesis that the parasympathetic activity of the autonomic nervous system is decreased. The science team showed also that simultaneous knowledge of HR and T_{resp} is required for the analysis of RSA as a tool for following up the progressive readaptation to normal gravity of HR autonomic control. This result stressed the importance of the influence of respiration on the interpretation of changes in heart rate variability, and the necessity for its control.

PUBLICATION(S)

Pattyn N, Migeotte PF, Morais J, Soetens E, Cluydts R, Kolinsky R. Crew performance monitoring: Putting some feeling into it. *Acta Astronautica*. 2009;65:325-329.

Pattyn N, Migeotte PF, Morais J, Kolinsky R. Cognitive performance during spaceflight: How psychophysiology sheds new light on an old question. *Psychophysiology*. 2006.

Migeotte PF, et al. Respiratory sinus arrhythmia: A marker of decreased parasympathetic modulation after spaceflight. *J Gravit. Physiol*. 2005;12(1):73-74.

This investigation is complete and all results are published.

CARDIOVASCULAR AND CEREBROVASCULAR CONTROL ON RETURN FROM ISS (CCISS)

Research Area: Cardiovascular and Respiratory Systems
Expeditions: 15, 16, 18-22
Principal Investigator(s):
- Richard Lee Hughson, PhD, University of Waterloo, Waterloo, Ontario, Canada


ISS015E14753 – View of Expedition 15 astronaut and flight engineer Clayton Anderson working with a Continuous Blood Pressure Device (CBPD) and computer during hardware set-up for the Cardiovascular and Cerebrovascular Control on Return from the International Space Station (CCISS) experiment in the U.S. Laboratory/Destiny.

RESEARCH OBJECTIVES

Cardiovascular and Cerebrovascular Control on Return from ISS (CCISS) studies the effects of long-duration spaceflight on crew members' heart functions and their blood vessels that supply the brain. Learning more about the cardiovascular and cerebrovascular systems could lead to specific countermeasures that might better protect future space travelers. This experiment is a collaborative effort with the Canadian Space Agency.

EARTH BENEFITS

The risk of fainting and falling is increased in older adults. Falls are very serious because they often cause a hip fracture, which is a major cause of prolonged disability and loss of independence; unfortunately, for a high percentage of individuals, the complications from the fracture often lead to disability and possibly death. Gaining better knowledge of the causes of loss of blood pressure and the warning signs that might predict risk helps reduce the incidence of fainting and falls in the elderly.

SPACE BENEFITS

Information from this study improves the understanding of the effects of spaceflight on cardiovascular and cerebrovascular functions. By gaining increased knowledge of the specific components of the cardiovascular and cerebrovascular systems that deviate from the normal Earth baseline responses, it is possible to recommend specific countermeasures that might better protect future space travelers after experiencing the effects of gravity on Earth or landing on the moon or Mars.

RESULTS

Early evidence from long-duration spaceflight indicated general cardiovascular fitness reduction; chronic elevations in arterial blood pressure in the brain; and elevated inspired carbon dioxide (CO_2) compared with normal upright posture on Earth. Recent studies investigated the spontaneous blood pressure feedback and markers of cardiovascular control, changes in heart rate (HR), as well as dynamic autoregulation of brain blood flow and CO_2

responsiveness in astronauts living for 2-6 months on the ISS. Overall, there was no change in indicators of cardiovascular stability during long-duration spaceflight and only relatively small changes postflight at rest in the seated position. In-flight measurements of heart rate (HR), blood pressure (BP), and BP regulation versus preflight revealed no significant changes. Very small increases in resting HR and a 25-34% reduction in the arterial blood pressure reflex response postflight reflected relatively modest levels of decreased cardiovascular muscle tone and fitness. It was also found that astronauts maintained their preflight heart rate during daily activities while living on the ISS (Fraser 2012). These postflight changes suggests that while the current countermeasures on ISS maintain cardiovascular stability in resting conditions in space; key aspects of cardiovascular health with potential long-term consequences are not yet protected (Hughson 2012). Studies have shown a consistent impairment of dynamic cerebrovascular autoregulation and CO_2 reactivity in astronauts chronically exposed to elevated atmospheric CO_2 from long-duration spaceflight; however, there were between-person differences in the magnitude of impairment. Evidence also suggests possible cerebrovascular damage, such as thickening of the cerebral arteries, from pro-longed elevation in cerebral blood pressure. It is unclear, at the moment, whether these changes have harmful effects associated with the complications in vision attributed to increased intracranial pressure. Future studies should investigate in-depth pre to postflight changes in cerebral blood flow and CO_2 reactivity to determine whether they are predictors of health complications resulting from long-duration spaceflight (Zuj 2012).

PUBLICATION(S)

Hughson RL, Shoemaker JK, Arbeille P. CCISS, Vascular and BP Reg: Canadian space life science research on ISS. *Acta Astronautica*. 2014;104(1);444-448.

Xu D, Shoemaker JK, Blaber AP, Arbeille P, Fraser KS, Hughson RL. Reduced heart rate variability during sleep in long-duration spaceflight. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*. July 15, 2013;305(2):R164-R170. doi: 10.1152/ajpregu.00423.2012.

Fraser KS, Greaves D, Shoemaker J, Blaber A, Hughson R. Heart rate and daily physical activity with long-duration habitation of the International Space Station. *Aviation, Space, and Environmental Medicine*. 2012; 83(6):577-584.

Hughson R, Shoemaker J, Blaber A, et al. Cardiovascular regulation during long-duration spaceflights to the International Space Station. *Journal of Applied Physiology*. 2012;112(5):719-727.

Zuj KA, Arbeille P, Shoemaker JK, et al. Impaired cerebrovascular autoregulation and reduced CO_2 reactivity after long-duration spaceflight. *American Journal of Physiology: Heart and Circulatory Physiology.* 2012; 302(12):H2592-H2598. doi: 10.1152/ajpheart.00029.2012.

This investigation is ongoing and additional results are pending publication.

24-Hour Pattern of Blood Pressure and Heart Rate in Weightlessness (Circa)

Research Area: Cardiovascular and Respiratory Systems

Expedition(s): 9

Principal Investigator(s):
- John M. Karemaker, University of Amsterdam, Netherlands
- Claude Gharib, Lyon Grange Blanche, Lyon, France

Research Objectives

24-hour Pattern of Blood Pressure and Heart Rate in Weightlessness (Circa) aims to measure the pattern of blood pressure and heart rate during a 24-hour period in an astronaut. The combined data from 2 instruments used in this experiment enables the science team to unravel the underlying physiology of circadian cardiovascular control in weightlessness.

Spanish European Space Agency astronaut Pedro Duque is wearing the experiment equipment. ESA image.

Results

This study showed that astronauts on short-duration missions may be subject to strong psychological stimuli. In particular, official moments like press conferences can induce surges of blood pressure and heart rate. The initial hypothesis is that spaceflight would show the same day/night changes as had been observed earlier in ground-based bed rest studies. However, unlike the simulations, blood pressure and heart rate were not very much changed inflight from preflight. Only daytime diastolic pressures and nighttime heart rate were significantly lower inflight than preflight. Actual spaceflight did not confirm the earlier bed rest findings for blood pressure levels and for daytime to nighttime changes. Daytime blood pressure levels were definitely higher than was expected. Strikingly, blood pressure and heart rate surges during the working days in space were often related to stressful moments like live media events but were not restricted to these moments. The authors hypothesized that the busy work schedule of short-stay astronauts added to the general level of excitement that was apparent from the measurements. Systemic vascular resistance dropped during the night, unlike bed rest study findings. Thus, actual spaceflight refuted earlier findings in bed rest studies both for blood pressure levels and for daytime to nighttime changes.

None of the postflight results were duplicated during preflight venous occlusion. In conclusion, some crew members showed abnormal orthostatic response 1 and 2 days after spaceflight. Overall, there were indications of increased sympathetic response to standing, even though it was expected that (partial) restoration of plasma volume may have taken place.

The combined observations led to the hypothesis that short-duration spaceflight may induce strong psychological stress in astronauts. When interpreting space-physiological observations this must be taken into account. This study also showed that extensive in-flight cardiovascular measurements were feasible, even in busy astronauts, while they were performing their normal duties. From these observations, researchers have learned to take the psychological aspects of spaceflight more into account when judging the adaptation to microgravity.

PUBLICATION(S)

Karemaker JM, Berecki-Gisolf J. Twenty-four hour blood pressure in space: The dark side of being an astronaut. *Respiratory Physiology and Neurobiology.* 2009;169:S55-S58. doi: 10.1016/j.resp.2009.05.006.

This investigation is complete and all results are published.

STUDY OF THE REGULATION AND BIOMECHANICS OF RESPIRATION IN SPACEFLIGHT (DYKHANIYE)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 15-23
Principal Investigator(s):
- Victor M. Baranov, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

The Study of the Regulation and Biomechanics of Respiration in Spaceflight (Dykhaniye) investigates upper respiratory functions in long-term orbital flight on the International Space Station (ISS) in order to improve the medical monitoring and countermeasures system for future long-duration crew members.

EARTH BENEFITS

Dykhaniye studies the condition of the respiratory system in weightlessness, but knowledge gained from the experiment can also benefit respiratory research on Earth.

Yury Lonchakov aboard the International Space Station during the Study of the Regulation and Biomechanics of Respiration in Spaceflight experiment. Roscosmos image.

SPACE BENEFITS

Investigating how weightlessness affects the respiratory system and regulation (including voluntary control) of this function in long-term spaceflight is important both for the study of space physiology and space medicine, since new findings serve as the basis for improving and developing special countermeasures for the deconditioning and rehabilitation of the respiratory muscles.

RESULTS

A large amount of scientific information was obtained during the experiment, and analysis showed that no statistically significant changes occurred in the volume/rate of breathing at rest or breathing reserve indicators in the group under spaceflight conditions. Analysis of spirometry (method in which breathing is voluntarily controlled after breathing at rest) parameters showed that in both the transition from Earth to spaceflight conditions and vice versa, voluntary control of respiratory movements was destabilized. Therefore, as a result of carrying out the Dykhaniye experiment on the ISS, no significant changes were found in external respiration volume/rate in the crew members tested. The increase in the duration of holding the breath, the decrease in variability of breathing pattern time parameters, and shifts in the voluntary control of respiratory movements were likely caused by changes in the system of breathing regulation, which requires further in-depth study.

Publication(s)

Popova JA, Baranov VM, Suvorov AV, et al. Features of external respiration and its regulation in long-term spaceflight. *XXI Congress of the I.P. Pavlov Physiological Society*, Kaluga, Russia; September 19-25, 2010.

Baranov VM, Suvorov AV, Dyachenko AI, Popova JA, Minyaeva AV, Kolesnikov VI. Respiration and respiratory control in long-term spaceflight. *17th IAA Humans in Space Symposium*, Moscow, Russia; June 7-11, 2009.

Morukov BV, Suvorov AV, Nichiporuk IA. Biomedical research to improve medical monitoring, countermeasures, and mitigate the negative effects of interplanetary manned spaceflight factors. *44th K.E. Tsiolkovsky Scientific Readings*, Kaluga, Russia; 2009.

Suvorov AV, Bogomolov VV. Medical support and bio-medical studies on ISS and perspectives for collaboration. *Microgravity Sciences II*, Malaysia; November 23-24, 2009.

Baevsky RM, Baranov VM, Bersenev YY, et al. Method of determining functional reserves for regulating the human cardio-respiratory system. *Federal Service for Intellectual Property*. 2240035. November 20, 2004.

Oleg Kononenko performs the Study of the Regulation and Biomechanics of Respiration in Spaceflight experiment. Roscosmos image.

This investigation is complete and all results are published.

Assessment of Endurance Capacity by Gas Exchange and Heart Rate Kinetics During Physical Training (EKE)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 19-ongoing
Principal Investigator(s):
- Uwe Hoffmann, German Sport University, Cologne, Germany
- Stefanos Fasoulas, PhD, University of Dresden, Dresden, Germany
- Dieter Essfeld, German Sport University, Cologne, Germany
  Tobias Dräger, German Sport University, Cologne, Germany

Research Objectives

Assessment of Endurance Capacity by Gas Exchange and Heart Rate Kinetics During Physical Training (EKE) assesses the endurance capacity and heart rate kinetics during physical training of International Space Station crew members. The current VO2Max protocol for determining astronaut fitness on a regular basis is quite time consuming. If EKE is successful in reducing the time spent on fitness evaluation in orbit, this will free up more time to be spent on other activities such as scientific research. Another goal of EKE is the development of a physiological model to explore the transport delay of the deoxygenated blood from the exercising muscle tissue to the lungs. This approach permits differentiation between the responses of heart, lungs, and exercising muscles for a more specific training prescription.

NASA astronaut Don Pettit, Expedition 30 flight engineer, performs a joint session of the European Space Agency's (ESA) Thermolab and Assessment of Endurance Capacity by Gas Exchange and Heart Rate Kinetics During Physical Training experiments in conjunction with NASA's VO2max experiment while using the Cycle Ergometer with Vibration Isolation System in the Destiny laboratory of the International Space Station. ESA/NASA image.

Earth Benefits

Data from this research also helps to improve our knowledge in general of the physiological mechanisms at work during the assessment of endurance capacity. The improvement of diagnostic techniques in space could also lead to improved diagnostic techniques of endurance capacity on Earth where VO2max is a standard technique.

Space Benefits

Assessment of crew member health and fitness (specifically their aerobic capacity) is a vital part of any mission, not only to secure the well-being of the crew member in question, but also to secure the aims and goals of the mission such as undertaking scientific research. The EKE experiment should help to reduce the amount of time that is spent making this type of cardiopulmonary health assessment on long-duration missions (thus increasing the time available for research activities) by the development of an improved diagnostic method for the assessment of endurance capacity which is less time intensive than currently used method (VO2max).

Results

Data from the experiment is currently being analyzed and processed prior to results publication.

This investigation is complete; however additional results are pending publication.

Physiological Parameters That Predict Orthostatic Intolerance After Spaceflight (Heart)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 9
Principal Investigator(s):
- John M. Karemaker, University of Amsterdam, Netherlands

Research Objectives

The objective of Physiological Parameters That Predict Orthostatic Intolerance After Spaceflight (Heart) is to predict orthostatic intolerance, ie, the inability to stand upright, of astronauts who have spent a long period in a weightless environment. Predictions are based on measurements of physical parameters such as blood pressure, electrocardiograms, thoracic impedance, and brain blood flow by ultrasound. This data serve as inputs for a computer model of blood circulation to assist in diagnosis of unexplained fainting in patients.

Results

Two of 5 space explorers showed abnormal orthostatic response 1 and 2 days after spaceflight. Although all subjects completed stand tests, 2 of 5 subjects had drastically reduced pulse pressures and an increase in heart rate of ~30 beats/min or more during standing. None of the postflight results were mimicked during preflight venous occlusion. Overall, there were indications of increased sympathetic response to standing, even though we can expect (partial) restoration of plasma volume to have taken place. Blood pressure levels in space were not very much changed from preflight; the circadian blood pressure rhythm seemed dampened. Only daytime diastolic pressures (both subjects) and nighttime heart rate (1 subject) were significantly lower in space. However, compared to the effect of a control tilt maneuver on the ground, even lower blood pressure values might have been expected. Striking were the blood pressure and heart rate surges during the working days in space, often related to stressful moments like live appearances on public TV. Systemic vascular resistance dropped during the night, unlike during bed rest research. Thus, actual spaceflight refuted earlier bed rest findings both for blood pressure levels and for daytime to nighttime changes.

The combined observations led to the hypothesis that short-lasting spaceflight may induce strong psychological stress in astronauts. When interpreting space-physiological observations this must be taken into account.

Publication(s)

Karemaker JM, Berecki-Gisolf J. Twenty-four hour blood pressure in space: The dark side of being an astronaut. *Respiratory Physiology and Neurobiology.* 2009;169:S55-S58. doi: 10.1016/j.resp.2009.05.006.

Karemaker JM, Berecki-Gisolf J, Stok WJ, van Montfrans GA. Twenty-four hour blood pressure in HDT-bed rest and short-lasting space flight. *Journal of Gravitational Physiology.* July 2007; 14(1):49-50.

Berecki-Gisolf J, Immink RV, Van Lieshout JJ, Stok WJ, Karemaker JM. Orthostatic blood pressure control before and after spaceflight, determined by time-domain baroreflex method. *Journal of Applied Physiology*. May 2005;98(5):1682-1690. doi: 10.1152/japplphysiol. 01219.2004.

This investigation is complete and all results are published.

Cardiac Atrophy and Diastolic Dysfunction During and After Long-duration Spaceflight: Functional Consequences for Orthostatic Intolerance, Exercise Capability and Risk for Cardiac Arrhythmias (Integrated Cardiovascular)

Research Area: Cardiovascular and Respiratory Systems

Expeditions: 19-30

Principal Investigator(s):

- Benjamin D. Levine, MD, University of Texas Southwestern Medical Center, Dallas, Texas
- Michael W. Bungo, MD, University of Texas Medical School, Houston, Texas

Research Objectives

Cardiac Atrophy and Diastolic Dysfunction During and After Long-Duration Spaceflight: Functional Consequences for Orthostatic Intolerance, Exercise Capability, and Risk for Cardiac Arrhythmias (Integrated Cardiovascular) aims to determine the extent, time course, and clinical significance of cardiac atrophy (decrease in the size of the heart muscle) associated with long-duration spaceflight and identify the mechanisms of this atrophy and the functional consequences for crew members who spend extended periods of time in space.

ISS026E015923 – NASA astronaut Catherine (Cady) Coleman, Expedition 26 flight engineer, performs tasks in the Kibo Laboratory of the International Space Station (ISS) while participating in the ambulatory monitoring portion of the Integrated Cardiovascular research experiment.

Earth Benefits

The information obtained from these spaceflight experiments has relevance for patients after prolonged confinement to bed rest, or chronic reduction in physical activity, as well as for patients with disease processes that alter cardiac stiffness such as congestive heart failure, ischemic heart disease, and normal ageing.

Space Benefits

Once the magnitude, time course, and inciting factors for cardiac atrophy are determined, effective countermeasures currently being developed by the investigators in parallel ground-based experiments may be applied to focus on maintaining cardiac health during long-duration spaceflight. Upon completion of these experiments, a number of important risks for long-duration spaceflight, such as cardiac function and arrhythmia risk, are deemed as manageable by current preventive measures or clearly defined for future countermeasure research.

RESULTS

To date, several subjects have completed data collection for the Integrated Cardiovascular experiment. Results are pending completion on all test subject before conclusive results are published.

This investigation is ongoing and additional results are pending publication.

ISS028E036071 – Astronaut Satoshi Furukawa prepares for an in-flight echocardiogram for the Integrated Cardiovascular experiment using the Ultrasound 2.

TEST OF MIDODRINE AS A COUNTERMEASURE AGAINST POSTFLIGHT ORTHOSTATIC HYPOTENSION – LONG- AND SHORT-DURATION BIOLOGICAL INVESTIGATION (MIDODRINE-LONG AND SDBI), TWO INVESTIGATIONS

Research Area: Cardiovascular and Respiratory Systems
Expeditions: 14-17
Principal Investigator(s):
- Steven Platts, PhD, Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

This investigation tests the ability of the drug Midodrine to reduce the incidence or severity of orthostatic hypotension. If successful, it will be employed as a countermeasure to the dizziness caused by the blood pressure decrease that many astronauts experience upon returning to the Earth's gravity.

EARTH BENEFITS

In addition to benefits for astronauts, millions of people on Earth suffer from orthostatic hypotension and may benefit from information gained from this experiment.

SPACE BENEFITS

Orthostatic hypotension (low blood pressure while standing) is a significant problem to astronauts returning from even short-term spaceflight, and the symptoms are more prevalent with longer-term flights. Often when returning home, an astronaut's body is unable to maintain blood pressure above the heart, which leads to decreased blood flow in the brain, resulting in lightheadedness and even fainting. Currently used countermeasures to the problem, such as increasing blood volume with saline, have not proven completely effective. If effective, postflight Midodrine administration may provide a relatively simple method for preventing a significant obstacle to long-term spaceflight, especially exploratory trips to the moon and Mars.

JSC2005E15226 – View of European Space Agency (ESA) astronaut Roberto Vittori and cosmonaut Sergei K. Krikalev participate in tilt table tests on April 11, 2005, in Baikonur, Kazakhstan.

RESULTS

Midodrine is an FDA approved drug used for treating orthostatic hypotension (OH), which is a sudden drop in blood pressure (BP) upon standing or stretching causing dizziness or fainting. This study administered 10 mg of Midodrine to a female space shuttle crew member after landing in a second flight who had experienced head rush or dizzy spell after a previous flight to see if the drug is effective in alleviating these symptoms. Her heart rate, blood pressure, and cardiac volume were compared between the 2 flights. Data show Midodrine prevented severe falls in stroke volume, cardiac output, systolic pressure, and severe increases in heart rate without increasing blood flow resistance, thus preventing orthostatic hypotension. The significance of this finding is that Midodrine appeared to protect a previously susceptible crew member from post-spaceflight OH. It appeared to do this primarily by maintaining venous blood return without causing increase in blood pressure. These results suggest a single, 10-mg oral dose of Midodrine shortly after landing may protect crew members from post-spaceflight orthostatic hypotension without causing a rise in blood pressure. A follow-up study with 5 male crew members who had not been susceptible to OH following their previous spaceflights shows there were no statistically significant differences between BP or cardiac output. No subject experienced reduced blood pressure or fainting symptoms during any test. These results, combined with bed rest studies, suggest that Midodrine may help prevent post-flight fainting and the drug appeared to be well tolerated in test subjects and could potentially be made available to crew members before reentry, allowing for the maximal benefit at landing (Platts 2004, 2006).

PUBLICATION(S)

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This investigation is complete; however additional results are pending publication.

EXHALED NITRIC OXIDE-1 (NOA-1)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 12, 13, 14, 17
Principal Investigator(s): ● Dag Linnarsson, Karolinska Institute, Stockholm, Sweden

ESA astronaut Thomas Reiter undertakes science activities for the Nitric Oxide Analyzer experiment in 2006. ESA image.

RESEARCH OBJECTIVES

Inhaled dust particles can cause inflammation in the airways of humans on Earth as well as in space. To study the effects of the inhaled dust particles in space, investigators examine the amount of the gaseous nitric oxide, which indicates airway inflammation, exhaled by crew members. During orbital space flight, and in future space exploration missions, crew members are exposed to an increased risk of airway inflammation due to inhalation of free-floating dust and particles. Analysis of Fractional Exhaled Nitric Oxide (FENO) is a simple method to monitor inflamed airway.

RESULTS

Results showed that during microgravity, FENO was significantly lower and fell to nearly half that of preflight value. In the centrifuge experiments, FENO was significantly elevated during exposure to 2 and 3 times the normal gravity. The findings of decreased exhaled NO in space, increased exhaled, and estimated alveolar NO values in hypergravity suggested that gravity-induced changes in alveolar-to-lung capillary gas transfer greatly affect FENO, but there was no clear trend over time during the stays on the International Space Station or after landing.

According to current models of NO transport, NO originates from conductive airways and alveoli, each source having a different impact on the exhaled amount. Additionally, NO is taken up by blood in the alveolar compartment. Thus, a change in FENO may come from an alteration of the overall balance between production and blood recapture as well as by a change in the airway production. The principal observation was that exhaled NO is gravity dependent: its values are lowered in microgravity and elevated in seated humans during hypergravity.

PUBLICATION(S)

Karlsson LL, Kerckx Y, Gustafsson LE, Hemmingsson TE, Linnarsson D. Microgravity decreases and hypergravity increases exhaled nitric oxide. *Journal of Applied Physiology.* 2009:1431-1437. doi: 10.1152/japplphysiol.91081.2008.

This investigation is complete and all results are published.

Exhaled Nitric Oxide-2 (NOA-2)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 12, 13, 17
Principal Investigator(s):
- Dag Linnarsson, Karolinska Institute, Stockholm, Sweden

Research Objectives

Decompression sickness (gas bubbles in the bloodstream) is a concern and common occurrence in scuba divers. It is unknown if astronauts experience the same type of phenomenon from extravehicular activities (EVA). NOA-2 is designed to compare the amount of nitric oxide that is exhaled before and after an EVA to determine if the astronauts experience decompression sickness.

ISS012E24271 – The Planton Unit and Medical kits in the Zvezda Service Module. The Platon unit, Nitric Oxide Analyzer, used in the European Space Agency Nitric Oxide 1 experiment, is in the mid-left of the image. This image was taken during Expeditions 12/13 Joint Operations.

Results

Exhaled nitric oxide was reduced in microgravity (it is important to know the baseline if exhaled nitric oxide is used to monitor airway health in future space activities). A baseline of exhaled nitric oxide in microgravity and reduced pressure was established. Molecular diffusion played an important role in nitric oxide turnover; this has implications for diagnosing and treating airway inflammation. Nitric oxide turnover with multiple exhalation flows and lung nitric oxide diffusing capacity were determined. EVA in the US space suit did not increase exhaled nitric oxide after EVA was completed (increased exhaled nitric oxide values could mean presence of venous gas emboli = decompressions sickness).

Publication(s)

Karlsson LL, Blogg SL, Lindholm P, Gennser M, Hemmingsson TE, Linnarsson D. Venous gas emboli and exhaled nitric oxide with simulated and actual extravehicular activity. *Respiratory Physiology and Neurobiology.* October 2009;169:s59-s62. doi: 10.1016/j.resp.2009.04.003.

Karlsson LL, Kerckx Y, Gustafsson LE, Hemmingsson TE, Linnarsson D. Microgravity decreases and hypergravity increases exhaled nitric oxide. *Journal of Applied Physiology.* 2009:1431-1437. doi: 10.1152/japplphysiol.91081.2008.

This investigation is complete; however additional results are pending publication.

Study of the Impact of Spaceflight Factors on the Vegetative Regulation of Blood Circulation, Respiration, and Contractile Function of the Heart in Long-Term Spaceflight (Pnevmocard/Pnevmocard Perfection), Two Investigations

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 14-34
Principal Investigator(s):
- Roman M. Baevsky, MD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Studying and monitoring the cardiorespiratory system of crew members in microgravity is dependent not only on the central role of this system in the adaptation responses of the entire body, but also on the specific living and working conditions. Loads on the cardiorespiratory system during physical loading (physical exercise, assembly work in outer space) can be extremely high, and optimizing them may become the priority for the medical support system. The goal of the Pnevmocard/Pnevmocard Perfection investigations is to obtain new scientific information to deepen the understanding of the mechanisms of cardiorespiratory system adaptation to long-term spaceflight conditions.

Russian cosmonaut performing the Pnevmocard space experiment on board the ISS. Roscosmos image.

Earth Benefits

The results obtained can be applied to various medical fields, such as clinical and preventative medicine, environmental medicine, and medicine of extreme conditions. The method enables ECG heart rhythm, rate of capillary blood flow in the finger, and air flow rate during breathing to be recorded. This method enables pre-morbid conditions to be diagnosed that precede the development of cardiovascular and respiratory system diseases.

Space Benefits

The task of the medical monitoring system is not only to identify the occurrence of irregularities in a timely manner, but also to predict them if possible. For space medicine and the practice of crew member medical monitoring, it is desirable to establish patterns of cardiorespiratory interaction in various functional states of the body, since it is known that disruptions in the regulation of physiological functions usually precede the development of dangerous health conditions. Further study of the cardiorespiratory system on the International Space Station (ISS) using the more modern Pnevmocard equipment makes it possible to obtain new scientific data on the processes of the body’s adaptation to long-term spaceflight and develop assessment criteria to predict possible anomalies in the regulatory mechanism. It is presumed that the Pnevmocard experiment will be a model for developing and improving the medical monitoring system for crew members. This involves introducing a prognostic approach to evaluating the functional state of crew members; the research goal is to identify prenosological and premorbid conditions (ie, conditions preceding disease) rather than pathological deviations. These data have practical importance for medical monitoring applications, and in the future it would make sense to apply them in the ongoing work of the medical team at mission control.

RESULTS

To date, the main focus of researchers has been on investigating peripheral blood flow as the leading activation mechanism for the body's reaction to orthostatic loading, and virtually no attention has been paid in studies of heart function in microgravity. The investigations carried out on the ISS using the Pnevmocard system were fundamentally a first in space medicine in which comprehensive material was obtained on hemodynamics, heart contractile function, and its regulation. The results of the Pnevmocard experiment showed that crew members tolerated flight well, fairly fully adapted to long-term microgravity, and their reactions to various flight stages is entirely adequate. This points to the high functional reserves of regulation systems during flight. In the postflight period according to data from orthostatic testing, the body's functional reserves were also maintained at a sufficiently high level.

PUBLICATION(S)

Pneumocard

Baevsky RM, Chernikova AG, Funtova II, Tank J. Assessment of individual adaptation to microgravity during long term spaceflight based on stepwise discriminant analysis of heart rate variability parameters. *Acta Astronautica*. 2011;69:1148-1152. doi: 10.1016/j.actaastro.2011.07.011.

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Pneumocard Perfection

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PATENTS(S)

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Baevsky RM, Baranov VM, Bersenev YY, Funtova II, Semyonov YN, Grigoriev AI, Prilutsky DA, inventors; Method of determining functional reserves for regulating the human cardio-respiratory system. *Federal Service for Intellectual Property*. Patent 2240035. November 20, 2004.

This investigation is complete; however, additional results are pending publication.

The Effects of EVA and Long-Term Exposure to Microgravity on Pulmonary Function (PuFF)

Research Area: Cardiovascular and Respiratory Systems
Expeditions: 3-6
Principal Investigator(s):
- John B. West, MD, PhD, University of California, San Diego, La Jolla, California

Research Objectives

Various breathing tests are performed before, during, and after flight to see if pulmonary function is affected by long-term exposure to microgravity or extravehicular activity (EVA or spacewalks). Changes because of long stays in-orbit, either from removal of gravity itself or from exposure to contaminants in the closed spacecraft environment, adversely affect crew health. Changes associated with spacewalks could indicate an increased risk of decompression sickness, commonly known as the bends.

Earth Benefits

On Earth, many people experience decompression sickness or "the bends" while diving. This is a result from the gases (oxygen, nitrogen, and small amounts of other gases) that are breathed in while diving. The gases are under pressure, causing not all the oxygen to be absorbed. Plus, nitrogen produces bubbles in the blood stream when the body is decompressed. The results from PuFF may help develop an improved SCUBA system that can maximize the amount of oxygen absorbed by the body while diving.

ISS006E07133 – Expedition 6 Flight Engineer Donald Pettit is performing a Pulmonary Function in Flight (PuFF) in the U.S. Laboratory/Destiny. The purpose is to measure changes in the evenness of gas exchange in the lungs and detecting changes in respiratory muscle strength.

Space Benefits

There is a large difference in pressure between the inside of the International Space Station (ISS) and in the spacesuit used for EVA. The effects of that difference in pressure pose a significant risk of decompression sickness for spacewalking astronauts (similar to a scuba diver getting the bends) including bubble formation within the blood. Even if symptoms of decompression sickness do not occur, venous gas micro bubbles can alter pulmonary function. Noninvasive tests of pulmonary function that are altered by changes in the pulmonary blood vessels are an ideal way to follow a subject over the course of multiple EVAs, especially since many EVAs are required for ISS construction and maintenance. This study also investigates the effects on pulmonary function of the buildup of particulates or other contaminating gases that can occur in the closed spacecraft environment. Results from this experiment help to develop countermeasures for pulmonary problems that occur aboard the ISS, further safeguarding crew health.

RESULTS

ISS006E22979 – View of the HRF PuFF Volume Calibration Syringe, PSC Kit, Cargo Transfer Bag in the U.S. Laboratory.

To determine if long-term exposure to microgravity aboard the ISS had any detrimental effects on lung function, pre-and post-flight measurements of lung function were performed on 10 crew members who lived for 130-196 days on board the ISS. The same crew members also performed lung function measurements while in microgravity. Lung volumes, maximum inspiratory and expiratory flows, respiratory muscle strength, resting gas exchange, and numerous indices of the uniformity of lung function were measured on several occasions before flight, and again on several occasions following return to Earth's gravity. Results show that, unlike many other organ systems in the human body, lung function returns to normal almost immediately after long-duration exposure to microgravity. The most important, and somewhat surprising, aspect is the almost complete absence of a change in lung function before and after spending 4-6 months in low-Earth orbit, despite the fact that the lung is highly sensitive to gravity, as shown by previous in-flight studies. The magnitude of the observed changes in the 10 subjects were so small that the conclusions, of no lasting effect of microgravity on lung function, would hold even if the study had included a greater sampling group. Investigators uphold that the subtle changes in lung function that persist soon after landing are possibly due to a reduction in circulating blood volume and alterations in lung fluid balance, and while statistically observable, have little physiological consequence. This finding is significant and encouraging since it proposes that lung function is not a concern under the normal oxygen and pressure environment such as that inside the ISS (Prisk 2005, 2006, 2008).

PUBLICATION(S)

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Cowell SA, Stocks JM, Evans DG, Simonson SR, Greenleaf JE. The exercise and environmental physiology of extravehicular activity. *Aviation, Space, and Environmental Medicine*. 2002;73(1):54-67.

This investigation is complete and all results are published.

STUDY OF VEGETATIVE REGULATION OF THE CARDIORESPIRATORY SYSTEM IN WEIGHTLESSNESS (PULS/PULS PERFECTION), TWO INVESTIGATIONS

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 5-13
Principal Investigator(s):
- Roman M. Baevsky, MD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia
- Irina I. Funtova, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

The cardiovascular system and respiration play a central role in the body's life support during changes in the environment. Establishment of ideal conditioning in the cardiorespiratory system depends on the regulatory mechanisms' ability to effectively control the interaction between the activity of the heart, vascular system, and respiratory apparatus. The Study of Vegetative Regulation of the Cardiorespiratory System in Weightlessness (Puls/Puls Perfection) obtains new scientific information to improve the understanding of the cardiorespiratory system's mechanisms for adapting to long-term spaceflight.

Cosmonaut during the Study of Vegetative Regulation of the Cardiorespiratory System in Weightlessness experiment session on the International Space Station. Roscosmos image.

EARTH BENEFITS

In the process of the examination, pneumo-tachograms, electrocardiograms, and photoplethysmograms are recorded, both at rest and during functional loadings. Using contemporary mathematical models of the regulation of the cardiovascular system, the following are evaluated: current functional status of the cardiovascular system, status of the sympathetic and parasympathetic component of cardiovascular system regulation, and the reserve capabilities of the cardiovascular and respiratory systems.

SPACE BENEFITS

For space medicine and for the practice of medical monitoring of crew members, it is important to establish patterns of cardiorespiratory interaction when the body is at various functional statuses, since, as is well known, disruptions to the regulation of physiological functions usually precede the development of dangerous disruptions to homeostasis. The scientific results obtained are used to improve the system for medically monitoring spaceflight crew members. In addition, the materials obtained are highly important for understanding individual particulars of the process of human adaptation to long-term weightlessness and open the door to creating a system for predicting the risk of developing health problems during flight.

Results

Ten ISS Russian crew members took part in the Puls experiment. The results of this scientific experiment showed that one important factor for evaluating the functional status of a crew member's body was the degree of stress on regulatory mechanisms at various stages of flight. In addition, it was demonstrated that long-term stress on the regulatory system leads to reduced functional reserves in the body. It was established that the tests performed in flight, involving set tempos for breathing and holding the breath at the inhalation and exhalation, were highly informative. One of the most important results of the experiments is the discovery of a direct link between the nature of adaptation to weightlessness and the individual's type of involuntary regulation.

The results of these studies were highly important not only theoretically, but also practically. First, knowledge of the individual type of involuntary regulation made possible the prediction of the nature of the crew member's adaptation reaction during flight. Second, evaluation of the status of autonomous regulation provided important information for the medical monitoring system, since disruptions to the involuntary balance that was developed in flight, shown as changes in the cardiac rhythm, significantly precede metabolic and structural disruptions in affected organs. Given an existing decline in self-regulation, the body is still capable, for a time, of maintaining high performance (while stress on the regulatory system is increasing). But then a break in adaptation may occur, in the form of various disruptions, including disruptions in the cardiovascular system. Thirdly, the increasing stress on the regulatory system during the flight required serious attention from the medical monitoring service, as a risk factor for the development of pathological changes.

The data obtained showed there was promise in further development of the proposed methods as applied to the task of improving the system for medical monitoring of crew members' health during long-term spaceflight.

Publication(s)

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This investigation is complete and all results are published.

Cardiovascular Adaptation to Weightlessness (Rhythm)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 7, 8
Principal Investigator(s):
- Andre Aubert, Katholieke Universiteit, Leuven, Belgium
- Frank Beckers, PhD, Katholieke Universiteit Leuven, Belgium

Research Objectives

Orthostatic intolerance (dizziness) is an indicator of cardiovascular deconditioning (a physical decline) following microgravity expeditions. Despite many studies, the origin of the cardiovascular deconditioning syndrome still remains unclear. A better knowledge of orthostatic intolerance following microgravity is crucial to the health of future space explorers on long-duration space expeditions.

Tilt test. ESA image.

Results

In this study, the non-linear dynamical control of heart rate fluctuations, quantified by the approximate entropy method, was demonstrated to be affected immediately after spaceflight in orthostatic tolerant cosmonauts. The difference in approximate entropy between standing and supine (lying face up) in baseline conditions was shown. The difference in approximate entropy was not present in the first days after return to Earth. The differences between standing and supine position disappeared immediately after spaceflight. If these changes are part of the mechanism to help maintain orthostatic tolerance, they should be explored further in the future. Up until now, no methods have been found successful in either detecting the sudden onset of orthostatic intolerance or even the prediction of it. Therefore, the exploration of non-linear fluctuations might be of interest in an orthostatic intolerant population. After 25 days the stand response was again similar to the preflight situation, indicating that the astronauts recovered rather quickly after their spaceflight. The fact that even orthostatic tolerant cosmonauts present with changes in non-linear heart rate control might open possibilities to study these control mechanisms in orthostatic intolerant astronauts.

Publication(s)

Vandeput S, Widjaja D, Aubert AE, van Huffel S. Adaptation of autonomic heart rate regulation in astronauts after spaceflight. *Medical Science Monitor*. January 4, 2013;19:9-17.

Beckers F, Verheyden B, Couckuyt K, Aubert AE. Non-linear heart rate control in orthostatic tolerant cosmonauts after short-duration spaceflight. *Microgravity Science and Technology*. 2007;19(5-6):98-101. doi: 10.1007/BF02919461.

Beckers F, Verheyden B, Aubert AE. Changes in heart rate and blood pressure variability induced by space flight. *Europace*. June 14, 2004.

Beckers F, Verheyden B, Morukov BV, Aubert AE. Impact of spaceflight on cardiovascular autonomic control. *35th COSPAR Scientific Assembly*, Paris, France; July 18-25, 2004. [Also: Beckers F, Verheyden B, Morukov BV, Aubert A. Impact of spaceflight on cardiovascular autonomic control. *Proceedings of the 55th IAC*, 2004, IAC-04-G.P.01, IAC.]

Beckers F, Verheyden B, Aubert AE. Evolution of heart rate variabilty before, during, and after spaceflight. *Journal of Gravitational Physiology.* 2003;10:107-108.

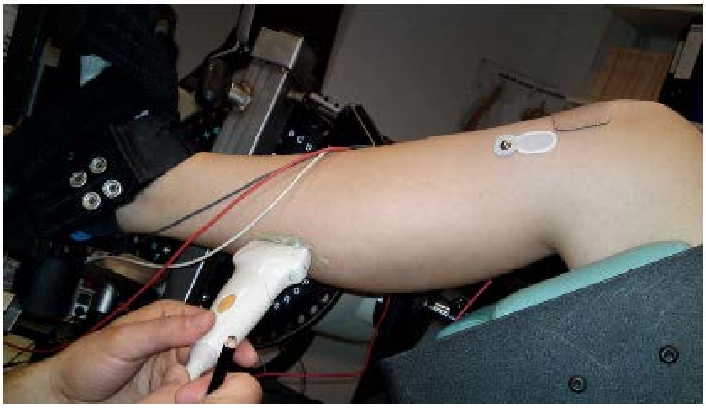
This investigation is complete and all results are published.

Myotendinous and Neuromuscular Adaptation to Long-term Spaceflight (Sarcolab)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 29-ongoing
Principal Investigator(s):
- Paolo Cerretelli, National Research Council, IBFM, Milan, Italy

Research Objectives

Myotendinous and Neuromuscular Adaptation to Long-term Spaceflight (Sarcolab) investigates the adaptation and deterioration of the soleus, or calf muscle, where it joins the Achilles tendon, which links it to the heel and carries loads from the entire body. Muscle fiber samples are taken from crew members before and after flight, and analyzed for changes in structural and chemical properties. MRI and ultrasound tests and electrode stimulation are conducted to help assess muscle and tendon changes caused by microgravity exposure.



Ultrasound scan of subject's calf muscle utilizing the Muscle Atrophy Research and Exercise System. ESA image.

Earth Benefits

By improving the understanding of the mechanisms behind loss of muscle mass in space and developing appropriate and effective countermeasures to any adverse effects, we can also draw conclusions and get insights into certain muscular conditions on Earth. An adaptation of countermeasures originally developed for in-space use by astronauts, or newly developed ground-based countermeasures, could be used within rehabilitation of patients affected by such medical conditions.

Space Benefits

By improving the understanding of the mechanisms behind loss of muscle mass in space, we in turn can develop more effective countermeasures for the crews, whether pharmacological, dietary or exercise-based in order to alleviate such adverse effects and hence improve/maintain the health and performance of our astronauts in orbit.

Results

No results are available yet as the investigation is still ongoing.

This investigation is ongoing and additional results are pending publication.

Studying the Body's Physiological Functions Using a Non-contact Method During Sleep During Long-term Space Flight (Sonocard)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 16-34
Principal Investigator(s):
- Irina I. Funtova, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

The Studying the Body's Physiological Functions Using a Non-contact Method During Sleep During Long-term Space Flight (Sonocard) studies the sleep-wake cycle in humans spending a prolonged period in space. Sonocard develops proposals to improve the system for medical monitoring of crew members, based on the use of a non-contact method of recording physiological data during sleep. During the Sonocard, microscopic oscillations associated with heart rate, respiration, and motor activity are recorded. The study focuses on cardiorespiratory homeostasis and mechanisms for regulating the cardiorespiratory system.

Earth Benefits

The results obtained are useful in various fields of medicine: clinical and preventive medicine, environmental medicine, and medicine for extreme environments.

Russian cosmonaut put the Sonocard device into place before sleep during performance of the Pneumocard experiment during spaceflight. Roscosmos image.

Space Benefits

Implementation of the experiment has opened the door to creating a fundamentally new type of medical monitoring system, one that allows the acquisition of information necessary for assessing the functional status of the crew during nighttime, with a minimal amount of work time required for performing medical experiments. In addition, this system could become an important element for assuring safety of manned flights, since it allows for the transition from periodic to constant monitoring.

Results

The main scientific result of the Sonocard experiment was confirmation of the capability to evaluate sleep quality and the effectiveness of restoring functional reserves without the use of cumbersome polysomnography equipment and the reality of using this new approach to perform practical tasks of medical monitoring. Fundamental scientific results included obtaining systematic data on pulse and respiratory rate during sleep in long-term microgravity and obtaining systematic data on the status of various elements of the involuntary regulation system during sleep in long-term weightlessness. Sonocard was also used in determining the unique aspects of reconstructing autonomous regulation at various stages of flight in relatively stable sleep conditions without the effects of stressor factors of the work regimen in flight and discovery of facts concerning the reduction of functional reserves in crew members' bodies during the acute period of weightlessness adaptation. Finally, it was utilized in obtaining the first nighttime recordings after the performance of an extravehicular activity (EVA); it was shown that each subsequent EVA was characterized by higher stress on the regulatory mechanisms. This required appropriate mobilization of the body's functional reserves. Overall, the results of the experiments performed showed the possibility of obtaining real-time information on cosmonauts' functional status and on processes for restoring functional reserves at various phases of flight.

PUBLICATION(S)

Bogomolov VV, Funtova II, Slepchenkova IN, and Chernikova AG. Prospects of medical monitoring of long duration spaceflights by means of non-contact recording of physiological functions during sleep time. *Human Physiology*. 2011;37:816-820. doi:10.1134/S036211971107005X.

Fedorova IN, Chernikova AG. Study of the possibility of obtaining real-time data on ISS crewmember health status using data from the Sonocard experiment. *8th Scientific Conference of Young Scientists*, Dubna, Russia; 2004.

Funtova II, Luchitskaya ES, Slepchenkova IN, Tank J, Baevsky RM. Comparative assessment of the results of daytime and nighttime research on heart rate variability on board the International Space Station. *5th All-Russian Conference on Analyzing Heart Rate Variability*, Izhevsk, Russia; October 26-28, 2011.

Luchitskaya ES, Funtova II, Katuntsev V, Baevsky RM. Analysis of heart rate variability during sleep before and after performing a spacewalk. *5th All-Russian Conference on Analyzing Heart Rate Variability*, Izhevsk, Russia; October 26-28, 2011.

Slepchenkova IN, Luchitskaya ES, Funtova II, Baevsky RM. Heart rate variability during sleep in weightlessness. *5th All-Russian Conference on Analyzing Heart Rate Variability*, Izhevsk, Russia; October 26-28, 2011.

Russian cosmonaut put the Sonocard device into place before sleep during performance of the Pneumocard experiment during spaceflight. Roscosmos image.

Baevsky RM, Funtova II, Chernikova AG, Slepchenkova IN. Research experiment Sonocard onboard the International Space Station: Methodology and opportunities. *14th Congress of the International Society for Holter and Noninvasive Electrocardiology*, Moscow, Russia; April 2011.

Baevsky RM, Funtova II, Luchitskaya ES, et al. Application of equipment Sonocard for functional reserves evaluation during extravehicular activity. *62nd International Astronautical Congress*, Cape Town, South Africa; 2011.

Funtova II, Baevsky RM, Luchitskaya ES, Slepchenkova IN, Drescher J, Tank J. Day- vs night time heart rate variability changes in microgravity: Experiments "Pneumocard" and "Sonocard". *62nd International Astronautical Congress*, Cape Town, South Africa; 2011.

Slepchenkova IN, Baevsky RM. Vegetative regulation of cardiac rhythm during sleep during prolonged isolation. *6th Russian Symposium with International Participation on Slow Oscillation Processes in the Human Body*, Novokuznetsk, Russia; 2011.

Baevsky RM. Current problems of space cardiology. *Human Physiology*. December 24, 2010; 36(7):754-765. doi: 10.1134/S0362119710070042. [Original Russian Text © Baevsky RM. *Aviakosmicheskaya i Ekologicheskaya Meditsina*. 2008;42(6): 1931.]

Baevsky RM, Bogomolov VV, Katuntsev V, Luchitskaya ES, Slepchenkova IN. How do cosmonauts sleep in microgravity?. *61st International Astronautical Congress*, Prague, Czech Republic; September 27-October 1, 2010.

Russian cosmonaut put the Sonocard device into place before sleep during performance of the Pneumocard experiment during spaceflight. Roscosmos image.

Luchitskaya ES, Chernikova AG, Funtova II, Baevsky RM. Analysis of heart rate variability in space medicine. Results of research on the International Space Station. *4th Russian National Congress on Clinical Electrocardiology*, Velikiy Novgorod, Russia; 2010.

Baevsky RM, Bogomolov VV, Funtova II, Slepchenkova IN, Chernikova AG. Potentiality of building-up the medical operations system for long-duration space missions by noncontact physiological functions recording during sleep time. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. November-December, 2009;43(6):3-8. doi: 10.1134/S036211971107005X.

Baevsky RM, Funtova II, Diedrich A. Dissociation of peripheral and central cardiovascular adaptation during long term spaceflight. 6*0th International Astronautical Congress*, Daejeon, Republic of Korea; October 12-16, 2009.

Chernikova AG, Funtova II, Baevsky RM. Evaluation of the functional state of the International Space Station crewmembers on the basis of heart rate variability analysis. 6*0th International Astronautical Congress*, Daejeon, Republic of Korea; October 12-16, 2009.

Fedorova IN, Funtova II, Chernikova AG, Bogomolov VV, Baevsky RM. Results and prospects of research experiment Sonocard aboard the International Space Station. *60th International Astronautical Congress*, Daejeon, Republic of Korea; October 12-16, 2009.

Chernikova AG, Funtova II, Baevsky RM. Evaluation of functional status of ISS crewmembers based on analysis of heart rate variability. *17th IAA Humans in Space Symposium*, Moscow, Russia; 2009.

Fedorova IN, Chernikova AG, Funtova II. Analysis of heart rate variability in ISS crewmembers during sleep. *11th All-Russian Scientific-Educational Forum Cardiolog*y-2009, MEDI-Ekspo, Moscow, Russia; 2009.

Fedorova IN, Funtova II, Chernikova AG, Bogomolov VV, Baevsky RM. First results of the Sonocard experiment on board the ISS. *17th IAA Humans in Space Symposium*, Moscow, Russia; 2009.

Russian cosmonaut put the Sonocard device into place before sleep during performance of the Pneumocard experiment during spaceflight. Roscosmos image.

PATENT(S)

Baevsky RM, Funtova II, Prilutsky DA, Strugov OM, Sedletskiy VS, Chernikova AG, inventors; System of non-contact, uninterrupted recording of heart rate, respiratory rate, and motor activity in cosmonauts for round-the-clock recording of signals. *Federal Service for Intellectual Property.* Patent 73772. June 10, 2008.

This investigation is complete and all results are published.

Thermoregulation in Humans During Long-term Spaceflight (Thermolab)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 21-ongoing
Principal Investigator(s):
- Hanns C. Gunga, Charité Universitätsmedizin, Berlin, Germany

Research Objectives

Thermoregulation in Humans During Long-term Spaceflight (Thermolab) investigates core temperature and heart rate during rest and exercise to determine the physiological strain index (PSI) in the course of a long-term microgravity exposure (International Space Station [ISS] mission). A newly developed thermosensor for core temperature is applied, which enables non-invasive study and is very convenient for core temperature measurement during rest and exercise in weightlessness.

Space Application

The information obtained by this study leads to a better basic understanding of heat transfer and the thermal regulation in humans under weightless conditions. Such data helps with monitoring and maintenance of astronaut health and well-being in orbit.

Earth Application

By studying alterations in heat balance, thermoregulation and circadian temperature rhythms in space, we also get a greater understanding behind the mechanisms by which these systems work on Earth.

Results

Core body temperature rises faster during exercise on the ISS than on Earth, probably caused by fluid shifts and modified heat flow away from the body. Data indicated that adaptation can be seen in the first 6 weeks on the ISS with an increase in core body temperature by around 1-1.5°C though this settles down to an increase of around 0.5 - 1°C above preflight core body temperature as the mission extends. With the core temperature rising faster on the ISS, it was also noticeable that the body temperature took longer to cool back down to core temperature after exercise.

The measurement of the core body temperature together with cardiovascular measurements during the NASA VO2Max protocol can be used to evaluate the subject's state of fatigue, which is very important for optimizing mission success. The non-invasive double sensor could be a very useful diagnostic tool for recognizing early warning signs of fatigue during, for example, spacewalks in orbit. On Earth, firefighters (to recognize exhaustion/overheating) or jet pilots, steel workers, miners, soldiers in combat, divers, etc, working in extreme conditions could all benefit from this technology. It could also be used for monitoring during critical hospital operations such as heart surgery or for monitoring babies in incubators.

This investigation is complete; however additional results are pending publication.

Test of Reaction and Adaptation Capabilities (TRAC)

Research Area: Cardiovascular and Respiratory System
Expedition(s): 14 and 15
Principal Investigator(s):
- Otmar Bock, PhD, German Sport University, Cologne, Germany

Research Objectives

Test of Reaction and Adaptation Capabilities (TRAC) tests the theory of brain adaptation during spaceflight by testing hand-eye coordination before, during, and after the mission.

ISS014E16213 – Expedition 14 flight engineer Sunita Williams works with the Test of Reaction and Adaptation Capabilities.

Earth Benefits

The results of this investigation may lead to improved medical treatments for patients who suffer from coordination deficits and neurological disorders.

Space Benefits

Understanding how the brain undergoes long-term adaptation to weightlessness will lead to improvement in procedures that require precise motor skills.

Results

The TRAC data suggested that this problem is caused by the brain having difficulty simultaneously processing a number of different challenges. This difficulty is also observed under conditions of stress. The process of adaptation itself may also introduce an extra neural "cost" that decreases performance of certain tasks.

Publication(s)

Bock O, Weigelt C, Bloomberg JJ. Cognitive demand of human sensorimotor performance during an extended space mission: A dual-task study. *Aviation, Space, and Environmental Medicine.* 2010;81(9):819-824. doi: 10.3357/ASEM.2608.2010.

This investigation is complete; however, additional results are pending publication.

CARDIOVASCULAR HEALTH CONSEQUENCES OF LONG-DURATION SPACEFLIGHT (VASCULAR)

Research Area: Cardiovascular and Respiratory System
Expedition(s): 21-ongoing
Principal Investigator(s):
- Richard Lee Hughson, PhD, University of Waterloo, Waterloo, Ontario, Canada

RESEARCH OBJECTIVES

This Cardiovascular Health Consequences of Long-Duration Space Flight (Vascular) research is performed to determine the impact of long-duration spaceflight on the blood vessels of astronauts. Spaceflight accelerates the aging process and we must understand this to determine the need for specific countermeasures. Data will be collected before, during, and after spaceflight to assess inflammation of the artery walls, and changes in blood vessel properties and cardiovascular fitness.

EARTH BENEFITS

This experiment will contribute to obtaining a better understanding of the mechanisms that might contribute to premature ageing of the cardiovascular system and detect early markers of potential atherosclerosis (condition in which fatty material collects along the walls of arteries) and inflammation.

SPACE BENEFITS

The expected long-term outcome of this research involves the development of appropriate countermeasures to prevent astronauts undertaking long-duration spaceflights from experiencing long-term cardiovascular health problems as a result of their time spent in space.

RESULTS

After 6 months in space, pulse wave transit time was increased while carotid artery distensibility was significantly reduced ($P = 0.03$, $n = 6$). Because walking or jogging for 40 minutes a day for 3 months reduces carotid and peripheral artery stiffness in older sedentary subjects, Vascular investigated whether astronauts who maintained physical fitness exhibited less change in pulse wave transit time to the finger. Although pulse wave transit time from preflight to postflight tended to be faster post-flight, there was no relationship to the change in physical fitness. Multiple factors are speculated to contribute to increased arterial stiffness with aging, including increased vasoconstrictor or reduced vasodilator factors, structural breakdown of elastin, accumulation of collagen, vascular smooth muscle cell proliferation, and increased extracellular matrix cross-linking. Animal models for unloading (spaceflight analogs) indicate cellular hypertrophy in the middle cerebral artery and increased cross-linkage in major elastic arteries. The possible roles of these factors related to the increased arterial stiffness with spaceflight have not been investigated in astronauts, and the Vascular experiment provides data to test these mechanisms.

PUBLICATION(S)

Hughson RL, Shoemaker JK, Arbeille P. CCISS, Vascular, and BP Reg: Canadian space life science research on ISS. *Acta Astronautica.* November 2014;104(1):444-448. doi: 10.1016/j.actaastro.2014.02.008.

Xu D, Shoemaker JK, Blaber AP, Arbeille P, Fraser KS, Hughson RL. Reduced heart rate variability during sleep in long-duration spaceflight. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology.* July 15, 2013;305(2):R164-R170. doi: 10.1152/ajpregu.00423.2012.

Fraser KS, Greaves DK, Shoemaker JK, Blaber AP, Hughson RL. Heart rate and daily physical activity with long-duration habitation of the International Space Station. *Aviation, Space, and Environmental Medicine.* June 2012;83(6):577-584.

Hughson RL, Shoemaker JK, Blaber AP, et al. Cardiovascular regulation during long-duration spaceflights to the International Space Station. *Journal of Applied Physiology*. 2012;112(5):719-727. doi: 10.1152/japplphysiol.01196.2011.

Zuj KA, Arbeille P, Shoemaker JK, et al. Impaired cerebrovascular autoregulation and reduced CO2 reactivity after long duration spaceflight. *American Journal of Physiology: Heart and Circulatory Physiology.* 2012;302(12):H2592-H2598. doi: 10.1152/ajpheart.00029.2012.

Blaber AP, Goswami N, Bondar RL, Kassam MS. Impairment of cerebral blood flow regulation in astronauts with orthostatic intolerance after flight. *Stroke.* 2011;42:1844-1850. doi: 10.1161/STROKEAHA.110.610576.

Robertson A, Greaves DK, Shoemaker JK, Arbeille P, Rush JW, Hughson RL. Carotid distensibility following a long-duration stay on the International Space Station. *62nd International Astronautical Congress*, Cape Town, South Africa; 2011.

Hughson RL. Recent findings in cardiovascular physiology with space travel. *Respiratory Physiology and Neurobiology*. 2009;169 Suppl 1:S38-S41. doi: 10.1016/j.resp.2009.07.017.

This investigation is ongoing and additional results are pending publication.

Vascular Echography (Vessel Imaging)

Research Area: Cardiovascular and Respiratory Systems
Expedition(s): 23-26, 29-ongoing
Principal Investigator(s):
- Philippe Arbeille, Universite Francois-Rabelais, Tours, France

NASA astronaut Mike Fossum performs an ultrasound scan on JAXA astronaut Satoshi Furukawa for the joint Vascular Echography (Vessel Imaging/Integrated Cardiovascular) protocol as part of research activities. NASA image.

Research Objectives

The European Space Agency'sVascular Echography (Vessel Imaging) experiment evaluates the changes in central and peripheral blood vessel wall properties and cross sectional areas of long-duration International Space Station crew members during and after long-term exposure to weightlessness. A Lower Body Negative Pressure program runs in parallel to Vessel Imaging. Flow velocity changes in the aorta and the middle cerebral and femoral arteries are used to quantify the cardiovascular response to fluid shifts. Vessel Imaging aims to optimize the countermeasures used routinely during long-duration space missions. The aim of the Integrated Cardiovascular experiment is to determine the degree, development, and clinical significance of cardiac atrophy and identify its mechanisms.

Earth Benefits

In response to gravitational stress and exercise, human blood vessel diameters change. After spaceflight it seems that vessels that normally should contract to maintain blood pressure do not perform as well as they did before the (long-duration) spaceflight. This research holds significance to similar conditions on Earth as they are the same processes that occur in elderly patients. As such findings from this experiment will help in improving and maintaining the health and well-being of an elderly population and provide insight into other cardiovascular conditions on Earth that encompass a similar impaired cardiovascular function.

Space Benefits

By improving the understanding of the mechanisms behind changes to the cardiovascular system in space we in turn can develop more effective countermeasures, whether pharmacological, dietary or exercise-based, in order to alleviate such adverse effects and hence improve/maintain the health and performance of astronauts working and living in orbit.

Results

Following conclusion of the in-orbit activities for the Vessel Imaging experiment in May 2013, the data has been undergoing analysis prior to publication of results.

This investigation is complete; however additional results are pending publication.

EVALUATION OF MAXIMAL OXYGEN UPTAKE AND SUBMAXIMAL ESTIMATES OF VO2MAX BEFORE, DURING, AND AFTER LONG DURATION INTERNATIONAL SPACE STATION MISSIONS (VO2MAX)

Research Area: Cardiovascular and Respiratory Systems
Expeditions: 19-ongoing
Principal Investigator(s):
- Alan D. Moore Jr, PhD, Johnson Space Center, Houston, Texas

ISS026E029180 (February 24, 2011) – NASA astronaut Catherine (Cady) Coleman, Expedition 26 flight engineer, performs VO2max portable Pulmonary Function System (PFS) software calibrations and instrument check while using the

RESEARCH OBJECTIVES

Evaluation of Maximal Oxygen Uptake and Submaximal Estimates of VO2max Before, During, and After Long Duration International Space Station Missions (VO2max) documents changes in maximum oxygen uptake for crew members aboard the International Space Station (ISS) during long-duration missions.

EARTH BENEFITS

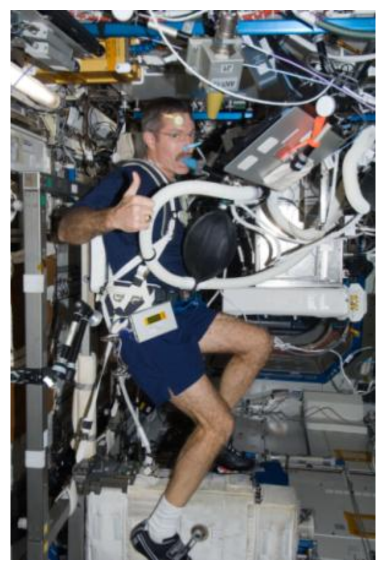
The data obtained from this study provides valuable insight into the aerobic capacity of teams in closed environments on Earth such as arctic bases and submarines.

SPACE BENEFITS

The results from this experiment provide NASA and the ISS International Partners definitive data to determine if submaximal exercise testing provides an accurate assessment of aerobic capacity during and following long-duration spaceflight.

RESULTS

VO2max declines very early upon arrival to microgravity and slowly recovers during flight, but the mean change for all subjects tested does not recover to preflight levels. The mean change in VO2max on R+1 is -14%. This is not significantly different than that observed during the last flight test. A substantial amount of variability exists between subjects in their responses during flight. Apparently, submaximal estimates of VO2max do not reliably track change in actual VO2max. Analysis of data from PFE-OUM is ongoing, conclusive results will be published upon completion of data analysis.



ISS030E007540 – View of astronaut Dan Burbank, Expedition 30 commander, using the Portable Pulmonary Function System (PPFS) hardware while exercising on the Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) in the U.S. Laboratory.

PUBLICATION(S)

Moore Jr AD, Lynn PA, Feiveson AH. The first 10 years of aerobic exercise responses to long-duration ISS flights. *Aerospace*

Medicine and Human Performance. December 1, 2015;86:78-86. doi: 10.3357/AMHP.EC10.2015.

Moore Jr AD, Everett M, Lee SM, Feiveson AH, Knudsen P, Ploutz-Snyder LL. Peak exercise oxygen uptake during and following long-duration spaceflight. *Journal of Applied Physiology*. August 1, 2014;117(3):231-238. doi: 10.1152/japplphysiol.01251.201.

This investigation is ongoing and additional results are pending publication.

Effect of Microgravity on the Peripheral Subcutaneous Veno-Arteriolar Reflex in Humans (Xenon1)

Research Area: Cardiovascular and Respiratory Systems
Expeditions: 3-5
Principal Investigator(s):
- Anders Gabrielsen, MD, Danish Aerospace Medical Center of Research National University Hospital, Copenhagen, Denmark

Research Objectives

The Effect of Micrograyity on the Peripheral Subcutaneous Veno-Arteriolar Reflex in Humans (Xenon1) study investigates the mechanism of orthostatic intolerance (the inability to regulate blood pressure while upright) to establish an important foundation for the development of treatments for orthostatic intolerance following spaceflight. Orthostatic intolerance occurring after spaceflight can interfere with normal brain function of crew members during re-entry and landing.

Earth Benefits

This study has great implications in the medical community on Earth. Currently, there are no specific tests for orthostatic intolerance for it is not completely understood what causes orthostatic intolerance. What this experiment may lead to is a better understanding and improved treatment programs for orthostatic intolerance.

Space Benefits

While a person is standing (orthostasis), blood has a tendency to pool in the legs and feet. This collecting of blood in the lower body can lead to a blood pressure drop in the upper body, and, if less blood gets to the brain, an individual may experience dizziness or fainting. It is a condition called orthostatic intolerance, and it can affect crew members for several days after returning from space. The exact mechanism that creates orthostatic intolerance is still not completely understood. When blood pooling is detected in the lower limbs, the body's normal response is tightening blood vessels below the skin to maintain blood pressure and blood supply to the brain. Treatments for this condition are currently under investigation (one is the drug Midodrine, which is being tested on crew members). This study's method of visualizing blood flow of the subcutaneous vessels and the venoarterial (V-A) reflex allows for possible treatments in the future.

During the Xenon1 experiment, the crew member is injected with small amounts of 133Xenon, which will act as a tracer. Xenon1 will test the local veno-arteriolar reflex in an effort to understand the source of, and ways to combat, postflight orthostatic intolerance. NASA's Johnson Space Center image.

RESULTS

The last group of subjects for this experiment returned after Expedition 5. Data from all subjects were collected successfully. Findings show venous-arteriolar reflex reduced subcutaneous blood flow by 37 +/- 9% before flight and by 64 +/- 8% following landing, with no statistical difference between the 2 responses. The mean arterial pressures and heart rates in supine astronauts were very similar before and after flight. These data indicate that this reflex is not attenuated by weightlessness and suggests that the venous-arteriolar reflex is not a contributor to postflight orthostatic intolerance (Gabrielsen 2006).

PUBLICATION(S)

Gabrielsen A, Norsk P. Effect of spaceflight on the subcutaneous veno-arteriolar reflex in the human lower leg. *Journal of Applied Physiology*. 2007;103(3):959-962. doi: 10.?1152/00899. 2006.

This investigation is complete and all results are published.

Study of Processes for Informational Support of In-Flight Medical Support using an Onboard Medical Information System Integrated into the Information Control System of the ISS Russian Segment (BIMS/BIMS Perfection), Two Investigations

ROSCOSMOS

Research Area: Crew Healthcare Systems
Expedition(s): 15, 16, and 22/23
Principal Investigator(s):
- Igor B. Goncharov, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Study of Processes for Informational Support of In-Flight Medical Support using an Onboard Medical Information System Integrated into the Information Control System of the ISS Russian Segment (BIMS/BIMS Perfection) uses telemedicine technologies to collect information by non-contact means from the ear, nose, and throat (ENT), gums, teeth, and small areas of skin from International Space Station (ISS) crews for medical support of manned spaceflights and in-flight biomedical research.

Example of static images of an ear (top), nose (middle), and throat (bottom) examination. Roscosmos image.

Earth Benefits

The experience gained and data obtained from analyzing the experiment results can be used to develop procedures and equipment for telemedicine service in remote locations on Earth where medical diagnostic capabilities are limited.

Space Benefits

Procedures and software developed for the BIMS experiment are used to carry out baseline and routine examinations of crew members in the MARS-500 experiment by the BIMS medical support team. An integrated information support network for the biomedical support of manned spaceflights is being developed from this work, which increases the effectiveness of the medical support of manned spaceflights, enables modern real-time information transmission methods and technologies to be introduced into the practice of medical support of space missions, and it standardizes the information support of biomedical research aboard the ISS Russian Segment.

Results

BIMS experimental sessions confirmed the feasibility of performing otoscopic, nasal, pharyngeal, dental, and dermatoscopic examinations in spaceflight conditions. At the same time, a large amount of scientific information was obtained

Cosmonaut O V Kotov performs the BIMS experiment.
Roscosmos image.

allowing evaluation of the oral and ENT condition of crew members. The telemedical information obtained (static digital images) on the condition of the outer ear canals (left and right ears), nasal passages (left and right), mucous membranes of the mouth and teeth, normal and damaged sections of skin and finger nail beds were processed, analyzed, and transferred to a data bank by medical specialists.

Publication(s)

BIMS

Popova II, Orlov OI, Revyakin YG. Main results of conducting the first stage of the BIMS space experiment. *Space Forum 2011 Dedicated on 50th Anniversary for Yu. A. Gagarin Flight*, Moscow, Russia; November 19, 2011.[Also: Manned missions to space. Biomedicine and life support. *Russian Academy of Sciences' Institute of Biomedical Problems*, Moscow; 2011:64.]

Popova II, Goncharov IB. Diagnostics and emergency medical care to members of ISS crew use of means of a telemedicine. *14th International Conference Anticrisis and Innovative Potential of Telemedicine and E-health*, Moscow, Russia; September 21-24, 2009.

Popova II, Goncharov IB, Anokhina LD. Information technologies for storing International Space Station medical support data. *Aviatsionnaya i Kosmicheskaya Meditsina*. 2007;41(1):56-58.

Revyakin YG, Orlov OI, Goncharov IB, Popova II, Bogoslavsky VE. Creation of integrated media of telemedical consultative service. *4th European Congress Medicine in Space and in Extreme Environments Achievements for Health Care on Earth*, Berlin, Germany; October 24-26, 2007.

Revyakin YG, Orlov OI, Gontharov IB, Popova II, Bogoslavsky VE. Creation of integrated media of telemedical consultative service. *4th European Congress Medicine in Space and in Extreme Environments Achievements for Health Care on Earth*. Berlin, Germany. October 24-26, 2007;34 -35.

Grigorev AI, Orlov OI. Telemedicine and Space Flight. *Aviation Space and Environmental Medicine*. 2002;73:688-693.

BIMS Perfection

Popova II, Orlov OI, Goncharov IB, Revyakin YG. Testing telemedicine support technologies for the medical support of manned missions during the first stage of the BIMS experiment.

International Space Station, Moscow, Russian Academy of Sciences' Institute of Biomedical Problems. 2011:219-228.

Goncharov IB, Popova II, Baranov MV, Anokhina LD. Testing and selecting hardware to simulate onboard telemetered examinations and to conduct scientific research on the Russian segment of the ISS. *Aviakosmicheskaya I ekologicheskaya meditsina*. 2005;39(5):59-60.

Goncharov IB, Popova II, Baranov MV. Scientific/experimental research in the field of space telemedicine. *Kachestvo i Zhizn*. 2004(4):99-103.

These investigations are complete and all results are published.

Blood Pressure Measurement Instrument (BMI)

Research Area: Crew Healthcare Systems
Expedition(s): 7, 8
Principal Investigator(s):
- Claude Gharib, Lyon Grange Blanche, Lyon, France

Research Objectives

Blood Pressure Measurement Instrument (BMI) demonstrates the functioning of equipment that are developed from a commercial instrument, dedicated to 24-hours monitoring of blood pressure and heart rate. BMI aims to investigate blood pressure circadian rhythms in microgravity.

Astronaut Robert Vittori working with the Blood Pressure Measurement Instrument equipment. ESA image.

Results

The Blood Pressure Measurement Instrument was successfully tested on the Marco Polo (Soyuz 4S/3S exchange) and Cervantes (Soyuz 7S/6S exchange) missions in 2002 and 2003 and also used as part of the Circa experiment during the DELTA (Soyuz 8S/7S exchange) mission in 2004. This International Space Station (ISS) experiment investigated blood pressure circadian rhythms and was dedicated to finding out if, and in which way, these change in weightlessness. The repeated use of the BMI by astronauts on the ISS successfully showed that permanent monitoring of cardiovascular activities can be achieved without major interference in daily activities, even while performing a highly demanding job.

This investigation is complete; however no publications are expected.

Flywheel Exercise Device (Flywheel)

Research Area: Crew Healthcare Systems
Expedition(s): 21 and 22
Principal Investigator(s): ● Michael Cork, European Space Agency, Noordwijk, Netherlands

Research Objectives

The Flywheel Exercise Device is used in Human Physiology studies of Muscular and Skeletal Systems to prevent muscle atrophy, bone mineral density loss, and impairment of muscle function in human beings as responses to long-duration weightlessness. It is a non-gravity dependent exercise device that has been designed for resistance exercise training primarily to counter neuro-muscular de-conditioning. The exercise device provides resistance against the subject through the use of a spinning mass which must be rotated by winding up and releasing an actuation belt. The Flywheel Exercise Device is a compact lightweight, resistive exercise device using the flywheel principle, which allows for back, trunk and upper and lower limb exercises. It is a multi-exercise device that will be tested as an onboard exercise countermeasure allowing for the squat, dead lift and heel raise and other important exercises.

Frank de Winne training on the Flywheel Exercise Device in October 2009 aboard the International Space Station. ESA image.

Results

The purpose of the on-orbit activities is to verify the proper operational use of the hardware onboard the ISS and assess a subset of the device's exercise modes from an operational point of view and with regard to vibrations. Frank de Winne, who was the ESA astronaut who undertook the on-orbit activities, was able to confirm that the exercise device withstood transportation to the ISS and was working normally. The vibrations caused by the Flywheel Exercise Device exercise protocols on board the ISS were measured. Such measurements are performed for each new training device as the strong movements caused by the device during use may disrupt the vibration-free condition for other experiments.

This investigation is complete and all results are published.

IntraVenous Fluid GENeration for Exploration Missions (IVGEN)

Research Area: Crew Healthcare Systems
Expeditions: 23-24
Principal Investigator(s):
- John McQuillen, Glenn Research Center, Cleveland, Ohio

Research Objectives

IntraVenous Fluid GENeration for Exploration Missions (IVGEN) demonstrates the capability to purify water to the standards required for intravenous administration, then mix the water with salt crystals to produce normal saline. This hardware is a prototype that will give flight surgeons more options to treat ill or injured crew members during future long-duration exploration missions.

Glenn researchers test the effectiveness of an IV fluid mixing method on NASA's zero-gravity aircraft. NASA's Glenn Research Center image.

Earth Benefits

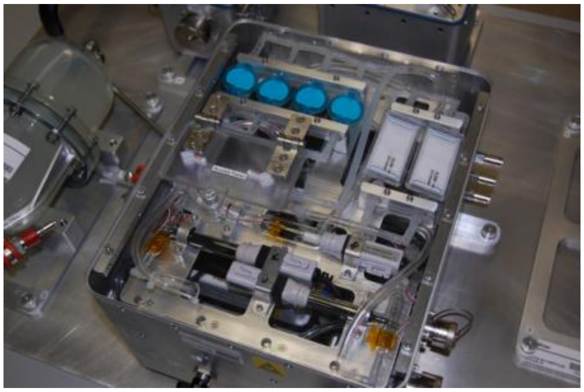
IVGEN technology could be used on Earth to generate IV fluid in Third World countries where medical resources are limited.

Space Benefits

Because of mass and volume limitations, space vehicles cannot carry sufficient IV fluid for medical contingencies. A filtering and mixing system that can make IV fluid in situ provides the treatment capability without the mass and volume constraints. IVGEN was designed and will be tested to meet that need.

Results

IVGEN generated intravenous (IV) fluid from ISS Water Processing Assembly (WPA) potable water using a water purification technique and pharmaceutical mixing system. The system operated onboard the ISS during May 2010 and produced 6, 1.5 liter bags of purified water. Two of these bags were mixed with sodium chloride to make 0.9% normal saline solution. These 2 bags were returned to Earth to test for contamination compliance with United States Pharmacopeia (USP) requirements. On-orbit results showed IVGEN met the experimental success criteria with the exception of the salt concentration. Problems with a large air bubble in the first bag of purified water resulted in a slightly too salty solution of 117% (USP permits a range from 95% to 105% of the target value) of the target value of 0.9 g/L. This problem can be resolved by placing a gas-liquid separator filter immediately upstream of the liquid inlet to the accumulator. The



Seen is the IVGEN subassembly that purifies water coming from the space vehicle. This subassembly also quantifies water cleanliness, the water flow rate within the system, and mixing uniformity in the IV solution. NASA's Glenn Research Center image.

second bag did not have enough salt premeasured in the mixing bag resulting in a slightly low salt concentration of 93.8% of the target value. Improvements for an operational system are being carried out based on lessons learned from the ISS experiment and include testing of the purification capacity and shelf life storage technique for the deionization (DI) resin cartridges (McQuillen 2011).

PUBLICATION(S)

McQuillen BJ, McKay LT, Griffin WD, Brown FD, Zoldak TJ. Final report for intravenous fluid generation (IVGEN) spaceflight experiment. *NASA/TM* - 2011-217033.

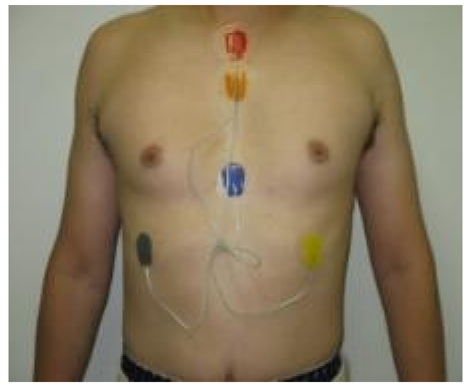
This investigation is complete; however additional results are pending publication.

CHECK OUT OF THE ON-ORBIT DIGITAL HOLTER ECG AND HDTV CAMERA MONITORING FOR TELEMEDICINE (JAXA HOLTER)

Research Area: Crew Healthcare Systems
Expedition (s): 18-20
Principal Investigator(s):
- Chiaki Mukai, MD, PhD, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

The JAXA Holter investigation involves recording 24 hours of Echocardiograph (ECG) data, to monitor cardiovascular and autonomic function of International Space Station (ISS) crew members by comparing preflight baseline data to inflight and postflight data.


Ground test subject with holter attached to collect ECG data. JAXA image.

EARTH BENEFITS

The technology of the telemedicine system on the ISS provides useful hints on promoting health for the general public.

SPACE BENEFITS

The development of a telemedicine system on the ISS contributes to enhanced medical data for future long-duration missions.

RESULTS

This investigation served to verify the functionality of the hardware aboard the ISS. The hardware performed as expected and could be deployed for use in monitoring crew health aboard the ISS.

PUBLICATION(S)

Sakata N, Tayama I, Ishida S, Ohshima H. A verification tri-study using high-definition video camera for tele-skin diagnosis in the International Space Station. Japan Society of Aero-Space and Environmental Medicine Journal. 2013;50:15-22.

Ishida S, Ohshima H, Tayama I, Tachibana S, Mukai C. Check out of the on-orbit digital holter ECG and HDTV camera monitoring for telemedicine**.** ISTS Web Paper Archives. *27th International Symposium on Space Technology and Science*. June 2009.

This investigation is complete and all results are published.

ONBOARD DIAGNOSTIC KIT (ODK)

Research Area: Crew Healthcare Systems
Expedition(s): 27-ongoing
Principal Investigator(s):
- Yoshinori Yoshimura and Shin Yamada, MD, PhD, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

The Onboard Diagnostic Kit (ODK) is a noninvasive, health-monitoring system capable of measuring, storing, and analyzing crew members' medical data while aboard the International Space Station (ISS). The medical data collected aboard are sent to the ground immediately, whereby doctors can quickly monitor and check health status of the ISS crew members.

EARTH BENEFITS

This mission establishes that space explorers can receive medical healthcare utilizing commercial off the shelf (COTS) medical equipment and communicating with medical doctors on the Earth to share test results using a Windows-based application. Although further user-friendliness needs to be improved, this system could allow people in remote communities to receive expert advice and support from medical doctors in a distant place.

Astronaut Satoshi Furukawa with an Electroencephalograph. JAXA image.

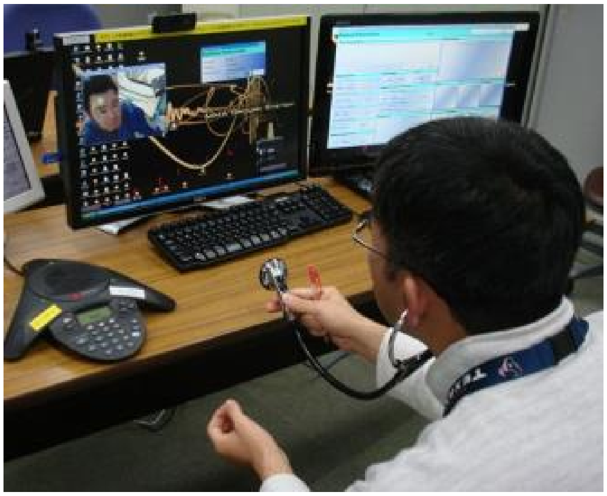
SPACE BENEFITS

Crew healthcare is one of the most important things for long-duration stays in space, or to explore other planets in the future. Therefore a platform of integrated medical systems needs to be constructed. Monitoring cardio autonomic functions is important for improving crew health technology during long-duration spaceflight.

RESULTS

Various medical data was collected and downlinked to investigate the performance of the system. After measuring the data, the crew recorded their feedback and suggestions to assist in the evaluation and upgrade of the system.

JAXA astronaut Satoshi Furukawa's 5 and a half-month mission allowed for the execution of an initial checkout of equipment and 3 sessions of data acquisition. A digital Holter, a pulse oximeter, a USB camera, a stethoscope, and an electroencephalograph were used to measure each healthcare data.



Demonstration test of the Onboard Diagnosis Kit (ODK) linking Astronaut Furukawa aboard the International Space Station (ISS) with Tsukuba Space Center. (Left monitor shows the electronic chart of health monitor. Right monitor shows USB camera image data from ISS. His feedback was reflected in the software updates. For example the explanation for the use of non-specialist was added on the electric chart, such as some reference nominal values of each medical measurement data and some brief description that measurement data means. In addition, a thermometer, a myodynamometer, and a sphygmanometer were newly added into ODK system. JAXA image.

The collection of medical data was loaded into the ODK software on the laptop and several graphs were generated. Astronaut Furukawa, a medical doctor, evaluated the operability, visibility, and data interfaces of the ODK system and had discussions with ground support medical doctors while reviewing the electronic medical recoding system (electronic chart) simultaneously through the real-time health consultation between ISS and Tsukuba Space center.

Pictured is a real-time health examination using electric stethoscope. JAXA image.

Astronaut Akihiko Hoshide, who is not a medical doctor, has performed 3 to 5 sessions of data acquisition. He has also evaluated the operability, visibility, and data interfaces. Real-time downlink from the Electric Stethoscope was performed using the wireless communication technology that allowed ground support doctors to clearly hear the sound of astronaut Akihiko Hoshide's heartbeat. This was the first time the clear sound of a heart's beat was simultaneously shared between ISS and the ground. In this session, we used S-band for the voice communication and K-band for data downlink of USB camera image and *auscultated* heart sound.

This investigation is complete; however no publications are expected.

Mechanism of Activity and Effectiveness of Various Countermeasures Intended to Prevent Disruptions to the Motor Apparatus in Microgravity (Profilaktika)

Research Area: Crew Healthcare System
Expedition(s): 4-17
Principal Investigator(s):
- Inessa B. Kozlovskaya, MD, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

The Mechanism of Activity and Effectiveness of Various Countermeasures Intended to Prevent Disruptions to the Motor Apparatus in Microgravity (Profilaktika) investigation is designed to assess the effectiveness of various physical exercise regimens in maintaining the body's adaptive capabilities in microgravity through the use of tests based on the use of modern measurement technologies. Each session of the experiment consists of several tests: locomotion (on the treadmill), cycle ergometer (on the cycle ergometer), and strength (using the force loader). During each test, gas analysis and blood analysis are performed, and an EKG was recorded.

Earth Benefits

The results of the experiment may be used for sports medicine, training civil aviation pilots, and training people for work in extreme conditions.

Space Benefits

The countermeasures system for short-term missions prevents the development of dehydration, orthostatic instability, physical deconditioning, and loss of muscular and vascular tone. If the duration of the flight extends to several months or a year, the countermeasures program is aimed at minimizing the effects of weightlessness and other detrimental factors, reducing the medical risk in flight, and easing the process of readaptation after return to Earth. Despite the use of countermeasures, during and after long-term spaceflights various bodily systems consistently exhibit a number of changes that are the residual manifestations of the effects of weightlessness. Based on the experimental data obtained, updates are being performed in the program for training cosmonauts for long-term spaceflights.

Performing a test on the treadmill. Roscosmos image.

RESULTS

The results of the Profilaktika experiment indicated that the crew member’s state of physical conditioning has clearly marked phases. During the first phase, their performance declined significantly, with subsequent restoration of the preflight (or near-preflight) level. This pattern was clearly reflected in the results of all tests. It must also be noted that the cost of the locomotion load was significantly higher than that of the cycle ergometer. This may be related to the fact that during performance of a running test with a load equivalent to 70% of one's body weight—a load that is absent during the cycle ergometer test—the physiological cost was determined through activity, not just dynamically, but through the tonic muscle system, which required greater expenditures to support its functionality.

Comparative analysis of the various modes of physical training used aboard the International Space Station demonstrated the high effectiveness of intense exercise characterized by sequencing intensive walking and quick running (so-called interval training) and the significantly lower effectiveness of training in the moderate capacity zone with an aerobic energy supply. Interval training provides a high level of physical performance and levels out the negative changes in the oxygen transport system caused by microgravity. The mechanisms of energy supply for muscle activity remained at the preflight level in a group of crew members who performed interval training in the course of one flight, while another group who trained at lower intensity exhibited a significantly higher physiological and energy costs (less efficient). Analysis of physical performance showed a significantly higher level in the locomotion test, which makes it possible to assess not only the level of physical conditioning. It was also possible to asses the physiological load caused by the need to maintain posture, which is reflected in the magnitude of shifts in autonomous functions and in energy supply mechanisms.

PUBLICATION(S)

Popov DV, Khusnutdinova DR, Shenkman BS, Vinogradova OL, Kozlovskaya IB. Dynamics of physical performance during long-duration spaceflight (First Results of “Countermeasure” Experiment). *Journal of Gravitational Physiology*. July 2004;11(2):231-232.

This investigation is complete and all results are published.

Stability of Pharmacotherapeutic (Stability-Pharmacotherapeutic)

Research Area: Crew Healthcare Systems
Expeditions: 13-18
Principal Investigator(s):
- Lakshmi Putcha, PhD, Johnson Space Center, Houston, Texas

Research Objectives

Stability of Pharmacotherapeutic studies the effects of radiation in space on complex organic molecules such as vitamins and commonly-used medicines. This helps researchers develop more stable and reliable pharmaceutical countermeasures suitable for future long-duration missions beyond low-Earth orbit.

Earth Benefits

The results of this investigation help to understand the effects of adverse environments on medicines, and assists Earth-based explorers in making healthy choices for long-term exploration of remote and adverse habitats like the Antarctic, Arctic, and the world oceans.

Scientists at NASA's Johnson Space Center (JSC) in Houston, Texas, analyzing the Stability-Pharmacotherapeutic samples returned on STS-121. NASA's Johnson Space Center image.

Space Benefits

Results of this investigation provide important information on the susceptibility of select pharmaceuticals to adverse environmental factors encountered during space missions.

Results

The Stability-Pharmacotherapeutic investigation studied the effects of radiation in space on medicine at varying time intervals. Thirty-five medications were examined in this experiment. The study found that 6 medications stowed for the longest duration of 28 months aboard the ISS showed physical alterations as compared with only 2 medications stowed on the ground for the same length of time. Also, 9 medications stowed for 28 months aboard the ISS met United States Pharmacopeia (USP) potency standards versus 17 medications stowed for the same length of time on the ground. Several formulations had lower potency, in general, after storage in space, and a larger amount of formulations failed USP potency requirements after each storage period interval in space than on Earth. The potency degradation rate was found to be faster for several medications in space than on Earth; this was the particular case for light-sensitive medications and may be the result of exposure to higher amounts of radiation aboard the spacecraft than on the ground. Repackaging of solid dosage forms from the original commercial containers into the custom-manufactured containers used to store medications in the space medical kits may also have had an influence on the stability of the medications. These findings will contribute to the future development of space resilient medications and medicine packaging technology (Du 2011).

PUBLICATION(S)

Wotring V. Chemical potency and degradation products of medications stored over 550 Earth days at the International Space Station. *American Association of Phamaceutical Scientists Journal*. January 2016;18(1):210-216. doi: 10.1208/s12248-015-9834-5.

Chuong M, Prasad D, LeDuc B, Du B, Putcha L. Stability of vitamin B complex in multivitamin and multimineral supplement tablets after space flight. *Journal of Pharmaceutical and Biomedical Analysis*. July 15, 2011;55(5):1197-1200. doi: 10.1016/j.jpba.2011.03.030.

Du B, Daniels VR, Vaksman Z, Boyd JL, Crady C, Putcha L. Evaluation of physical and chemical changes in pharmaceuticals flown on space missions. *American Association of Phamaceutical Scientists Journal*. 2011;13(2):299. doi: 10.1208/s12248-011-9270-0.

This investigation is complete; however additional results are pending publication.

Bodies in the Space Environment (BISE)

Research Area: Human Behavior and Performance
Expedition(s): 19-24
Principal Investigator(s):
- Laurence R. Harris, PhD, York University, North York, Ontario, Canada

Research Objectives

The Bodies in the Space Environment (BISE) aims to find out how input from the senses is combined and used to make judgments of object orientation in space. Testing before going into space, in the early and late periods of long periods of spaceflight, as well as after returning to Earth, enables researchers to find out how judgments of orientation change as a result of weightlessness.

ISS020E010310 – Expedition 20 flight engineer Robert Thirsk utilizes Neurospat hardware to perform the Bodies in the Space Environment experiment.

Earth Benefits

Tools developed for the BISE can also help people on Earth who experience balancing problems or are prone to falling, including seniors and people with conditions such as Parkinson's disease.

Space Benefits

Findings from BISE are expected to help astronauts perceive up and down in microgravity, which creates a safer work environment in space. BISE uses the space environment to improve the safety of space travel by designing countermeasures against specific problems.

Results

BISE measured perceived orientation in 7 astronauts before, during, and after long-duration spaceflight using the oriented character recognition test (OCHART), shape from shading, and luminous line probes (Dyde 2006). OCHART measured the orientation at which a letter probe was perceptually upright. On Earth, OCHART was performed while upright and lying right-side-down. By varying the background orientation and the orientation of the subjects, the relative contribution of vision, gravity, and the body were determined. On the International Space Station (ISS), crew members performed OCHART early and late in flight. A reduction in visual influence was observed in flight, with lower-than-baseline levels maintained throughout 6 months in orbit. Visual influence was still lower than baseline levels several months after returning to Earth. It was concluded that sensory weightings were altered by long-term exposure to microgravity and did not recover within 6 months of return to Earth.

ISS020E007545 – European Space Agency astronaut Frank De Winne, Expedition 20 flight engineer, uses Neurospat hardware to perform the Bodies in the Space Environment.

PUBLICATION(S)

Dyde RT, Jenkin MR, Jenkin HL, Zacher JE, Harris LR. The effect of altered gravity states on the perception of orientation. *Experimental Brain Research.* 2009;194(4):647-660.

Haji-Khamneh B, Harris LR. How long do intrinsic and extrinsic visual cues take to exert their effect on the perceptual upright? *Vision Research.* July 2009;49(16):2131-2139. doi: 10.1016/j.visres.2009.06.003.

This investigation is complete; however additional results are pending publication.

Cardiac Adapted Sleep Parameters Electrocardiogram Recorder (CASPER)

Research Area: Human Behavior and Performance
Expedition(s): 14
Principal Investigator(s):
- Marc O'Griofa, University College, Dublin, Ireland

Research Objectives

Sleep deprivation can detrimentally affect mission success and crew member performance. The effects are often compounded by the isolation, confinement, and the lack of normal psychosocial interactions on space missions. Cardiac Adapted Sleep Parameters Electrocardiogram Recorder (CASPER) investigates the use of cardiopulmonary coupling (CPC) as a surrogate marker for sleep stability in comparison to a variety of other traditional markers of sleep and circadian rhythm disruption in extreme environments. The two primary study measurements are a single lead electrocardiogram and a subjective sleep diary that was completed both pre-sleep and post-sleep.

Space Application

CASPER also resulted in the development of a non-contact, non-invasive, state-of-the-art Radio Frequency Impedance Interrogation (RFII) hemodynamic monitor. The chest-mounted unit is worn on various missions as a technology demonstrator and in conjunction with traditional electrocardiogram (ECG) to correlate both signals. Both the peak and period of the RFII signal are used for analysis as the signal results from hemodynamic motion as opposed to cardiac autonomic activity. The RFII signal and data correlate significantly in both the low- and high-frequency spectrums against both CPC and traditional ECG HRV. Preliminary research is also completed using the RFII signal for unique subject identification.

ESA astronaut Thomas Reiter wears the Cardiac Adapted Sleep Parameters Electrocardiogram Recorder vest right before going to sleep. ESA image.

Earth Application

The results and technology development from CASPER and this research create groundbreaking advancements and remove many of the impediments involved in the monitoring of physiology and performance in extreme operational environments ranging from spaceflight to remote habitats on Earth.

Results

CASPER showed the effective use of CPC in a variety of extreme operational environments by demonstrating the strong correlation between traditional ECG heart rate variability (HRV) and CPC high-frequency components across all missions. In contrast there was a weak correlation between ECG HRV and CPC low-frequency components across all missions. This was contributed largely to the noise component in the low-frequency band of ECG HRV signal. In an examination of individual nights from all missions, the ECG HRV signal measured 51 nights >80% in the low frequency range. In contrast, the CPC signal measured only 1 night >80% in the low-frequency range. Correlation for the CPC signal was also much stronger to responses from the subjective sleep diary questions than traditional ECG HRV. It was clear that that the CPC signal was far more closely aligned with the subjective feedback of the crews across all environments in regards to their sleep quality, patterns, and experiences. The data also strongly indicated that CPC is a valuable and useful tool for monitoring sleep stability in extreme and operational environments.

This investigation is complete; however additional results are pending publication.

CULTURAL DETERMINATIONS OF CO-WORKING, PERFORMANCE AND ERROR MANAGEMENT IN SPACE OPERATIONS (CULT)

Research Area: Human Behavior and Performance
Expedition(s): 13, 14
Principal Investigator(s):
- Gro M. Sandal, PhD, University of Bergen, Bergen, Norway

RESEARCH OBJECTIVES

One of the complex and previously neglected areas in aerospace research concerns the effect of cultural variability within the astronaut corps and in the more complex environment of multinational space operations. The overall aim of the proposed project is to assess the potential effects of individually and culturally related values, attitudes and behavioral preferences on operational and interpersonal factors in relation to multinational space missions, including such aspects as crew interaction and cohesion, group identification, leadership, conflict resolution, decision-making, and error management. Specifically, Cultural Determinations of Co-working, Performance, and Error Management in Space Operations (Cult) investigates the impact of such differences for co-working and co-living of resident crews aboard the International Space Station (ISS).

EARTH BENEFITS

Results can also be used in international diplomatic relations as well as in international business ventures to better understand other countries and their cultures.

European Space Agency astronaut Thomas Reiter (left), Expedition 13 flight engineer; cosmonaut Pavel V Vinogradov, commander representing Russia's State Space Corporation; and astronaut Jeffrey N Williams, NASA space station science officer and flight engineer. NASA image.

SPACE BENEFITS

This research gives us a better understanding of the way the different agencies work together, the trouble spots to work on, and the cultural differences to respect. This will provide more efficient use of the station because there will be less conflict.

RESULTS

Data from the experiment is currently being analyzed and processed prior to results publication.

This investigation is complete; however additional results are pending publication.

Crew Member and Crew-Ground Interaction During International Space Station Missions (Interactions)

Research Area: Human Behavior and Performance
Expeditions: 2-9
Principal Investigator(s):
- Nick A. Kanas, MD, Veterans' Affairs Medical Center and University of California, San Francisco; San Francisco, California

Research Objectives

Weekly questionnaires are completed to identify and define important interpersonal factors that may impact the performance of the crew and ground support personnel during International Space Station (ISS) missions. Results are used to improve the ability of future crew members to interact safely and effectively with each other and ground support personnel. The results may also be used to improve methods for crew selection, training, and in-flight support.

Earth Benefits

Results from this study help to improve the behavioral performance of people living and working under similar isolated conditions here on Earth.

Space Benefits

The Interactions studies are expected to yield information about the importance of language and dialect commonality and the relationships of crew heterogeneity and cultural comfort to crew tension and cohesion. Emphasis on culture and language is included on the ISS where there are more international interactions. Identification and definition of these important interpersonal factors leads to improved methods for crew selection, training, in-flight support, and transitioning back to society insuring successful space missions.

Results

Long-duration stays aboard an orbital space station represent but one step in the evolution of human space exploration, which also aims at much more ambitious endeavors such as an outpost on the moon or an expedition to Mars, and these can produce serious psychological and interpersonal consequences. After reviewing the body of behavioral research results for space crew members, the International Academy of Astronautics Study Group on Psychology and Culture in Long-Duration Space Missions issued a final report outlining a set of recommendations for long-duration future human space missions, including both transit and planetary surface operations on the moon, Mars, and beyond. This information is designed to provide guidelines for astronaut selection and training, in-flight monitoring and support, and postflight recovery and re-adaptation. (1) Group survival training should be considered since crew members had mentioned its cohesive effect on a team. (2) Future spaceflight crew members should train together in flight operations. If they can better know each other and understand their strong and weak points, they can learn to solve problems in space. The longer they train together, the smoother their future interactions will be. (3) Training should also involve people from mission control to enhance the bonding and improve the communication between crew members and people on the ground. (4) Group sensitivity training for astronauts and cosmonauts could reduce the influence of personal, cultural, national, and other peculiarities of behavior during the mission. (5) Conflict resolution and communication training already widely used in modern industry could be tailored for use among space crews, with special attention to cultural differences. This includes the necessity to study the language of one's foreign crewmates, with special focus on words and terms describing everyday life so that crew members can discuss not only their work, but also talk about other social aspects of their lives. (6) The opinion of crew members should be solicited and taken into account regarding access to logistics, fair workload distribution, etc, so that potential sources of quarrels can be identified and offset. (7) Crew members sharing space aboard the ISS should have many lines of communication, both among themselves and with people on Earth. (8) Finally, research needs to be done involving the effects of increased crew autonomy during manned space missions. Crew members working on the lunar surface or participating in an expedition to Mars will be more autonomous and less dependent on mission control direction and support than crew members engaged in an in-orbit mission. Little is known about how this autonomy will affect operations, and the ISS could provide a test bed for studies that explore this issue (Kanas 2008, 2009).

ISS005E6055 – Expedition 5 Flight Engineers Peggy Whitson (left) and Sergei Treschev (right) work with a laptop in the Destiny Laboratory on June 27, 2002. Crew members that participated in the Interactions investigation completed confidential questionnaires on a laptop and then downloaded the files to the ground-based investigators. The Mission Control Center crews completed similar questionnaires.

PUBLICATION(S)

Boyd JE, Kanas NA, Salnitskiy VP, et al. Cultural differences in crewmembers and mission control personnel during 2 space station programs. *Aviation, Space, and Environmental Medicine*. 2009;80(6):532-546. doi: 10.3357/ASEM.2430.2009.

Kanas NA, Sandal GM, Boyd JE, et al. Psychology and culture during long-duration space missions. *Acta Astronautica*. April-May, 2009;64(7-8):659-677. doi: 10.1016/j.actaastro.2008.12.005.

Kanas NA, Gushin VI. Problems and possibilities of astronauts – Ground communication content analysis validity check. *Acta Astronautica*. 2008;63(7-10):822-827. doi: 10.1016/j.actaastro.2008.01.007.

Kanas NA, Ihle EC, Saylor SA, Ritsher JB. Psychological adaptation and salutogenesis in space: Lessons from a series of studies. *Acta Astronautica*. 2007;60(4-7):336-340. doi: 10.1016/j.actaastro.2006.09.002.

Kanas NA, Salnitskiy VP, Boyd JE, et al. Crew member and mission control personnel interactions during International Space Station missions. *Aviation, Space, and Environmental Medicine*. 2007;78(6):601-607.

JSC2004E25790 – Expedition 9 crew members, International Space Station (ISS) Science Officer Michael Fincke (right) and ISS Commander Gennady Padalka (left), use video and audio channels to communicate with Mission Control Center in Houston on June 18, 2004. Everyone is celebrating the recent birth of Fincke's daughter. The primary focus of the Interactions investigation is to improve communications between the support personnel and the expedition crew.

Kanas NA, Salnitskiy VP, Gushin VI, et al. Psychosocial interactions during ISS missions. *Acta Astronautica*. 2007;60(4-7):329-335. doi: 10.1016/j.actaastro.2006.09.001.

Ritsher JB, Kanas NA, Ihle EC, Saylor SA. Psychological adaptation and salutogenesis in space: Lessons from a series of studies. *Acta Astronautica*. 2007;60(4-7):336-340. doi: 10.1016/j.actaastro.2006.09.002.

Clement JL, Ritsher JB, Kanas NA, Saylor SA. Leadership challenges in ISS operations: Lessons learned from junior and senior mission control personnel. *57th International Astronautical Congress*, Valencia, Spain; 2006.

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Ritsher JB, Kanas NA, Salnitskiy VP, et al. Cultural and language backgrounds of International Space Station program personnel. *57th International Astronautical Congress*, Valencia, Spain; 2006.

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Robinson JA, Slack KJ, Trenchard MH, et al. Patterns in crew-initiated photography of Earth from ISS – Is Earth observation a salutogenic experience? *57th International Astronautical Congress*, Valencia, Spain; 2006.

Clement JL, Ritsher JB. Operating the ISS: Cultural and leadership challenges. *56th International Astronautical Congress*, Fukuoka, Japan; 2005 11 pp.

Kanas NA, Ritsher JB. Leadership issues with multicultural crews on the International Space Station: Lessons learned from Shuttle/Mir. *Acta Astronautica*. 2005;56:932-936. doi: 10.1016/j.actaastro.2005.01.020.

Kanas NA, Salnitskiy VP, Ritsher JB, et al. Human interactions in space: ISS vs. Shuttle/Mir, *56th International Astronautical Congress*, Fukuoka, Japan; 2005. IAC-05-AI.5.02.

Ritsher JB, Kanas NA, Gushin VI, Saylor SA. Cultural differences in patterns of mood states on board the International Space Station. *56th International Astronautical Congress*, Fukuoka, Japan; 2005 4 pp.

This investigation is complete and all results are published.

BEHAVIORAL ISSUES ASSOCIATED WITH ISOLATION AND CONFINEMENT: REVIEW AND ANALYSIS OF ASTRONAUT JOURNALS (JOURNALS)

Research Area: Human Behavior and Performance
Expeditions: 8-18, 29-ongoing
Principal Investigator(s):
- Jack W. Stuster, PhD, CPE, Anacapa Sciences, Inc, Santa Barbara, California

RESEARCH OBJECTIVES

Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of Astronaut Journals (Journals) obtains information on behavioral and human issues that are relevant to the design of equipment and procedures and sustained human performance during extended-duration missions. Study results provide information to help prepare for future missions to low-Earth orbit and beyond.

EARTH BENEFITS

Results from this study help to improve the behavioral performance of people living and working under a variety of conditions here on Earth.

SPACE BENEFITS

Studies conducted on Earth have shown that analyzing the content of journals and diaries is an effective method for identifying the issues that are most important to a person. The method is based on the reasonable assumption that the frequency that an issue or category of issues is mentioned in a journal reflects the importance of that issue or category to the writer. The tone of each entry (positive, negative, or neutral) and phase of the expedition also are variables of interest. Study results will lead to recommendations for the design of equipment, facilities, procedures, and training to help sustain behavioral adjustment and performance during long-duration space expeditions to the ISS, asteroids, moon, Mars, and beyond.

RESULTS

Results from the Journals investigation provided the first measurable data from space operations on which to base a rank-ordering of behavioral issues. Personal journals generated by 10 NASA astronauts who lived and worked aboard the International Space Station (ISS) for an average of 188 days were analyzed to obtain information concerning a wide range of behavioral issues. Responses to questions asked before, during, and after the expeditions suggested that living and working aboard the ISS were not as difficult as the astronauts anticipated before starting their 6-month tours of duty. Astronauts reported that they benefited personally from writing in their journals because it helped them maintain perspective on their work and relations with others. It was apparent from the journal entries analyzed that conditions aboard the ISS were far better than tolerable but short of what was necessary to support optimum human performance for sustained periods of routine operations. Crews performed admirably, as expected, and the journals contained many positive statements about living and working in space; however, the tone and content of some entries described problems and conveyed levels of frustration and annoyance. It was also noticed that the crew members shared an unusually well-developed sense of self-awareness. The crew members participating in this study demonstrated a keen awareness of their capabilities and limitations, a personal quality believed to distinguish them from nearly everyone else. Recommendations include application of study results and continuation of the experiment to obtain additional data as crew size increases and operations evolve.

PUBLICATION(S)

Stuster JW. Behavioral issues associated with long-duration space expeditions: Review and analysis of astronaut journals experiment 01-E104 (Journals): Final report. *NASA Technical Memorandum*; 2010.

ISS013E66729 – Flight Engineer-2 Thomas Reiter (left); ISS Expedition 13 Commander Pavel V. Vinogradov (middle); and Flight Engineer-1 Jeffrey N. Williams (right) pose for a picture with extravehicular activity (EVA, or spacewalk) suits on the International Space Station (ISS). The primary focus of the Journals investigation is to help the crew cope with isolation during long-duration exploration.

ISS013E05853 – The primary focus of the Journals investigation is to help NASA design equipment and procedures to allow astronauts to best cope with isolation during long-duration exploration.

This investigation is ongoing and additional results are pending publication.

Study of the Individual Features of the Psychological and Physiological Regulator of the State and Reliability of Work Performance in Crewmembers in Long-Term Spaceflight (Pilot-Regulation/Pilot-Robot/Pilot-Activity), Three Investigations

Research Area: Human Behavior and Performance

Expedition(s): 7-12, 14-26

Investigator(s):

- Victor P. Salnitsky, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

The Study of the Individual Features of the Psychological and Physiological Regulator of State and Reliability of Work Performance in Crewmembers in Long-term Spaceflight (Pilot) assesses and predicts the reliability of crew members performing complex and critical dynamic vehicle manual control tasks in various stages of long-term spaceflight and to study the features of crew member psycho-physiological reactions when exposed to stressful requirements in flight. Pilot is composed of 3 distinct investigations. Pilot-Regulatiion studies the individual features of crewmember psycho-physiological reactions when exposed to stress factors in flight; Pilot-Activity studies the reliability of crewmember performance during simulated manual control tasks for the final approach and docking of a Soyuz vehicle to the ISS; Pilot-Robot studies the dynamics of critical operator skills to manually control a robotic arm simulator in various stages of space flight.

Russian cosmonaut performs the Pilot experiment aboard the International Space Station. Roscosmos image.

Earth Benefits

New insights, equipment, and training developments for maintaining work performance and reliability in space can be applied to remote manipulation tasks on Earth such as robotic handling of hazardous materials or robotic surgery.

Space Benefits

Diagnosing the current status of crew member skills at various stages of long-term spaceflight and maintaining them at the highest level is an effective way of increasing the likelihood of successful and safe robotic arm operation. Effective ways to enhance and personalize onboard training programs are to diagnose the status of critical skills, determine deteriorating skills, and restore them to the required level for subsequent integration into overall performance. The results of this work are used to develop recommendations on improving the onboard simulator and to optimize the procedure and timeline for training sessions to refresh and maintain work skills in flight.

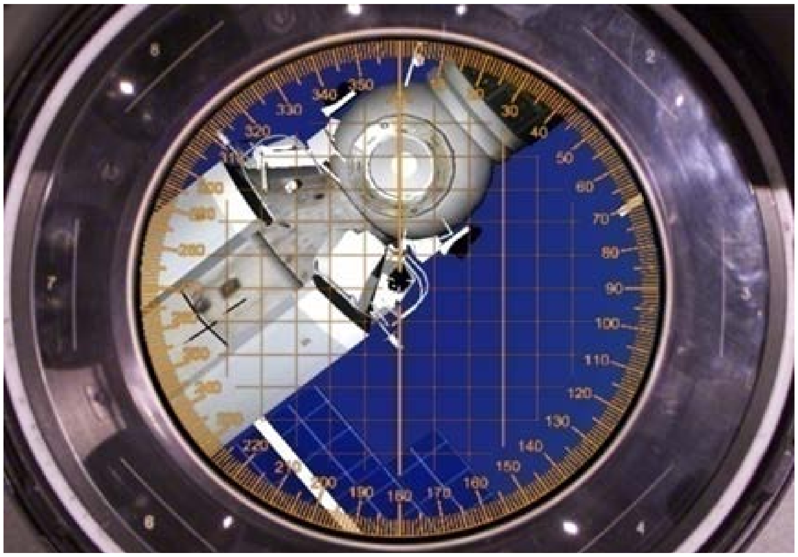


Image of the ISS presented to the operator on the laptop screen. Roscosmos image.

This investigation is complete and all results are published.

RESULTS

Russian International Space Station crew members demonstrated a high level of training skills during simulated station keeping and final approach tasks. Typical of the majority of crew members is a continuous increase in the quality of performing simulated final approach and docking tasks during flight. An interval of 30-35 days in training sessions to refresh space vehicle final approach/docking manual control skills enabled work skills to be maintained at the required level.

Psychomotor Vigilance Self Test on the International Space Station (Reaction Self Test)

Research Area: Human Behavior and Performance
Expeditions: 21-ongoing
Principal Investigator(s):
- David F. Dinges, PhD, University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania

Research Objectives

The Psychomotor Vigilance Self Test on the International Space Station (Reaction Self Test) is a portable 5-minute reaction time task that will allow the crew members to monitor the daily effects of fatigue on performance while aboard the International Space Station (ISS).

Earth Benefits

The principal investigator (PI) developed the original 10-minute Psychomotor Vigilance Test (PVT), which the Reaction Self Test was derived from, to measure changes in psychomotor speed, lapses of attention, wake state instability, and impulsivity induced by fatigue and other performance-degrading factors commonly found in operational environments. Based on research supported by federal and non-U.S. federal agencies as well as the pharmaceutical industry, the 10-minute PVT has been extensively validated in laboratory studies, simulators, and operational environments to be sensitive to a variety of performance-degrading fatigue-related factors.

ISS022E097239 – Jeffrey Williams, Expedition 22 commander, performs Reaction Self Test in the U.S. Laboratory.

Space Benefits

The Reaction Self Test aids crew members to objectively identify when their performance capability is degraded by various fatigue-related conditions that can occur as a result of ISS operations and time in space. The project addresses a number of high-priority NASA Behavioral Health and Performance (BHP) research gaps including: (1) identification of the best measure for assessing decrements in cognitive function because of fatigue and other aspects of spaceflight; (2) determination of an individual crew member’s vulnerability to sleep loss; (3) establishment of cognition decline or change during long-duration missions (LDM); and (4) facilitation of ways for crew members and ground support to detect and compensate for decreased cognitive readiness to perform in space.

Results

Results from Reaction Self Test are pending completion of testing on all subjects before conclusive results are published.

This investigation is ongoing and additional results are pending publication.

Sleep-Wake Actigraphy and Light Exposure During Spaceflight – Long and Short (Sleep), Two Investigations

Research Area: Human Behavior and Performance
Expeditions: 14-26
Principal Investigator(s):
- Charles A. Czeisler, MD, PhD, Harvard Medical School, Boston, Massachusets
- Laura K. Barger, PhD, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusets

Research Objectives

Sleep-Wake Actigraphy and Light Exposure During Spaceflight examines the effects of space flight and ambient light exposure on the sleep-wake cycles of crew members during shuttle missions and long-duration stays aboard the International Space Station (ISS). Advancing state-of-the-art technology for monitoring, diagnosing, and assessing treatment of sleep patterns is vital to treating insomnia on Earth and in space.

Earth Benefits

A better understanding of insomnia is relevant to the millions of people on Earth who suffer nightly from insomnia. The advancement of state-of-the-art technology for monitoring, diagnosing, and assessing treatment effectiveness is vital to the continued treatment of insomnia on Earth. This work has the potential to greatly benefit the health, productivity, and safety of groups with a high prevalence of insomnia, such as shift workers and the elderly.


S104E5114 – Astronaut Janet Kavandi on STS-104 is wearing an Actiwatch on her right wrist for recording activities.

Space Benefits

The information gained from this study leads to a better understanding of the effects of spaceflight on sleep-wake cycles. The countermeasures that may be developed based on the findings of this study could improve sleep during missions, which, in turn, help to maintain alertness and lessen fatigue of the crew during long-duration spaceflights.

Results

Even when speeding at over seventeen thousand miles an hour, astronauts find it tough to catch enough Z's. A comprehensive analysis of results, collected over a ten-year span, shows that Shuttle and International Space Station crew members have difficulty falling asleep and typically do not get the full amount of sleep recommended for them each night. Sleep researchers studied diary entries and rest/activity monitor data of 78 individual crew members from 80 shuttle flights (from 2001 to 2011) and 21 ISS missions (from 2005 to 2011) and found that, on average, space travelers get about 6 hours of sleep per night while in space and only slightly more during the data collect interval scheduled about three months prior to launch. The intensity of the pre-flight training and travel schedule may have contributed to insufficient sleep in the pre-flight data collection interval. During space missions, roughly three quarters of shuttle and ISS crew members reported taking sleep-promoting medication. Shuttle crew members reported taking sleep-promoting medications on about half of their nights in space, including nights prior to performing extra vehicular activity (EVA) work the next day which were extra mentally and physically demanding. The sleep-aid drug Zolpidem (brand name Ambien) was reported as the most often taken by shuttle crew members. The high prevalence of sleeping pill use during spaceflight, despite chronic sleep deficiency and improved sleeping conditions and quarters on the ISS, may suggest that some other aspect of the space environment, such as microgravity itself, might contribute to sleep disturbance. The use of sleep-promoting medication did not significantly increase the amount of sleep that astronauts obtained and only increased the sleep efficiency of shuttle crew members by about one percent. The minimal sleep improvement on nights when sleep-promoting medications were used emphasizes the need for further investigation into the stability, absorption, and effectiveness of such drugs in-flight. Sleep and the use of sleep-promoting medications during spaceflight needs further investigation, including the effect of chronic sleep deficiency and hangover effects from sleep promoting medications on operational performance, to develop and recommend best practices for ISS crew members. The sleep duration of crew members aboard long duration ISS missions was similar to that of crew members aboard short-duration shuttle missions. Monitoring and assessment of sleep duration and timing should continue in future spaceflight missions as a medical requirement, including collection of baseline data before astronaut selection for flight to estimate more accurately individual baseline sleep duration. Development of other more effective countermeasures to promote sleep in-flight is crucial, and might include scheduling modifications, strategically timed exposure to specific wavelengths of light and behavioral strategies to ensure adequate sleep, which is essential for maintaining optimal health, performance, and safety. Further research of sleep is planned for the future 1-year ISS missions, twice the normal length of previous ISS missions, which might provide information on trends in sleep over longer durations, which is especially relevant for future exploration class missions beyond low Earth orbit.

ISS014E05119 – The Sleep-Long Actiwatch is visible on the left arm of astronaut Michael Lopez-Alegria the Expedition 14 commander. The Actiwatch monitors light and activity patterns of crew members.

PUBLICATION(S)

Barger LK, Flynn-Evans EE, Kubey A, et al. Prevalence of sleep deficiency and use of hypnotic drugs in astronauts before, during, and after spaceflight: An observational study. *Lancet Neurology*. September 2014;13(9):904-912. doi: 10.1016/S1474-4422(14)70122-X.

This investigation is complete; however additional results are pending publication.

Special Event Meals

Research Area: Human Behavior and Performance
Expedition(s): 14
Principal Investigator(s):
- Alain Maillet, Centre National D'Etudes Spatiales (CNES), Toulouse, France

Research Objectives

The goal of the Special Event Meals project was to provide the International Space Station (ISS) crew with high-quality food cans that could be the core of celebration meals such as New Year, the arrival of new crew, birthdays, etc. This gives the crew the possibility to break the monotony of ISS standard daily food, thus helping psychological support (useful for long-duration flights).

First use of the Special Event Meals during the Astrolab mission in 2006. ESA image.

Results

Since 2008, these meals have formed part of the NASA food list for crew bonus containers. The food was not only used in bonus containers and special meals for the crews but also used to support scientific experiments when the experiment requires a special imposed diet, such as within the ENERGY experiment. For the ENERGY experiment, the crew was eating this food first during the baseline data collection before flight and then during the flight (normally after having passed 3 months in space). The ENERGY menus' container was composed of 4 meals (2 breakfasts, 1 lunch, and 1 dinner), which was taken by the crew at the beginning of the experimental session (ie, day 0 and day 1).

In 2006, 10 different recipes were available; today 25 recipes are available either for physiology and nutrition experiments support or for bonus containers.

This investigation is complete; however additional results are pending publication.

Human Factors Assessment of Vibration Effects on Visual Performance During Launch (Visual Performance)

Research Area: Human Behavior and Performance
Expeditions: 18-20
Principal Investigator(s):
- Kritina Holden, PhD, Lockheed Martin, Houston, Texas

Research Objectives

The Human Factors Assessment of Vibration Effects on Visual Performance During Launch (Visual Performance) investigation tests visual performance limits during operational vibration and g-loads on the space shuttle, specifically through the determination of minimum readable font size during ascent using planned Orion display formats.

Image of a training session for the Visual Performance - Human Factors Assessment of Vibration Effects on Visual Performance During Launch. NASA's Johnson Space Center image.

S119E005001 – Shuttle image of the Visual Performance - Human Factors Assessment of Vibration Effects on Visual Performance During Launch with the visual placard used during the study, still on the mid-deck lockers shortly after orbit. NASA's Johnson Space Center image.

Earth Benefits

Data from Visual Performance provide insight into designing displays for those who need to read displays under extreme vibration such as pilots or race car drivers.

Space Benefits

Previous studies were not systematically validated with flight data, and were performed using older displays and controls, in contrast to the glass cockpit concepts currently planned for future exploration vehicles. The Visual Performance investigation determines middeck crew visual performance and provide data for further ground testing, and also validated flight data from which performance requirements can be developed.

Results

Data analysis for this investigation is ongoing. Final results will be published upon completion of data analysis.

This investigation is complete; however additional results are pending publication.

MONITORING GROUP ACTIVITY BY CREWMEMBERS DURING SPACEFLIGHT (VZAIMODEYSTVIYE)

Research Area: Human Behavior and Performance

Expedition(s): 19-42

Principal Investigator(s):
- Vadim I. Gushchin, MD, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

Monitoring Group Activity by Crewmembers During Spaceflight (Vzaimodeystviye) obtains new data on interpersonal interaction and behavioral patterns of the ISS crews during long-term spaceflight. Results are used to improve the ability of future crew members to interact safely and effectively with each other and ground support personnel. The results may also be used to improve methods for crew selection, training, and inflight support.

EARTH BENEFITS

The individual experimental data that are obtained make it possible to conduct research on individual psychological parameters; these can be used to develop effective and reliable methods of diagnosing and predicting the organization level of small groups having various purposes that are involved in mutual activities (expeditions, sports, manufacturing, experiments, etc.).

ISS037E028227 – Nine crew members gather for a group portrait in the Kibo laboratory following a joint crew news conference. Pictured clockwise (from bottom right) are European Space Agency astronaut Luca Parmitano and NASA astronaut Karen Nyberg, both Expedition 37 flight engineers; Russian cosmonaut Fyodor Yurchikhin, Expedition 37 commander; Russian cosmonaut Mikhail Tyurin, Russian cosmonaut Sergey Ryazanskiy, NASA astronaut Rick Mastracchio, Expedition 38 flight engineers; Russian cosmonaut Oleg Kotov, Expedition 38 commander; Japan Aerospace Exploration Agency astronaut Koichi Wakata and NASA astronaut Michael Hopkins, both Expedition 38 flight engineers.

SPACE BENEFITS

The results of the Vzaimodeystviye are used to improve systems for psychological selection and monitoring of group activity in flight, and also to identify sociopsychological problems and determine the presence of stress in interpersonal relationships within the crew. Consideration for the particulars related to the increasing number of crewmembers, and their different nationalities improves the effectiveness of joint habitation and work by the crew, particularly during long-term spaceflights.

RESULTS

In order to fulfill the approved objectives of the experiment, it is necessary to study at least 20 ISS crew members. Scientific analysis of the results is performed upon accumulation of sufficient amount of data for statistical analysis in order to determine general patterns of group dynamics in an international ISS crew.

It is shown that the most marked changes took place over the course of the first month of flight. During the following 4 months of the increment, assessment oneself remained virtually unchanged. During the last month of flight, more marked changes describing communication, mood, and self-control come to the foreground. Thus, the results obtained confirm the proposed hypothesis that under the influence of stress at various stages of long-term spaceflight, a partial change takes place in self-perception and perception of other crewmembers, including the most significant criteria reflecting the person's basic values. Experimental data confirm the high significance and relevance of studying the degree of psychological closeness (similarity) of members of an international space crew, particularly taking into account the specific features of the current phase of work on the ISS, which are characterized by an increased number of cosmonauts and astronauts and their different nationalities.

PUBLICATION(S)

Vinokhodova AG, Gushin VI. Study of values and interpersonal perception in cosmonauts on board of International Space Station. *Acta Astronautica*. January 2014;93:359-365. doi: 10.1016/j.actaastro.2013.07.026. [Also: Presented during the 63rd IAC in Naples.]

Johnson PJ, Asmaro D, Suedfeld P, Gushin VI. Thematic content analysis of work–family interactions: Retired cosmonauts' reflections. *Acta Astronautica*. 2012;81(1):306-317. doi: 10.1016/j.actaastro.2012.07.032. [Also: Presented during the 62nd IAC in Cape Town.]

Suedfeld P, Brcic J, Johnson PJ, Gushin VI. Personal growth following long-duration spaceflight. *Acta Astronautica*. October 2012;79:118-123. doi: 10.1016/j.actaastro.2012.04.039.

This investigation is complete; however, additional results are pending publication.

DIFFERENTIATION OF BONE MARROW MACROPHAGES IN SPACE (BONEMAC)

Research Area: Immune System

Expeditions: 18

Principal Investigator(s):
- Stephen Keith Chapes, PhD, MPH, Kansas State University, Manhattan, Kansas

RESEARCH OBJECTIVES

This experiment investigates how long-term exposure to microgravity, which would be experienced on missions to the moon and Mars, effects production of cells critical to the human immune system.

EARTH BENEFITS

Investigation of the effects of bone loss on blood cell production helps to improve the effectiveness of treatments for similar conditions suffered by patients on Earth.

S126E008304 – Astronaut Heidemarie Stefanyshyn-Piper, STS-126 mission specialist, works with Group Activation Packs (GAP) on the middeck of Space Shuttle Endeavour while docked with the International Space Station (ISS).

SPACE BENEFITS

Spaceflight crew members traveling to the moon or Mars may experience degradation of their immune system function because of disruption of blood cell production mechanisms. The results of this experiment help in the development of medicines to counteract disruptions to blood cell production and to minimize potential crew sickness from exposure to altered or new bacteria and viruses.

RESULTS

Experiments were carried out in vitro (outside the living animal) over the course of a 2-week space shuttle mission, on macrophages (a type of white blood cell) from mice bone marrow stem cells, to test the theory that changes in the receptor for macrophage colony stimulating factor (M-CSF) may have been responsible for the effects of spaceflight on bone marrow macrophage enhanced growth. Bone marrow cells were analyzed in this study as a complete bone marrow population and as cell subpopulations distinguished by size and internal complexity. Results showed the number of bone marrow-derived macrophages increase faster during spaceflight compared to ground controls confirming previous findings.

Macrophage cells counts in both living and preserved cell cultures increased an average of 5.7 fold in flight and an average of 3.9 fold on the ground after 14 and 17 day periods. However, no changes in receptor expression for M-CSF and no consistent pattern of advanced or retarded macrophage differentiation (the process of cells becoming more specialized) during spaceflight were found. There also was a surprising pattern of spaceflight influence on genes involved in coagulation. Observed changes in gene duplication suggest impacts on the cells from spaceflight were of a global nature not just on specific cellular communication pathways. There were no significant differences in gross bone morphology between treatment groups or changes in the bone marrow cell numbers between flight and ground-control mice. So, spaceflight did not radically disrupt the distribution of bone marrow cell subpopulations. These data confirm spaceflight can impact the in vitro development of macrophages from mouse bone marrow cells (Ortega 2009, 2012).

PUBLICATION(S)

Ortega MT, Lu N, Chapes S. Evaluation of in vitro macrophage differentiation during spaceflight. *Advances in Space Research*. 2012;49(10):1441-1455. doi: 10.1016/j.asr.2012.02.021.

Ortega MT, Pecaut MJ, Gridley DS, Stodieck LS, Ferguson VL, Chapes S. Shifts in bone marrow cell phenotypes caused by spaceflight. *Journal of Applied Physiology*. February 2009;106(2):548-555. doi: 10.1152/japplphysiol.91138.2008.

This investigation is complete and all results are published.

Cell Culture Module - Immune Response of Human Monocytes in Microgravity (CCM-Immune Response)

Research Area: Immune System
Expeditions: 15
Principal Investigator(s):
- William Wiesmann, MD, Hawaii Chitopure, Honolulu, Hawaii

Research Objectives

Cell Culture Module - Immune Response of Human Monocytes in Microgravity (CCM-Immune Response) is a Department of Defense Space Test Program research that uses cell culture in microgravity as a model of reduced immune function. This investigation examines the response of human immune cells in microgravity to new chitosan-based antibacterials.

Earth Benefits

Where textile dressings stem the loss of blood by direct pressure, chitosan bandages actively clot the wound. These bandages are now standard issue for U.S. soldiers serving in Iraq and Afghanistan. This investigation provides a test of chitosan as a cell culture matrix and more information into its bacteriological properties, which further development of chitosan for military and civilian uses.

Space Benefits

Spaceflight crews traveling to the moon or Mars in microgravity may experience injury or trauma. The chitosan-based experiment results help to find new and improved wound-healing treatment for crew members as well as for the needs of military personnel in space and for future space travel.

S118E10350 – Seen in this image is the hardware that houses the Cell Culture Module - Immune Response of Human Monocytes in Microgravity (CCM-Immune Response) and the Cell Culture Module - Effect of Microgravity on Wound Repair: In Vitro Model of New Blood Vessel Development (CCM-Wound Repair) experiments. The experiments were flown on STS118/13A.1 in August 2007.

Results

Preliminary results from CCM-Immune Response show that the cells were successfully cultured and returned to Earth. Monocytes without chitosan did not survive the bacterial infection; whereas, the monocytes with chitosan were protected and survived. Preliminary analysis shows the potential for a new pharmaceutical to fight large-scale bacterial infections.

This investigation is complete; however additional results are pending publication.

Cell Culture Module - Effect of Microgravity on Wound Repair: In Vitro Model of New Blood Vessel Development (CCM-Wound Repair)

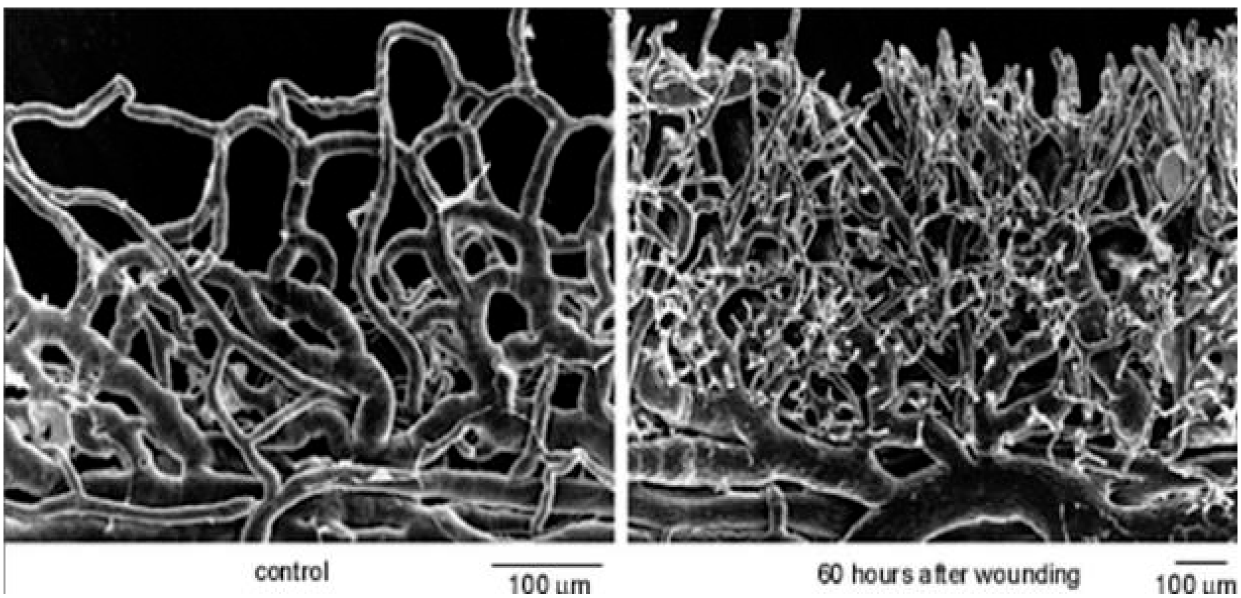
Research Area: Immune System

Expeditions: 15

Principal Investigator(s):
- James B. Hoying, PhD and Stuart K. Williams, PhD, The University of Arizona, Tucson, Arizona

Research Objectives

Cell Culture Module - Effect of Microgravity on Wound Repair: In Vitro Model of New Blood Vessel Development (CCM-Wound Repair) is a Department of Defense Space Test Program research that uses cell culture in microgravity as a model of wound healing. This investigation is directed at the use of adipose-derived adult stem cells for use in injury repair and how the microgravity alters new blood vessel development, which is a key component of wound and tissue repair.



Pictured is new capillary formation in response to wounding. Image from Alberts B, Bray D, Lewis J, et al., Molecular Biology of the Cell, 5th Edition, 2007, Pg. 1279-1283.

Earth Benefits

This unique cell culture in microgravity serves as a model system for understanding necrosis of tissue following severe injuries. Using adipose-derived adult stem cells may accelerate new blood vessel development, which is a key component of wound and tissue repair. Results will be applied to help prevent the loss of limbs following severe injuries with life-changing benefits in military and civilian applications.

Space Benefits

Astronauts traveling to the moon or Mars in microgravity may experience injury or trauma, initiating the wound healing process. The blood vessel experiment seeks potential treatments to reduce any negative effects of microgravity on wound healing and blood vessel formation.

Results

Preliminary results from CCM-Wound Repair show that the cells were successfully cultured and returned to Earth. Data analysis is ongoing to determine deviations in cell pathology between flight and ground cells used to characterize the microgravity induced stresses on the flight samples.

This investigation is complete; however additional results are pending publication.

Spaceflight Induced Reactivation of Latent Epstein-Barr Virus (Epstein-Barr)

Research Area: Immune System

Expeditions: 5, 6, 11-17

Principal Investigator(s):
- Raymond P. Stowe, PhD, Microgen Laboratories, La Marque, Texas

Research Objectives

The Spaceflight-Induced Reactivation of Latent Epstein-Barr Virus (Epstein-Barr) experiment performs tests to study changes in the human immune function using blood and urine samples collected before and after spaceflight. The study provides insight for possible countermeasures to prevent the potential development of infectious illness in crew members during flight.

Earth Benefits

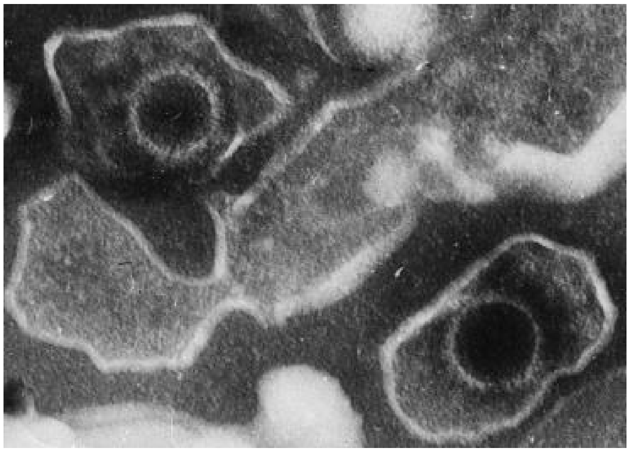
This type of study sheds light on infectious diseases, how they are related to stress here on Earth, and how they can be treated.

Space Benefits

In the United States, approximately 90% of adults have been infected with Epstein-Barr virus (EBV), one of the most common human viruses. It establishes a lifelong dormant infection inside the body, but can be reactivated by illness or stress. Once active, it can cause infectious mononucleosis (also known as mono). Decreased cellular immune function is observed during and after human spaceflight. With longer-duration space missions, latent viruses are more likely to become reactivated, placing the crew at risk of developing and spreading infectious illness. If this is the case, drug therapies must be created to protect crew members during long-term and interplanetary missions (ie, trips to Mars). This study will help provide information related to immune function and virus activity in space to develop such remedies and ensure future exploratory space missions.

Results

A goal of the Epstein-Barr Virus (EBV) study was to determine whether changes in EBV gene expression (reactivation) occurred after short- and long-duration spaceflight. All astronaut and control subjects (24) tested positive for antibodies indicating past EB infection. In shuttle astronauts, a pattern of immediate-early and early viral gene transcription (the first step in gene production) was observed indicative of EBV reactivation. Altogether, there was a significant increase in the number of immediate early and early gene replications in shuttle astronaut samples as compared to healthy control samples. Although EBV reactivation did occur in shuttle astronauts, productive EBV replication in peripheral blood B-lymphocytes did not. In contrast, samples from 3 ISS astronauts after flight show strong evidence that complete productive EBV replication is occurring in the peripheral blood B cells of these astronauts, and data clearly show full activation EBV in the B-cells of ISS astronauts. For these crew members who flew longer (6 months) in space, latent gene expression and late lytic (involves the destruction of the host cell) gene transcripts were both more frequent and diverse. Overall,



Electron microscopic image of 2 Epstein Barr Virus virions (viral particles) shows round capsids—protein-encased genetic material—loosely surrounded by the membrane envelope. Public Library of Science image (the original author of this photo is Liza Gross).

there was a significant increase in the number of immediate early and early gene transcripts in ISS astronaut samples as compared to healthy control samples and shuttle astronauts at landing. A related study focused on "monocytes," a type of white blood cell, which play multiple roles within the immune system. Evidently, the more complex and greater the workload and associated stress crew members experienced, the more their immune function (in this case monocyte parameters) appeared to be compromised, mainly in the reduction of the body's defense signaling capability and pronounced suppression of the immune system's ability to identify and neutralize potential pathogens. Researchers also found increases in the stress hormone cortisol in shuttle crew members, presumably due to the rigors of preflight training, which were accompanied by significant changes in white blood cells even days prior to launch. It is important to note, however, that for short-duration crew members, these immune system changes do not appear to linger beyond a few days after mission completion. (Stowe 2011, Crucian 2011).

PUBLICATION(S)

Mehta SK, Crucian BE, Stowe RP, et al. Reactivation of latent viruses is associated with increased plasma cytokines in astronauts. *Cytokine*. 2012;61(1):205-209. doi: 10.1016/j.cyto.2012.09.019.

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Stowe RP, Sams CF, Pierson DL. Adrenocortical and immune responses following short- and long-duration spaceflight. *Aviation, Space, and Environmental Medicine*. June 2011;82(6):627-634. doi: 10.3357/ASEM.2980.2011.

Crucian BE, Stowe RP, Sams CF, Pierson DL. Immune system dysregulation following short- vs long-duration spaceflight. *Aviation, Space, and Environmental Medicine*. 2008;79(9):835-843. doi: 10.3357/ASEM.2276.2008.

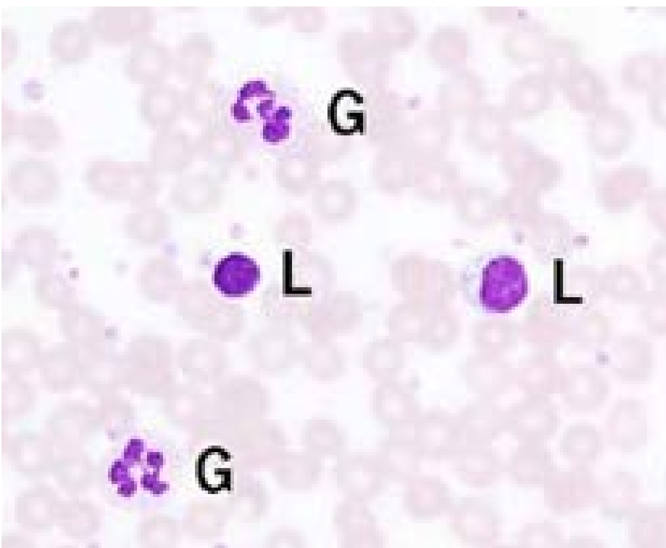
This investigation is ongoing and additional results are pending publication.

Neuroendocrine and Immune Responses in Humans During and After Long Term Stay at ISS (Immuno)

Research Area: Immune System
Expedition(s): 12-16, 29, 30-ongoing
Principal Investigator(s):
- Alexander Chouker, MD, University of Munich, Germany
- Boris Morukov, MD, PhD, Institute for Biomedical Problems, Moscow, Russia

Research Objectives

Neuroendocrine and Immune Responses in Humans During and After Long Term Stay at ISS (Immuno) provides an understanding for the development of pharmacological tools to counter unwanted immunological side-effects during long-duration missions in space. The investigation will also provide insight into the disease process of immune-compromised humans on Earth.



Blood sample shows white blood cells: Lymphocytes (L) and Granulocytes (G). ESA image.

Space Application

Immuno aims to provide the understanding for the development of pharmacological tools to countermeasure unwanted immunological side effects during long-duration missions into space.

Earth Application

The Immuno investigation will provide insight into the disease process of immunocompromised humans on Earth.

Results

Thirty cosmonauts on short-duration (8-11 days) and long-duration (125-195 days) missions to the International Space Station (ISS) were studied before launch and after landing in order to detect changes in the immune system, which had been reported in previous studies with short- and long-duration space missions in low-Earth orbit.

The first results on the Humoral Immune Response (HIR) of ISS cosmonauts focused on peripheral blood antibodies, T- and B-lymphocyte white blood cell (WBC) populations, cytokines (cell-signaling agents), as well as natural killer (NK) cells activity in the body’s defense against bacteria, viruses, and toxins.

No notable changes in the antiviral antibody levels after long- and short-term missions were observed, and specific antibodies for Epstein-Barr viruses (EBVs), which were often reactivated in microgravity, also did not change. Although the total number of WBCs increased significantly upon landing, the overall population of T and B lymphocytes did not change appreciably after long-duration spaceflights. However, T-lymphocyte function was decreased, which supports previous observations and recently confirmed from a study of 12 Russian cosmonauts after long-duration missions. Researchers proposed that a long-duration spaceflight, perhaps coupled with several extravehicular activities (EVA), activated and suppressed T-lymphocytes' response to proliferate, thus resulted in an immune deficit against potential infections. The investigation also showed gross individual differences in concentration of cytokines before launch possibly due to preflight stress. The random changes after short- and long-term missions suggest that cytokines may be highly sensitivity to the factors associated with re-entry and readaptation to Earth's gravity. Also, a decrease in natural killer (NK) cells population and activity in the long-duration crew members may be an indication of a weakened immune system, plus the reduced NK activity in some subjects on the first day after short-duration could very well be an acute response to landing stress.

Many improvements have been made to the living conditions of orbital vehicles and the scope of spaceflight immunological research expanded since the first human was flown into space 50 years ago. However, ISS crew members still exhibit negative shifts in the immune system during initial readaptation to gravity. Such alterations, scientists suspect, could lead to compromised defenses against infections by limiting the immune system's communicating and disease fighting capabilities. In light of these results, full characterization of all aspects of the innate and adaptive immune system after prolonged and brief flights appears essential for understanding the relationship of microgravity and stress effects of spaceflight on human space explorers.

PUBLICATION(S)

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Strewe C, Feuerecker M, Nichiporuk IA, et al. Effects of parabolic flight and spaceflight on the endocannabinoid system in humans. *Reviews in the Neurosciences*. September 2012;23(5-6):673-680. doi: 10.1515/revneuro-2012-0057.

Morukov BV, Rykova MP, Antropova EN, Berendeeva T, Ponomaryov S, Larina IM. T-cell immunity and cytokine production in cosmonauts after long-duration space flights. *Acta Astronautica*. 2011;68:739-746. doi: 10.1016/j.actaastro.2010.08.036.

Rykova MP, Antropova EN, Larina IM, Morukov BV. Humoral and cellular immunity in cosmonauts after the ISS mission. *Acta Astronautica.* 2008;63:697-705. doi: 10.1016/ j.actaastro.2008.03.016.

This investigation is complete; however additional results are pending publication.

Validation of Procedures for Monitoring Crew Member Immune Function (Integrated Immune)

Research Area: Immune System
Expeditions: 16-ongoing
Principal Investigator(s):
- Clarence F. Sams, PhD, Johnson Space Center, Houston, Texas

Research Objectives

Validation of Procedures for Monitoring Crew Member Immune Function (Integrated Immune) estimates the clinical risks resulting from the adverse effects of spaceflight on the human immune system to validate a flight-compatible immune monitoring strategy. Immune system changes are monitored by collecting and analyzing blood, urine, and saliva samples from crew members before, during, and after spaceflight.

Earth Benefits

The data collected during this investigation lead to a greater understanding of how the immune system is affected by different factors from stress to the environment. This data could potentially be used to help develop new treatments and preventative measures for immune dysfunctions.

Space Benefits

The study validates a monitoring strategy that allows the development of effective countermeasures. When implemented, this safeguards the health of the crew during long-duration space missions.

ISS030E257695 – In the International Space Station's (ISS) Destiny Laboratory, NASA astronaut Dan Burbank (foreground) and European Space Agency astronaut Andre Kuipers prepare for venous blood sample draws in the Columbus Laboratory of the ISS. Following the blood draws, the samples are temporarily stowed in the Minus Eighty Laboratory Freezer for ISS 1 (MELFI-1) and later packed together with saliva samples on the Soyuz TMA-22 for return to Earth for analysis.

Results

Researchers collected multiple preflight and postflight samples from shuttle and ISS crew members from 2007 onward. They found that shuttle crew members on short missions of about 2 weeks experienced greater initial stress, even prior to launch, than crew members leaving for a longer 6-month tour on the ISS. After short-duration missions, white blood cell (WBC) counts were elevated and typical stress-induced shifts were observed, and a general immunity assessment confirmed a parallel decrease in immune function. Changes in monocyte, a type of

WBC, parameters and defense signaling capacity may also have an impact on overall crew member immune system health. ISS crew members, by contrast, did not show increased cortisol stress hormone levels at any time prior to launch. A plausible explanation is the training, which differs greatly for these astronauts who are prepared mentally for long-duration flights that are psychologically challenging, is much longer and diverse than shuttle astronauts. Stress hormones returned to preflight levels for both groups after a few days back on earth. Also, approximately 50% of the subjects had very high WBC counts, which have typically been associated with increased stress hormones, at landing. Unexpectedly, some subsets of white blood cells did not show normal response to the rise in stress hormones for long-duration crew members. Further study is needed to determine if this is a failure of these WBCs to properly respond to acute stress or if the blood production process is altered during long-duration spaceflight. The authors conclude the current ISS training successfully reduces stress and interventions employed during this period in which astronauts are most accessible would likely produce the desired effects. These results agree with prior studies demonstrating the significance of mission duration in the magnitude of these immune system changes.

PUBLICATION(S)

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Crucian BE, Zwart SR, Mehta SK, et al. Plasma cytokine concentrations indicate that in vivo hormonal regulation of immunity is altered during long-duration spaceflight. *Journal of Interferon and Cytokine Research*. October 2, 2014;34:778-786. doi: 10.1089/jir.2013.0129.

Crucian BE, Stowe RP, Mehta SK, et al. Immune system dysregulation occurs during short duration spaceflight on board the space shuttle. *Journal of Clinical Immunology*. February 2013;33(2):456-465. doi: 10.1007/s10875-012-9824-7.

Crucian BE, Stowe RP, Quiriarte HD, Pierson DL, Sams CF. Monocyte Phenotype and Cytokine Production profiles are dysregulated by short-duration spaceflight. *Aviation, Space, and Environmental Medicine.* 2011;82(9):857-862. doi: 10.3357/ASEM.3047.2011.

Kaur I, Simons ER, Kapadia AS, Ott CM, Pierson DL. Effect of spaceflight on ability of monocytes to respond to endotoxins of gram-negative bacteria. *Clinical and Vaccine Immunology*. October 2008;15(10):1523-1528. doi: 10.1128/CVI.00065-08.

Kaur I, Simons ER, Castro VA, Ott CM, Pierson DL. Changes in monocyte functions of astronauts. *Brain, Behavior, and Immunity*. November 2005; 19(6):547-554. doi: 10.1016/j.bbi.2004.12.006.

Crucian BE, Lee P, Stowe RP, et al. Immune system changes during simulated planetary exploration on Devon Island, high arctic. *BMC Immunology*. May 23, 2001; 8(7). doi: 10.1186/1471-2172-8-7.

This investigation is ongoing and additional results are pending publication.

RESEARCH ON INTERCELLULAR INTERACTION IN SPACEFLIGHT (INTERCELLULAR INTERACTION)

Research Area: Immune System
Expedition(s): 7-12
Principal Investigator(s):
- Lyudmila B. Buravkova, MD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

The Research on Intercellular Interaction in Spaceflight (Intercellular Interaction) investigation assesses the cytotoxic activity of lymphocytes isolated from human blood when co-cultured with K-562 myeloblasts in microgravity.

EARTH BENEFITS

Laboratory experiments and inflight experiments demonstrate the possibility and effectiveness of using a modified method of studying the cytotoxic activity of natural killer (NK) cells *in vitro*. The results of the studies performed on the cytotoxic activity of NK cells co-cultured with K-562 myeloblasts in microgravity allow for more in-depth understanding of certain processes that form the foundation of intercellular interactions.

SPACE BENEFITS

The studies performed opened up new opportunities for researching the role of stimuli in the functioning of immunocompetent cells *in vitro* in microgravity conditions. The results of the work corroborate theoretical ideas regarding the effect of microgravity conditions on the intercellular interaction of NK lymphocytes and target cells of line K-562. The data obtained are of practical significance, since they substantiate the methodological approaches to direct, in-flight research on the status of anti-viral immunity in space explorers, which is the foundation for developing medical monitoring equipment at various phases of long-term missions.

Cosmonaut Yu Malenchenko performs the Research on Intercellular Interaction in Spaceflight experiment aboard ISS-7. Roscosmos image.

RESULTS

A number of researchers on cultures of isolated mononuclear cells discovered that the functional activity of T-cells was inhibited by the disruption of their interaction with helper cells, which occurred through signals necessary for expression of regulatory molecules. The study performed showed that the microgravity factor did not have an inhibitory effect on the function of NK lymphocytes; in fact, half of the inflight experiments demonstrated a significant activation of the functional activity of NK cells.

PUBLICATION(S)

Buravkova LB, Grigorieva OV, Rykova MP. The effect of microgravity on the in vitro NK cell function during six International Space Station Missions. *Microgravity Science and Technology.* 2007;19(5-6):145-147. doi: 10.1007/BF02919470.

Buravkova LB, Grigorieva OV, Rykova MP. The effects of microgravity on interaction between human immune cells and target cells in vitro (flight experiments during ISS-7–ISS-12 missions. *Science on European Soyuz Mission to the International Space Station (2001-2005)*, Toledo, Spain; 2006.

Grigorieva OV, Rykova MP, Buravkova LB. Intercellular interaction of immune cells and target cells in vitro in microgravity (ISS-7–ISS-12). *13th Conference on Space Biology and Aerospace Medicine*, Moscow, Russia; 2006.

Rykova MP, Gertsik YG, Antropova EN, Buravkova LB. Serum levels of immunoglobulins, allergen-specific IgE antibodies, and interleukin-4 in cosmonauts before and after short flights on the International Space Station. *Human Physiology.* 2006;32(4):457-460. doi: 10.1134/S0362119706040128.

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Buravkova LB, Rykova MP, Grigorieva OV. Results of Intercellular Interaction in-flight experiment (ISS-7–ISS-11). *6th International Applied Science Conference on Manned Spaceflight*, Star City, Russia;2005.

This investigation is complete and all results are published.

INCIDENCE OF LATENT VIRUS SHEDDING DURING SPACEFLIGHT (LATENT VIRUS)

Research Area: Immune System
Expeditions: 1, 2, 4, 5, 11, 13-15
Principal Investigator(s):
- Duane L. Pierson, PhD, Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

The Incidence of Latent Virus Shielding During Spaceflight (Latent Virus) study supports and expands information on latent viruses—or those inactive in the human system—that can reactivate in spaceflight such as a cold sore. Latent virus reactivation could be an important threat to crew health during extended space missions, as crew members live and work in a closed environment. Potential applications of this research include the development of a rapid and sensitive diagnostic method for identifying crew members at increased risk of illness because of viral infections. New technology from this investigation benefits both NASA and commercial applications.

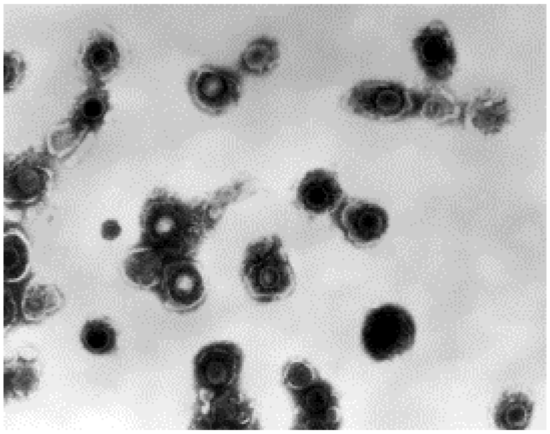
EARTH BENEFITS

The viral-specific saliva DNA test currently used for spaceflight investigations are applied to the rapid diagnosis of herpes virus disease in clinics. These studies of latent virus reactivation in the very healthy, superbly-conditioned flight crews provide new insight into stress, immunity, and viral disease in the general population.

SPACE BENEFITS

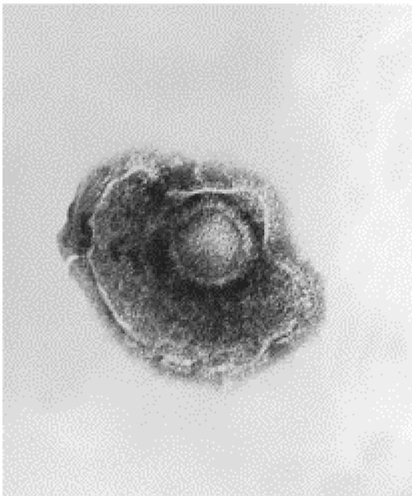
This investigation helps determine the clinical risk of asymptomatic reactivation and shedding of latent viruses to astronaut health and the need for countermeasures to reduce or eliminate the risk. Stress-induced viral reactivation may also prove useful in monitoring early changes in immunity prior to onset of clinical disease.

RESULTS



Electron micrograph of a Varicella-Zoster Virus. Center for Disease Control and Prevention image, Atlanta, Georgia.

Saliva samples collected from crew members traveling on the shuttle to and from the International Space Station (ISS) have provided valuable data for the Latent Virus investigation. Epstein-Barr (EBV) and Varicella zoster (VZV) viruses were studied and results indicate that these latent viruses can become active under stressful conditions such as spaceflight. The pattern and amount of EBV shedding in the astronauts are likely related to spaceflight conditions. The types, levels, and combination of stresses experienced before, during, and after flight, as well as the different ways individuals cope with stress may result in changes in the EBV shedding frequency. Healthy astronauts from 3 shuttle missions along with ground volunteers were also studied to determine the cause of VZV reactivation. Before flight, all samples from the experimental subjects were negative for VZV DNA, during flight VZV DNA was detected in 87% of the astronauts; following return to Earth VZV DNA was detected in only 19% of the astronauts tested. During this same time frame, no VZV DNA was detected from the control subjects. In conclusion, both VZV and EBV can reactivate during stressful situations such as spaceflight (Mehta 2004, Pierson 2005).



Transmission electron micrograph of varicella-zoster virions. Center for Disease Control and Prevention image, Atlanta, Georgia.

PUBLICATION(S)

Pierson DL, Stowe RP, Phillips TM, Lugg DJ, Mehta SK. Epstein-Barr virus shedding by astronauts during spaceflight. *Brain, Behavior, and Immunity*. 2005;19(3):235-242. doi: 10.1016/j.bbi.2004.08.001.

Stowe RP, Phillips TM, Lugg DJ, Pierson DL, Mehta SK. Epstein-Barr virus shedding by astronauts during spaceflight. *Brain, Behavior, and Immunity*. 2005;19(3):235-242. doi: 10.1016/j.bbi.2004.08.001.

Mehta SK, Cohrs RJ, Forghani B, Zerbe G, Gilden DH. Stress-induced subclinical reactivation of varicella zoster virus in astronauts. *Journal of Medical Virology*. 2004;72:174-179. doi: 10.1002/jmv.10555.

PATENT(S)

Harding RE, Cohrs RJ, Gilden DH, Pierson DL, Mehta SK, inventors; Methods for the diagnosis of Varicella Zoster Virus Infection. United States Patent and Trademark Office 20110262895. October 27, 2011.

This investigation is complete and all results are published.

Advanced Diagnostic Ultrasound in Microgravity (ADUM)

Research Area: Integrated Physiology and Nutrition
Expeditions: 8-12
Principal Investigator(s):
- Scott A. Dulchavsky, MD, PhD, Henry Ford Hospital, Detroit, Michigan

Research Objectives

The Advanced Diagnostic Ultrasound in Microgravity (ADUM) experiment involves crew members conducting ultrasound exams on one another to determine the accuracy of ultrasound use to diagnose certain types of in-orbit injuries and illnesses, as well as to assess the feasibility of ultrasound for monitoring in-flight bone alterations.

Earth Benefits

The use of a relatively small piece of medical equipment to diagnose various health problems, in the absence of nearby specialized medical personnel, could save lives and reduce healthcare costs. Patients could transmit ultrasound information to doctors over great distances, resulting in efficient remote medical diagnosis and treatment to a high degree of confidence. This technology essentially allows anyone in the world the potential to access unique clinical imaging expertise remotely.

The techniques established by the Advanced Diagnostic Ultrasound in Microgravity (ADUM) research on the International Space Station (ISS) can rapidly and economically improve medical care in underserved areas. This photo shows an obstetrical examination conducted on an Inuit mother in the high Arctic Circle. A just-in-time training program developed for the astronauts was modified to allow novice operators to perform ultrasounds to determine the status of pregnant women. This technique will provide important guidance as to whether the delivery will be safe in her village or whether potential complications will require the mother to travel, seeking additional attention from a higher level of care. Scott A. Dulchavsky, MD, PhD, Henry Ford Health System, Detroit, Michigan image.

Space Benefits

Aboard the International Space Station (ISS), there is not enough room for a fully functioning hospital or staff of doctors. It is also not feasible for a crew member to return quickly to Earth for medical diagnosis. This experiment allows for efficient testing for medical problems with minimal use of onboard resources. The ability of crew members to use an ultrasound machine with remote instruction, along with ground analysis, promotes timely treatment and averts unnecessary evacuation. Using a modification of this technology, crew members as far away as Mars could obtain remote examinations from doctors on Earth. This type of capability is essential for long-term space exploration.

Results

The ISS ADUM experiment demonstrated that minimal training, along with audio guidance from a certified sonographer, produced ultrasound imagery of diagnostic quality. The ISS crew members, acted as operators and subjects, completing comprehensive scans of the cardiothoracic and abdominal organs as well as limited scans of the dental, sinus, and eye structures. The experiment also included multiple musculoskeletal exams such as a detailed exam of the shoulder muscles. Analysis of ultrasound video downlinks to ground teams at the NASA Johnson Space Center (JSC) TeleScience Center showed excellent results. Many trauma centers around the world use ultrasound technology as a first-line diagnostic procedure to assess abdominal trauma. The use of ultrasound does not require performance by a radiologist for accurate results. Previous research studies cover this topic of expanding ultrasound technology use by non-radiologists in remote locations to provide diagnostic information on acute clinical conditions. The use of ultrasound technology as a diagnostic tool on the ISS required an onboard proficiency enhancement program, visual cue cards, procedures, and direction from ground-based trained radiological personnel (Sargsyan 2004). The high-fidelity image captures of the thoracic, cardiac, and vascular systems from the Expedition 8 crew demonstrated the capability of minimally-trained, non-medical personnel ultrasound operations. This investigation laid the groundwork for using ultrasound as a diagnostic tool, without an available physician, in microgravity and remote locations on Earth. There is a scientific paper discussing these results, which crew members sent directly from orbit (Foale 2005).

The educational program and remote expert guidance concepts developed for Advanced Diagnostic Ultrasound in Microgravity (ADUM) on the International Space Station (ISS) was modified for terrestrial use. There are a great number of medically under-served regions on the Earth. For example, high altitude climbers are at risk of serious lung problems, because of the thin air at heights. This photo shows a Swedish climber performing a comprehensive chest ultrasound examination at Advanced Base Camp on Mt. Everest. The climber operator had never seen an ultrasound before and was remotely guided to perform the examination over the Internet via a satellite phone and a solar panel charged portable ultrasound device. The exam was completed in 10 minutes and showed increased lung fluid because of exposure to high altitudes. Scott A. Dulchavsky, MD, PhD, Henry Ford Health System, Detroit, Michigan image.

Crew members' ultrasound images of the shoulder during Expedition 9 showed the diagnostic quality of the ultrasound imagery for the evaluation of shoulder integrity. An example application of this technology is if a crew member were to sustain a shoulder injury during a strenuous extravehicular activity (EVA or spacewalk), these techniques would enable evaluation and diagnosis of possible injuries (Fincke 2005).

Following a traumatic event to the head or face, eye examination is a very important component of the physical examination. Significant orbital or facial swelling can complicate the examination. The Expedition 10 crew's examination of the eye through a closed eyelid using ultrasound addressed this issue. This examination can determine a number of problems with the eye that are signs of other more significant trauma of the head (Chiao 2005, Sargsyan 2009).

In addition to the importance of establishing ultrasound techniques for examination and diagnosis on the ISS, this study established ultrasound as a key tool for clinical medicine on future vehicles, the moon, and eventually Mars. The success of ADUM may also lead to additional applications of ultrasound on Earth as users adapt the remote guidance paradigm for patients in rural/remote areas, disaster relief, and the military. Using existing communication systems, a minimally trained person (eg, nurse, physician's assistant, military medic, etc.) could perform an ultrasound exam on a patient with guidance from an expert at a medical facility hundreds or thousands of miles away. This would expand the tools for the rural medical community, provide the ability to triage a mass casualty, and help in the decisions to conduct medical transport of patients.

Publication(s)

Hamilton DR, Sargsyan AE, Martin DS, et al. On-orbit prospective echocardiography on International Space Station crew. *Echocardiography.* 2011;28(5):491-501. doi: 10.1111/j.1540-8175.2011.01385.x.

Sargsyan AE, Hamilton DR, Melton SL, Amponsah D, Marshall NE, Dulchavsky SA. Ultrasonic evaluation of pupillary light reflex. *Critical UltraSound Journal.* 2009. doi: 10.1007/s13089-009-0012-9.

Chiao LN, Sharipov S, Sargsyan AE, et al. Ocular examination for trauma; clinical ultrasound aboard the International Space Station. *Journal of Trauma: Injury Infection and Critical Care*. 2005;58(5): 885-889.

Fincke EM, Padalka G, Lee D, et al. Evaluation of shoulder integrity in space: First report of musculoskeletal US on the International Space Station. *Radiology*. 2005;234(2):319-322.

Foale CM, Kaleri AY, Sargsyan AE, et al. Diagnostic instrumentation aboard ISS: Just in time training for non-physician crewmembers. *Aviation, Space, and Environmental Medicine.* 2005;76:594-598.

Sargsyan AE, Hamilton DR, Jones JA, et al. FAST at MACH 20: Clinical ultrasound aboard the International Space Station. *Journal of Trauma: Injury Infection and Critical Care*. 2004;58(1):35-39. doi: 10.1097/01.TA.0000145083.47032.78.

This investigation is complete and all results are published.

Biochemical Status of Humans in Long-term Spaceflight (Biotest)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 3-10
Principal Investigator(s):
- Irina M. Larina, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives
Biochemical Status of Humans in Long-term Spaceflight (Biotest) studies metabolic adaptation to extended spaceflight conditions to broaden the existing information base on changes in metabolism and its hormonal regulation in microgravity.

KB-03 container with biological samples returned on the Soyuz TMA-3 descent module. Roscosmos image.

Earth Benefits
Biotest promotes the development of space and ground medicine.

Space Benefits
Biotest data improves medical monitoring, training, and postflight rehabilitation of crew members for long-term spaceflight.

Results
Ground laboratories measured the hormonal, metabolic, and biochemical indicators of the space adaptation process in blood samples collected from crew members. Overall results were found to be within accepted normal standards. In the final stage of long-term spaceflight, no increase in the secretion of the stress hormones, glucocorticoids, and mineralocorticoids of the adrenal cortex was noted. The association between reproductive hormones and pancreatic hormone indicators was also not affected during long-term spaceflight. The pattern of the changes in thyroid hormones before, during, and after long-term spaceflight reflected the state of metabolism, functional activity, and the main metabolism level in crew members while the thryotrophic hormone-thyroid hormone regulation feedback loop remains normal. The dynamic of water/salt metabolism parameters and its regulation correlates to flight duration and the age of crew members.

Publication(s)

Smith SM, Westney ME, O'Brian KO, et al. Bone indicators, metabolism, and calcium kinetics during long-term flights on the Mir orbital station. *Gravitatsionnaya Fiziologiya*. 2005;20(2):208-218.

Grigoriev AI, Larina IM, Noskov VB. Effect of spaceflight on the status and regulation of water/electrolyte metabolism. *I.M. Sechenov Russian Journal of Physiology*. 2006:92(1).

This investigation is complete and all results are published.

Blood and Oxidative Stress (BOS)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 10, 11
Principal Investigator(s):

- Angela Maria Rizzo, PhD, Berra University of Milan, Italy
- Laura Adorni, Berra University of Milan, Italy
- Gigliola Montorfano, Berra University of Milan, Italy
- Manuela Negroni, Berra University of Milan, Italy
- Stefania Zava, Berra University of Milan, Italy

Research Objectives

Loss of red blood cell mass, volume of blood plasma, and hemoglobin (space anemia) has been continuously observed in space explorers. Blood and Oxidative Stress (BOS) aims to determine the degree of stress that the red blood cells have undergone to bring about cell damage, the quantity of substances in blood serum that would prevent this damage (antioxidants), the damage to red blood cell membranes, and the time it takes to recover. BOS aims to find methods to reduce the current effects of oxidative space anemia by integrating appropriate dietary elements and natural compounds that act as antioxidants. These results also impact medical planning for future longer duration space missions beyond low-Earth orbit.

Results

To determine the effects of spaceflight on the erythrocyte antioxidant potential, an assay of the glutathione content and the enzyme connected with Reactive Oxygen Species (ROS) detoxification was made. Spaceflight reduced glutathione content and also the activity of glutathione peroxidase. Both these parameters were recovered 15 days postflight with an increase of peroxidases activity. It was possible to observe that all the activities were significantly reduced in other enzymes involved in ROS detoxification after flight, in particular the activity of glutathione reductase. All the enzymes were increased at 15 days postflight. Also erythrocyte cell membrane was affected by spaceflight with a reduction of the cholesterol and phospholipid contents indicating that the phospholipids/cholesterol ratio was maintained constant. At 15 days postflight, there was an increase of phospholipids and consequently of the phospholipid/cholesterol ratio. All together these data indicated that a short time spaceflight might induce “space anemia” with a reduction in hemoglobin content of red blood cells.

Over the past 15 years, space medicine has become increasingly concerned with the effects of spaceflight on hematological processes; astronauts have consistently returned from spaceflight with a decreased red blood cell mass spaceflight anemia and plasma volume. Although plasma volume is known to be labile, current theories for the control of erythropoiesis cannot account for a decrease in red blood cell mass of 10% in <10 days. Experimental data confirmed these observations and point out: a decrease of antioxidant defenses in red blood and a modification of cell membrane composition. These might be the consequences of increased cell aging due to exposure during flight to increased oxidative stress. The data on enzyme activities could be the first reported in literature, even though they need further investigation to confirm their importance. If these observations are confirmed, they might be utilized to integrate astronaut’s diet with appropriate antioxidant aliment or supplements.

PUBLICATION(S)

Rizzo AM, Adorni L, Montorfano G, Negroni M, Zava S, Berra B. Blood and oxidative stress (BOS): Soyuz mission "Eneide." *Microgravity Science and Technology.* September 2007;19(5-6):210-214. doi: 10.1007/BF02919484.

This investigation is complete and all results are published.

Study of Fluid and Electrolyte Metabolism and Hormonal Regulation of Fluid Volume in Spaceflight Conditions (Diurez)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 3-11
Principal Investigator(s):
- Irina M. Larina, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Diurez gathers new data on the state of fluid and electrolyte metabolism and hormonal regulation of the body's fluid volume in microgravity conditions and in the readaptation period after spaceflight. Analyses of bio samples (venous and capillary blood, and urine) help to characterize the final stage of fluid and electrolyte metabolism in microgravity.

Container KB-03 for returning urine and blood samples. Roscosmos image.

Earth Benefits

Diurez promotes the development of medicine to counteract space-induced metabolic changes, which may also be applied to related ailments on Earth.

Space Benefits

The results obtained from Diurez help to improve the medical support system for long-term spaceflight, including how work and rest schedules, medical monitoring, training, and postflight rehabilitation of crew members are organized.

Results

Initial data showed that, during flight, the volume of morning fluid consumption decreased significantly, which could be caused by activity features of the work/rest routine. Data showed a close connection between the age and the BMI of crew members with other studied indicators. These factors must be considered when evaluating the nutritional status and the physical activities of the crew members.

In microgravity and postflight, a decrease was observed in the blood concentration of prolactin, which indirectly indicates an increase in dopaminergic (signaling) activity of the central nervous system. These effects must be considered when planning the level of postflight physical and mental activity of the crewmembers.

Publication(s)

Morukov BV, Nichiporuk IA, Tret'yakov VS, Larina IM. Biochemical markers of bone tissue metabolism in cosmonauts after a prolonged spaceflight. *Human Physiology*. 2005;31(6):684-687. doi: 10.1007/s10747-005-0115-z.

This investigation is complete and all results are published.

Astronaut's Energy Requirements for Long-term Space Flights (Energy)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 29-ongoing
Principal Investigator(s):
- Stephane Blanc, PhD, University of Strasbourg, France

Research Objectives

Astronaut's Energy Requirements for Long-Term Space Flights (Energy) measures change in energy balance in crew members following long-term spaceflight. Energy also measures adaptations in the components of total energy expenditure of crew members, so that an equation to determine the energy requirements of crew members during spaceflight may be derived. Such knowledge of energy requirements is of a great importance to ensure health, good performance, and the overall success of a mission, and also contributes to ensure adequate exercise load and cargo allotments for food during spaceflight.

Japan Aerospace Exploration Agency astronaut Aki Hoshide, conducts an Oxygen Uptake Measurement for the Energy experiment in the ISS Columbus laboratory. NASA/ESA image.

Earth Benefits

The techniques used within this research for assessment of energy expenditure are also used for assessment of energy expenditure on Earth.

Space Benefits

The knowledge of energy requirements for spaceflight is needed to ensure health, performances, and the overall success of a mission. In addition, it will contribute to ensure adequate, but not excessive, cargo supplies for food. In this regard, the determination of energy requirements as a function of exercise load is a prerequisite for planned long-term manned spaceflight.

Results

No final results are available yet as the experiment is ongoing

This investigation is ongoing and additional results are pending publication.

Research on the Particulars of Pharmacological Effects During Long-term Spaceflight (Farma)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 2-12
Principal Investigator(s):
- Igor B. Goncharov, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Research on the Particulars of Pharmacological Effects During Long-term Spaceflight (Farma) provides information on absorption, distribution, and excretion of pharmaceuticals during spaceflight. The objective is to conduct an integrated study of the mechanism of change in the pharmacokinetics of drugs during long-term spaceflight.

Reflotron-4 set used in the Farma investigation. Roscosmos image.

Earth Benefits

If a long-term (1 month or more) course of drug therapy is necessary, a non-invasive method for evaluating the kinetics of pharmaceuticals makes it possible to constantly monitor the level of the medication in the body, thereby determining its therapeutic efficacy. The use of non-invasive methods for evaluating the effectiveness of medications in order to optimize the schedule of preventive and therapeutic assistance and to minimize medical risks is justified not only in conditions of orbital and interplanetary spaceflight missions but in other extreme conditions: at polar stations, during long-term submarine voyages, etc.

Space Benefits

The information obtained on the particulars of absorption, distribution, and excretion of the drug make it possible to note general patterns of changes in pharmacokinetics and pharmacodynamics in microgravity, to determine the main tiers of disruption of these processes, and to develop corrective measures. The results obtained must be considered when determining a schedule of drug therapy during long-term manned spaceflights as well as for pharmaceuticals having negative side effects complicating the ingestion of acetaminophen. The complex, non-invasive studies performed aboard the International Space Station of the pharmacokinetics of acetaminophen make it possible to optimize dosages and schedules of drug therapy and to minimize medical risks when selecting non-narcotic painkiller medications in spaceflight conditions.

RESULTS

For the first time during spaceflight, the bioavailability of a drug was studied. It was shown that after a single dose of the drug in spaceflight conditions, the relative biological availability of acetaminophen was significantly higher in the majority of flight test subjects than in baseline studies. Research on liver function after ingestion of acetaminophen showed that spaceflight conditions did not lead to disruption of liver function, therefore it was unlikely that a change in the first-pass effect, which occurs in the liver, would be the key point in the change observed in the pharmacokinetics of acetaminophen. It was also the first time a comparative study was performed on the pharmacokinetics of tablet versus capsule forms of acetaminophen. It was shown that the capsule form of acetaminophen was preferable to the tablet form when taken for treatment purposes in spaceflight.

PUBLICATION(S)

Kovachevich IV, Kondratenko SN, Starodubtsev AK, Zolkina IV. Study of pharmacokinetics of paracetamol in terms of the dynamics of its distribution in the blood and saliva of volunteers. *Applied Scientific Conference on Clinical Pharmacology in Russia*; 2004;104.

Kovachevich IV, Goncharov IB, Repenkova LG. Particulars of pharmacokinetics of drugs during spaceflights on the ISS. *Rossiĭskii fiziologicheskiĭ zhurnal imeni I.M. Sechenova / Rossiĭskaia akademiia nauk*. 2004;90(8):335-336.

This investigation is complete and all results are published.

Physiological Factors Contributing to Post-flight Changes in Functional Performance (Functional Task Test)

Research Area: Integrated Physiology and Nutrition
Expeditions: 21-ongoing
Principal Investigator(s):
- Jacob J. Bloomberg, PhD, Johnson Space Center, Houston, Texas

Research Objectives

The Physiological Factors Contributing to Postflight Changes in Functional Performance (Functional Task Test) payload tests crew members on an integrated suite of functional and physiological tests before and after long-duration spaceflight. The study identifies critical mission tasks that may be impacted, maps physiological changes to alterations in physical performance, and aids in the design of countermeasures that specifically target the physiological systems responsible for impaired functional performance.

JSC2008E156464 – Subject demonstrating the Rock Translation Test at NASA's Johnson Space Center (JSC), Houston, Texas.

Earth Benefits

A better understanding of the physiological factors that influence functional performance aids in defining more effective rehabilitation interventions in clinical populations. For example, in the elderly population, activities of daily living are often impaired by multiple physiological causes. The information obtained from this study helps in the design of clinical interventions and rehabilitation programs that can target specific systems responsible for decline in functional performance.

Space Benefits

Information obtained from this study aids in the design of targeted countermeasures which can reduce bodily changes that can have a negative impact on wellbeing and function of crew members in space.

Results

Ongoing data collection continues to improve the statistical power required to map changes in functional task performance to alterations in physiological systems. The information obtained from this study will be used to design and implement countermeasures that specifically target the physiological systems most responsible for the altered functional performance associated with spaceflight.

PUBLICATION(S)

Laughlin MS, Guilliams M, Nieschwitz BA, Hoellen D. Functional fitness testing results following long-duration ISS missions. *Aerospace Medicine and Human Performance.* December 1, 2015;86:87-91. doi: 10.3357/AMHP.EC11.2015.

Madansingh S, Bloomberg JJ. Understanding the effects of spaceflight on head–trunk coordination during walking and obstacle avoidance. *Acta Astronautica*. October 2015; 115:165-172. doi: 10.1016/j.actaastro.2015.05.022.

JSC2008E156462 - Subject demonstrating the Torque Generation Test at NASA's Johnson Space Center (JSC) in Houston, Texas.

Miller CA, Peters BT, Kofman I, et al. A comparison of tandem walk performance between bed rest subjects and astronauts. *39th Annual Meeting of the American Society of Biomechanics*, Columbus, OH; August 5-8, 2015; JSC-CN-33118:3.

Miller CM, Peters BT, Kofman I, et al. A comparison of torso stability between bed rest subjects and astronauts during tandem walk: Preliminary findings. *37th American Society of Biomechanics*, Omaha, NE; September 4-7, 2013:2.

Arzeno NM, Stenger MB, Bloomberg JJ, Platts SH. Spaceflight-induced cardiovascular changes and recovery during NASA's Functional Task Test. *Acta Astronautica*. November 2013;92(1):10-14. doi: 10.1016/j.actaastro.2012.05.023

This investigation is ongoing and additional results are pending publication.

Study of Morphofunctional Properties of Blood Cells and Intensity of Erythropoiesis in Humans Subjected to Spaceflight Factors (Gematologiya/ Gematologiya Perfection), Two Investigations

Research Area: Integrated Physiology and Nutrition
Expedition(s): 6-8,10 and 12
Principal Investigator(s):
- Svetlana M. Ivanova, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

The Study of Morphofunctional Properties of Blood Cells and Intensity of Erythropoiesis in Humans Subjected to Spaceflight Factors (Gematologiya/ Gematologiya Perfection) obtains new data on the effect of spaceflight factors on the human blood system in order to expand its diagnostic and predictive capabilities and uncover the mechanisms of shifts in hematological indicators.

Taking samples of capillary blood. Roscosmos image.

Earth Benefits

Although the Gematologiya facilitates the development of space medicine, it is conceivable that results can help reveal the mechanisms of shifts in hematological indicators for medical conditions such as anemia and lymphocytosis on Earth.

Space Benefits

The data obtained from the Gematologiya experiment make possible the solution of a number of practical issues in the medical care system for long-term spaceflights, particularly medical monitoring, training, and postflight rehabilitation of crew members.

Results

Stimulation of erythropoiesis (increased erythropoietin, reduced level of iron in the blood, removal of poor-quality and old erythrocytes) during the re-adaptation period was aimed at supporting the optimal level of red blood cells necessary for the increased oxygen demand in tissues subjected to terrestrial gravity and increased muscular loads. Thus, the results obtained from the Gematologiya experiment indicated that the observed effect of spaceflight factors corresponded with the expected effect. The assumption that the cause of space anemia has many factors in addition to the decrease in RBC production was confirmed. The reduction in the number of erythrocytes may also be linked to the activation of ineffective erythropoiesis, the disruption of iron exchange, a shift in the metabolic status of the cells, and destabilization of the cell membrane, which may lead to premature removal of erythrocytes from the bloodstream.

Publication(s)

Gematologiya

Ivanova SM, Brazhe NA, Luneva OG, et al. Physical-chemical properties of plasma membrane and function of erythrocytes of cosmonauts after long-term spaceflight. *Acta Astronautica*. 2011;68:1517-1522. doi: 10.1016/j.actaastro.2010.06.046.

Grigoriev AI, Ivanova SM, Morukov BV, Maksimov GV. Development of cell hypoxia induced by factors of long-term spaceflight. *Doklady Biochemistry and Biophysics.* 2008;422:308-311. doi: 10.1134/S1607672908050141.

Grigoriev AI, Ivanova SM, Morukov BV, Maksimov GV. Onset of cellular hypoxia during long-term spaceflight. *Reports of the Academy of Sciences: Biochemistry, Biophysics, Molecular Biology*. 2008;422(6):823-826.

Ivanova SM, Maksimov GV, Morukov BV, et al. Role of the elasticity and permeability of the plasma membrane of erythrocytes in regulating the effectiveness of hemoglobin oxygen transport in humans after completion of a spaceflight. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine*). 2007;41(2):41-44.

Morukov BV, Ivanova SM, Maksimov GV, et al. Investigation of the fluidity and permeability of human erythrocyte plasma membrane and the efficacy of oxygen transfer by hemoglobin during rehabilitation period after spaceflight. *Journal of Gravitational Physiology*. 2006;13(1):139-141.

Ivanova SM, Morukov BV, Labetskaya OI, Yarlikova YV, Levina AA, Kozinets GI. Morphobiochemical research on the red blood cell system in primary crewmembers on the International Space Station. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2006;40(3):9-16.

Ivanova SM, Morukov BV, Labetskaya OI, Yarlikova YV, Levina AA, Shishkanova ZG. Red blood of cosmonauts during missions aboard the International Space Station (ISS). *Human Physiology*. 2004;11(2):79-80.

Gematologiya Perfection

Ivanova SM, Morukov BV, Yarlikova YV, Labetskaya OI, Levina AA, Kozinets GI. Condition of red blood cells in men during long-term antiorthostatic hypokinesia. *Aviakosmicheskaya i ekologicheskaya meditsina*. 2005;39(6):17–22.

Grigoriev AI, Maksimov GV, Morukov BV, et al. Investigation of erythrocyte shape, plasma membrane fluidity and conformation of hemoglobin hemoporphyrin under the influence of long-term spaceflight. *Journal of Gravitational Physiology*. 2004;11(2):79–80.

This investigation is complete and all results are published.

BIOMEDICAL ANALYSIS OF HUMAN HAIR EXPOSED TO LONG-TERM SPACE FLIGHT (HAIR)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 22-ongoing
Principal Investigator(s):
- Chiaki Mukai, MD, PhD, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

Hair root cells actively divide in a hair follicle and as a result, they can reflect the physical condition of the body. The hair shaft has an advantage in that it records the metabolic conditions of the environment where the subject resides. The purpose of this experiment is to examine the effect of long-duration spaceflight on gene expression and trace element metabolism in human body by analyzing human hair.

EARTH BENEFITS

In space experiments, hair is one of the most suitable specimens, for there are neither special hardware nor handling necessary to collect samples and retrieve them from the orbit. The research is expected to support the development of an effective and easy diagnostic measure for the ISS crew.

SPACE BENEFITS

The results obtained from this research will facilitate the understanding of the relations between human metabolism and hair. The research is expected to support the development of alternative diagnostic methods for blood or urine tests.

Sample collection in the ISS by astronaut. JAXA image.

RESULTS

Sample collection from 10 ISS crew members have been completed. As preliminary results, RNA was extracted successfully from the samples and some changes in gene expression have been already detected. Distribution of trace elements has been evaluated with Electron Probe Micro Analyzer (EPMA). Additional detailed analysis of these samples is underway.

This investigation is ongoing and additional results are pending publication.

Nutritional Status Assessment (Nutrition)

Research Area: Integrated Physiology and Nutrition
Expeditions: 14-ongoing
Principal Investigator(s):
- Scott M. Smith, PhD, Johnson Space Center, Houston, Texas

Research Objectives

Nutritional Status Assessment (Nutrition) is a comprehensive in-flight study designed to understand changes in the human body during long-duration spaceflight. This study includes measures of bone metabolism, oxidative damage, chemistry and hormonal changes as well as assessments of the nutritional status of the crew members participating in the study. The results have an impact on the definition of nutritional requirements and development of food systems for future exploration missions to the moon and Mars. This experiment also helps researchers understand the effectiveness of measures taken to counteract the effects of spaceflight, as well as the impact of exercise and medicine countermeasures on nutritional status and nutrient requirements for crew members.

Earth Benefits

Increased understanding of the role of nutrition in physiological adaptation to spaceflight has a broader application on Earth. One example is that understanding the relationship of nutrition to bone loss is potentially valuable for patients suffering from osteoporosis on Earth.

Space Benefits

The inclusion of in-flight blood and urine collections, and expansion to include additional samplings to better monitor nutritional status, are required in order to better understand the role of nutrition in bone health, changes in body composition, oxidative damage, and to better define nutritional requirements for spaceflight. Maintaining and monitoring nutritional status is important for ensuring crew health during spaceflight and is critical as we embark on exploration missions of much longer duration in the future.

Results

This experiment is ongoing; urine and blood samples for several crew members have been collected before, during, and after ISS Expeditions. Since the experiment design calls for the combination and comparative analysis of data from all Expeditions, final results are not yet available. Preliminary results have been presented, reviewed, and published in multiple forums. Operationally, the data have been valuable in troubleshooting the Urine Processing Assembly (UPA) after the unit developed problems in orbit in 2009, and also in developing operational plans for using this unit. Vitamin D results from spaceflight and ground-based analog studies led to revised vitamin D supplementation recommendations on ISS, and the results of this experiment have documented the effectiveness of this new dose. The ground-based findings from Antarctic research were cited in the Institute of Medicine's revision of the recommended dietary intakes for North Americans.

PUBLICATION(S)

Smith SM, Heer MA, Zwart SR. Nutrition and bone health in space. *Nutrition and Bone Health*. 2015:687-705. doi: 10.1007/978-1-4939-2001-3_41.

Zwart SR, Pierson DL, Mehta SK, Gonda S, Smith SM. Capacity of omega-3 fatty acids or eicosapentaenoic acid to counteract weightlessness-induced bone loss by inhibiting NF-kappaB activation: From cells to bed rest to astronauts. *Journal of Bone and Mineral Research*. May 25, 2010:1049-1057. doi: 10.1359/jbmr.091041.

Smith SM, Zwart SR, Block G, Rice BL, Davis-Street JE. The nutritional status of astronauts is altered after long-term spaceflight aboard the International Space Station. *Journal of Nutrition*. 2005;135(3): 437-443.

This investigation is ongoing and additional results are pending publication.

Study of the Condition of Periodontal Tissues in Space Flight (Parodont)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 1-8
Principal Investigator(s):
- Alexei I. Volozhin, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Significant changes in the local immunity and microbial (bacteria) system of the periodontium (tissue near the teeth) qualify as risk factors for the development of inflammatory diseases of the periodontium and possibly are one of the specific manifestations of the postflight readaptation state of crew members' bodies. Parodont studies the condition of local immunity and microflora in the mouth of crew members participating in missions on the International Space Station (ISS).

Earth Benefits

The studies make it possible to open new fields of research to monitor the condition of microflora in the mouth. A beneficial application kit is developed from the research, lactobacterin immobilized on a collagen sponge, and successfully underwent clinical testing (for the prevention of periodontitis).

Space Benefits

A preventative probiotic product, a periodontal patch, is developed, in the form of a lyophilized substance as a strip containing lactobacilli immobilized on collagen. Results obtained from the study help researchers to conclude that the use of the periodontal patch is the best way of locally treating chronic generalized periodontitis in the flare-up stage.

Russian cosmonaut V.N. Dezhurov collecting samples for the Parodont experiment. Roscosmos image.

Results

Laboratory analysis of the returned materials are performed on the ground and involved quantitative measurements of the concentration of opportunistic pathogenic microflora in the mouth. The Parodont experiment established that during spaceflight significant changes occurred in local immunity and microflora in the tissues that surround and support the teeth of crew members, which increased the risk factors for the development of inflammatory diseases of the dentomaxillofacial system in crew members. It was noted that after flight the beneficial microflora in crew members was reduced against the growth of harmful microflora. This phenomenon increased the likelihood of periodontal disease.

This investigation is complete and all results are published.

Dietary Intake Can Predict and Protect Against Changes in Bone Metabolism during Spaceflight and Recovery (Pro K)

Research Area: Integrated Physiology and Nutrition
Expeditions: 21-ongoing
Principal Investigator(s):
- Scott M. Smith, PhD, Johnson Space Center, Houston, Texas

Research Objectives

The Dietary Intake Can Predict and Protect Against Changes in Bone Metabolism during Spaceflight and Recovery (Pro K) investigation is NASA's first evaluation of a dietary countermeasure to lessen bone loss of astronauts. Pro K proposes that a flight diet with a decreased ratio of animal protein to potassium will lead to decreased loss of bone mineral. Pro K has impacts on the definition of nutritional requirements and development of food systems for future exploration missions and could yield a method of counteracting bone loss that would have virtually no risk of side effects.

Earth Benefits

Given the growing trend in the United States toward diets high in animal protein, the proposed research has direct public health significance.

Space Benefits

If successful, the study could lead to improvements in bone health during spaceflight, with use of a countermeasure that requires no additional stowage, crew time, power, or other constrained resources.

Results

Pro K is an ongoing investigation data, and conclusive results will be published following completed data collection and analysis.

This investigation is ongoing and additional results are pending publication.

Renal Stone Risk During Spaceflight: Assessment and Countermeasure Validation (Renal Stone)

Research Area: Integrated Physiology and Nutrition
Expeditions: 3-6, 8, 11-14
Principal Investigator(s):
- Peggy A. Whitson, PhD, Johnson Space Center, Houston, Texas

Research Objectives

The Renal Stone experiment collects urine samples from crew members and tests a possible countermeasure for preventing kidney stone formation.

Earth Benefits

Understanding how the disease may form in otherwise healthy crew members under varying environmental conditions provides insight into stone-forming diseases on Earth.

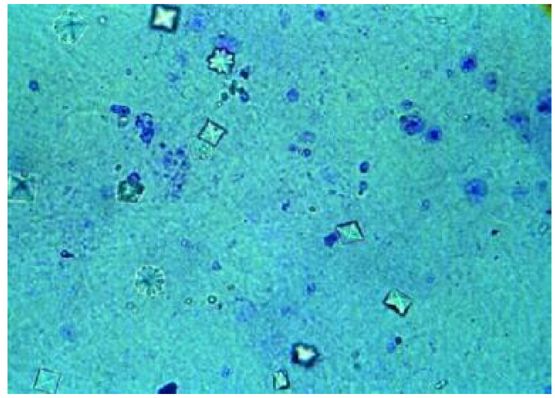
Space Benefits

Human exposure to microgravity results in a number of physiological changes. Among these are changes in renal function, fluid redistribution, bone loss, and muscle atrophy, all of which contribute to an altered urinary environment and the potential for renal stone formation during and immediately after flight. In-flight changes previously observed include decreased urine volume and urinary citrate and increased urinary concentrations of calcium and sodium. The formation of renal stones could have severe health consequences for crew members and negatively impact the success of the mission. This study gives a better understanding of the risk factors associated with renal stone development during and after flight, as well as test the effectiveness of potassium citrate as a countermeasure to reduce this risk.

ISS013E56052 – ISS Expedition 13 Flight Engineer Thomas Reiter, seen aboard ISS, processes samples for the Renal Stone investigation.

Results

The Renal Stone investigation contained 2 sequential sampling groups in its single-trial, 2-phase design. Phase 1 of the study sampled 12 male astronauts and cosmonauts during NASA-Mir spaceflights in 129- to 208-day missions and served as a control group with no treatment. Phase 2 collected data from 18 ISS crew members in a double-blind study that included control and treatment with potassium citrate (K-Cit) pill supplements in 93- to 215-day missions from ISS Expeditions 3-14. Urine samples were collected and analyzed before, during, and after mission, as was dietary information from crew members to document urine chemistry and mineral-nutrient throughput. As a safety measure, all phase 2 participants were K-Cit-tolerance tested before launch, and none showed any adverse reactions. Renal stones come in the forms of calcium stones (calcium oxalate (CAOX) and calcium phosphate (Brushite)), uric acid stones, and struvite stones (ammonium magnesium phosphate), with the CAOX type being the most common. Astronauts are at an increased risk for developing calcium oxalate, calcium phosphate, and uric acid stones during space missions when crew's urine typically becomes supersaturated with the chemical species of these stone-forming salts as a result of decreased urine output and pH. Potassium citrate is known to bind with calcium to impede the growth of calcium-containing crystals, which can become kidney stones. The Renal Stone study quantifies the effectiveness of K-Cit in lowering the elevated risk factors for renal stone formation during space missions, and shows significant decrease in CAOX and uric-acid superstaturation risks in crew members ingesting K-Cit versus the control groups. K-Cit also increases urinary pH without elevating the risk for forming brushite stones, and appears to be well tolerated over the entire course of the study. Results from this investigation suggest that supplementation with potassium citrate may decrease the risk of renal stone formation during and immediately after space exploration missions. Renal stones can be extremely debilitating and medical therapy options, widely available on Earth, are severely limited during long-duration space exploration, hence prevention is the most logical and cost-effective approach. The Renal Stone study, while collecting valuable scientific data, stresses the importance of maintaining a balance between pharmacological safety and effectiveness in conducting medical research involving crew members. Related results are expected from an ISS investigation in progress with bisphosphonates for mitigating bone loss, and a bed rest clinical ground study prescribing magnesium potassium citrate (MKCIT) for reducing the risk of renal stone formation (Whitson 2009).


The micrograph shows calcium oxalate crystals in urine. These small crystals can develop to form renal stones. NASA's Marshall Space Flight Center image.

PUBLICATION(S)

Smith SM, Heer MA, Shackelford LC, et al. Bone metabolism and renal stone risk during International Space Station missions. *Bone*. October 8, 2015;81:712-720. doi: 10.1016/j.bone.2015.10.002.

Whitson PA, Pietrzyk RA, Jones JA, Nelman-Gonzalez MA, Hudson EK, Sams CF. Effect of potassium citrate therapy on the risk of renal stone formation during spaceflight. *Journal of Urology*. 2009;182:2490-2496. doi: 10.1016/j.juro.2009.07.010.

This investigation is complete and all results are published.

National Aeronautics and Space Administration Biological Specimen Repository (Repository)

Research Area: Integrated Physiology and Nutrition
Expeditions: 16-ongoing
Principal Investigator(s):
- Kathleen A. McMonigal, MD, Johnson Space Center, Houston, Texas

Research Objectives

The National Aeronautics and Space Administration Biological Specimen Repository (Repository) is a storage bank that is used to maintain biological specimens over extended periods of time and under well-controlled conditions. This repository supports scientific discovery that contributes to our fundamental knowledge in the area of human physiological changes and adaptation to a microgravity environment and provides unique opportunities to study changes in human physiology spanning many missions. This investigation archives biosamples, including blood and urine from the International Space Station (ISS), for use as a resource for future spaceflight-related research.

Earth Benefits

Advances in space biomedical research often lead to medical advances to better serve patients on Earth. Future research investigations that can help ensure the health and safety of crew members as well as enable exploration class missions provide valuable health benefits to society.

ISS022E091397 – View of Jeffrey Williams, Expedition 22 commander, performing blood draw - Nutrition with Repository in the Japanese Experiment Module (JEM) Pressurized Module (JPM).

Space Benefits

The development of Repository allows for the collection, processing, storage, maintenance, and ethical distribution of biosamples to meet goals of scientific and programmatic relevance to the space program. Archiving of the biosamples provides future research opportunities including investigating patterns of physiological changes, analysis of components unknown at this time, or analyses performed by new and improved methods.

Results

Results from Repository are pending completion of testing on all subjects before conclusive results are prepared.

This investigation is ongoing and additional results are pending publication.

SODIUM LOADING IN MICROGRAVITY (SOLO)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 17-ongoing
Principal Investigator(s):
- Martina A. Heer, PhD, University of Bonn, Germany
- Petra Frings-Meuthen, Institute of Aerospace Medicine, Cologne, Germany
- Natalie Kamps, Institute of Aerospace Medicine, Cologne, Germany
- Friedhelm Baisch, Institute of Aerospace Medicine, Cologne, Germany
- Peter Norsk, MD, University of Copenhagen, Copenhagen, Denmark

RESEARCH OBJECTIVES

SOdium LOading in Microgravity (SOLO) is a continuation of extensive research into the mechanisms of fluid and salt retention in the body during bed rest and spaceflights. It is a metabolically-controlled study. During long-term space missions astronauts participate in 2 study phases, 5 days each. Subjects follow a diet of constant either low or normal sodium intake, fairly high fluid consumption, and isocaloric nutrition.

ESA astronaut André Kuipers undertaking Body Mass Measurement for the SOdium LOading in Microgravity experiment. ESA/NASA image.

RESULTS

Data from the SOLO experiment are currently being analyzed and processed prior to publication.

This investigation is complete; however additional results are pending publication.

STUDY OF CHANGES IN BODY COMPOSITION AND DISTRIBUTION OF FLUIDS WITHIN THE HUMAN BODY DURING LONG-TERM SPACEFLIGHT (SPRUT-2)

Research Area: Integrated Physiology and Nutrition
Expedition(s): 25-34
Principal Investigator(s):
- Viktor B. Noskov, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

The Study of Changes in Body Composition and Distribution of Fluids Within the Human Body During Long-term Spaceflight (Sprut-2) studies the change in body composition and fluid distribution in the human body during long-term spaceflight in order to evaluate adaptation mechanisms and improve countermeasures. Gravity plays the most important role in the restructuring of many metabolic parameters, including the hydration status of the body.

Russian cosmonaut A.N. Shkaplerov during a session of the Sprut-2 investigation aboard the International Space Station. Roscosmos image.

EARTH BENEFITS

The use of the polysegmental impedancemetry, apart from the evaluation of gravitational displacement of bodily fluids, allows one to significantly reduce the margins of error in evaluating body composition caused by a different electrical properties of various regions of the body, and a new diagram for placing the electrodes increases the precision of the analysis through consideration of the individual parts of the subject's body.

SPACE BENEFITS

A study of the fluid spaces of the body is not only of great scientific interest but has practical applicability in correcting the hydration status of crew members in order to increase their postflight orthostatic stability. Performing Sprut-2 facilitates direct, real-time medical monitoring of the state of the crew’s metabolism and their hydration status during long-term spaceflights. The results of the experiment make it possible to predict and substantiate targeted corrections to the hydration level at various stages of flight in order to improve crew members’ performance. This study shows it is possible to perform autonomous medical monitoring during long-term expeditions, including interplanetary ones, and to perform targeted correction of water-salt exchange and the training regimen at various stages of flight, in order to improve crew performance.

RESULTS

The use of impedancemetry aboard the International Space Station (ISS) made it possible to study the mechanisms for adaptation and restructuring of homeostasis, as well as to monitor the effectiveness of current countermeasure efforts. Upon completion of each session of the experiment, electronic files were created, containing data suitable for further analysis. It was discovered that the body's total water content as well as the volume of extracellular and cellular fluid decreased in flight in the majority of subjects studied. A deficit in body mass developed due to the loss of lean body mass and a decrease in fatty components. Report materials on the experiment as a whole will be presented after all the results obtained are fully analyzed. Performance of the Sprut-2 space experiment is slated to continue among members of subsequent ISS expeditions.

PUBLICATION(S)

Noskov VB, Nichiporuk IA, Grigoriev AI. Changes in fluid media and body composition during long-term spaceflight (bioimpedance analysis). *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2007;41(3):3-7.

Noskov VB, Nikolayev DV, Tuykin SA, Kozharinov VI, Grachev VA. Portable impedancementer for evaluating the body's fluid spaces during spaceflight. *Meditsinskaia Tekhnika (Biomedical Engineering)*. 2007(2):45-47.

Grigoriev AI, Larina IM, Noskov VB. Effect of spaceflights on status and regulation of water-electrolyte exchange. *Rossiĭskii fiziologicheskiĭ zhurnal imeni I.M. Sechenova / Rossiĭskaia akademiia nauk*. 2006;92(1):5-17.

Noskov VB, Nichiporuk IA, Morukov BV, Malenchenko YI. Study of the state of human bodily fluids during long-term spaceflight. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2005;39(1):27-31.

Russian cosmonaut D.Yu. Kondratyev during a session of the Sprut-2 investigation aboard the International Space Station. Roscosmos image.

This investigation is complete and all results are published.

STUDY OF THE STATE OF FLUIDS IN THE HUMAN BODY DURING LONG-TERM SPACEFLIGHT (SPRUT-MBI/SPRUT-MBI PERFECTION), TWO INVESTIGATIONS

Research Area: Integrated Physiology and Nutrition
Expedition(s): 1, 3, 5, and 7-12
Principal Investigator(s):
- Viktor B. Noskov, PhD, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

The Study of the State of Fluids in the Human Body During Long-term Spaceflight (Sprut-MBI/Sprut-MBI Perfection) obtains data on the status of fluid systems of the human body during long-term spaceflight in order to evaluate adaptation mechanisms of human physiology and improve microgravity countermeasures aboard the International Space Station for crew health.

Cosmonaut during the Study of the State of Fluids in the Human Body During Long-term Spaceflight experiment session aboard the International Space Station. Roscosmos image.

EARTH BENEFITS

New results for the changes in the body's hydration level and composition that are obtained via bioimpedance analysis align well with results previously obtained via invasive methods and do not conflict with long-standing ideas on the nature of the adaptation of water-electrolyte homeostasis to microgravity. This investigation demonstrates the advantages bioimpedance analysis has over other methods in the field of space medicine due to its safety and adaptability. The method of 2-frequency bioimpedancemetry is a non-invasive, quick, and safe method for determining body composition and the volume of bodily fluids, based on the electrical properties of biological tissues. Moreover, it provides the necessary precision, and the information obtained is processed immediately during the examination. The portability and high interference-resistance makes the use of Sprut technology possible in field conditions—for example, in ambulances—and also for performing specific tasks of disaster medicine and other extreme situations causing disruption of water-electrolyte homeostasis.

SPACE BENEFITS

Water-electrolyte homeostasis plays an important role in the processes of general adaptation of the human body to new living conditions and to microgravity in particular. Spaceflight causes restructuring of water-electrolyte homeostasis, ie, the lack of gravity and other spaceflight factors have a specific effect on the fluid systems of the body. In turn, these changes have direct and indirect effects on the physiological and metabolic functions of the body. Studying the changes of restructuring water-electrolyte exchange during spaceflight and the early postflight period is of great practical significance, since changes in water-electrolyte balance play an important role in developing postflight orthostatic instability and other detrimental changes in the cardiovascular system. Impedancemetry experiments aboard the space station using the Sprut-K Set demonstrate that it is possible to perform automatic measurement of the main fluid volumes of a crew member's body in real time in long-term spaceflight conditions and show the possibility for using the bioimpedance method in weightlessness. The results of this experiment make it possible to use bioimpedance analysis for real-time medical monitoring since a crew member's hydration status can be determined using the onboard impedance meter multiple times and at any moment.

RESULTS

Results of SPRUT-MBI showed that the gravitation factor played the most important role in reaching another level of water-electrolyte homeostasis. The use of a non-invasive, spaceflight-compatible method of bioimpedancemetry for the first time in the world's space programs made it possible to evaluate the hydration status of the human body directly during long-term spaceflight. Use of the Sprut-K onboard impedancemeter allowed the first repeat measurements in real time of the main fluid systems in 12 cosmonauts during 6-month orbital flights and the diagnosis of the development of dehydration of the body. Analysis of the obtained results showed that all 12 cosmonauts exhibited hydration decrease, and the range of individual changes during flight was quite narrow: from 5 to 10% for various fluid systems. The results showed the uniform loss of fluid from various fluid systems in the body during long-term spaceflight.

The maximum values for the shortage of fluids were noted immediately after the cosmonauts returned to Earth, which spoke to the particular intensity of the effects that the final phase of flight and landing have on water-electrolyte exchange. The development in weightlessness of hypohydration was discovered, expressed as a uniform decrease in fluid spaces, and characteristic changes in body composition. Moreover, the changes in and tempo of the reduction of fluid volumes, as well as the fat and muscle mass of the body, were closely comparable in character and magnitude. The majority of cosmonauts studied showed, despite individual variations, a clear reduction in the level of hydration during long-term exposure to weightlessness accompanied by a simultaneous loss of muscle mass. One week after flight completion, all parameters being studied showed a clear trend towards restoration of preflight hydration status and body mass.

PUBLICATION(S)

Noskov VB, Nichiporuk IA, Grigoriev AI. Dynamics of the body liquids and composition in long-duration Spaceflight (Bioimpedance Analysis). *Human Physiology*. 2011;37:821-825. doi: 10.1134/S0362119711070231.

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Noskov VB, Nikolayev DV, Tuykin SA, Kozharinov VI, Grachev VA. Portable impedancementer for evaluating the body's fluid spaces during spaceflight. *Meditsinskaia Tekhnika (Biomedical Engineering)*. 2007(2):45-47.

Noskov VB, Kotov AN, Morukov BV, Nichiporuk IA, Shargin YG. Bioimpedance analysis of fluids and body composition under the conditions of short-term Spaceflight or hypokinesia. *Human Physiology*. 2006;32(5):622-625. doi: 10.1134/S0362119706050197. [Also: Noskov VB, Kotov AN, Morukov BV, Nichiporuk IA, Shargin YG. Bioimpedance analysis of fluids and body composition during short-term spaceflights and hypokinesia. *Fiziologiya Cheloveka*.2006;32(5):136–139.]

Noskov VB, Kotov AN. Impedancemetric research of hydration status and body composition during antiorthostatic. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2005;39(4):41-45.

Noskov VB, Nichiporuk IA, Morukov BV, Malenchenko YI. Study of the state of human bodily fluids during long-term spaceflight. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2005;39(1):27-31.

Noskov VB, Nichiporuk IA. Changes in the volume of the fluid spaces in the body of a cosmonaut during long-term spaceflight. *Rossiĭskii fiziologicheskiĭ zhurnal imeni I.M. Sechenova/Rossiĭskaia akademiia nauk*. 2004;90(8):76.

This investigation is complete and all results are published.

Stability of Nutritional Compounds (Stability-Nutrition)

Research Area: Integrated Physiology and Nutrition
Expeditions: 13-18
Principal Investigator(s):
- Scott A. Smith, PhD, Johnson Space Center, Houston, Texas

Research Objectives

Stability of Nutritional Compounds (Stability-Nutrition) studies the effects of the spaceflight environment, including radiation, on complex organic molecules such as vitamins and other compounds in food. This helps researchers develop more stable and reliable foods, packaging materials, and nutritional countermeasures suitable for future long-duration missions beyond low-Earth orbit.

Earth Benefits

The results of this investigation help in understanding the effects of adverse environments on food, this information assists Earth-based explorers in making healthy choices for long-term exploration of remote and harsh places like the Antarctic.

Space Benefits

Results of this investigation provide important information on the susceptibility of select foods and vitamins to adverse environmental factors encountered during space missions.

Results

The Stability investigation studied the effects of radiation in space on complex organic molecules such as vitamins and other compounds in food at varying time intervals. Nutritional items examined were tortillas, salmon, almonds, broccoli au gratin, dried apricots, a multivitamin, and vitamin D supplements. In general, the study found that, while there were differences between the vitamin concentrations of food flight samples and ground samples, the degradation rates of nutrients were comparable in both sets. These results made it clear that long duration storage had a considerably larger impact on nutrient stability than flight in space. Prominent changes as a result of storage included the approximate 50% decrease of both folic acid and thiamin in tortillas, 15% to 20% decrease of folic acid and vitamins K and C in broccoli au gratin, 10% to 35% decrease of riboflavin and vitamins A and C in the multivitamin, and 200% increase of hexanal, which indicates that an increase in lipid peroxidation (and flavor) occurred in almonds. Exposure to low-Earth orbit radiation had no effect on nutrient quantities. The results from this study will aid in the design of future food packaging and preservation systems for both ISS and long-term space exploration missions (Zwart 2009).

Publication(s)

Zwart SR, Morgan JL, Smith SM. Iron status and its relations with oxidative damage and bone loss during long-duration spaceflight on the International Space Station. *American Journal of Clinical Nutrition*. July 2013;98(1):217-223. doi: 10.3945/ajcn.112.056465.

Smith SM, Heer MA, Wang Z, Huntoon CL, Zwart SR. Long-duration spaceflight and bed rest effects on testosterone and other steroids. *Journal of Clinical Endocrinology and Metabolism*. January 2012; 97(1):270-278. doi: 10.1210/jc.2011-2233.

Zwart SR, Gibson CR, Mader TH, et al. Vision changes after spaceflight are related to alterations in folate- and vitamin B-12-dependent one-carbon metabolism. *Journal of Nutrition*. March 1, 2012;142(3):427-431. doi: 10.3945/jn.111.154245.

Zwart SR, Kloeris VA, Perchonok MH, Braby LA, Smith SM. Assessment of nutrient stability in foods from the space food system after long-duration spaceflight on the ISS. *Journal of Food Science.* 2009;74(7). doi: 10.1111/j.1750-3841.2009.01265.x.

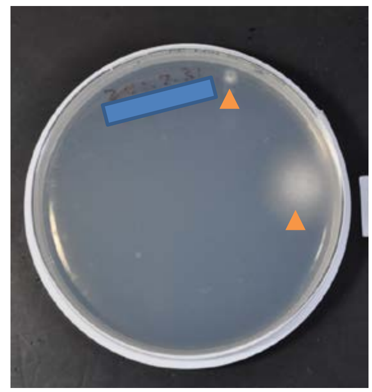
This investigation is complete; however additional results are pending publication.

Mycological Evaluation of Crewmember Exposure to ISS Ambient Air (Myco)

Research Area: Microbiology
Expedition(s): 21-29
Principal Investigator(s):
- Chiaki Mukai, MD, PhD, Japan Aerospace Exploration Agency, Tsukuba, Japan

Research Objectives

Microflora on crew members are thought to strongly reflect the condition of the International Space Station (ISS) environment, which is a completely closed orbital living space in microgravity. The objective of this study is to evaluate the risk of microorganism inhalation, and adhesion to exposed skin, to the ambient air during stays aboard the ISS.



Cultivated colonies from an airway sample. JAXA image.

Earth Benefit

The result is possible to be applied to air quality and radiation exposure measurements in terrestrial air travel and other environments.

Space Benefit

This provides a standard for the basic data collection in space environmental measurement, the space medicine field, and the life science field. It is possible to use this information for the verification, and the operation method, of the radiation exposure prediction calculation model.

Results

Preliminary results showed that the number of Colony Forming Units (*CFU)* tended to decrease aboard the ISS and recovered after the return. On the other hand, the amount of fungal DNA extracted from skin samples increased during spaceflight. Additional detailed microbial analysis of these samples by culture-based methods and the latest molecular-genetic methods are underway.

Publication(s)

Makimura K, Satoh K, Sugita T, Yamazaki TQ. Fungal biota in manned space environment and impact on human health. *Nippon Eiseigaku Zasshi*. 2011;66(1):77-82. doi: 10.1265/jjh.66.77.

This investigation is ongoing and additional results are pending publication.

Study of microbial Communities Exposed to Weightlessness (Sample)

Research Area: Microbiology

Expedition(s): 8, 9, 12 and 14

Principal Investigator(s):
- Hermie Harmsen, PhD, University of Gronigen, Groningen, Netherlands
- Gjalt Welling, PhD, University of Gronigen, Groningen, Netherlands
- Janneke Krooneman, PhD, Bioclear Environmental Biotechnology, Groningen, Netherlands

Research Objectives

The primary scientific objectives of the Study of microbial Communities Exposed to Weightlessness (Sample) experiment are to evaluate which microbial species might benefit from growth conditions in life support systems and to investigate the mechanisms of microbial adaptation to weightlessness. The focus is on potentially pathogenic and destructive microbes, looking at the origin and distribution of species on different sample sites and looking at the changes of normal micro-biota of space explorers and the relation with the micro-biota in the International Space Station (ISS) during spaceflight.

ESA Astronauts, Andre Kuipers (right) and Gerhard Thiele (left) in training for the Study of microbial Communities Exposed to Weightlessness at Star City, Russia. Photo courtesy of Hermie Harmsen, Ph.D.,University of Gronigen. Image courtesy of ESA.

Earth Benefits

Sample will generate knowledge and tools to investigate hygienic conditions in hospitals. Sample techniques are currently being used to analyze the spread of microbes in intensive care units (ICUs) with special attention to methicillin-resistant *Staphylococcus aureus* (MRSA).

Space Benefits

Based on Sample results, a machine may be designed that can monitor microbial growth in space without sending samples to Earth. Developers of future habitability procedures can use the knowledge gained from this experiment to better protect crew health on long-duration missions

Results

Two problems occurred that would affect the results of the experiment. The culture swabs taken were not stored in tubes with storage medium to enable survival, and the culture swabs, body samples, and the specimen case were transported from the landing site in a cool box with a temperature that dropped below 0°C, which would damage the living bacteria present in the samples.

Primary data analysis was, however, undertaken, cosmonaut samples were cultured, and DeoxyriboNucleic Acid (DNA)-analysis performed. The swab samples of the ISS were analyzed by conventional culturing and by DNA analysis methods. Culturing showed that some of the sites were colonized with bacteria, yeasts, and fungi. However, the actual number of microbes present could be higher than was found, as storage and transport issues may have resulted in possible death of part of the microbes. The DNA methods were far less hampered by cell death and enabled very accurate samples analysis. One method, quantitative real-time Polymerase Chain Reaction (PCR), showed that surfaces were colonized with human bacteria, such as *staphylococci*, in some samples in relatively high numbers. This was in concordance with the culture results although the culturing numbers were a few orders of magnitude lower. Another method, fluorescence in situ hybridization (FISH method), showed a similar picture of high numbers of bacteria, human bacteria, yeasts, and fungi.

The results showed that the microbial contamination of the ISS can be monitored with these methods and so optimizes the hygiene and health status. Both DNA methods are robust, can be automated, and have a potential to be used in space. In addition, the analysis of the bacteria in the specimen case showed no adhesion adaptation following exposure to space conditions for ten days.

PUBLICATION(S)

Van Tongeren SP, Degener JE, Harmsen HJ. Comparison of three rapid and easy bacterial DNA extraction methods for use with quantitative real-time PCR. *European Journal of Clinical Microbiology & Infectious Diseases*. 2011 February 11; 30(9): 1053-1061. DOI: 10.1007/s10096-011-1191-4.

This investigation is complete; however, additional results are pending publication.

MENTAL REPRESENTATION OF SPATIAL CUES DURING SPACEFLIGHT (3D-SPACE)

Research Area: Nervous and Vestibular Systems
Expedition(s): 17-28
Principal Investigator(s):
- Gilles Clement, International Space University, Strasbourg, France

RESEARCH OBJECTIVES

The Mental Representation of Spatial Cues During Spaceflight (3D-Space) experiment investigates the effects of exposure to microgravity on the mental representation of spatial cues by astronauts during and after spaceflight. The absence of the gravitational frame of reference during spaceflight could be responsible for disturbances in the mental representation of spatial cues, such as the perception of horizontal and vertical lines, the perception of an object's depth, and the perception of a target's distance. The results of this study could have important consequences for human performance during spaceflight.

RESULTS

Visual illusions based on perspective are less intense in microgravity. This suggests that the perspective cue is less crucial for depth perception. When a subject in space adjusted the dimensions of a 3-D cube so that it looked normal, its height was shorter and its depth was greater than when performing this test in normal gravity; when a subject in space drew a Necker cube with the eyes closed, its height was shorter and its depth was greater. This indicated that the cognitive and the sensory-motor representations of 3-D objects both adapt to space.

European Space Agency astronaut Paolo Nespoli, conducts the Mental Representation of Spatial Cues During Spaceflight (3D-Space) experiment in the Columbus laboratory of the International Space Station. 3D-Space involves distance, written and illusion exercises, and is testing the hypothesis that altered visual perception affects motor control. NASA image.

It is well known that perception of size and distance are usually related. When underestimating the distance of an object, people tend to attribute a small size to this object. In agreement with this, it was observed that space subjects indeed underestimated (by up to 20%) distance more than on Earth. These results indicated that the visual space of the astronauts (ie, the visual component of the perceptual representation of the world around them) was distorted in space. Interestingly, similar effects have been recently reported in spatial neglect and vestibular-defective patients. The speed of drawing and writing was less in microgravity compared to ground. The asymmetry between up and down vertical motion also tended to disappear in microgravity. These results confirmed those obtained previously in pointing experiments.

The European Space Agency Multipurpose Laptop with a prepared Hard Disk Drive, data storage on a PCMCIA memory card, and an electronic pen table connected to it to be used by the Expedition 20 crew during the French/CNES neuroscientific research experiment Mental Representation of Spatial Cues During Space Flight. NASA image.

Publication(s)

Clement G, Skinner A, Lathan CE. Distance and size perception in astronauts during long-duration spaceflight. *Life.* December 13, 2013;3(4):524-537. doi: 10.3390/life3040524.

Clement G, Skinner A, Richard G, Lathan CE. Geometric illusions in astronauts during long-duration spaceflight. *NeuroReport.* 2012;23(15):894-899. doi: 10.1097/WNR. 0b013e3283594705.

This investigation is complete and all results are published.

ELaboratore Immagini TElevisive - Space 2 (ELITE-S2)

Research Area: Nervous and Vestibular Systems
Expeditions: 16-17
Principal Investigator(s):
- Francesco Lacquaniti, MD, University of Rome Tor Vergata, Rome, Italy

Research Objectives

ELaboratore Immagini TElevisive - Space 2 (ELITE-S2) investigates the connection between brain, visualization, and motion in the absence of gravity. By recording and analyzing the 3-dimensional motion of crew members, this study helps engineers apply ergonomics into future spacecraft designs and determines the effects of weightlessness on breathing mechanisms for long-duration missions. This experiment is a cooperative effort with the Italian Space Agency (ASI).

Garret Reisman executing the ELITE S2 protocol IMAGE aboard ISS. NASA image.

Earth Benefits

This study has important implications not only for understanding basic mechanisms of motor control but also for rehabilitative training of neurological patients with impaired motor control. New rehabilitation techniques are based on virtual reality and mental rehearsal of motor actions.

Space Benefits

This study allows for the application of ergonomics in the design of future spacecraft and determines the effects of microgravity on breathing mechanisms for long-duration missions.

Results

ELITE-S2 is pending completion of all data analysis before conclusive results are published.

This investigation is complete; however additional results are pending publication.

Eye Tracking Device (ETD)

Research Area: Nervous and Vestibular Systems
Expedition(s): 9, 11, 13, 14, 16
Principal Investigator(s):
- Andrew Clarke, PhD, Charité Universitätsmedizin, Berlin, Germany

Research Objectives

The Eye Tracking Device (ETD) determines the influence of prolonged microgravity and the accompanying vestibular (inner ear) adaptation on the orientation of Listing's Plane (a coordinate framework, which is used to define the movement of the eyes in the head). This study has important implications for understanding basic mechanisms of motor control in microgravity and for rehabilitative training of neurological patients with impaired motor control.

Earth Benefits

This study has important implications in understanding basic mechanisms of motor control in microgravity and for rehabilitative training of neurological patients with impaired motor control.

Space Benefits

Examination of the orientation of the Listing's Plane during the course of a prolonged space mission is of particular interest; as on Earth, the Listing's Plane appears to be dependent on input from the vestibular system, ie, detected through the head position with relation to gravity. By exposing the astronaut to the weightlessness of space, this experiment can follow the subsequent adaptation of the astronaut's vestibular system during the flight and after re-entry.

Results

Visual functions were observed in flight for 31 astronauts under prolonged microgravity conditions. The precision and speed parameters of visual tracing such as fixational rotations of the eyes (saccades), smooth tracking of linear and curved movements of a focal point stimulus, and following a vertical pendulum-like movement stimuli became worse. In a number of cases, a complete disintegration of the smooth tracing reflex occurred as well as an increase in the time taken to fix the gaze on a target (by factors of 2 or more) and decreased in the frequency of stimulus tracking. During the initial period of

European Space Agency astronaut Thomas Reiter wears the Eye Tracking Device on the International Space Station in 2006. ESA image.

adaptation to spaceflight and periodically during prolonged flight, the system of smooth visual tracking was found to undergo a transition to a strategy of saccadic approximation (abrupt rapid movements of both eyes). These impairments, seen in virtually all the crew members, were apparently due to vestibular deprivation in space.

Pre and postflight examinations of 9 cosmonauts participating in ISS missions were completed using a computer-aided method to investigate eye motion control and vestibular function after long-term stay in microgravity (126-195 days). Studies of the vestibular function, intersensory interactions, and the tracking function of the eyes in the crew members were performed on days 1-2, 4-5, and 8-9 after return to Earth. The role and significance of the vestibular system (the vestibule and semicircular canals of the inner ear and the vestibulocochlear nerve that work with the brain to maintain balance and orientation) in eye tracking were determined.

Results of the postflight examinations showed a significant change in the accuracy, velocity, and temporal characteristics of eye tracking and the muting of the vestibular response. Although, microgravity does not directly influence visual functions, changing the level and pattern of inner ear sensory/receptor input leads to a decrease in the accuracy and velocity of all forms of visual tracking. Eye destabilization related to an increase in slow drift, the appearance of a great number of saccadic (abrupt fast) movements, and the emergence of spontaneous nystagmus (involuntary eye movement) was found. Similar disturbances, as those previously seen during flight, in the accuracy of saccadic and smooth tracking (especially in the vertical plane) and the development of a new tracking strategy (the gaze approaches a target and follows its movement using a set of saccadic movements) were demonstrated and lead to a considerable increase (by a factor of three or more) in the time required for examining and identifying a target and setting the gaze on targets post landing. In the selected period of examination (9 days after the flight), no recovery of the indices of the tracking eye function to the baseline level was observed; however, a tendency for normalization was recorded.

Publication(s)

Clarke AH, Just K, Krzok W, Schonfeld U. Listing's plane and the 3D-VOR in microgravity--the role of the otolith afferences. *Journal of Vestibular Research*. January 1, 2013;23(2):61-70. doi: 10.3233/VES-130476.

Clarke AH, Kornilova LN. Ocular torsion response to active head-roll movement under one-g and zero-g conditions. *Journal of Vestibular Research.* 2007;17(2-3):99-111.

Kornilova LN, Alekhina MI, Temnikova VV, et al. The effect of a long stay under microgravity on the vestibular function and tracking eye movements. *Human Physiology.* 2006;32(5):547-555. doi: 10.1134/S0362119706050082.

Kornilova LN. The role of gravitation-dependent systems in visual tracking. *Neuroscience and Behavioral Physiology.* 2004;34(8):773-781. doi: 10.1023/B:NEAB.0000038127.59317.c7.

This investigation is complete and all results are published.

Effects of Altered Gravity on Spinal Cord Excitability (H-Reflex)

Research Area: Nervous and Vestibular Systems
Expedition(s): 2-4
Principal Investigator(s):
- Douglas Watt, MD, PhD, McGill University, Montreal, Québec, Canada

Research Objectives

Effects of Altered Gravity on Spinal Cord Excitability (H-Reflex) will study the prolonged loss of muscle strength, muscle volume, and bone density, due to the weightlessness environment. These conditions can cause reduced spinal cord excitability, which can lead to loss of loco-motor function in the legs. Spinal cord excitability was isolated and measured to study possible ways to reverse the process while still in flight. Reversal of this process will result in a healthier crew following long-duration spaceflight.

JSC2001E34377 – Expedition 3 commander Culbertson sits in the shuttle middeck performing the Effects of Altered Gravity on the Spinal Cord Excitability experiment.

Earth Benefits

The information gained by this investigation may help researchers develop countermeasures to overcome decreases in spinal excitability. There are many disorders that involve decreases in nerve impulses and loss of sensitivity. Countermeasures that are used in orbit may lead to advances on Earth in treatment of various nerve disorders and spinal injuries.

Space Benefits

The most basic unit of exercise is the contraction of a small group of muscle fibers innervated by the projections of a single nerve cell. If this and other nerve cells in the spinal cord become less excitable during spaceflight, it would be more difficult to make muscle fibers contract. As a result, more effort would be required to produce the same level of exercise, or if the same apparent effort were maintained, the actual level of exercise would decrease. If present after landing, it would be more difficult to stand and walk. However, depending on the underlying mechanisms, it may be possible to reverse the process while still in flight.

Results

Spinal Cord Excitability (SCE) was measured with the H-reflex (Hoffmann reflex) method: 60 shocks of varying lengths were applied to the posterior tibial nerve and the electromyography response detected at the soleus. H-Reflex was conducted repeatedly before, during, and after flight. There was high variation between subjects but the H-reflex was observed to decrease by about 35 percent after 5 days in space and remain at the new level for the duration of the flight. Upon return to 1 g, full recovery took about 10 days. This indicates a reduction of spinal cord excitability in microgravity due to a partial response to signals from the nervous system. The consequence is that muscle mass decreases at 0 g even with exercise and implies there may be limits to the capacity of exercise to maintain muscle and bone mass as well as cardiac muscle strength on long-duration missions. The decrease in SCE is observed in space but not in prolonged bed rest, suggesting it may be partly a nervous system response and not simply due to disuse of the legs. Decreased SCE is therefore of high concern for long-duration missions and will require more adequate countermeasures.

PUBLICATION(S)

Watt DG. Effects of altered gravity on spinal cord excitability (final results). *Bioastronautics Investigators' Workshop,* Galveston, TX; 2003.

Watt DG, Lefebvre L. Effects of altered gravity on spinal cord excitability. First Research on the International Space Station. *Conference and Exhibit on International Space Station Utilization*, Cape Canaveral, FL; 2001.

This investigation is complete; however additional results are pending publication.

Cutaneous Hypersensitivity and Balance Control in Humans (Hypersole)

Research Area: Nervous and Vestibular Systems
Expedition(s): 23-28
Principal Investigator(s):
- Leah Bent PhD, University of Guelph, Guelph, Ontario, Canada

Research Objectives

Cutaneous Hypersensitivity and Balance Control in Humans (Hypersole) will use a vibration device and monofilaments (similar to fishing line) to record the sensitivity of these receptors in 9 astronauts. Researchers are documenting, for the first time, any changes in the skin sensitivity of each astronaut's foot sole in order to identify which receptors may be influenced by a period of weightlessness. Coupled with tests that assess changes in astronauts' abilities to maintain their balance, these measures will help establish how increased skin sensitivity contributes to balance control.

Image shows the set up for the vibrotactile sensitivity threshold test performed during the experiment. Changes in sensitivity were assesses on 3 locations on the plantar surface of the foot using a mini shaker applying vibration through a probe with a contact surface area of 2 mm in diameter. Foam templates were developed for each crew member using orthopedic foam. Holes were made to allow room for the insertion of the vibration probe for each of the three testing locations on the plantar surface of the foot. Image courtesy of Leah Bent, University of Guelph.

Earth Benefits

Project results are expected to add significantly to existing studies of the aging process, which includes reductions in information relayed by skin sensors that lead to a loss of balance control and, among the elderly especially, a greater incidence of falls.

Space Benefits

Anecdotal evidence from astronauts suggests that the tingling sensation some feel in their feet while in space and for short periods back on Earth may be the response of different sensory receptors in the skin that naturally compensate for the re-weighting of sensory information due to the decreased input from the vestibular, or inner ear, system in an environment of microgravity. The research has the potential to impact future applications to further understand skin contributions to balance control in an altered gravity-inertial environment for space exploration.

Results

Vibration frequencies were chosen to target the 4 classes of mechanoreceptors: 3 and 25Hz for slowly-adapting receptors; 60 and 250Hz for fast-adapting receptors. Functional balance test scores (computerized dynamic posturography [CDP]) were compared to skin sensitivity changes. It was hypothesized that skin sensitivity would increase following spaceflight and correlate to balance changes. Data from 11 astronauts before and after short missions (12-16 d) indicate decreased skin sensitivity on landing day at 3 and 25Hz on the great toe. Hypersensitivity was found only for a subset of astronauts (n = 6) with significantly increased sensitivity to 250Hz at the heel. This subset also displayed substantially reduced CDP equilibrium scores on landing compared to non-hypersensitive participants (mean= 39 versus 68). Selective changes in skin sensitivity are apparent after spaceflight. Observed hyposensitivity of slowly adapting receptors may indicate a strategy to reduce pressure input during periods of unloading. Hypersensitivity of fast-adapting receptors coupled with reduced equilibrium scores may reflect targeted sensory re-weighting. Altered gravito-inertial environments reduce vestibular function in balance control, which may trigger increased weighting of fast-adapting receptors. Understanding modulations to skin sensitivity has translational implications for mitigating postural disequilibrium following spaceflight.

PUBLICATION(S)

Strzalkowski ND, Lowrey CR, Perry SD, Williams DR, Wood SJ, Bent LR. Selective weighting of cutaneous receptor feedback and associated balance impairments following short duration space flight. *Neuroscience Letters.* April 2015;592:94-98. doi: 10.1016/j.neulet.2015.02.046.

Lowrey C, Perry S, Strzalkowski N, Williams DR, Wood SJ, Bent LR. Selective skin sensitivity changes and sensory reweighting following short-duration space flight. *Journal of Applied Physiology.* March 15, 2014;116(6):683-692. doi: 10.1152/japplphysiol.01200.2013.

This investigation is complete; however additional results are pending publication.

Promoting Sensorimotor Response Generalizability: A Countermeasure to Mitigate Locomotor Dysfunction After Long-Duration Space Flight (Mobility)

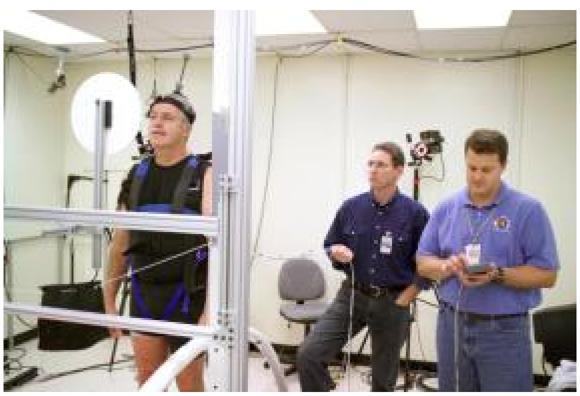
Research Area: Nervous and Vestibular Systems
Expeditions: 5-12
Principal Investigator(s):
- Jacob J. Bloomberg, PhD, Johnson Space Center, Houston, Texas

Research Objectives

Promoting Sensorimotor Response to Generalizability: A Countermeasure to Mitigate Locomotor Dysfunction After Long-duration Spaceflight (Mobility) studies changes in posture and gait after long-duration spaceflight. Anticipated results help in the development of an in-flight treadmill training program for International Space Station (ISS) crew members, which could facilitate rapid recovery of functional mobility after long-duration spaceflight.

Earth Benefits

As people age on Earth, they sometimes experience instabilities in standing and walking. The development of unique walking and balance training procedures like the ones proposed in this study can be used to help prevent falling and injury in the elderly population.



JSC2004E51814 - On November 24, 2004, astronaut John L. Phillips (left), Expedition 11 NASA space station science officer and flight engineer, participates in a mobility session of the Integrated Treadmill Locomotion Test (ITLT) at NASA's Johnson Space Center (JSC). Jacob Bloomberg (center) and Brian Peters assisted Phillips.

Space Benefits

Following long-duration spaceflight, crew members have trouble standing and walking. The magnitude and duration of postflight instability increases with longer exposure to microgravity and can pose a risk to crew safety and to mission objectives during extravehicular operations during planetary exploration. Presently, no operational countermeasure is available to mitigate these balance and locomotor disturbances. This study proposes to develop a unified, multi-disciplinary countermeasure system designed to enhance postflight adaptive locomotor function that can be easily integrated with the existing ISS treadmill procedures without requiring more commitment of valuable crew resources. If successful, this experiment will provide methods for overcoming one of the most significant obstacles to long-term spaceflights, including trips to the moon and Mars.

Results

Following their return to Earth, astronauts experience disturbances in their ability to walk and maintain postural stability due to the brain's adaptation floating weightless in space. The goal was to characterize the effects of long-duration spaceflight on astronaut locomotor control and functional mobility. The Mobility investigation was conducted with 18 ISS crew members over the course of Expeditions 5-12. Locomotor function was assessed before and after spaceflight using 2 tests of gait function. The first test characterized alterations in several systems responsible for the control of locomotion. For this test, subjects walked on a treadmill to assess changes in dynamic visual acuity and lower limb coordination strategies. The second test provided a corresponding assessment of overall functional mobility by testing the subjects' ability to negotiate a complex obstacle course. Toe clearance (minimum height of the toe as the foot swings forward) during treadmill walking was assessed to determine whether astronauts are at an increased risk of tripping after their return from long-duration spaceflight. Test performed on landing day showed reduced toe clearance and an increased risk of tripping during walking one day after spaceflight. However, tripping risk on subsequent days was not different than preflight (Miller 2010). Postflight changes in gaze control produced decreases in the ability to see clearly during walking. Recovery in visual performance occurred during the 2-week postflight recovery period (Peters 2011). Results from the obstacle course indicated adaptation to spaceflight led to a 48% increase in time to traverse the course one day after landing, and recovery of function took an average of 15 days to return to within 95% of their preflight level of performance. This recovery was characterized by a 2-stage re-adaptation process characterized by a fast learning response using cognitive supervision followed by a slower learning process designed to ultimately automate re-learned gait patterns (Mulavara 2010). This research provides valuable data on the extent of postflight locomotor dysfunction, the rate of improvement, and the expected duration of dysfunction of crew members following long-duration spaceflight. These findings will be important in the design of interventions to reduce or eliminate spaceflight related locomotor disturbances.

ISS010E24001 – Astronaut Leroy Chiao, Expedition 10 commander and NASA International Space Station (ISS) science officer, equipped with a bungee harness, exercises on the Treadmill Vibration Isolation System (TVIS) in the Zvezda Service Module of the ISS. Crew members completing standard exercise protocols on ISS are the experimental controls for the Mobility experiment.

PUBLICATION(S)

Cohen HS, Kimball KT, Mulavara AP, Bloomberg JJ, Paloski WH. Posturography and locomotor tests of dynamic balance after long-duration spaceflight. *Journal of Vestibular Research*. January 1, 2012; 22(4):191-196. doi: 10.3233/VES-2012-0456.

Peters BT, Miller CA, Brady RA, Richards JT, Mulavara AP, Bloomberg JJ. Dynamic visual acuity during walking after long-duration spaceflight. *Aviation, Space, and Environmental Medicine.* 2011;82(4):463-466. doi: 10.3357/ASEM.2928.2011.

Miller CA, Peters BT, Brady RA, et al. Changes in toe clearance during treadmill walking after long-duration spaceflight. *Aviation, Space, and Environmental Medicine*. 2010;81(10):919-928. doi: 10.3357/ASEM.2680.2010.

Mulavara AP, Feiveson AH, Fiedler J, et al. Locomotor function after long-duration spaceflight: Effects and motor learning during recovery. *Experimental Brain Research*. 2010. doi: 10.1007/s00221-010-2171-0.

This investigation is complete and all results are published.

Motion Perception: Vestibular Adaptation to G-Transitions (MOP)

Research Area: Nervous and Vestibular Systems
Expedition(s): 8-12, 16, 18-20
Principal Investigator(s):
- Eric Groen, TNO Human Factors, Soesterberg, Netherlands

Research Objectives

Motion Perception: Vestibular Adaptation to G-Transitions (MOP) provides insight in the process of vestibular adaptation to a gravity transition. Adaptation will be assessed by rating motion perception as a result of body movements. MOP will also correlate susceptibility to space adaptation syndrome (SAS) with susceptibility to sickness induced by centrifugation (SIC). The results will allow the team to establish the time course of the adaptation process and thereby set a further step in the determination of key parameters in vestibular adaptation.

Results

The main results concern the correlation between SIC and SAS. Eight astronauts rated their individual susceptibility to SIC and SAS on an 11-point rating scale in both the in-flight study and the ground-based centrifuge study. Other than the previous observations, where susceptibility to SAS was reported in a binary way (“yes” or “no”), the ratings from the MOP questionnaire allowed for a more detailed comparison. Data showed that the correlation between the maximum SAS-rating reported in flight and the maximum SIC-rating reported post-centrifuge is statistically, highly significant ($R=0.89$; $p=0.003$). This indicated that the extent to which an individual astronaut suffered from SIC after centrifugation, was related to that from SAS in flight.

The Netherlands Organization for Applied Scientific Research (TNO) rotation chair combines vestibular stimuli (tilt and/or rotation) with visual stimuli (optic flow in roll). Used for addressing motion and attitude perception. ESA image.

The detailed ratings obtained within the MOP study provided scientific evidence for previous anecdotal observations that, different from sickness induced by car, ship, or aircraft motion on Earth, SIC is highly correlated with the in-flight SAS. It was concluded that any transition from Earth’s gravity to another causes vestibular adaptation problems. Additional tests performed during the Baseline Data Collection showed that the centrifuge run affected orientation responses, which depend on vestibular information about the direction of the Earth vertical. With these results, space authorities and researchers now have a validated paradigm available to assess and study SAS on Earth, which was lacking so far.

Publication(s)

Nooij SA, Bos JE, Groen EL, Bles W, Ockels WJ. Space sickness on earth. *Microgravity Science and Technology*. September 2007;19(5-6):113-117. doi: 10.1007/BF02919464.

This investigation is complete and all results are published.

Directed Attention Brain Potentials in Virtual 3-D Space in Weightlessness (Neurocog)

Research Area: Nervous and Vestibular Systems
Expedition(s): 5, 7-11
Principal Investigator(s): ● Guy Cheron, Université Libre de Bruxelles, Brussels, Belgium

Research Objectives

A key concept in the field of neuromotor control is that of defining the frames of reference used by the central nervous system (CNS) to interpret sensory information and to control movements. At the level of individual sensors and effectors, the coordinate systems employed are well defined. It is not in the coordinate system of an individual receptor, but rather, in examining the coordination of sensory and motor activity that the question of reference frames becomes interesting. This experiment tests the role of gravity in defining the reference frames used for 3-D navigation and for representing the orientation of our own bodies and the orientation of visual stimuli. A series of psychophysical tests are used to compare how human subjects perform these types of task both on the ground and in the weightless conditions of orbital flight. Evoked potentials are also measured through surface electrodes applied to the scalp in order to measure the spatial and temporal components of information processing in the brain in the absence of gravity.

Results


Execution of Neurocog experiment using visual tunnel. ESA

Three main results were shown in the Neurocog experiment. First, weightlessness specifically affects visual-evoked potential related to the presentation of a virtual 3-D navigation tunnel: subjects observed a simulated passive movement through a virtual tunnel. Each tunnel contained a bend. After subjects emerged from the end of the tunnel, they were asked to report the perceived turn angle by adjusting a visual indicator with a trackball. On Earth, the estimation of pitch turns is greater for forward (nose-down) turns versus backward (nose-up) turns. This asymmetry does not exist to this extent in weightlessness. Second, weightlessness increases the alpha rhythm gain during the transition between eyes-closed and eyes-opened states. Finally, moving in virtual navigation induces midfrontal N200 event related potentials supported by a transient theta ringing altered in weightlessness.

The research from this experiment is continuing with a follow-on experiment (Neurocog-2), which is embedded within the ESA-sponsored Neurospat experiment.

Publication(s)

Cheron G, Leroy A, Palmero-Soler E, et al. Gravity influences top-down signals in visual processing. *PLOS ONE.* January 6, 2014;9(1):e82371. doi: 10.1371/journal.pone.0082371.

de Saedeleer C, Vidal M, Lipshits M, et al. Weightlessness alters up/down asymmetries in the perception of self-motion. *Experimental Brain Research.* April 2013;226(1):95-106. doi: 10.1007/s00221-013-3414-7.

Leroy A, de Saedeleer C, Bengoetxea A, et al. Mu and Alpha EEG Rhythms during the arrest reaction in microgravity. *Microgravity Science and Technology.* 2007;19(5-6):102-107. doi: 10.1007/BF02919462.

Cheron G, Leroy A, de Saedeleer C, et al. Effect of gravity on human spontaneous 10-Hz electroencephalographic oscillations during the arrest reaction. *Brain Research*. 2006;1121(1): 104-116. doi: 10.1016/j.brainres.2006.08.098.

Lipshits M, Bengoetxea A, Cheron G, McIntyre J. Two reference frames for visual perception in two gravity conditions. *Perception.* 2005;34(5):545-555. doi: 10.1068/p5358.

This investigation is complete and all results are published.

Effect of Gravitational Context on EEG Dynamics: A Study of Spatial Cognition, Novelty Processing and Sensorimotor Integration (Neurospat)

Research Area: Nervous and Vestibular Systems

Expedition(s): 19-ongoing

Principal Investigator(s):

- László Balázs, Hungarian Academy of Sciences, Budapest, Hungary
- Guy Cheron, Universite Libre de Bruxelles, Brussels, Belgium
- István Czigler, Hungarian Academy of Sciences, Budapest, Hungary
- George Karmos, Hungarian Academy of Sciences, Budapest, Hungary
- Márk Molnár, Hungarian Academy of Sciences, Budapest, Hungary
- Elemér Nagy, Central Hospital of Ministry of the Interior, Budapest, Hungary
- Livia Gabriella Pató, Hungarian Academy of Sciences, Budapest, Hungary
- Jerzy Achimowicz, University of Finance and Management, Warsaw, Poland
- Caty de Saedeleer, Universite Libre de Bruxelles, Brussels, Belgium
- Ana Cebolla, Universite Libre de Bruxelles, Brussels, Belgium
- Alain Berthoz, College de France, Paris, France
- Ana Bengoetxea, Universite Libre de Bruxelles, Brussels, Belgium
- Joseph McIntyre, College de France, Paris, France

Research Objectives

Effect of Gravitational Context on EEG Dynamics: A Study of Spatial Cognition, Novelty Processing and Sensorimotor Integration (Neurospat) tests prefrontal brain functions and spatial cognition to determine the effect of gravitational context on brain processing. The experiment involves recording of the electroencephalographic activity of the brain (EEG dynamics) and event related potentials (ERP) during performance of a visual-orientation perception and visuo-motor tracking task that humans and astronauts may encounter on a daily basis. Specifically, 5 cognitive processes (perception, attention, memorization, decision, and action) are studied.

Earth Benefits

Understanding how the neural processes of perception adapt to weightlessness in turn provides an insight into exactly how perception is altered by the presence of gravity. This research could therefore improve our fundamental knowledge of how the human central nervous system functions on Earth. Furthermore drawing similarities between the disorientation experienced by astronauts when first adapting to weightlessness and certain medical conditions on Earth where disorientation can be an important symptom, can provide important information of the areas of the brain responsible, which could help with the treatment of such conditions. The development of these electrophysiological experimental protocols promises to provide a new tool for clinical testing of spatial cognition, altered in pathological conditions and in normal aging.

Space Benefits

Previous neuroscience research has highlighted various differences between perception on Earth and in space. Without gravity to act as a stimulus, some of the most important neural sensors in the body cannot provide the assistance they would normally provide for orientation purposes. Astronauts therefore rely more heavily on visual perception for orientation. For this reason understanding what altered visual perception occurs in weightlessness, and what areas of the brain are responsible, is an important element in making sure that this does not present any issues for undertaking mission activities, especially key activities such as spacewalks and dockings/undockings. Results generated could form a key part of mission planning and therefore optimize the chances of achieving all mission goals and secure optimal mission success. It could also potentially feed into the design of equipment for use in orbit.

Results

Data from the Neurospat experiment is currently being analyzed and processed prior to publication.

ESA's Andre Kuipers performs his first orbital the Effect of Gravitational Context on EEG Dynamics: A Study of Spacial Cognition, Novelty Processing and Sensorimotor Integration session. Andre is wearing an Electroencephalogram electrode cap and optimizing channel impedance of the electrodes before starting measurements. NASA image.

Publication(s)

Cheron G, Leroy A, de Saedeleer C, et al. Effect of gravity on human spontaneous 10-Hz electroencephalographic oscillations during the arrest reaction. *Brain Research.* 2006;1121(1):104-116. doi: 10.1016/j.brainres.2006.08.098.

This investigation is ongoing and additional results are pending publication.

Otolith Assessment During Postflight Re-adaptation (Otolith)

Research Area: Neurological and Vestibular Systems
Expedition(s): 17-28
Principal Investigator(s): ● Andrew H. Clarke, PhD, Charite Medical School, Berlin, Germany

Research Objectives

Otolith Assessment During Postflight Re-adaptation (Otolith) explores the adaptive processes in the human vestibular (inner ear) system as it readapts to ground conditions after spaceflight. Given that the loss of the gravitational force represents a loss of this sense for the otolith organs, the working hypothesis is that the dynamic otolith-ocular reflex (OOR) will be enhanced in microgravity. Immediately after return to the 1-g environment, a corresponding increase in the OOR gain should be observed, and over the course of the following days return to preflight baseline level. This should also be the case with subjective visual vertical (SVV) estimation. The same theory applies to the vestibular evoked myogenic potentials (VEMPs); an increase in their amplitude is expected during the period after re-entry. The re-adaptation process is expected to proceed largely over the first 12 days after landing.


Rotating drum vestibular testing with multi-axis tilt device. ESA image.

Results

The SVV findings indicated that after a 10-day mission, the readaptation of otolith function proceeded over a period of 8-10 days. Considerable interindividual variability in response change and adaptive time constants. The SVV data support the idea of a labyrinth dominance, rather than a morphological asymmetry, as proposed previously.

Publication(s)

Clarke AH, Just K, Krzok W, Schonfeld U. Listing's plane and the 3D-VOR in microgravity--the role of the otolith afferences. *Journal of Vestibular Research*. January 1, 2013;23(2):61-70. doi: 10.3233/VES-130476.

Kornilova LN, Naumov IA, Makarova SM. Static torsional otolith-cervical-ocular reflex after prolonged exposure to weightlessness and a 7-day immersion. *Acta Astronautica*. May – June, 2011;68(9-10):1462-1468. doi: 10.1016/j.actaastro.2010.04.016.

Clarke AH. Listing's plane and the otolith-mediated gravity vector. *Berlin: Progress in Brain Research* (2008); 2008.

Clarke AH. Listing's plane and the 3D-VOR in microgravity. *Life in Space for Life on Earth Symposium*, Angers, France; June 22-27, 2008; 2. [Also: Clarke AH. Listing's plane and the 3D VOR in microgravity. *J Gravit. Physiol*. 2008;15(1):29-30.]

Clarke AH, Kornilova LN. Ocular torsion response to active head-roll movement under one-g and zero-g conditions. *Journal of Vestibular Research*. 2007;17(2-3):99-111.

This investigation is complete and all results are published.

Scaling Body-related Actions in the Absence of Gravity (Passages)

Research Area: Nervous and Vestibular Systems
Expedition(s): 21-30
Principal Investigator(s):
- Marion Luyat, University of Lille Nord, Lille, France
- Joseph McIntyre, College de France, Paris, France

Research Objectives

Scaling Body-related Actions in the Absence of Gravity (Passages) tests how astronauts interpret visual information in microgravity. From a theoretical perspective, the experiment tests a specific hypothesis from experimental psychology, which states that human visual perception is tuned to invariants of the visual field to determine what actions are afforded (offered or permitted) by the environment. The experiment examines how perception strategies have evolved within the constraints imposed by gravity. From a more practical viewpoint, the experiment tests whether Earth-adapted strategies lead to modifications or outright errors in the perception of visual space during spaceflight. Passages is based on a known observation that human beings unconsciously use eye height to calibrate physical dimensions in the visual field. The perceptual mechanism relies on the fact that on Earth eye height above the floor can be known by the observer through proprioception and an internal representation of body scheme.

NASA astronaut Dan Burbank performs a session of the Scaling Body-related Actions in the Absence of Gravity experiment in the Columbus laboratory of the International Space Station. NASA/ESA image.

Results

At the time of compilation of this document the experiment data was still being analysed prior to publication of results.

This investigation is complete; however additional results are pending publication.

Perceptual-Motor Deficits in Space (PMDIS)

Research Area: Nervous and Vestibular Systems
Expedition(s): 14-15
Principal Investigator(s):
- Barry Fowler, PhD, York University, North York, Ontario, Canada

Research Objectives

Perceptual-Motor Deficits in Space (PMDIS) investigates why astronauts experience difficulty with hand-eye coordination while in orbit. In-flight data distinguishes between 3 possible explanations: the brain not adapting to the near weightlessness of space; the difficulty of performing fine movements when floating in space; and stress due to factors such as space sickness and sleep deprivation.

ISS014E09626 – Expedition 14 flight engineer Astronaut Suni Williams performs the Perceptual Motor Deficits in Space. This investigation will test the hand-eye coordination of the International Space Station crew members during their mission.

Earth Benefits

Understanding how the brain adapts to physiological changes that the International Space Station (ISS) crew members undergo are applicable on Earth as well as space. The results from this experiment will give insight on how the brain overcomes stresses that are not normally part of the day-to-day life. This new information can be applied in many areas of research that deal with neurological diseases in order to provide improved treatments.

Space Benefits

A mini-centrifuge with daily sessions has been suggested as a means for countering the physiological effects of long-term spaceflight, eg, a Mars mission. This raises the possibility of continual changes in eye-hand coordination as the gravity signal changes on a daily basis. Understanding the cause of coordination loss is therefore critical to developing countermeasures.

Results

The results from PMDIS contradict the microgravity hypothesis because a major prediction of this hypothesis, that performance would be degraded using either the stylus or the joystick, was not supported. Rather, performance degradation only occurred with the more mentally demanding dual task using the joystick. These results suggest that the loss of hand-eye coordination in space can be attributed to a variety of interacting stressors that lead to cognitive overload. These factors include lack of body stability, degree of learning on the task and its complexity, space sickness, and sleep deprivation.

Publication(s)

Fowler B, Meehan S, Singhal A. Perceptual-motor performance and associated kinematics in space. *Human Factors.* December 2008;50(6):879-892. doi: 10.1518/001872008X374965.

This investigation is complete and all results are published.

SPACE HEADACHES: INCIDENENCE AND CHARACTERISTICS (SPACE HEADACHES)

Research Area: Nervous and Vestibular Systems
Expedition(s): 29-ongoing
Principal Investigator(s):
- Alla Vein, Leiden University, Leiden, Netherlands

RESEARCH OBJECTIVES

Headaches are a common complaint during spaceflight. The Space Headaches experiment improves our understanding of such conditions, which helps in the development of methods to alleviate associated symptoms and improve the well-being and performance of crew members in orbit. This can also improve our knowledge of similar conditions on Earth.

NASA image shows a close-up of astronaut John Grunsfeld performing a spacewalk to work on the Hubble Space Telescope. Astronauts who have no history of bad headaches can be prone to disabling attacks while in space, a phenomenon that suggests "space headaches" deserve a medical category all of their own, neurologists said

SPACE BENEFITS

Headaches during spaceflight can negatively affect mental and physical capacities of crew members, which can influence performance during a space mission. Data from this experiment improve our understanding of such conditions, providing a stepping stone to development of countermeasures to alleviate associated symptoms, thus improving the well-being of our crew members in orbit and in turn improving astronaut performance.

EARTH BENEFITS

Headaches are also common on Earth, either as an isolated condition or as one symptom of another medical condition. Improving the knowledge we gather in space of the nature and occurrence of headaches could also provide an insight to associated conditions on Earth.

RESULTS

No results are available yet as the investigation is still ongoing.

This investigation is ongoing, and additional results are pending publication.

VALIDATION OF CENTRIFUGATION AS A COUNTERMEASURE FOR OTOLITH DECONDITIONING DURING SPACEFLIGHT (SPIN)

Research Area: Nervous and Vestibular Systems

Expedition(s): 16, 17, 19-22, 29, 30

Principal Investigator(s):

- Floris Wuyts, PhD, University of Antwerp, Belgium
- Steven T. Moore, PhD, Mount Sinai School of Medicine, New York, New York
- Hamish G. MacDougall, PhD, University of Sydney, Sydney, Australia
- Gilles Clement, PhD, International Space University, Strasbourg, France
- Bernard Cohen, PhD, Mount Sinai School of Medicine, New York, New York
- Nathalie Pattyn, MD, PhD, Royal Military Academy, Brussels, Belgium
- Andre Diedrich, MD, PhD, Vanderbilt University Medical Center, Nashville, Tennessee

RESEARCH OBJECTIVES

The Validation of Centrifugation as a Countermeasure for Otolith Deconditioning During Spaceflight (Spin) experiment investigates the effect of microgravity on otolith-ocular reflexes and autonomic function to correlate the otolith-ocular reflex on orthostatic tolerance. The effect of microgravity on subjective perception of verticality is also researched.

RESULTS

Statistical analysis showed a significant decrease of intervals between 2 heart beats (RRI) during the counter-clockwise rotation measured preflight, compared to before rotation stimulus.

Final check before centrifugation of cosmonaut Youri Malenchenko who is seated on the Visual and Vestibular Integration System (VVIS) in Star City GCTC - Moscow. ESA image.

Comparison of the preflight data with those measured postflight revealed a trend that is reoccurring during each postflight measurement (Return+1, +4 and +9 days), ie, a decrease of RRI during both rotations compared to the baseline recordings. The decrease was significant for data measured on Return +9 days. Statistical analysis revealed no significant effects for the phase of the respiratory sinus arrhythmia (RSA - a naturally occurring variation in heart rate that occurs during a breathing cycle). The effects seen on the heart rate during the first counter-clockwise rotation could be explained by an “anticipative” stress effect of the subjects, causing an increase of sympathetic activation and thus increased heart rate. The subsequent heart rate decrease during the clockwise rotation could be attributed to a habituation of the subjects to the rotation. Interestingly, this effect was not observed during the testing days after their re-entry. On the contrary, the heart rate increased even more during the second rotation. This reflects a delayed or hampered recovery of the sympathetic nervous system after activation. It might be possible that spaceflight is at the base of this recovery problem because of a vestibular and a cardiovascular deconditioning. As expected, the analysis revealed that the influence of T_{resp} is larger (and more significant) than the possible effect of microgravity on RSA amplitude. With the small number of subjects and the large inter-subject variability the statistical power is too low to permit a proper multifactorial statistical analysis for RSA. Imposing a particular breathing pattern to the subjects is not feasible during centrifugation. Therefore, more subjects are necessary to increase the power to elucidate possible effects.

Publication(s)

Buytaert KI, MacDougall HG, Moore ST, et al. Validation of centrifugation as a countermeasure for otolith deconditioning during spaceflight: Preliminary data of the ESA SPIN study. *Journal of Vestibular Research*. January 1, 2013;23(1):23-31. doi: 10.3233/VES-130469.

Weerts AP, Migeotte PF, Pattyn N, et al. Heart rate variability during centrifugation in astronauts prior to and after long duration spaceflight: Preliminary data. *2010 Life in Space for Life on Earth*, Trieste, Italy; June 13-18, 2010:2.

This investigation is complete; however additional results are pending publication.

Sympathoadrenal Activity in Humans During Spaceflight (Sympatho)

Research Area: Nervous and Vestibular Systems
Expedition(s): 5, 8, 11
Principal Investigator(s):
- Niels J. Christensen, University of Copenhagen, Copenhagen, Denmark

Research Objectives

Sympathoadrenal Activity in Humans During Spaceflight (Sympatho) studies the influence of microgravity on adrenal activity in the sympathetic nervous system, which has importance for cardiovascular system regulation such as accelerating heart rate, constricting blood vessels, and raising blood pressure in short-duration space explorers. Ground-based experiments have shown that the sympathetic activity is decreased in response to displacement of the blood from the lower part of the body to the heart-lung area after changing from the upright or sitting position to the supine (lying on back) position. In space, sympathetic activity is expected to be decreased but experiments have suggested that it actually increases during weightlessness. This is the core element of the Sympatho experiment.

Freezer Kriogem-03 for storage of blood samples. ESA image.

Results

Long-term changes in sympathoadrenal activity were measured through platelet norepinephrine and epinephrine levels. Ten normal, healthy subjects were studied before and during head-down bed rest (HDBR) of 2 weeks duration, as well as during an ambulatory study period of a similar length. Platelet norepinephrine and epinephrine concentrations (preflight and postflight) were studied in 5 cosmonauts who participated in 3 different Soyuz missions to the International Space Station (ISS). Due to the long half-life of norepinephrine and epinephrine in platelets (approximately 2 days), data obtained early after landing would still reflect the microgravity state. Platelet norepinephrine decreased markedly during HDBR. During microgravity platelet norepinephrine and epinephrine increased in 4 of the 5 cosmonauts. Platelet norepinephrine and epinephrine concentrations expressed in percentage of preflight and pre-HDBR values, respectively, were significantly increased during microgravity as compared to HDBR. The increase in platelet norepinephrine and epinephrine during microgravity is most likely due to an increase in sympathoadrenal activity. The reason why sympathoadrenal activity does not decrease to low levels during microgravity as one would expect remains to be resolved.

The exact interrelationship in microgravity between the increase in cardiac output, the decrease in plasma volume and the increase in sympathoadrenal activity during spaceflight remains to be clarified. Plasma volume decreases inflight, but this change is unlikely to explain the increase in sympathetic nervous activity. There did not appear to be a pronounced early increase in urine output during weightlessness, but there may be a relative increase compared to the intake of fluid because the intake of fluid and food tend to decrease. It is likely that vasoconstriction is maintained or increased in the lower part of the body inflight. Thus sympathetic activity may be increased to counteract the increase in blood flow to the brain and to other organs above the heart level during microgravity. In conclusion, a relative high sympathoadrenal activity as compared to preflight values seems to be an integrated part of the regulatory response to microgravity. Furthermore, HDBR cannot be applied to simulate changes in sympathoadrenal activity in humans during microgravity.

PUBLICATION(S)

Christensen NJ, Heer MA, Ivanova K, Norsk P. Sympathetic nervous activity decreases during head down bed rest but not during microgravity. *Microgravity Science and Technology*. September 2007;19(5-6):95-97. doi: 10.1007/BF02919460.

Christensen NJ, Heer MA, Ivanova K, Norsk P. Sympathetic nervous activity decreases during head-down bed rest but not during microgravity. *Journal of Applied Physiology*. June 16, 2005; 99(4):1552-1557. doi: 10.1152/japplphysiol.00017.2005.

This investigation is complete and all results are published.

SYMPATHOADRENAL ACTIVITY IN HUMANS DURING SPACEFLIGHT-2 (SYMPATHO-2)

Research Area: Nervous and Vestibular Systems
Expedition(s): 14, 19-22, 25-ongoing
Principal Investigator(s):
- Niels J. Christensen, University of Copenhagen, Copenhagen Denmark

RESEARCH OBJECTIVES

Sympathoadrenal Activity in Humans During Spaceflight-2 (Sympatho-2) studies the influence of microgravity on adrenal activity in the sympathetic nervous system, which has importance for cardiovascular system regulation such as accelerating heart rate, constricting blood vessels, and raising blood pressure in long-duration space explorers. Ground-based experiments have shown that the sympathetic activity is decreased in response to displacement of the blood from the lower part of the body to the heart-lung area after changing from the upright or sitting position to the supine (lying on back) position. In space, sympathetic activity is expected to be decreased but experiments have suggested that it actually increases during weightlessness. This is the core element of the Sympatho experiment

RESULTS

Eight male astronauts were studied between third and sixth months of flight on the International Space Station. It was observed that sympathetic nervous system activity but not plasma epinephrine values were very high during the mission and the level corresponded to values obtained in sitting position on Earth. This response was most likely related to the decrease observed in systemic vascular resistance and arterial blood pressure observed during the mission. The mechanism of the decrease in vascular resistance during spaceflight has not been clarified, but it is likely to be related to the blood and fluid shift to the upper part of the body as observed during microgravity. Clearly a high sympathetic nervous system activity is required for astronauts to maintain an adequate blood pressure level in space. Further studies of the mechanisms involved are therefore of major importance.

Centrifuge Plasma-03 to separate blood into plasma and serum. ESA image.

This investigation is complete; however additional results are pending publication.

Study of the Typological Characteristics of ISS Crew Operator Activity During Long-term Space Flight (Tipologia/Tipologia Perfection), Two Investigations

Research Area: Nervous and Vestibular System
Expedition(s): 19-34
Principal Investigator(s):
- Alexander A. Antonov, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

The Study of the Typological Characteristics of ISS Crew Operator Activity During Long-term Space Flight (Tipologia/TipologiaPerfection) identifies behavioral characteristics in the actions of crew members, which could be used to determine the current psychological state, to predict future states, and to modify the performance quality of skill tasks undertaken in spaceflight conditions. The experiment aims to reveal the individual traits of the crew member's operational activity and to evaluate the forecasting capabilities of indicators, using the computer games Sapior (Sapper) and Tetris as models of skill activity.

Russian cosmonaut G.I. Padalka performs the Study of the Typological Characteristics of ISS Crew Operator Activity During Long-term Space Flight experiment on the International Space Station. Roscosmos image.

Earth Benefits

Tipologia uses a new (for space medicine) strategy of breaking down the test subject's activity into statistical probability and predetermined. This new division is based on the neuropsychological approach to the functional role of different areas of the cerebral cortex. It should be noted that this approach is supported by multiple clinical and experimental observations and histological studies.

Space Benefits

The results of this experiment are connected to the development of new methods and tools used to increase the reliability of the operator's performance and decrease the risk of incorrect actions when solving skill problems. The experiment provides information necessary for gaining insight into such fundamental issues as the connection of the brain's electrical phenomenon and the behavioral act, the formation of readiness for skill activity, and understanding the mechanisms responsible for changing response quality while under the effect of spaceflight including weightlessness. It is possible that the results serve as a foundation for developing new methods for operational skill assessment, future predictions and improvement of crew members' skill performance, during flight.

Results

Russian crew participants demonstrated a high level of professional skill training when performing logical and spatial types of tasks, as well as adaptive biological control. During preflight training, all subjects are able to successfully develop adaptive biological control skills and learned to control their readiness skill when solving logical and spatial problems. When solving spatial problems, the ABC effect was observed mostly starting from the third training session. This was confirmed by the increase of the productivity indicators. When solving logical problems, the ABC effect was observed starting from the third or fourth training session. By the last training session, the ABC skill, when solving logical and spatial problems, had been developed in all cosmonauts.

However, in spaceflight conditions, adaptive skill suffered in all subjects: the ABC effect was not observed in the type of activity, which is difficult for the cosmonaut because of his particular behavioral characteristics. The logical activity proved more difficult for most cosmonauts. Only one subject was able to reproduce the ABC skill he had developed earlier when solving logical problems in spaceflight conditions. It should also be mentioned that during postflight analysis, the ABC skill, when solving spatial and logical problems, was expressed distinctly in almost all of the subjects, regardless of how it was affected during spaceflight.

Publication(s)

Tipologia

Antonov AA, Ershova TA. Effect of adaptive biological control session on the indicators of modeled activity in the experiment Mars – 105. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2010;44(4):17-23.

Antonov AA, Ershova TA. Preservation of the ABC skill when controlling the process of synchronizing the bioelectrical activity of the human cerebral cortex in an argon-nitrogen-oxygen environment with various concentrations of oxygen. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2009;43(5):27-31.

Savchenko VV. Feedback mechanisms when supporting the operator's functionality in the "human-machine" system, when in a state of readiness to perform experimental activity. *Zhurnal Sistemnyi Analiz i Upravleniye s Biomeditzinskikh Sistemakh (System Analysis and Control in Biomedical Systems)*. 2005;5(4):477-481.

Tipologia Perfection

Antonov AA. Adaptive control method based on biofeedback of values for spatial cortex zones synchronization activity as operator maintenance asset. *Aviakosmicheskaya i Ekologicheskaya Meditsina (Aerospace and Environmental Medical Science)*. 2007;41(2):21-28.

This investigation is complete and all results are published.

On the Contribution of Visceral Receptors to the Sense of Subjective Vertical (Visual Subjective Vertical)

Research Area: Nervous and Vestibular Systems
Expedition(s): 10, 11
Principal Investigator(s):
- Colonel Enrico Tomao, Italian Air Force, Rome, Italy

Research Objectives

On Earth, the subjective sense of vertical is due to many sensory inputs, which are mainly related to the visual, vestibular, and proprioceptive systems, utilizing special sensors located respectively in the eye, inner ear, and in joints and muscles. A further contribution to the detection of subjective vertical is observed from visceral receptors sensitive to blood mass shifts, mainly located in the kidneys and in the thorax, specific data on the contribution of visceral receptors to the detection of subjective vertical in a specific environment is still lacking. The aim of this experiment is the analysis of visceral receptor performance in weightlessness.

Subjective Vertical Analyser. ESA image.

Eye Movement Recording Subsystem Electronics Box. NASA image.

Results

The subjective visual vertical (SVV) can be significantly influenced by the presence of a displaced visual field, as in the case of the rod and frame test (RFT). A series of studies showed the effects of blood mass shifts to and from the lower limbs on SVV due to visceral mechanoreceptors (VM) located at the level of the kidneys and of the thorax. These sensors may be artificially activated with a lower body negative pressure (LBNP) device. In this study, the role of visual and VM cues to orientation perception were evaluated using the RFT and the LBNP devices under a microgravity environment. A preliminary investigation was conducted in a sample of military pilots to develop a RFT protocol to be used in microgravity environments. This protocol was adopted to evaluate the contribution of VM to the SVV in a cosmonaut before, during, and after a 10-day spaceflight, with and without concurrent activation of LBNP.

The same test sequence, including LBNP exposure, was repeated a few months later on Earth on the same subject. As expected, the influence of the frame on rod positioning was statistically significant in all test conditions. During the in-flight experimental step, a substantial lack of significant changes compared to the preflight condition was observed. Moreover, substantially no effects due to LBNP were observed. A mild rod displacement from the body axis was detected under microgravity compared to the preflight recording. Such a finding was in part reduced during LBNP. The same findings were observed during the postflight repeat of the experiment. Results showed an absence in this subject of significant effects on the RFT due to microgravity. In conclusion, no effects from subject's VM on the RFT and minor changes in the SVV could be detected.

PUBLICATION(S)

Lucertini M, De Angelis C, Martelli M, Zolesi V, Tomao E. Subjective Visual Vertical in Erect/Supine Subjects and Under Microgravity: Effects of Lower Body Negative Pressure. Eur Arch Otorhinolaryngol. 2011;268(7):1067-1075. doi: 10.1007/s00405-011-1493-2.

van Loon JWA, Medina FJ, Stenuit H, Istasse E, Heppener M, Marco R. The National-ESA Soyuz missions Andromède, Marco Polo, Odissea, Cervantes, DELTA and Eneide. *Microgravity Science and Technolog*. 2007;19(5-6):9-32. doi: 10.1007/BF02919448.

This investigation is complete and all results are published.

AMBIGUOUS TILT AND TRANSLATION MOTION CUES AFTER SPACE FLIGHT (ZAG)

Research Area: Nervous and Vestibular Systems

Expedition(s): 16-28

Principal Investigator(s):
- Gilles Clement, International Space University, Strasbourg, France

RESEARCH OBJECTIVES

Ambiguous Tilt and Translation Motion Cues After Space Flight (Zag) investigates the exposure to combined tilt and translation motion profiles for space explorers who have experienced microgravity. It also examines the effects of stimulus frequency (0.15-0.6Hz) on adaptive changes in eye movements and motion perception and evaluates how a tactile prosthesis can be used to improve control performance.

Test subject in the Variable Radius Centrifuge. ESA image.

RESULTS

In summary, results were consistent with the hypothesis that adaptive changes in the neural integration of otolith input leads to perceptual illusions and impaired manual control after spaceflight. The postflight recovery of motion perception and manual control performance was complete within 1 week following short-duration space missions. Further study is needed to examine the effect of longer-duration missions. The results of the studies are also consistent with the otolith asymmetry hypothesis as contributing to the physiological basis for tilt-translation disturbances. The strong correspondence between tilt perception errors and manual control performance decline suggested that these adaptive changes in sensorimotor function have operational consequences for vehicular control. These measures are relevant to how impairments in otolith processing may affect other vehicular control tasks, such as driving with vestibular impairments. Finally, it was demonstrated that a relatively simple tactile prosthesis is sufficient to bring landing day performance to preflight levels. The refinement of a tactile prosthesis to improve spatial orientation can serve as a countermeasure for tilt-translation disturbances on a variety of acceleration platforms. Validation of simple sensory aids is applicable to balance prosthesis applications for vestibular loss patients and the elderly to mitigate risks due to falling or loss of orientation.

PUBLICATION(S)

Clement G, Wood SJ. Motion perception during tilt and translation after space flight. *Acta Astronautica*. November 2013;92(1):48-52. doi: 10.1016/j.actaastro.2012.03.011.

Clement G, Wood SJ. Eye movements and motion perception during off-vertical axis rotation after spaceflight. *Journal of Vestibular Research*. January 1, 2013;23(1):13-22. doi: 10.3233/VES-130471.

This investigation is complete and all results are published.

ANOMALOUS LONG-TERM EFFECTS IN ASTRONAUTS' CENTRAL NERVOUS SYSTEM (ALTEA)

Research Area: Radiation Impacts on Humans

Expeditions: 13-15

Principal Investigator(s):

- Livio Narici, PhD, University of Roma Tor Vergata and INFN Roma2, Rome, Italy

RESEARCH OBJECTIVES

Anomalous Long-term Effects in Astronauts' Central Nervous System (ALTEA) integrates several diagnostic technologies to measure the effect of the exposure of crew members to cosmic radiation. ALTEA improves the understanding of the impact that radiation has on the human central nervous system functions and will study the flashes from cosmic radiation that astronauts have reported since the Apollo flights. It also provides an assessment of the radiation environment in the International Space Station (ISS).

ISS128E007282 – View of astronaut Tim Copra with the Anomalous Long Term Effects in Astronauts' Central Nervous System (ALTEA) Silicon Detector kit in U.S. Laboratory Destiny.

EARTH BENEFITS

Data provided from ALTEA lead to further understanding of how radiation may affect brain function on Earth as well as in space. While the levels of heavy ion radiation are much higher in space than on Earth, any understanding into the way radiation may alter brain function is extremely useful to neuroscientists. Ion therapies to treat brain tumors benefit from the ALTEA results.

SPACE BENEFITS

Crew members from Apollo missions onward have reported seeing unexplained light flashes (phosphenes), which were attributed to abnormal brain function caused by space radiation. Outside the protection of Earth's magnetic shield, ISS crew members are exposed to increased radiation, but the radiation environment is even more severe as exploration crews leave Earth's geomagnetic field and transit to other planets. The tests conducted using the ALTEA hardware help scientists characterize how the heavy ion radiation of space impacts the brain and whether or not that radiation causes any temporary or permanent abnormalities in the brain function and the visual system in particular.

RESULTS

Since the Apollo flights to the moon, it has been known that most astronauts experience sudden visual light flashes during spaceflight. Described in early reports as occurring in darkness and typically before falling asleep, these light flashes are thought to originate as an effect of high-energy particles, abundant in space, interacting with the eye and/or the visual anatomy. The ALTEA project, active on ISS since August 2006 and currently investigating the ISS-US Lab radiation environment (ALTEA-DOSI, ALTEA-SHIELD/survey), has also been studying the risks of possible damage to the brain from particle radiation in space (ALTEA-CNSM). It is proposed that these interaction effects may go well beyond light flashes and could constitute a new kind of risk for longer space voyages. One study focus was on these abnormal visual perceptions and the impact on retinal and brain visual structures. ALTEA, with its 6 double detectors covering most of the astronaut's head, permits a 3-dimensional reconstruction of the energy released in the brain by ionizing particles. In addition, ALTEA monitors the functional state of the optical pathway in order to interpret the biophysical mechanisms generating abnormal perceptions. A survey was conducted in 2003 with 59 astronauts on the perception of light flashes, or "phosphenes", during missions. It was found that 80% of space explorers experience light flashes at some point (mainly before sleep when the eyes are night adjusted). As many as 20% of the respondents thought that light flashes sometimes disturbed their sleep. Light flashes are predominantly white, but other colors are mentioned, in particular yellow (10%). Most light flashes have an elongated shape, like stripes or comets, and are associated with a perception of motion. The motion is left-right or in-out, but never up-down, and about 8% of light flashes have a "blob" shape. There is a positive correlation between light flashes and radiation flux, and the majority of light flash in space is most likely produced by a direct interaction of an ion with the retina, although there is indirect indication that light flashes can result from interaction between particles and brain structures as well.

ISS019E005340 – View of the Anomalous Long Term Effects in Astronauts Central Nervous System (ALTEA) experiment and Silicon Detector Units designed to measure cosmic radiation passing through the brain. Photo taken in the U.S. Laboratory/Destiny during Expedition 19.

Solar Particle Events (SPEs) could represent a high radiation hazard for the ISS crew. During most of the December 2006 SPE, the ALTEA detector collected continuous data inside the U.S. Lab module. Results indicate that a SPE significantly affects radiation energy levels in the ISS, producing a substantial increase of low energy radiation rate, which reaches the highest values in quite short periods. This confirms the need to consider SPEs in those biological processes for which radiation rate plays an important role. These results provide the first information for charged radiation risk assessment in space habitats during a SPE.

PUBLICATION(S)

Larosa M, Casolino M, De Santis C, et al. Ion rates in the International Space Station during the December 2006 solar particle event. *Journal of Physics G: Nuclear and Particle Physics.* 2011;38(9). doi: 10.1088/0954-3899/38/9/095102.

Zaconte V, Casolino M, Di Fino L, et al. High energy radiation fluences in the ISS-USLab: Ion discrimination and particle abundances. *Radiation Measurements*. 2010;45:168?172. doi: 10.1016/j.radmeas.2010.01.020.

La Tessa C, Di Fino L, Larosa M, Narici L, Picozza P, Zaconte V. Estimate of the space station shielding thickness at a USLab site using ALTEA measurements and fragmentation cross sections. *Nuclear Instruments and Methods in Physics Research Section B: Beam interactions with materials and atoms.* 2009;267(9):3383-3387. doi: 10.1016/j.nimb.2009.06.107.

Narici L. Heavy ions light flashes and brain functions: Recent observations at accelerators and in spaceflight. *New Journal of Physics.* 2008;10. doi: 10.1088/1367-2630/10/7/075010.

Zaconte V, Belli F, Bidoli V, et al. ALTEA: The instrument calibration. *Nuclear Instruments and Methods in Physics Research Section B: Beam interactions with materials and atoms*. 2008;266(9):2070-2078.

Narici L, Belli F, Bidoli V, et al. The ALTEA/ALTEINO projects: Studying functional effects of microgravity and cosmic radiation. *Advances in Space Research.* 2004;33(8):1352-1357.

This investigation is complete and all results are published.

Area PAssive Dosimeter for Life Science Experiments in Space (Area PADLES)

Research Area: Radiation Impacts on Humans
Expedition(s): 17-ongoing
Principal Investigator(s):
- Aiko Nagamatsu, PhD, Japan Aerospace Exploration Agency, Tsukuba, Japan

Research Objectives

JAXA Area Passive Dosimeter for Life Science Experiments in Space (Area PADLES) is an investigation that uses area dosimeters to continuously monitor the radiation dose aboard the International Space Station (ISS). Radiation exposure can have significant biological effects on living organisms, and on the biological investigations being done on ISS and on the Japanese Experiment Module Kibo; therefore, by installing area dosimeters at 17 fixed locations inside the Kibo Module, continuous area radiation monitoring can be provided throughout the ISS Kibo program.

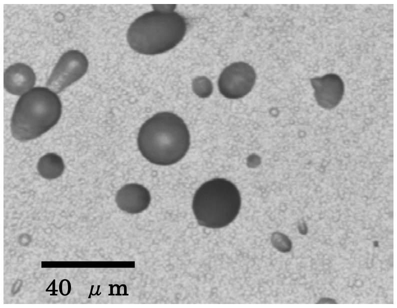
JAXA astronaut Satoshi Furukawa holding Area PADLES. NASA/JAXA image.

Earth Benefit

The dosimeters have been applied to dosimetry for radiobiology experiments and ground performance test for study of shielding effect with heavy-ion particles. Dosimetric methods are also used for area radiation monitoring due to high energy accelerators.

Space Benefit

The measurement of radiation environmental parameters in space is essential to support radiation risk assessment for crew members and to be a benchmark of simulation codes of space radiation models for present, and future, human space activities. Full understanding of space radiation, and the doses surrounding crew members, is essential to dose management and space radiation protection. Accumulated data and knowledge are beneficial to design new active and passive types of radiation monitoring, shielding, and the design of future space vehicles.



A photograph featuring 256 gray-level images of etch pits on the post-etching surfaces of the CR-39 PNTDs in package No. 1 of Area PADLES#6 on the FWD OVHD. JAXA image.

Results

Radiation monitoring system was flown aboard Soyuz spacecraft, installed in the Kibo module aboard the ISS with Area and Exp PADLES dosimeters and collected data. Results from returned dosimeters found that the particle fluxes change more than twice depending on the installation orientation, since space radiation environment in low-Earth orbit aren't isotropic.

The dosimetric results obtained by area dosimeters are published in JAXA's PADLES database and utilized to support the planning of Life Science experiments in Kibo and astronauts' flights, as well as to estimate the shielding effects of the JPM wall thickness or modify Japanese radiation simulation codes, and will be based on the next future human spaceflight.

PUBLICATION(S)

Nagamatsu A, Murakami K, Kitajo K, Shimada K, Kumagai H, Tawara H. Area radiation monitoring on ISS Increments 17 to 22 using PADLES in the Japanese Experiment Module Kibo. *Radiation Measurements*. December 2013;59:84-93. doi: 10.1016/j.radmeas.2013.05.008.

This investigation is ongoing and additional results are pending publication.

Bonner Ball Neutron Detector (BBND)

Research Area: Radiation Impacts on Humans

Expedition(s): 2-3

Principal Investigator(s):
- Haruhisa Matsumoto, Japan Aerospace Exploration Agency, Tsukuba, Japan
- Kiyokazu Koga, Japan Aerospace Exploration Agency, Tsukuba, Japan
- Hideki Koshiishi, Japan Aerospace Exploration Agency, Tsukuba, Japan

Research Objectives

Bonner Ball Neutron Detector (BBND) measures neutron radiation (low-energy, uncharged particles), which can deeply penetrate the body and damage blood forming organs. Neutron radiation is estimated to be 20% of the total radiation on the International Space Station (ISS). This study characterizes the neutron radiation environment to develop safety measures to protect future ISS crews.

Earth Benefit

The technology developed for BBND will also have application in monitoring the environment of high-radiation facilities on Earth.

ISS002E5716 – Voss with Bonner Ball Neutron Detector Control Unit in Destiny laboratory. This unit will process and store neutron information recorded by six spherical detectors scattered around the Station. JAXA image.

Space Benefit

A neutron is an elementary particle. Since a neutron has no electric charge, it can penetrate most substances. Even low-energy neutrons can reach the internal human organs, including bone marrow. It is said that 5% to 30% of the whole radiation dose astronauts receive is neutron energy. The obtained data is to be used for the enhancement of space radiation exposure management technology, needed for further human activity aboard the ISS.

Results

BBND characterized the neutron radiation aboard the ISS during Expeditions 2 and 3 and determined that galactic cosmic rays were the major cause of secondary neutrons measured inside the ISS habitats. The neutron energy spectrum was measured from March 23, 2001, through November 14, 2001, in the U.S. Laboratory Module. The timeframe enabled neutron measurements to be made during a time of increased solar activity (solar maximum) as well as observe the measurements from a solar flare on November 4, 2001.

BBND results show that the overall neutron environment at the ISS orbital altitude is influenced by highly energetic galactic cosmic rays, except in the South Atlantic Anomaly (SAA) region where protons trapped in the Earth's magnetic field cause a more severe neutron environment.

However, the number of particles measured per second per square cm per MeV obtained by BBND is consistently lower than that of the previous investigations. The average dose-equivalent rate observed through the investigation was 3.9 micro Sv/hour or about 10 times the rate of radiological exposure to the average U.S. citizen. In general, radiation damage to the human body is indicated by the amount of energy deposited in living tissue, modified by the type of radiation causing the damage; this is measured in units of Sieverts (Sv). The background radiation dose received by an average person in the United States is approximately 3.5 milli Sv/year. Conversely, an exposure of 1 Sv can result in radiation poisoning and a dose of 5 Sv will result in death in 50% of exposed individuals. The average dose-equivalent rate observed through the BBND investigation is 3.9 micro Sv/hour, or about 10 times the average U.S. surface rate. The highest rate, 96 micro Sv/hour was observed in the SAA region.

On November 4, 2001, a solar flare and the associated geomagnetic activity caused the most severe radiation environment inside the ISS during the BBND experiment. The increase of neutron dose-equivalent due to those events was evaluated to be 0.19mSv, which is less than 1% of the measured neutron dose-equivalent measured over the entire 8-month period.

Although this experiment did not characterize the neutron radiation environment outside of Earth's magnetic field, the BBND sampling equipment provided results without return of equipment to Earth and proved that similar measurement systems could be used on missions to the moon and Mars to monitor real-time radiation risks (Expedition 2 and 3 One Year Postflight Report).

PUBLICATION(S)

Yajima K, Yasuda H, Takada M, et al. Measurements of cosmic-ray neutron energy spectra from thermal to 15 MeV with Bonner Ball Neutron Detector in aircraft. *Journal of Nuclear Science and Technology*. January 2010;47(1):31-39. doi: 10.1080/18811248.2010.9711934.

Koshiishi H, Matsumoto H, Chishiki A, Goka T, Omodaka T. Evaluation of the neutron radiation environment inside the International Space Station based on the Bonner Ball Neutron Detector experiment. *Radiation Measurements*. October 2007;42(9):1510-1520. doi: 10.1016/j.radmeas.2007.02.072.

Sato T, Niita K, Iwase H, Nakashima H, Yamaguchi Y, Sihver L. Applicability of particle and heavy ion transport code PHITS to the shielding design of spacecrafts. *Radiation Measurements*. October 2006;41(9-10):1142-1146. doi: 10.1016/j.radmeas.2006.07.014.

Koshiishi H, Matsumoto H, Goka T, Koga K. Evaluation of low-energy neutron environment inside the International Space Station. *Technical Report of Institute of Electronics, Information, and Communications Engineers*. 2003;103(486):11-14. [Japanese]

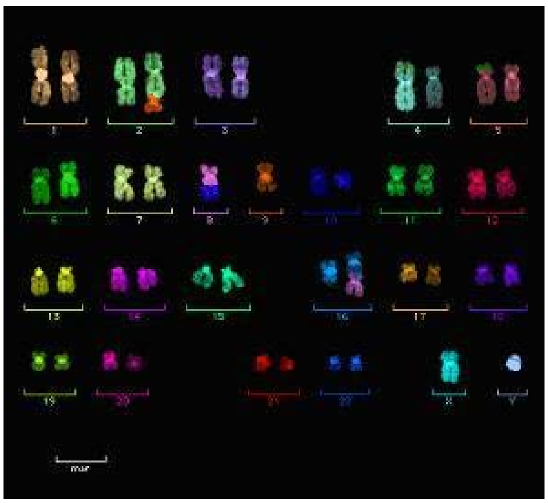
This investigation is complete and all results are published.

Biodosimetry in Astronauts (Biodosimetry)

Research Area: Radiation Impacts on Humans
Expedition(s): 4, 10
Principal Investigator(s):
- Marco Durante, PhD, University Federico II, Naples, Italy

Research Objectives

It is known that DNA is damaged by ionizing radiation, which may lead to chromosomal aberrations (ie, malfunction or malformation of chromosomes). This in turn could lead to elevated risks of cancer and other disorders. Biodosimetry in Astronauts (Biodosimetry) measures the frequency of chromosomal aberrations preflight and postflight from short-duration mission space explorers.



Multi-fluorescent chromosome map of a cell exposed to cosmic radiation. ESA image.

Results

To evaluate the possible alteration of cellular response to ionizing radiation, extracted whole blood was exposed to X-rays before and after the mission. The previous data on chromosome aberrations in peripheral lymphocytes of the same astronaut after the Marco Polo mission in 2002 (Soyuz 4S / 3S exchange) showed a significant increase in the yield of total aberrations. This observation suggested a higher radio sensitivity of lymphocytes when collected after flight compared to preflight. However, this effect was not reproduced during the Eneide mission in 2005 (Soyuz 10S / 9S exchange).

Similar results were obtained after exposure to gamma rays of blood samples of astronauts involved in short-duration missions. The results suggested that intra-individual variations in radiation sensitivity can be significant, but they cannot be related to the spaceflight. Follow-up data showed a reduced radio-sensitivity compared to both preflight and postflight Marco Polo data. This may be seen as a result of an increased resistance from repeat exposure or longer stay in space. This observation was consistent with data reported in Russian cosmonauts, also showing evidence for a possible acquired radiation adaptation. The yield of baseline chromosomal aberrations in the blood not exposed on Earth was not modified after Marco Polo or Eneide, and this was consistent with the low dose absorbed in these short-term space missions. However, while no significant alterations were observed in metaphase samples, a slight increase was measured in premature chromosome condensation (PCC). This may reflect the occurrence of slowly cycling aberrant cells undetectable at mitosis and caused by the high-LET space radiation.

Publication(s)

Bertucci A, Durante M, Gialanella G, et al. Biological dosimetry in the ENEIDE mission on the International Space Station. *Microgravity Science and Technology*. 2007;19(5-6):206-209. doi: 10.1007/BF02919483.

Durante M, Snigiryova G, Akaeva E, et al. Chromosome aberration dosimetry in cosmonauts after single or multiple spaceflights. *Cytogenetic and Genome Research.* 2003;19:40.

Greco O, Durante M, Gialanella G, Grossi G, Pugliese M, Scampoli P. Biological dosimetry in Russian and Italian astronauts. *Advanced Space Research*.2003;31:1495.

Wu H, George K, Willingham V, Cucinotta FA. Comparison of chromosome aberration frequencies in pre- and post-flight astronauts lymphocytes irradiated in vitro with gamma rays. *Physica Medica.* 2001;17:229.

This investigation is complete and all results are published.

Chromosomal Abberations in Blood Lymphocytes of Astronauts (Chromosome-1)

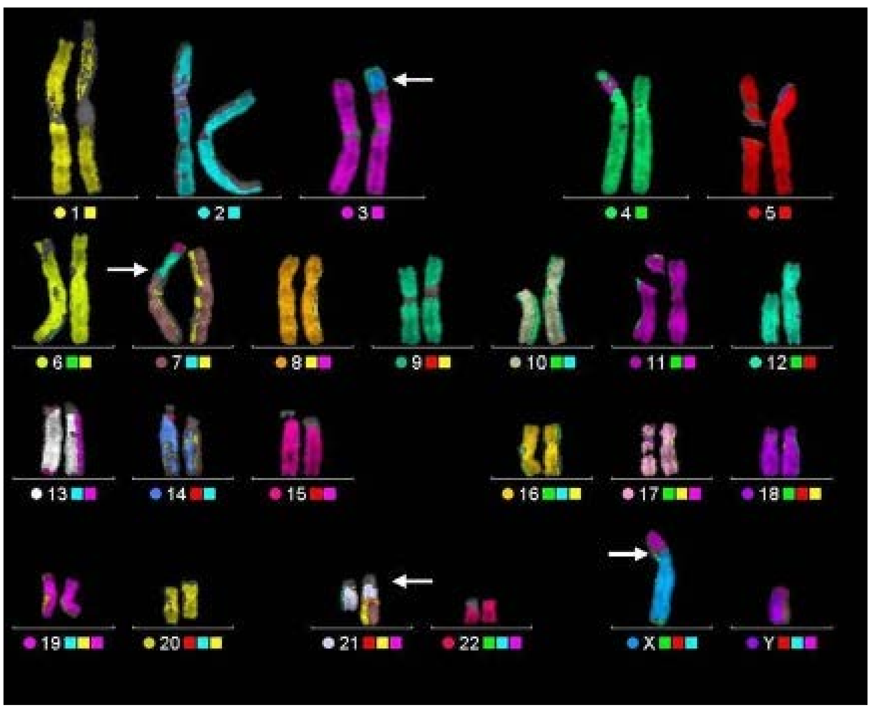
Research Area: Radiation Impacts on Humans

Expedition(s): 5, 7, 8, 10, 11

Principal Investigator(s):
- Günter Obe, PhD, University of Duisburg-Essen, Essen, Germany

Research Objectives

Chromosomal Aberrations in Blood Lymphocytes of Astronauts-1 (Chromosome-1) studies space radiation on humans, providing an insight into the exact chromosome from which particular mutations arise. From this study scientists may be able to better assess risk factors for genetic damage in space and help develop new methods for protecting crew members through strategies such as radiation shielding, dietary supplements, pharmaceutical intervention, etc. Understanding and reducing the risk of radiation is important for safe long-duration space exploration.



Multi-color fluorescence in situ hybridization (mFISH) metaphase with a complex translocation pattern. Translocations are present between chromosome 3 and the X-chromosome; chromosomes 7 and 21, and chromosomes 7, 12, and 15. Image courtesy of University of Duisburg-Essen.

Space Benefits

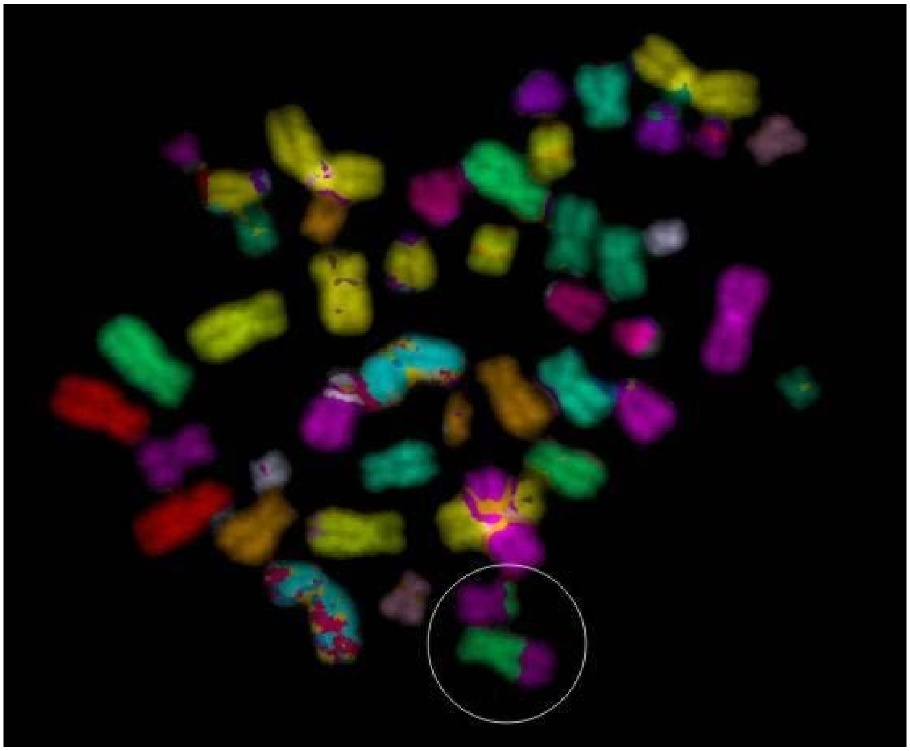
From this study, scientists may be able to better assess risk factors for genetic damage in space and help develop new methods for protecting crew members. Understanding and reducing the risk of radiation is important for safe long-duration travel in space, including stays on the moon and travel to Mars.

Earth Benefits

The knowledge gained from this investigation will give scientist's insight into the exact chromosome from which particular mutations arise.

Results

The lymphocyte cultures from the blood samples of the 4 short-duration crew members grew well and gave good preparations for scoring of chromosomal aberrations. The analyses of the blood samples of the 4 short-duration crew members revealed no overall increase of aberrations. For comparison, the mean values of 11 long-duration flight crew members were included. While the increase of mutated cells by a factor of 1.4 was significant for the latter group, no such increase was found for the 4 short-duration subjects.



Multi-color fluorescence in situ hybridization (mFISH) metaphase with a reciprocal translocation between chromosomes 9 and 11 (encircled). University of Duisburg-Essen image.

Before the flights, only chromosomal fragments were detected (all values in control range). After the flight, few dicentrics could be observed. No other aberration types (which are considered to be radiation induced) were found. These results are in contrast with the observations in long-duration crew members. Following missions of approximately 6-month periods, various types of aberrations increased after return to Earth.

PUBLICATION(S)

George KA, Rhone J, Chappell LJ, Cucinotta FA. Cytogenetic biodosimetry using the blood lymphocytes of astronauts. *Acta Astronautica.* November 2013;92(1):97-10. doi: 10.1016/j.actaastro.2012.05.001.

Durante M. Biomarkers of space radiation risk. *Radiation Research.* 2005;164(4 Pt 2):467-473.

Horstmann M, Durante M, Johannes C, Pieper R, Obe G. Space radiation does not induce a significant increase of intrachromosomal exchanges in astronaut lymphocytes. *Radiation and Environmental Biophysics.* 2005;44:219-224. doi: 10.1007/s00411-005-0017-0.

Durante M, Ando K, Furusawa Y, Obe G, George KA, Cucinotta FA. Complex chromosomal rearrangements induced in vivo by heavy ions. *Cytogenetic and Genome Research.* 2004;104:240-244. doi: 10.1159/000077497.

Durante M, Snigiryova GP, Akaeva E, et al. Chromosome aberration dosimetry in cosmonauts after single or multiple space flights. *Cytogenetic and Genome Research.* 2003;103:40-46. doi: 10.1159/000076288.

Greco O, Durante M, Gialanella G, et al. Biological dosimetry in Russian and Italian astronauts. *Advances in Space Research*. 2003;31(6):1495-1503. doi: 10.1016/S0273-1177(03)00087-5.

This investigation is complete and all results are published.

Cytogenetic Effects of Ionizing Radiation in Peripheral Lymphocytes of ISS Crew members (Chromosome-2)

Research Area: Radiation Impacts on Humans

Expedition(s): 12-16

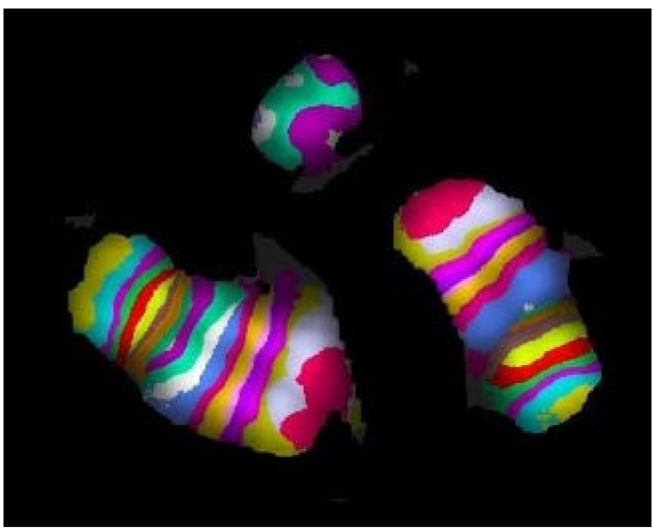
Principal Investigator(s):
- Christian Johannes, PhD, University of Duisburg-Essen, Essen, Germany

Research Objectives

Cytogenetic Effects of Ionizing Radiation in Peripheral Lymphocytes of ISS Crew Members (Chromosome-2) is a continuation of the Chromosome-1 investigation. Chromosome-2 examines lymphocytes using different analytical methods to determine quantity and quality of genetic changes resulting from exposure to cosmic radiation, particularly ionizing radiation. From this study, scientists may be able to better assess risk factors for genetic damage in space and help develop new methods for protecting crew members through strategies such as radiation shielding, dietary supplements, pharmaceutical intervention, etc. Understanding and reducing the risk of radiation is important for safe long-duration travel in space.

Results

Frequencies of aberrant cells varied considerably between the experiment test subjects. An aberrant cell is considered to include any type of aberration, eg, fragments, dicentrics, ring chromosomes. The comparison of preflight and postflight scorings for individual crew members revealed increasing values with no clear tendency. There was no significant difference between short and long-duration crew members. Most of the aberrations obtained in preflight and postflight samples were simple chromatid breaks. This aberration type is not considered to be a marker for radiation exposure. Dicentric chromosomes and other interchanges that are considered to be radiation indicators were found rarely and showed no significant increase after return from short- or long-mission flights. The final result after scoring the remaining samples will help to clarify this question.



The mBAND method is used to detect aberrations within chromosomes as shown in the photo. An interstitial piece is lost from one of the two chromosomes 5. University of Duisburg-Essen image.

Dicentric chromosomes are considered to be the “gold standard” of radiation exposure. This aberration type was only found in a single postflight sample of a long-duration crew member. The frequency of dicentrics was therefore not elevated above the spontaneous level of unirradiated subjects.

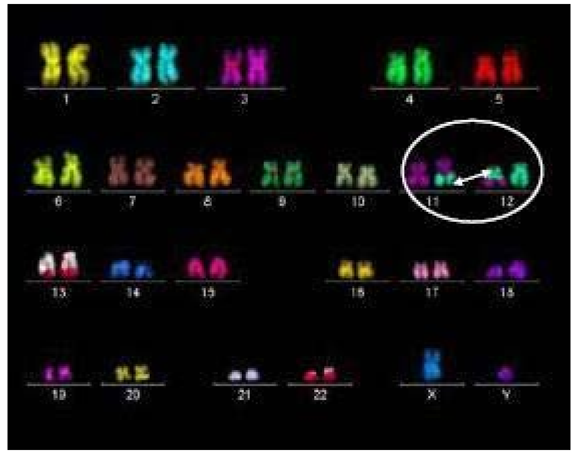
Publication(s)

George KA, Rhone J, Beitman A, Cucinotta FA. Cytogenetic damage in the blood lymphocytes of astronauts: Effects of repeat long-duration space missions. *Mutation Research - Genetic Toxicology and Environmental Mutagenesis.* August 30, 2013;756(1-2):165-169. doi: 10.1016/ j. mrgentox .2013.04.007.

George KA, Chappell LJ, Cucinotta FA. Persistence of space radiation induced cytogenetic damage in the blood lymphocytes of astronauts. *Mutation Research - Genetic Toxicology and Environmental Mutagenesis.* August 2010;701(1):75-79. doi: 10.1016/j.mrgentox .2010.02.007.

Cucinotta FA, Kim MY, Willingham V, George KA. Physical and biological organ dosimetryaAnalysis for International Space Station astronauts. *Radiation Research.* July 2008;170(1):127-138. doi: 10.1667/RR1330.1.

George KA, Durante M, Cucinotta FA. Chromosome aberrations in astronauts. *Advances in Space Research.* 2007;40(4):483-490. doi: 10.1016/j.asr.2007.03.100.



Researchers use mFISH to study human chromosomal pairs. This photo shows that there has been a reciprocal exchange (translocation between chromosomes 11 and 12 and between 13 and 22) in blood lymphocytes of a crew member after spaceflight.

Cucinotta FA. Space radiation organ doses for astronauts on past and future missions. *NASA Technical Publication;* 2006.

Durante M. Biomarkers of space radiation risk. *Radiation Research*. 2005;164(4 Pt 2):467-473.

George KA, Willingham V, Cucinotta FA. Stability of chromosome aberrations in the blood lymphocytes of astronauts measured after space flight by FISH chromosome painting. *Radiation Research*. 2005;164(4):474-480. doi: 10.1667/RR3323.1.

This investigation is complete and all results are published.

DOSIMETRIC MAPPING (DOSMAP)

Research Area: Radiation Impacts on Humans
Expeditions: 2
Principal Investigator(s):
- Günter Reitz, PhD, German Aerospace Center, Köln, Germany

RESEARCH OBJECTIVES

Dosimetric Mapping (DOSMAP) allows mapping of radiation levels throughout the internal environment of the International Space Station (ISS) and in the immediate vicinity of each crew member. The resulting data help determine the best radiation shielding locations aboard the ISS, thereby providing the crew with the best possible protection during unusually high levels of radiation that is due to solar flares and other cosmic phenomena.

EARTH BENEFITS

This experiment is teaching scientists more about the use of devices for data collection and how to monitor real-time data. This could prove beneficial to radiation monitoring of commercial airline crews and military flight crews.

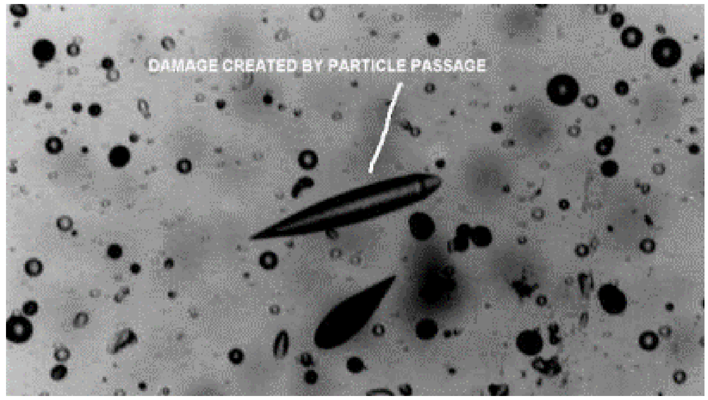
SPACE BENEFITS

DOSMAP will produce a clearer image of the radiation environment aboard the ISS, revealing what segments provide better radiation shielding and examining the radiation levels immediately surrounding crew members. DOSMAP research will help scientists more accurately predict radiation exposure in long-duration spaceflight, both in low-Earth orbit and outside Earth's magnetic field. With this information, it will be possible to develop countermeasures that will protect crews in space on longer missions to Mars and the moon, and it may also help lead to technologies to protect people working in potentially radioactive areas on Earth such as nuclear power plants and nuclear submarines.

ISS002E7814 (June 26, 2001) - James S. Voss, Expedition Two flight engineer, sets up the Human Research Facility's (HRF) Dosimetric Mapping (DOSMAP) Power Distribution Unit (PDU) in Destiny.

RESULTS

Radiation damage to the human body is indicated by the amount of energy deposited in living tissue by the type of radiation causing the damage. The background radiation dose received by an average person in the United States is approximately 10 microSv/day. An exposure of 1 Sv/hour can result in radiation poisoning and a dose of 5 Sv/hour will result in death in 50% of exposed individuals. An average dose from all detectors during Expedition 2 was found to be 532 microSv/day. Three important conclusions were drawn from this experiment that will help with future monitoring activities: The corrections that were needed measuring instrument errors were negligible and had only a small influence on dose rate estimates. About 15% of the tissue-damaging dose (effective dose) is from short-ranged neutrons and protons that were created within the spacecraft materials, and about 90% of the crew member dose is due to particles that deposit less than 150 keV/micron (Reitz 2005).



High-energy particles leave tracks (dark streak in center of the image) on CR39 plastic film contained within DOSMAP's Nuclear Track Detector Packages. European Space Agency (ESA) image.

PUBLICATION(S)

Beaujean R, Reitz G, Dachev TP, et al. Space radiation measurements aboard ISS - the DOSMAP experiment. *Radiation Protection Dosimetry.* 2005;116(1-4):374-379. doi: 10.1093/rpd/nci262.

Reitz G, Beaujean R, Benton ER, et al. Space radiation measurements on-board ISS - the DOSMAP experiment. *Radiation Protection Dosimetry*. 2005;116(1-4):374-379. doi: 10.1093/rpd/nci262.

Beaujean R, Dachev TP, Reitz G, et al. Dosimetric mapping. *Conference and Exhibit on International Space Station Utilization*, Cape Canaveral, Florida; 2001.

This investigation is complete and all results are published.

Extra Vehicular Activity Radiation Monitoring (EVARM)

Research Area: Radiation Impacts on Humans

Expedition(s): 4-6

Principal Investigator(s):
- Ian Thomson, PhD, Thomson and Nielsen Electronics, Ottawa, Ontario, Canada

Research Objectives

The aim of the Extra Vehicular Activity Radiation Monitoring (EVARM) investigation is to determine the levels of radiation dose received to the skin, eyes, and blood-forming organs (BFOs) of crew members during extravehicular activity (EVA). The data determined which parts of the human body are exposed to the highest radiation levels so that routine dosage monitoring in future missions can be done on the appropriate parts of the human body.

ISS005E22017 – International Space Station Expedition 5 Commander Valery Korzun during an extravehicular activity (EVA). The Extra Vehicular Activity Radiation Monitoring experiment measures the amount of radiation that astronauts absorb during EVA.

Earth Benefits

The shielding designed for this experiment can also be used to protect people who receive X-rays and CAT scans and people working in areas exposed to high levels of radiation, such as nuclear power plants.

Space Benefits

The information gathered will help determine which parts of the body are exposed to the highest levels of radiation, in order to improve spacesuit shielding.

Results

In the EVARM experiment, radiation was measured by means of 3 dosimeters in the form of small badges. These dosimeters are metal-oxide semiconductor field effect transistors (MOSFETs) carried in pockets inside the astronaut's spacesuit during EVAs. Data recorded by these badges were then transferred to a laptop computer and sent to researchers. The EVARM experiment measured the radiation delivered to the most sensitive organs: the skin, eyes, bone marrow, and lymphatic organs. Spacesuit shielding influences the quantity and type of radiation absorbed by astronauts. Overexposure may burn the skin, cause cataracts in the lens of the eye and the immediate depletion of blood cells, as well as increase the risk of cancer. A comparison of the internationally recognized limits of radiation exposure for workers and the maximum allowed doses for astronauts shows 0.50, 0.15, and 0.02 sieverts per year for skin, eye, and blood-forming organs in nuclear industry workers, while astronauts receive 3.00, 2.00 and 0.50 sieverts per year. Radiation exposure for astronauts is therefore 6 times higher to the skin, 13 times higher to the eyes, and 25 times higher to the blood-forming organs.

PUBLICATION(S)

Reynolds R, Delclos G, Cooper S, Rahbar M. Radiation dosimetry in space: A systematic review. *WebMedCentral, Environmental Medicine.* 2014;5(3):WMC004578.

Shamin A, Arsalan M, Roy L, Shams M, Tarr G. Wireless dosimeter: System-on-chip versus system-in-package for biomedical and space applications. *IEEE Transactions on Circuits and Systems –II: Express Briefs.* 2008;55(7):643-647.

This investigation is complete and all results are published.

MATROSHKA-1

Research Area: Radiation Impacts on Humans
Expedition(s): 9, 10, 11
Principal Investigator(s):
- Günter Reitz, PhD, German Aerospace Center, Cologne, Germany
- Victor M. Petrov, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

Space radiation hazards are a key concern for human spaceflight. Accurate risk assessment requires knowledge of equivalent doses in critical radiosensitive organs rather than only skin doses or ambient doses from area monitoring. Matroshka measures space radiation doses from the diverse components of ionizing space radiation were measured at the surface and at different locations inside a human phantom positioned outside the International Space Station, thereby simulating an extravehicular activity of a space explorer.

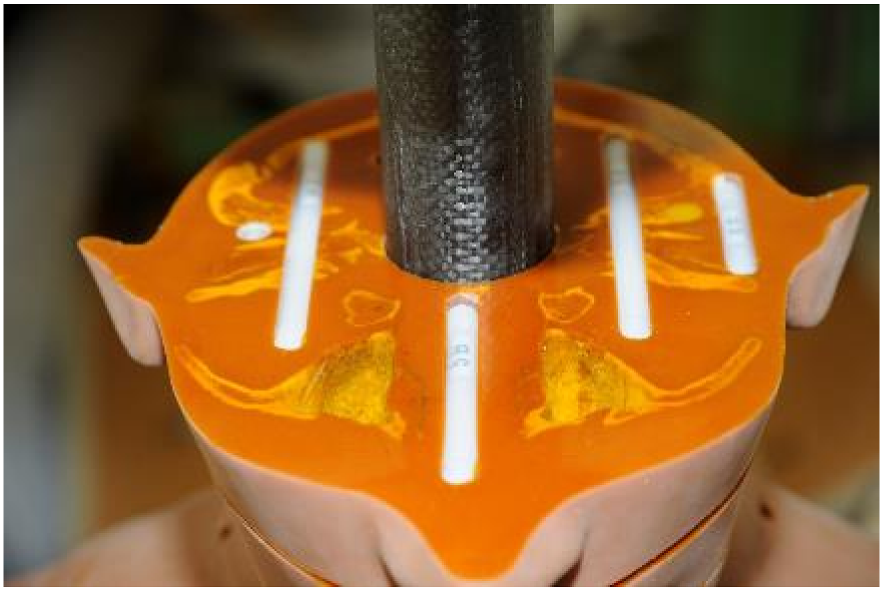
RESULTS

The relationships between the skin and organ absorbed doses obtained in such an exposure showed a steep gradient between the doses in the uppermost layer of the skin and the deep organs with a ratio close to 20. This decrease due to the body self-shielding and a concomitant increase of the radiation quality factor by 1.7 highlighted the complexities of an adequate dosimetry of space radiation.

ISS011E13009 – Cosmonaut Sergei K. Krikalev, Expedition 11 commander representing Russia's State Space Corporation, works with the European Space Agency (ESA) Matroshka radiation experiment in the Zvezda Service Module of the International Space Station. Matroshka, a human-torso-like device, was retrieved from the exterior of the station during an August spacewalk for return to Earth. The experiment is designed to better understand the exposure of astronauts, including those making spacewalks, to radiation.

Matroshka data showed the interpolated depth distribution of dose rates including the skin measurement. It highlighted the very steep decline within the first 8 mm by a factor of about 10. From this depth-dose distribution, an average organ dose rate was determined for each critical organ as the average of the dose rates in those volume elements that were assigned to it in the voxel model. The calculated skin dose rate represents an average of the outermost 3 mm. With about 1 mGy/day, it is by far the highest, followed by the dose rate in the eye. With the exception of the breast and the salivary glands, the dose rates for the other organs were in the range from 0.2 to 0.3 mGy/day.

The depth-dose distributions established by Matroshka serve as benchmarks for space radiation models and radiation transport calculations that are needed for mission planning.



The photo shows a close-up view on how the sensors are arranged inside the head part of the Matroshka-Kibo torso. The light-yellow structures are reassembling the bones of the human scull. ESA image.

PUBLICATION(S)

Berger T, Bilski P, Hajek M, Puchalska M, Reitz G. The MATROSHKA experiment: Results and comparison from extravehicular activity (MTR-1) and intravehicular activity (MTR-2A/2B) exposure. *Radiation Research.* November 19, 2013;180(6):622-637. doi: 10.1667/RR13148.1.

Beck P, Zechner A, Rollet S, et al. MATSIM: Development of a voxel model of the MATROSHKA astronaut dosimetricphantom. *IEEE Transactions on Nuclear Science.* 2011;58(4):1921-1926. doi: 10.1109/TNS.2011.2157704.

Bilski P, Hajek M, Berger T, Reitz G. Comparison of the response of various TLDs to cosmic radiation and ion beams: Current results of the HAMLET project. *Radiation Measurements*. 2011;46:1680-1685. doi: 10.1016/j.radmeas.2011.03.023.

Petrov VP, Kartashov DA, Akatov YA, Kolomensky AV, Shurshakov VA. Comparison of space radiation doses inside the matroshka-torso phantom installed outside the ISS with the doses in a cosmonaut body in orlan-m spacesuit during EVA. *Acta Astronautica*. 2011;68(9-10):1448-1453. doi: 10.1016/j.actaastro.2010.06.002.

Sihver L, Puchalska M, Sato T, Berger T, Reitz G. Monte Carlo simulations of MATROSHKA experiment outside ISS. *IEEE Aerospace Conference*, Big Sky, MT; 2011.

Durante M, Reitz G, Angerer O. Space radiation research in Europe: Flight experiments and ground-based studies. *Radiation and Environmental Biophysics*. 2010;49(3):295-302. doi: 10.1007/s00411-010-0300-6.

Zhou D, Semones E, O'Sullivan D, et al. Radiation measured for MATROSHKA-1 experiment with passive dosimeters. *Acta Astronautica.* 2010;66(1-2):301-308. doi: 10.1016/l.actaastro.2009.06.014.

Reitz G, Berger T, Bilski P, et al. Astronaut's organ doses inferred from measurements in a human phantom outside the International Space Station. *Radiation Research.* 2009;171(2):225-235. doi: 10.1667/RR1559.1.

Zhou D, O'Sullivan D, Semones E, Zapp EN, Benton ER. Research on sensitivity fading of CR-39 detectors during long time exposure. *Radiation Measurements.* 2009;44(9-10):909-912. doi: 10.1016/j.radmeas.2009.09.004.

Dettmann J, Reitz G, Gianfiglio G. MATROSHKA—The first ESA external payload on the International Space Station. *Acta Astronautica.* 2007;60(1):17-23. doi: 10.1016/ jactaastro.2006.04.018.

Reitz G, Berger T. The MATROSHKA Facility--dose determination during an EVA. *Radiation Protection Dosimetry.* 2006;120(1-4):442-445.

This investigation is complete and all results are published.

Measuring Radiation Hazards in Space (Matroshka-2A)

Research Area: Radiation Impacts on Humans

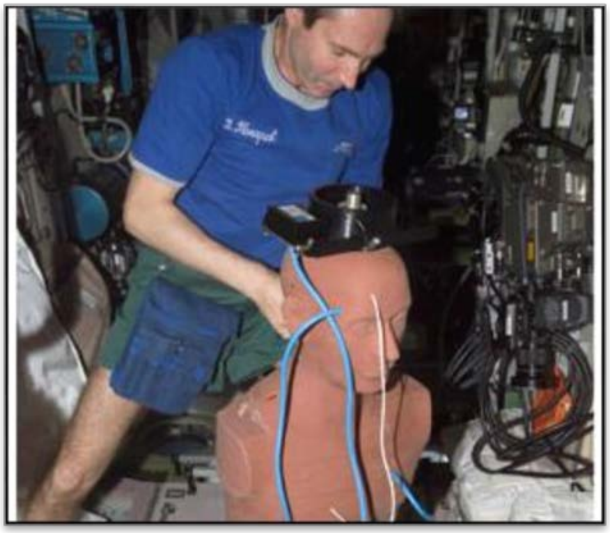
Expedition(s): 12, 13, 14

Principal Investigator(s):

- Günter Reitz, German Aerospace Center, Cologne, Germany
- Thomas Berger, German Aerospace Center, Cologne, Germany
- Rudolf Beaujean, PhD, University of Kiel, Kiel, Germany
- Wolfgang Heinrich, PhD, Universitat GH Siegen, Siegen, Germany
- Marlies Luszik-Bhadra, Physikalisch Technische Bundesanstalt, Braunschweig, Germany
- Michael Scherkenbach (DE), Rheinisch-Westfälische Technische Hochschule Aachen, Aachen, Germany
- Pawel Olko, Institute for Nuclear Physics, Krakow, Poland
- Pawel Bilski, Institute of Nuclear Physics, Krakow, Poland
- Sandor Deme, KFKI Atomic Research Institute, Budapest, Hungary
- Jozsef K. Palfalvi, Atomic Energy Research Institute, Budapest, Hungary
- Epaminondas G. Stassinopoulos, Goddard Space Flight Center, Greenbelt, Maryland
- Jack Miller, Lawrence Berkeley National Laboratory, Berkeley, California
- Cary Zeitlin, Lawrence Berkeley National Laboratory, Berkeley, California
- Francis Cucinotta, PhD, University of Nevada, Las Vegas, Nevada
- Victor M. Petrov, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Matroshka-2A measures the radiation dose distribution of crew members inside the International Space Station (ISS). Matroshka-2A combined with data from Matroshka-1 allows the comparison of skin and depth dose measurements performed with the same facility inside and outside the International Space Station. The results will give the radiation dose distribution inside a human phantom torso for a better correlation between skin and organ dose and for better risk assessment in future long-duration spaceflight.



ISS012E22711 – Cosmonaut Valery I. Tokarev, Expedition 12 flight engineer works with the European Matroshka-R Phantom experiment in the Zvezda Service Module of the International Space Station.

Results

For MTR-2A, the phantom from MTR-1 was used again, but fitted with a fresh set of passive detectors. The data generated with passive thermoluminescence detectors at over 1 600 measurement points in the phantom gave an impressive view of the dose distribution through a human body (see figure). During a spacewalk the skin dose may reach values as high as 2.5 mGy/day (MTR-1), while inside the ISS the skin dose drops down to 160 - 260 µGy/day (MTR-2A), depending on the local shielding conditions. In combination with results from plastic nuclear track detectors, the evaluated dose distributions served as data input to calculate organ dose equivalents and effective doses needed for radiation risk assessment.

Publication(s)

Berger T, Bilski P, Hajek M, Puchalska M, Reitz G. The MATROSHKA experiment: Results and comparison from extravehicular activity (MTR-1) and intravehicular activity (MTR-2A/2B) exposure. *Radiation Research.* November 19, 2013;180(6):622-637. doi: 10.1667/RR13148.1.

Beck P, Zechner A, Rollet S, et al. MATSIM: Development of a voxel model of the MATROSHKA astronaut dosimetric phantom. *IEEE Transactions on Nuclear Science*. 2011;58(4):1921-1926. doi: 10.1109/TNS.2011.2157704.

Reitz G, Berger T, Sundblad P, Dettmann J. Reducing radiation risk in space: The MATROSHKA project. *ESA Bull.* 2010;141:28-36.

This investigation is complete and all results are published.

STUDY OF THE DEPTH DOSE DISTRIBUTION INSIDE A HUMAN PHANTOM USING THE MATROSHKA FACILITY ONBOARD THE RUSSIAN SEGMENT OF THE INTERNATIONAL SPACE STATION (MATROSHKA-2B)

Research Area: Radiation Impacts on Humans
Expedition(s): 16, 17, 18
Principal Investigator(s):

- Günter Reitz, German Aerospace Center, Cologne, Germany
- Thomas Berger, German Aerospace Center, Cologne, Germany
- Rudolf Beaujean, PhD, University of Kiel, Kiel, Germany
- Wolfgang Heinrich, PhD, Universitat GH Siegen, Siegen, Germany
- Marlies Luszik-Bhadra, Physikalisch Technische Bundesanstalt, Braunschweig, Germany
- Michael Scherkenbach (DE), Rheinisch-Westfälische Technische Hochschule Aachen, Aachen, Germany
- Pawel Olko, Institute for Nuclear Physics, Krakow, Poland
- Pawel Bilski, Institute of Nuclear Physics, Krakow, Poland
- Sandor Deme, KFKI Atomic Research Institute, Budapest, Hungary
- Jozsef K. Palfalvi, Atomic Energy Research Institute, Budapest, Hungary
- Epaminondas G. Stassinopoulos, Goddard Space Flight Center, Greenbelt, Maryland
- Jack Miller, Lawrence Berkeley National Laboratory, Berkeley, California
- Cary Zeitlin, Lawrence Berkeley National Laboratory, Berkeley, California
- Francis Cucinotta, PhD, University of Nevada, Las Vegas, Nevada
- Victor M. Petrov, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

Study of the Depth Dose Distribution Inside a Human Phantom Using the Matroshka Facility Onboard the Russian Segment of the International Space Station (Matroshka-2B) is a continuation of Matroshka-2A investigation that studies the radiation dose distribution of crew members inside the International Space Station (ISS). The combined data from all Matroshka investigations allows the comparison of skin and depth dose measurements performed with the same facility inside and outside the ISS. The results will give the radiation dose distribution inside a human phantom torso for a better correlation between skin and organ dose and for better risk assessment in future long duration spaceflight.

Results

For MTR-2B, the phantom from previous Matroshka experiments was used once more, but fitted with a fresh set of passive detectors. The average dose rate recorded in the Zvezda Docking Compartment (MTR-2B) was about 40% lower than the dose rate measured earlier in the Pirs Service Module (MTR-2A). The difference was attributed to higher shielding levels in Zvezda. These findings are in line with additional ISS research.

ISS018E040944

Cosmonaut Yury Lonchakov works with the European Matroshka Phantom experiment in the Zvezda Service Module of the International Space Station. Matroshka, the name for the traditional Russian set of nestling dolls, is an antroph-amorphous model of a human torso designed for radiation studies. NASA image

Publication(s)

Berger T, Bilski P, Hajek M, Puchalska M, Reitz G. The MATROSHKA experiment: Results and comparison from extravehicular activity (MTR-1) and intravehicular activity (MTR-2A/2B) exposure. *Radiation Research.* November 19, 2013;180(6):622-637. doi: 10.1667/RR13148.1.

Beck P, Zechner A, Rollet S, et al. MATSIM: Development of a voxel model of the MATROSHKA astronaut dosimetric phantom. *IEEE Transactions on Nuclear Science.* 2011;58(4):1921-1926. doi: 10.1109/TNS.2011.2157704.

Reitz G, Berger T, Sundblad P, Dettmann J. Reducing radiation risk in space: The MATROSHKA project. *ESA Bull.* 2010;141:28-36.

This investigation is complete and all results are published.

Study of Depth Dose Distribution Inside a Human Phantom using the Matroshka Facility (Matroshka-Kibo)

Research Area: Radiation Impacts on Humans

Expedition(s): 23-26

Principal Investigator(s):

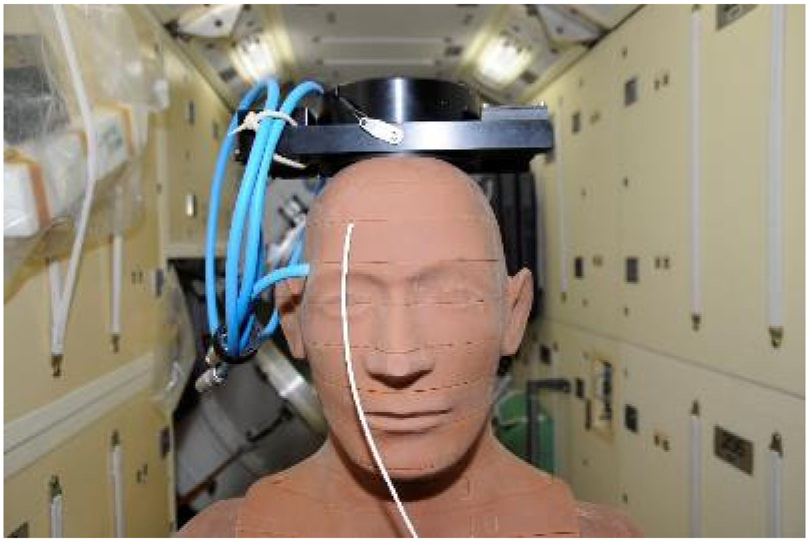
- Günter Reitz, German Aerospace Center, Cologne, Germany
- Rudolf Beaujean, PhD, University of Kiel, Germany
- Wolfgang Heinrich, PhD, Universitat GH Siegen, Germany
- Marlies Luszik-Bhadra, Physikalisch Technische Bundesanstalt, Braunschweig, Germany
- Michael Scherkenbach (DE), Rheinisch-Westfälische Technische Hochschule Aachen, Germany
- Pawel Olko, Institute for Nuclear Physics, Krakow, Poland
- Pawel Bilski, Institute of Nuclear Physics, Krakow, Poland
- Sandor Deme, KFKI Atomic Research Institute, Budapest, Hungary
- Jozsef K. Palfalvi, Atomic Energy Research Institute, Budapest, Hungary
- Epaminondas G. Stassinopoulos, NASA's Goddard Space Flight Center, Greenbelt, Maryland
- Jack Miller, Lawrence Berkeley National Laboratory, Berkeley, California
- Cary Zeitlin, Lawrence Berkeley National Laboratory, Berkeley, California
- Francis Cucinotta, PhD, University of Nevada, Las Vegas, Nevada
- Victor M. Petrov, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Matroshka-Kibo continues to measure the radiation dose distribution of crew members inside the International Space Station (ISS) and specifically in the Japanese Kibo laboratory. Matroshka-Kibo combined with data from Matroshka-2A and -2B allows to spot and to quantify differences in the radiation environment in three crew locations on the ISS (MTR-2A: Pirs, MTR-2B: Zvezda, MTR-Kibo: Kibo).

Results

For Matroshka-Kibo, the phantom from MTR-1/MTR-2A/MTR-2B was used again, but fitted with a fresh set of passive detectors. The passive detectors were installed inside the Matroshka phantom for 10 months between May 2010 and March 2011 with the facility taking measurements from its location within the Japanese Kibo laboratory. Publication of results is currently under preparation.



The Matroshka-KIBO radiation dosimeters stayed from May 2010 until March 2011 inside the Matroshka phantom. During this period, Matroshka was located in the Japanese KIBO laboratory. This photo of Matroshka was taken in the Russian Zarya module were it is stored as of spring 2011. ESA image

This investigation is complete; however additional results are pending publication.

ORGAN DOSE MEASUREMENT USING THE PHANTOM TORSO (TORSO)

Research Area: Radiation Impacts on Humans

Expeditions: 2

Principal Investigator(s):

- Gautam D. Badhwar, PhD, Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Organ Dose Measurement Using the Phantom Torso (Torso) measures the amount of radiation that a human received during an extended spaceflight. The measurements are taken using an anatomical model of a male head and torso that contains different types of radiation sensors. This experiment is important for future human long-duration space exploration.

EARTH BENEFITS

This experiment is teaching scientists more about the use of embedded devices for data collection and how to monitor real-time data. This could prove beneficial to radiation monitoring of commercial airline crews and military flight crews.

ISS002E6080 – The Phantom Torso, seen here in the Human Research Facility (HRF) section of the Destiny/U.S. Laboratory on the International Space Station (ISS), is designed to measure the effects of radiation on organs inside the body by using a torso that is similar to those used to train radiologists on Earth. The torso is equivalent in height and weight to an average adult male.

SPACE BENEFITS

The Torso experiment helps scientists more accurately predict the radiation exposure astronauts will experience inside their bodies, especially to critical blood-forming organs. No previous experiment has had the capacity to measure radiation doses in multiple, discrete locations in the body. By performing this experiment aboard the International Space Station (ISS), scientists also learn how long human beings can remain in space before the body absorbs dangerous levels of radiation. The experiment may lead to protective procedures to safely prolong human exposure to radiation.

RESULTS

Torso results were combined with results from various experiments on previous missions to validate NASA's organ dose database for astronauts. Preliminary results suggest that organ dose and dose equivalent can be projected to a +/- 25% accuracy using a combination of dosimetry and radiation transport models. This accuracy is a great improvement relative to the current accuracy of organ-specific cancer risk projections. Further analyses and incorporation of these radiation results into operational planning for exploration is ongoing. Overall, the dose rates measured in Torso are in good general agreement with other measured values and with the models used to predict these values. So far, the largest difference observed between measured data and the simulations is 15%. In addition, a model that considers orbital altitude, attitude, and solar cycle emissions agrees within 25% of the measured data. It is determined that the majority of radiation energy deposited in human tissues (about 80%) was due to galactic cosmic radiation. This is because of spacecraft material providing effective reduction from the protons trapped in the Earth's magnetic field. Finally, this experiment indicated that the contribution to both skin and organ doses from secondary neutrons is not negligible. Radiation assessments from chromosomal damage in lymphocyte cells of 19 ISS crew members were conducted as a follow-up study. These results were compared with space radiation transport models, irradiation of pre-flight blood samples, and results from the phantom torso experiments. The ISS crew members sampled include the earliest missions near the solar maximum, and concluding with Increment 15 astronauts, near the solar minimum. During this timeframe, 67 Solar Particle Events occurred. However, the extended solar maximum (particular to this solar cycle) decreased the galactic cosmic ray levels. Average effective doses for a 6-month stay on the ISS were 72 mSv. At least 80% of the organ radiation exposures come from galactic cosmic rays. Another important result shows that the models are predictive within about 10%. The authors conclude that many uncertainties about space radiation remain - both levels and types of radiation and effects inside the spacecraft. Continued research and analyses are required (Cucinotta 2008).


ISS002E5952 – The Phantom Torso, seen here in the Destiny laboratory on the International Space Station (ISS), is designed to measure the effects of radiation on organs inside the body by using a torso that is similar to those used to train radiologists on Earth. The torso is equivalent in height and weight to an average adult male. It contains radiation detectors that will measure, in real-time, how much radiation the brain, thyroid, stomach, colon, and heart and lung area receive on a daily basis.

PUBLICATION(S)

Cucinotta FA, Kim MY, Willingham V, George KA. Physical and biological organ dosimetry analysis for International Space Station astronauts. *Radiation Research*. July 2008;170(1):127-138. doi: 10.1667/RR1330.1.

This investigation is complete and all results are published.

Image Reversal in Space (IRIS)

Research Area: Vision
Expedition(s): 19 and 20
Principal Investigator(s):
- Gilles Clement, PhD, International Space University, Strasbourg, France

Research Objectives

Image Reversal in Space (IRIS) is an educational experiment developed by students at the International Space University (Strasbourg, France) to study the effects of microgravity on perception of 2-dimensional (2-D) and 3-dimensional (3-D) objects. IRIS will measure how astronauts respond to a series of optical illusions, and compare their image recognition time with data recorded while the crew was on Earth.

Earth Benefits

The experiment and its software were designed by a multidisciplinary group of students, giving them valuable experience in developing science destined for space implementation. Furthermore, results from IRIS experiments that will allow the development of improved training methods, countermeasures and treatments for adaptation to changes in gravity will also find other applications in medicine and biotechnology.

ISS020E017981 – Canadian Space Agency astronaut Dr. Robert "Bob" Thirsk, Expedition 20 flight engineer, sets up the A31p for the Iris experiment in the Destiny Laboratory aboard the International Space Station.

Space Benefits

The IRIS payload supports the objective to explore and support decisions related to human exploration as well as promoting international participation in exploration. It also supports International Space Station (ISS) activities in terms of supporting space exploration goals with an emphasis on understanding how the space environment affects astronauts' health, capabilities, and developing countermeasures. The results of this research will help minimize risks and optimize crew performance during transit and planetary operations.

Results

Preliminary results obtained with 1 crew member aboard the ISS suggest that the frequency of percept reversal decreases in-flight relative to pre-flight. New experiments will include 2-D figures that should not be affected by 0 g. For all phases of the spaceflight, we will determine the time for first reversal and the number of perceived reversals of 3-D and 2-D reversible figures, as well as the probability for seeing each view/reversal within a figure to confirm that gravity affects interpretation of depth-based stimuli and interferes with visual perception stability.

PUBLICATION(S)

Clement G, Ngo-Anh JT. Space Physiology II: Adaptation of the central nervous system to space flight - Past, current, and future studies. *European Journal of Applied Physiology.* July 2013;113(7):1655-1672. doi: 1007/s00421-012-2509-3.

Clement G, Skinner A, Richard G, Lathan CE. Geometric illusions in astronauts during long-duration spaceflight. *NeuroReport.* 2012;23(15):894-899. doi: 10.1097/WNR.0b013e3283594705.

Merali T, Demel M, Steinberg M, Thirsk RB, Clement G. Image reversal in space. Student International Space Station Education. *Canadian Space Summit*, Kingston, Canada; November 22, 2009.

Merali T, Demel M, Thirsk RB, Clement G. Image reversal in space. Student International Space Station Experiment. *60th International Astronautical Congress*, Daejeon, Republic of Korea; October 14, 2009.

Urbina D, Demel M, Kohl S, Merali T, Steinberg M, Thirsk RB, Clement G. IRIS experiment. *Columbia Geomatics Week*, Bogota, Columbia; October 29, 2009.

This investigation is complete; however additional results are pending publication.

Study of Cosmonauts' Capabilities when Performing Visual/Instrument Observations and Test Tasks during the First Orbits and Days of Flight (Vitok-2), Four Investigations

Research Area: Vision
Expedition(s): 1
Principal Investigator(s):
- Valery V. Morgun, PhD, Yu.A. Gagarin Research and Test Center for Cosmonaut Training, Star City, Moscow region, Russia

Research Objectives

The Study of Cosmonauts' Capabilities when Performing Visual/Instrument Observations and Test Tasks during the First Orbits and Days of Flight (Vitok-2) consists of 4 distinct investigations which obtained experimental data on International Space Station (ISS) crew members' capabilities when performing visual/instrument observations and test tasks during the first orbits and days of flight, when acute adaptation to spaceflight occurs. The most serious effect is weightlessness, accompanied by space motion sickness.

Russian cosmonaut Yu.M. Baturin performs the Vitok-2 experiment aboard the International Space Station. Roscosmos image.

The goal of the Vitok-2 experiment is to obtain experimental data on the capacities of cosmonauts to conduct visual/ instrument observations and test tasks on the first orbits and days of flight during acute adaptation to spaceflight factors. On the first orbits and days of spaceflight, a crewmember works under conditions of acute adaptation to spaceflight factors, the most serious of which is weightlessness and its accompanying space motion sickness. At this time, flow of information a crewmember receives about the surrounding environment drops sharply, which is related to the distortion of the majority of perception by mechanoreceptors about the position of the body and its individual parts in weightlessness and structural limitations on position and locomotion activity. Under these conditions, the flow of information received through the visual analyzer significantly increases for the crewmember. It has been established that in weightlessness, no indicators from sensory organs, except vision, are providing reliable information for spatial orientation. The majority of tasks performed by crewmembers in flight involve the participation of vision, including: controlling the position of a manned space vehicle, monitoring instrument readings, looking for, identifying, and recognizing various objects, etc. Therefore it is deemed that the visual analyzer provides the crewmember with up to 90% of information. The Vitok-2 experiment is the first attempt made to comprehensively assess the impact of spaceflight factors on the types of crewmember work skills enumerated above using cutting-edge equipment and procedures.

1. Виток-2 [Vitok-2(Z)] – Using a personal computer, dynamics of the functional state of the visual system is assessed, as are the functional psycho-physiological capabilities of operator higher mental functions and performance.
2. Виток-2Н [Vitok-2(N)] – Using a video camera and voice recorder, ground observation objects are noted and described (verbally).
3. Виток-2(А) [Vitok-2(A)] – One of 10 space objects whose image is presented on a PC screen is identified and experiment results recorded on the PC.
4. Виток-2(М) [Vitok-2(M)] – Manual final approach is performed during the simulated motion of a manned transport vehicle and an orbital station on a PC.

Earth Benefits

The effects of space conditions on a person are the focus in this experiment. New knowledge is expected to be the major benefit of this investigation

Space Benefits

Vitok-2 experimental research characterizes crew members' physiological condition, their vision organs, and their ability to perform skill tasks aboard manned spacecraft, beginning with the first orbits and days of spaceflight during the period of acute adaptation to spaceflight factors. The data obtained in the experiment make it possible to update crew training methods.

Results

Виток-2 [Vitok-2(3)]. In the Виток-2 [Vitok-2(3)] experiment, for the first time both the functional state of the visual system and the interaction among different levels of its organization were studied in an integrated system. Analysis of the results indicates that there are some changes in the level of visual analysis function of a human operator in spaceflight compared to the pre- and post-flight periods. Results of the performed tests demonstrate sufficiently high stability of performance and resistance when exposed to negative work factors during short-term spaceflight, using visual acuity as an integrated parameter of the visual system.

Vitok-2(N). In this experiment, the operator used "free search," in other words was not presented with specific objects on the Earth's surface for identification that are supposed to appear in the operator's field of view at a given time during Soyuz vehicle flight. The reliability of observation results was assessed by combining them with analogous results from previous studies, a coordinate reference point along the flight path in the observation area, analysis of video footage shot during the space experiment, and operator narration on a dictaphone.

Vitok-2(A). The results of the Vitok-2(A) experiment indicate that the Vitok-2(A) software enables the necessary experimental data to be obtained in order to determine the capabilities of the crewmember/operator to perform a task of identifying a space object in the first orbits and days of vehicle spaceflight.

Vitok-2(M). The results obtained from the studies conducted make it possible to conclude that with an adaptive system of operator selection to perform tasks in the first days of flight, sufficient training with the crewmember reaching the necessary skill level, complex dynamic tasks can be performed on a vehicle during the acute adaptation period to spaceflight factors. The results of the Vitok-2(M) study indicate that in operators there is no failure of elements of operator skill, and they have the capacity to reliably perform dynamic vehicle control tasks beginning with the first orbits and days of spaceflight.

The recording of the best indicators of all functional and physiological characteristics of crew members during orbits 8-9 of a flight made it possible to conclude that the vision system achieved the optimal level of adaptation to spaceflight factors within this period.

The data obtained showed that the vision system's resolving power and the visual acuity being assessed had a high level of stability and resistance to the effects of spaceflight and the effect of the particulars of visual and skill activity of the crew member. Analysis of a crew member ability to identify space objects (simulation on the PC screen) showed that:

- A crew member is capable, during the first orbits and days of spaceflight, of confidently identifying space objects having angular dimensions of about 1°.
- The average time to identify space objects and the number of erroneous identifications during the first orbits of flight increases by 10-27% and reaches baseline levels during the second day of flight (orbit 19) in the manned spacecraft.
- The number of unidentified objects during flight corresponds to the baseline values obtained during the training process.
- A crew member with a low (imperceptible) level of space motion sickness is able to perform visual/instrument observations immediately after a manned spacecraft is inserted into satellite orbit around the Earth.

These investigations are complete; however no publications are expected.

PHYSICAL SCIENCES

Much of our understanding of physics is based on the inclusion of gravity in fundamental equations. Using a laboratory environment found nowhere else, the U.S. Destiny laboratory on space station provides the only place to study long-term physical effects in the absence of gravity, without the complications of gravity-related processes such as convection and sedimentation. This unique microgravity environment allows different physical properties to dominate systems, and these have been harnessed for a wide variety of investigations in the physical sciences.

Burning and Suppression of Solids (BASS)

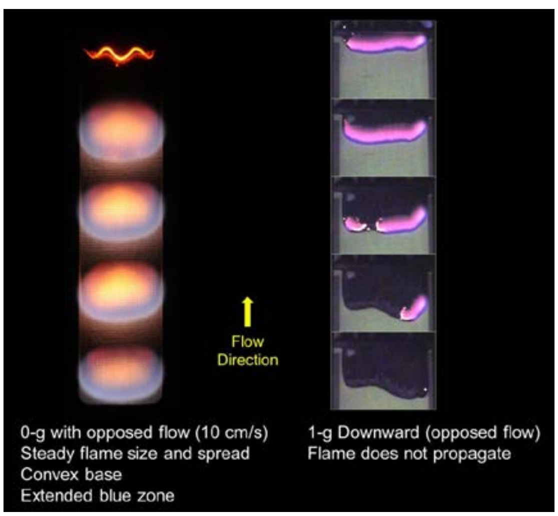
Research Area: Combustion Science
Expedition(s): 29-ongoing
Principal Investigator(s):
- Paul V. Ferkul, PhD, National Center for Space Exploration Research, Cleveland, Ohio

Research Objectives

The Burning and Suppression of Solids (BASS) investigation examines the burning and extinction characteristics of a wide variety of fuel samples in microgravity. BASS experiment will guide strategies for extinguishing accidental fires in microgravity. BASS results contribute to the combustion computational models used in the design of fire detection and suppression systems in microgravity and on Earth.

Earth Benefits

BASS results provide essential guidance to ground-based microgravity combustion research efforts. Detailed combustion models are validated using the simpler flow environment afforded by tests in microgravity. Once validated, they can be used to build more complex combustion models needed to capture the important details of flames burning in normal gravity. These models have wide applicability to the general understanding of many terrestrial combustion problems.



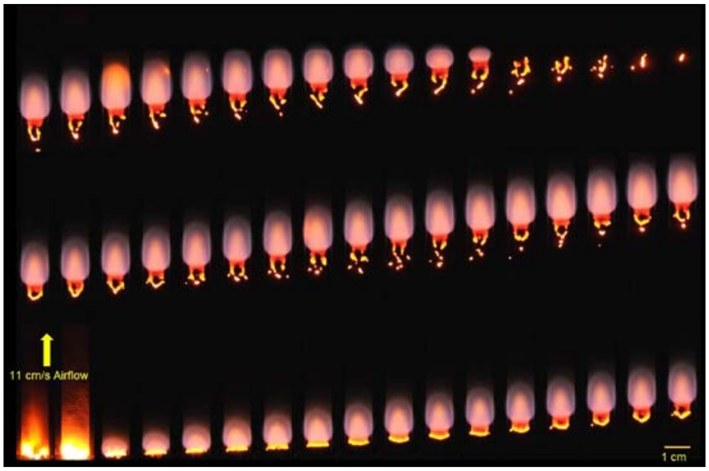
Comparison of 0-g and 1-g flames in opposed flow. Image sequences shows flames spreading from top down. National Center for Space Exploration Research image, Cleveland, Ohio.

Space Benefits

The current NASA spacecraft materials selection is based on a standard test method that segregates material based on 1-g behavior without consideration of low-gravity effects. A critical element of this understanding is the radiative heat emission from the flame. These results are used in first-order models and predictions of heat release in spacecraft fires and as a means to extend heat release data from tests like the NASA cone calorimeter test to a performance-based material selection process. Using nitrogen as a flame suppressant in microgravity provides a direct link to current and planned extinguishment techniques.

Results

Flat cotton-fiberglass fabric samples were burned in long-duration microgravity tests aboard the International Space Station (ISS). The samples were burned with airflow in the same direction and in the opposite direction of the flame. The custom-made fabric performed very well, with none of the complications caused by the burnout of ordinary cellulosic fuel samples like paper. The main influencing factor was airflow speed and it had a major effect on the flame



Digital still images for 1-cm-wide fuel (cotton-fiberglass fabric) with concurrent air flow = 11 cm/s. Images are taken every 1.125 sec (starting at bottom and moving from left to right). The flame reaches steady state after about 10 seconds. National Center for Space Exploration Research image, Cleveland, Ohio.

as suggested in earlier studies. This is the first time that detailed transient flame growth data was obtained in purely forced flows in microgravity for a thin fuel material with uniform burnout characteristics. In addition, by decreasing same-direction airflow speed to a very low value (around 1 cm/s), quenching extinction was observed providing a direct verification of the theoretically predicted U-shaped flammability boundary for a thin fuel. For the opposed flow configuration, the flame quickly reached a steady spread for each flow speed, and the spread rate was fastest at an intermediate value of flow speed. These tests show the enhanced flammability in microgravity for this geometry, since, in normal gravity air, a flame self-extinguishes in the opposed-flow geometry (downward flame spread). For the concurrent-flow configuration, a limiting length and steady spread rate were obtained only in low-flow speeds. However, flame base spread rate was constant and increased linearly with increasing flow for all tests. The valuable results from these long-duration experiments validate a number of theoretical predictions and also provide the data for a transient flame growth model under development (Ferkul 2013).

PUBLICATION(S)

Olson SL, Ferkul PV. Microgravity flammability of PMMA rods in concurrent flow. *9th U.S. National Combustion Meeting*, Cincinnati, Ohio; May 17-20, 2015:11.

Zhao X, T'ien JS, Ferkul PV, Olson SL. Concurrent flame growth, spread, and extinction over composite fabric samples in low speed purely forced flow in microgravity. *9th U.S. National Combustion Meeting*, Cincinnati, Ohio; May 17-20, 2015:9.

Ferkul PV, Olson SL, Johnston MC, T'ien JS. Flammability aspects of fabric in opposed and concurrent air flow in microgravity. Paper # 070HE-0218 presented at the *8th U. S. National Combustion Meeting* May 19-22, 2013.

This investigation is ongoing and additional results are pending publication.

COMBUSTION SYNTHESIS UNDER MICROGRAVITY CONDITIONS (COSMIC)

Research Area: Combustion Science
Expedition(s): 5
Principal Investigator(s): ● Ludo Froyen, Katholike Universiteit, Leuven, Belgium

RESEARCH OBJECTIVES

Snapshots of a combustion synthesis process, including the ignition stage and the movement of the combustion wave through the formed pellet. Institute of Structural Macrokinetics, Russian Academy of Sciences image.

COmbustion Synthesis Under MIcrogravity Conditions (COSMIC) studies the microstructure formation of aluminum-titanium-boron (Ti-Al-B) compressed powder samples during self-propagating high-temperature combustion synthesis (SHS). Within the combustion zone, a number of gravity-dependent phenomena occur including the convection of molten components, buoyancy of inert solid particles, droplet coalescence, and densification of liquid products. Under certain conditions, gravity-dependent secondary processes may also occur in the heat-affected zone several minutes after combustion.

RESULTS

COSMIC focused on the synthesis of intermetallic matrix composites (IMCs) based on the Al-Ti-B system. Depending on the composition, different intermetallic compounds (TiAl and $TiAl_3$) can be formed as matrix phase while TiB_2 represents the reinforcing particulate phase. During the International Space Station mission, all 6 sample reactors with a relatively high “green,” or unreacted, density of 65% theoretical density (TD) were successfully processed. It was concluded that reaction depths increased as the molar ratio of intermetallic component (Ti-Al) over the boride component (Ti-B) was increased. X-ray analyses showed that in some cases, the samples consisted of a reacted (liquefied) zone and a sintered (charred but not molten) part. Combustion front propagated relatively slower as the amount of aluminum in the mixture increases. This result confirmed the corresponding decrease in self-generated heat and system reactivity relative to the higher aluminum content in the mixture.

PUBLICATION(S)

Orru R, Licheri R, Locci A.M, et al. Self-propagating combustion synthesis of intermetallic matrix composites in the ISS. *Microgravity Science and Technology*. 2007;19(5-6):85-89. doi: 10.1007/BF02919459.

This investigation is complete and all results are published.

Flame Extinguishment Experiment (FLEX)

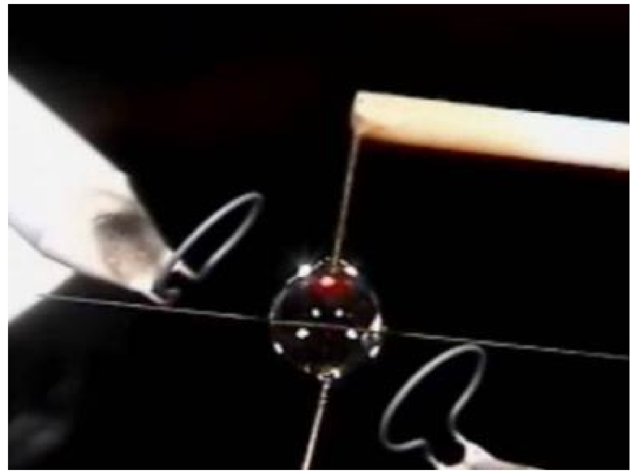
Research Area: Combustion Science

Expedition(s): 18-30

Principal Investigator(s):
- Forman A. Williams, PhD, University of California, San Diego, La Jolla, California

Research Objectives

The Flame Extinguishment Experiment (FLEX) examines the effectiveness of fire suppressants in microgravity and quantifies the effect of different possible crew exploration atmospheres on fire suppression. The goal of this research is to provide definition and direction for large-scale fire suppression tests and to select the fire suppressant for next-generation crew exploration vehicles.



ISS024M041721519 – In this NASA video capture, a fuel droplet is dispensed on positioning wire prior to being set aflame by ring-wire igniters during Flame Extinguishment Experiments inside the Multi-user Drop Combustion Apparatus.

Earth Benefits

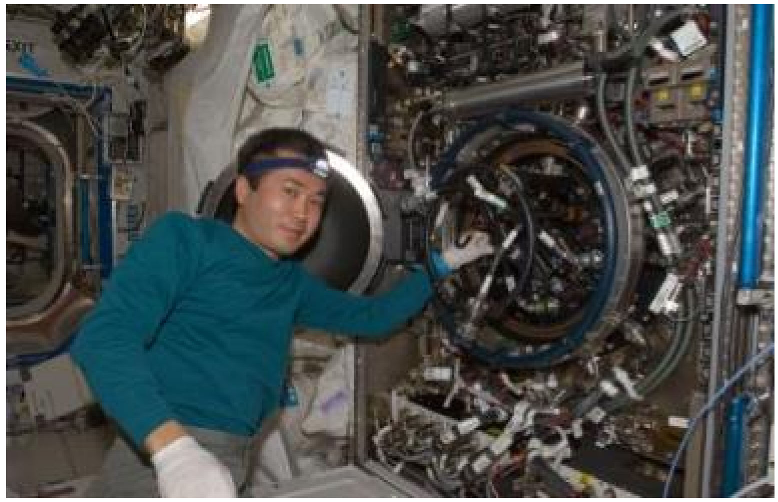
FLEX will help us understand combustion-generated pollution and address fire hazards associated with using liquid combustibles on Earth.

Space Benefits

FLEX will help us develop more efficient energy production and propulsion systems on Earth and in space.

Results

Hot gases do not rise in microgravity, so an entirely different process called molecular diffusion drives flame behavior. So far, researchers have seen some unexpected phenomena from FLEX results. The most surprising discovery is the apparent continuous “burning” of heptane droplets after flame extinction under certain conditions. First, the droplet undergoes normal transient (short-lived) burning with a visible flame surrounding the droplet and extinguishes at a relatively large droplet size. This event is followed by continuous, rapid, almost steady vaporization of the droplet without the visible flame, which ends abruptly at a point called “cool-flame extinction,” leaving behind a smaller droplet. It then either experiences normal evaporation in the surrounding hot environment or grows slightly through condensation of the vapor in the cloud that forms upon extinction or through migration of the vapor-cloud particles to the droplet surface. This behavior is not explained by conventional theories of droplet combustion and is hypothesized as a low-temperature chemical reaction (cool flame) that continues after the 'hot' flame extinction. Cool flames typically occur in premixed systems (this is a diffusion flame), are transient (this is quasi-steady), and lead to a hot-flame ignition (this is a hot-flame leading to a cool flame that extinguishes), which is a very unique observation with very significant theoretical and practical implications.


ISS019E015912 – Japan Aerospace Exploration Agency astronaut Koichi Wakata, Expedition 19 flight engineer, works on the Combustion Integrated Rack Multi-user Drop Combustion Apparatus.

Cool flames usually occur in premixed fuel systems where they are known to spread and eventually lead to ignition that establishes hot-flame combustion, generating ignition pulses commonly associated with engine-knocks in automobiles. Also, flames in space burn with a lower temperature, at a slower rate, and with less oxygen than in normal gravity. This means that materials used to extinguish fires in microgravity must be present in higher concentrations. Through microgravity flame investigations scientists hope to gain a better knowledge of droplet burning, improved spacecraft fire safety, and ideas for more efficient utilization of liquid fuels on Earth (Nayagam 2012).

PUBLICATION(S)

Farouk TI, Hicks MC, Dryer FL. Multistage oscillatory "Cool Flame" behavior for isolated alkane droplet combustion in elevated pressure microgravity condition. *Proceedings of the Combustion Institute*. 2015;35:1701-1708. doi: 10.1016/j.proci.2014.06.015.

Shaw BD, Vang CL. Oxygen Lewis number effects on reduced gravity combustion of methanol and n-heptane droplets. *Combustion Science and Technology*. 2016;188(1):150716065835002. doi: 10.1080/00102202.2015.1072176.

Dietrich DL, Nayagam V, Hicks MC, et al. Droplet combustion experiments aboard the International Space Station. *Microgravity Science and Technology*. October 2014;26:65-76. doi: 10.1007/s12217-014-9372-2.

Liu YC, Xu Y, Avedisian CT, Hicks MC. The effect of support fibers on micro-convection in droplet combustion experiments. *Proceedings of the Combustion Institute*. August 2014;35(2):1709-1716 .

Paczko G, Peters N, Seshadri K, Williams FA. The role of cool-flame chemistry in quasi-steady combustion and extinction of n-heptane droplets. *Combustion Theory and Modeling*. July 24, 2014;18(4-5):515-531. doi: 10.1080/13647830.2014.934296.

Shaw BD. ISS droplet combustion experiments - Uncertainties in droplet sizes and burning rates. *Microgravity Science and Technology*. June 19, 2014;26:89-99. doi: 10.1007/s12217-014-9377-x.

Nayagam V, Dietrich DL, Hicks MC, Williams FA. Methanol droplet combustion in oxygen-inert environments in microgravity. *8th U.S. National Combustion Meeting*, Park City, Utah; May 19-22, 2013; 070HE-0303:11.

Nayagam V, Dietrich DL, Ferkul PV, Hicks MC, Williams FA. Can cool flames support quasi-steady alkane droplet burning? *Combustion and Flame*. December 2012;159(12):3583-3588. doi: 10.1016 /j. combustflame. 2012.07.012.

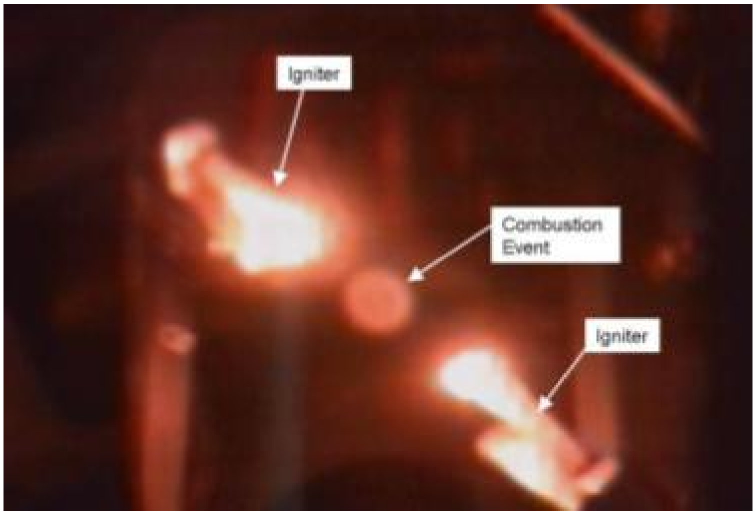
This investigation is complete and all results are published.

Flame Extinguishment Experiment – 2 (FLEX-2)

Research Area: Combustion Science
Expedition(s): 21-ongoing
Principal Investigator(s):
- Forman A. Williams, PhD, University of California, San Diego, La Jolla, California

Research Objectives

Flame Extinguishment Experiment-2 (FLEX-2) is the second investigation on the International Space Station (ISS) that uses small droplets of fuel to study the special burning characteristics of fire in space. FLEX-2 studies the rate and manner in which fuel is burned, the conditions that are necessary for soot to form, and the way in which a mixture of fuels evaporate before burning. The results from FLEX-2 will help scientists better understand how fire behaves in space. It will also provide important information that will be useful in increasing the fuel efficiency of engines using liquid fuels.



Video screen shot of FLEX Ignition 1 on March 5, 2009 (GMT 64/17:21). Beginning of combustion event in cabin air. NASA image.

Earth Benefits

FLEX-2 helps us understand and deal with combustion generated pollution, and addresses fire hazards associated with using liquid combustibles on Earth.

Space Benefits

FLEX-2 results will help in fire safety designs for future space exploration vehicles.

Results

FLEX-2 data collection is ongoing; results will be published following data analysis.

This investigation is ongoing and additional results are pending publication.

Smoke and Aerosol Measurement Experiment (SAME)

Research Area: Combustion Science
Expedition(s): 15 and 23/24
Principal Investigator(s):
- David L. Urban, PhD, NASA's Glenn Research Center, Cleveland, Ohio

Research Objectives

The Smoke and Aerosol Measurement Experiment (SAME) measures smoke properties, or particle size distribution, of typical particles from spacecraft fire smokes to provide data to support requirements for smoke detection in space and identify ways to improve smoke detectors on future spacecraft.

A candle flame in Earth's gravity (left) and microgravity (right) showing the difference in the processes of combustion in microgravity. NASA image.

Earth Benefits

The smoke detectors developed from the results of SAME can also be useful in other extreme environments on Earth, such as submarines or underwater laboratories. Accurate detection of smoke in these environments can save lives.

Space Benefits

The SAME investigation will provide technology for an advanced fire detector for future spacecraft that will be used for long-duration missions. SAME will provide quantitative data on the sensitivity of these detectors to reduced gravity smokes that will allow evaluation of the adequacy of these existing technologies using relevant data. The current Fire Prevention, Detection, and Suppression (FPDS) program plan allows for the re-evaluation of future sensor technology to allow new technology and capability to be utilized. The results from SAME are needed to provide the reduced gravity baseline data against which future detection technology developments can be evaluated.

Results

Overall, 30 samples were tested comprising of 6 samples each of 5 different materials: Teflon™, Kapton™, silicone rubber, cellulose, and dibutyl-phthalate (a chemical used to make flexible plastic) deposited on a porous wick were tested for SAME at different airflow rates, heating temperatures, and smoke aging durations (Urban 2008).

Smoke properties from different materials were determined using detectors to measure different particulate sizes and their relative abundances in order to describe the overall smoke distribution. A substantial portion of the aerosol mass is in particles that are larger than 1 micron. Teflon smoke is comprised primarily of particles having diameters less than 1 um. The effect of aging is consistent with particle coagulation with limited wall loss; the overall number count decreases substantially while the mass concentrations remain relatively steady. This is reasonable given the broader size distribution for silicone smoke containing significant numbers of both large and small particles. Although the arithmetic mean diameters are all in the 100 to 200 nanometer (nm) range, interpreting particle sizes by only 1 statistic can be deceptive due to the nature of the particle size distribution. In general, since the mass increases with the cube of the diameter, the larger particles do not affect the arithmetic mean diameter (AMD) as much as they affect the light scattering signal that corresponds with the particle mass. Consequently, although the AMD for silicone rubber is 227 nm, almost half the particle mass is larger than 1000 nm. The lamp wick showed similar behavior in the experiment (Urban 2009).

ISS015E26265 – View of Smoke and Aerosol Measurement Experiment (SAME) hardware in the Microgravity Science Glovebox (MSG) in the US Laboratory/Destiny. SAME aims to test the performance of ionization smoke detectors and evaluate the performance of the photoelectric smoke detectors.

All samples produced significant numbers of sub-micron particulate that are better detected using an ionization smoke detector, however a light scattering detector would perform very well for most of the cases. Depending on the conditions, results suggest broader smoke particulate size distributions can be produced from pre-fire overheat events, thus detection methods that can measure a wider spectrum of particulate size might show more successful and reliable detection. Spacecraft and associated missions outside of low-Earth orbit will require increased reliability of fire detection systems in addition to robust false alarm resistance. Given the constrained space on any spacecraft, the target for the fire detection system is necessarily the early phase and not established flaming fires; consequently, the primary target for detection is the pre-fire heating products and not the soot and ash. This research will help to improve design of future detectors (Urban 2009).

Publication(s)

Mulholland G, Meyer M, Urban DL, et al. Pyrolysis smoke generated under low-gravity conditions. *Aerosol Science and Technology*. March 6, 2015;49:310-321. doi: 10.1080/02786826.2015.1025125.

Urban DL, Ruff GA, Mulholland G, Cleary T, Yang J, Yuan Z. Measurement of smoke particle size under low-gravity conditions. *SAE International Journal of Aerospace*. 2009;1(1):317-324. doi: 10.4271/2008-01-2089.

Urban DL, Ruff GA, Sheredy WA, et al. Properties of smoke from overheated spacecraft materials in low-gravity. *47th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; January 5-8, 2009.

Urban DL, Ruff GA, Brooker JE, et al. Spacecraft fire detection: Smoke properties and transport in low-gravity. *46th Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2008.

This investigation is complete and all results are published.

Structure and Liftoff In Combustion Experiment (SLICE)

Research Area: Combustion Science
Expedition(s): 27-30
Principal Investigator(s):
- Marshall B. Long, PhD, Yale University, New Haven, Connecticut

Research Objectives

The Structure and Liftoff in Combustion Experiment (SLICE) investigates the nature of flames in microgravity. The results from these experiments could lead to improved fuel efficiency and reduce pollutant emissions in practical combustion on Earth.

Earth Benefits

SLICE enables improvements in the design of practical combustion devices such as engines and furnaces. The improved design capability leads to reduced time and cost for the development of new products.

Space Benefits

SLICE findings could possibly aid the development of future space-based combustion devices such as solid waste processing for example.

Results

Once data analysis of the SLICE investigation is complete, results will be published.

The lifted nature of the flames can be discerned from the outward flare of the flame base in the example images below (which are not at the same scale) and the distance from the nozzle tip (which is not visible). NASA Glenn Research Center image.

Publication(s)

Cao S, Ma B, Bennett BV, et al. A computational and experimental study of coflow laminar methane/air diffusion flames: Effects of fuel dilution, inlet velocity, and gravity. *Proceedings of the Combustion Institute*. 2015;35:897-903. doi: 10.1016/j.proci.2014.05.138.

Ma B, Cao S, Giassi D, et al. An experimental and computational study of soot formation in a coflow jet flame under microgravity and normal gravity. *Proceedings of the Combustion Institute*. June 2014;35(1):839-846. doi: 10.1016/j.proci.2014.05.064.

This investigation is complete; however additional results are pending publication.

Smoke Point In Co-flow Experiment (SPICE)

Research Area: Combustion Science
Expedition(s): 18-20
Principal Investigator(s):
- David L. Urban, PhD, NASA's Glenn Research Center, Cleveland, Ohio

Research Objectives

The Smoke Point In Co-flow Experiment (SPICE) determines the point at which gas-jet flames (similar to a butane-lighter flame) begin to emit soot (dark carbonaceous particulate formed inside the flame) in microgravity. Studying soot-emitting flames is important in understanding the ability of fire to spread and for the control of soot in practical combustion systems space.

Earth Benefits

Smoke-point phenomena is a classical metric in the understanding of the heat release and spread rate of fires. It is commonly used in fire modeling on Earth and to understand the soot growth and emission by flames. The dominant characteristics of many flames of practical interest are non-buoyant. SPICE seeks to extend our understanding by looking at the interaction of ambient flow with the smoke point, enabling us to better predict heat release from non-buoyant flames in practical combustors (eg jet engines and furnaces).

Space Benefits

Current NASA spacecraft materials selection stems from a simplified test method that segregates material based upon behavior on Earth without real consideration of microgravity effects. A critical element of this understanding is the radiative heat emission from the flame. This heat emission is strongly influenced by the extent of soot formation.

ISS018E035923 – View of the Smoke Point In Co-flow Experiment during Expedition 18.

Improved understanding of soot formation and thereby the heat release from microgravity fires will allow more complete and effective utilization of the flammability test results. These results can be used to create models of heat release during fires to learn the best methods of smoke control in microgravity.

Results

SPICE successfully completed over 250 combustion tests with gaseous fuel mixtures of ethane, ethylene, propane, propylene, and propylene with nitrogen. More than 70 smoke points were found, and these are helping researchers understand the effects of microgravity and co-flowing (flowing in the same direction as fuel gas flow) air speed on smoke points.

The smoke point measurements yielded estimates of soot-forming conditions and flame dimensions. Flames of propylene and propylene mixtures were generally more luminous than the others, attributed to increased soot volume fractions. Periodic flame motion was observed in some flames, especially those with high air velocity, large burners, and long flames, and is attributed to unsteady co-flow air stream causing slight increase in the uncertainties in smoke points under these conditions. Smoke points for propane and ethylene were generally identified by the onset of gradual dimming, reddening, and rounding of the luminous flame tip. The brightest flames, generally for propylene and propylene mixtures, normally did not display significant dimming and reddening near their tips except when much longer than their smoke points. Smoke points for these flames were identified by the rapid transition to open-tipped flames. Open-tipped flames are common in both normal gravity and microgravity when smoke points are far exceeded and are generally associated with local flame extinguishment along the centerline and soot emission in an annular shell. For conditions sufficiently above the smoke points, a glowing stream of particles could be seen leaving the flame. Smoke-point lengths in co-flow generally increase with decreasing burner diameter and increasing co-flow velocity in agreement with normal-gravity results. This is expected because a decrease in burner—or an increase in co-flow velocity—decreases the residence time (the time a fuel molecule takes to pass through the entire flame) available for soot formation. It also decreases the radiative heat loss fraction, making the flame shorter and narrower.

ISS018E030371 – View of the flame ignited in the SPICE (Smoke Point In Co-flow Experiment) payload performed in the MSG and controlled by its A31p with SPICE microdrives. Photo was taken by Expedition 18 crew.

Microgravity smoke points are of interest to spacecraft fire safety. Microgravity allows improved control over residence time and provides better understanding of the different mechanisms responsible for smoke points in normal gravity and microgravity (Dotson 2011).

Publication(s)

Dotson KT, Sunderland PB, Yuan Z, Urban DL. Laminar smoke points of co-flowing flames in microgravity. *Fire Safety Journal*. November 2011; 46(8):550-555. doi: 10.1016/j.firesaf.2011.08.002.

Dotson KT, Sunderland PB, Yuan Z, Urban DL. Laminar smoke points in co-flow measured aboard the International Space Station. *48th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; 2010.

Dotson KT. Smoke points of microgravity and normal gravity co-flow diffusion flames. Master's Thesis, University of Maryland, College Park, MD; 2009.

This investigation is complete and all results are published.

BINARY COLLOIDAL ALLOY TEST - 3 (BCAT-3), THREE INVESTIGATIONS

Research Area: Complex Fluids

Expedition(s): 8-13, 16-20, 27-ongoing

Principal Investigator(s):

- Peter N. Pusey, PhD and Andrew B. Schofield, PhD, University of Edinburgh, Edinburgh, United Kingdom
- Arjun Yodh, PhD and Jian Zhang, University of Pennsylvania, University Park, Pennsylvania
- David A. Weitz, PhD and Peter J. Lu, PhD, Harvard University, Cambridge, Massachusets

RESEARCH OBJECTIVES

The Binary Colloidal Alloy Test-3 (BCAT-3) hardware supports 3 investigations in which International Space Station (ISS) crews photographed samples of colloidal particles (tiny nanoscale spheres suspended in liquid) to document liquid/gas phase changes, growth of binary crystals, and the formation of colloidal crystals confined to a surface. Colloids are small enough that in a microgravity environment without sedimentation and convection, they behave much as atoms. By controlling aspects of colloidal mixtures, they can be used to model all sorts of phenomena.

EARTH BENEFITS

ISS008-E-20613 (April 5, 2004) – Astronaut C. Michael Foale, Expedition 8 commander and NASA International Space Station science officer, works with a Slow Growth Sample Module for the Binary Colloidal Alloy Test-3 experiment.

The binary alloy (BCAT-3-BA) study provides information that may allow improvement of fiber optics and allow development of new computers that process data with light instead of electricity. The surface crystallization (BCAT-3-SC) investigation provides information that may identify the use of fields and gradients to control order in self-assembled colloidal systems and microemulsions for advanced materials. The critical point (BCAT-3-4-CP) investigation has numerous applications in a wide variety of fields. Product shelf-life may be improved with a better understanding of colloidal suspensions and have an enormous commercial impact.

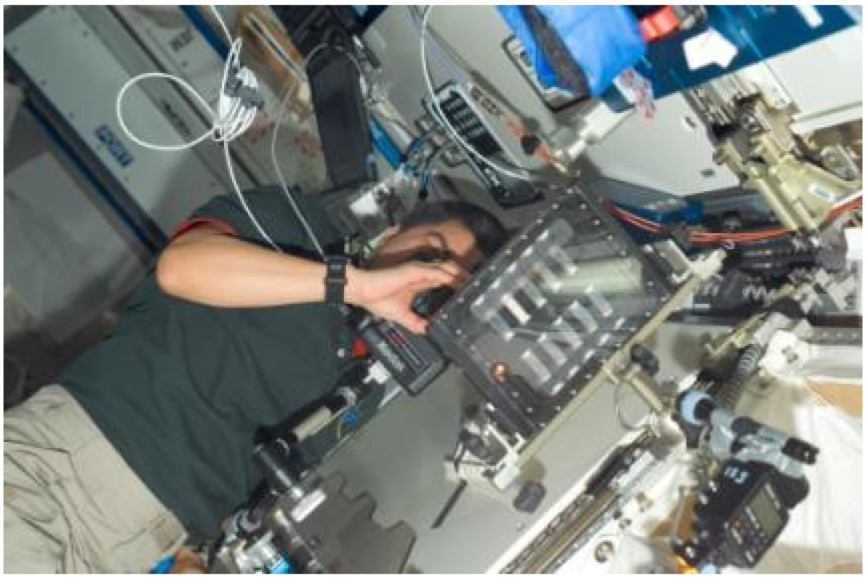
SPACE BENEFITS

BCAT-3 addresses basic physics questions, but some of the areas may eventually have applications for space exploration. The binary alloy (BCAT-3-BA) investigation examines colloids; colloids are technologically interesting because they are the right size to manipulate light. The surface crystallization (BCAT-3-SC) investigation examines whether materials in fluids prefer to first crystallize at a surface or in the fluid volume when gravity is removed. This impacts how fluids should be stored. Supercritical fluids, which are one of the applications of the critical point (BCAT-3-4-CP) experiment, are of potential application in propulsion systems for future spacecraft design.

Results

BCAT-3-BA (Pusey)

Unfortunately, the BCAT-3-BA sample dried out before crystallizing could occur aboard ISS.



ISS016E027863 – Astronaut Dan Tani photographing the Binary Colloidal Alloy Test - 3 Sample Module using his own design for a ceiling mount in Node 2 of the International Space Station. Great high contrast pictures of difficult-to-capture images resulted from using this setup.

BCAT-3-SC (Yodh)

During the surface crystallization (BCAT-3-SC) experiment, astronauts photographed samples of suspended colloidal particles in a liquid that contains a small amount of polymer to document the formation of colloidal crystals. Under the right circumstances these suspended particles will prefer to crystallize on the container surfaces, rather than in the sample volume. Three BCAT-3-SC samples will study the formation of colloidal crystals confined to a surface, allowing comparison with bulk 3-D crystallization, to begin testing how geometry affects crystallization itself. Results will help scientists develop fundamental physics concepts previously hindered by the effects of gravity. Ordered arrays of these micron-sized particles might be ideal for switching and controlling light. Imagery for the BCAT-3-SC was collected over several missions and is still undergoing analysis.

BCAT-3-4-CP (Weitz)

The BCAT-3-4-CP samples have yielded some surprising results; the samples that separated on Earth also separated in space; the samples that did not separate on Earth also did not separate in microgravity, indicating that the tendency for phase separation is not linked to gravity. However, for those samples that separated into different phases, the rates of separation for the microgravity samples were very different from the same mixtures on Earth.
Those samples with concentrations closest to the critical point took weeks to months in microgravity, compared with a couple of days on Earth (Lu 2007).

This dynamic data will help determine the boundary conditions for future models of critical behavior. Present observations also include a determination of the shape of the interface and which part of the sample wets the cell.

The long-term observation of which samples phase-separate will allow precise determination of the critical point of this colloidal mixture and will allow inference of the fundamental physics underlying critical point behavior.

The BCAT Critical Point samples are comprised of colloids and polymers diffusing in a background solvent; this model system mimics the behavior of molecular liquids and gases in microgravity. The network structure that appears in the phase separation images has a characteristic length scale. How this length changes with time gives insight into the thermodynamics driving the phase separation and can be quantified using image correlation (an optical method that employs tracking and image registration techniques for accurate 2- and 3-dimension measurements of changes in the length) computer programs. By creating different program coding, running in parallel with various computing platforms, many orders of magnitude improvement in analysis speed were achieved over standard "off-the-shelf" programs. The speed increases allow for very rapid analysis of images downlinked from the ISS and quick advantageous feedback to astronauts in orbit in time to make changes while the experiment is still running (Lu 2009, 2010).

PUBLICATION(S)

Lu PJ, Oki H, Frey CA, et al. Orders-of-magnitude performance increases in GPU-accelerated correlation of images from the International Space Station. *Journal of Real-Time Image Processing*. 2010;5(3):179-193. doi: 10.1007/s11554-009-0133-1.

Lu PJ, Weitz DA, Chamitoff GE, et al. Long-time observation of near-critical spinodal decomposition of colloid-polymer mixtures in microgravity. *47th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; 2009.

Lu PJ, Weitz DA, Foale CM, et al. Microgravity phase separation near the critical point in attractive colloids. *45th Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2007.

This investigation is complete; however additional results are pending publication.

Binodal Colloidal Aggregation Test – 4: Polydispersion (BCAT-4-Poly)

Research Area: Complex Fluids

Expedition(s): 16-20, 29-ongoing

Principal Investigator(s):
- Paul M. Chaikin, PhD, New York University, New York, New York

Research Objectives

Binodal Colloidal Aggregation Test-4 (BCAT-4-Poly) is an experiment of 2 samples containing microscopic spheres suspended in a liquid that are designed to determine how crystals can form from the samples after they have been well mixed. The 2 samples have the same average sphere size but 1 of them has a wider range (more polydisperse) of sizes in order to demonstrate the dependence of crystallization on particle size range. Results from these experiments help scientists develop fundamental physics concepts that will enable the development of a wide range of next generation technologies (such as in high-speed computers and advanced optical devices).

BCAT-4 setup aboard International Space Station during Expedition 20.

Earth Benefits

Generally, colloidal nucleation experiments seek an understanding of the most fundamental liquid/solid transition. Though direct applications of that understanding do not drive the research, growth of ordered colloidal phases has attracted interest in a number of areas like ceramics, composites, optical filters, and photonic bandgap materials. Moreover, there is currently great interest in using fields and gradients to control order in self-assembled systems such as diblock copolymers and microemulsions for advanced materials.

Space Benefits

BCAT-4-Poly will ultimately impact our understanding of the strength and thermal conductivity of materials by providing insight into the effects of size variation in dense suspensions of particles. For example, the careful selection of crystallization promoters for controlling the crystallite size and size distribution may lead to improvement in materials fabrication processes. The suppression of crystal nucleation in polydisperse colloids has important implications for the morphology of polycrystalline materials.

Results

Data analysis is ongoing, and results are yet to be published.

This investigation is ongoing and additional results are pending publication.

Binary Colloidal Alloy Test (BCAT-5), Four Investigations

Research Area: Complex Fluids

Expedition(s): 19-22, 25-ongoing

Principal Investigator(s):

- Arjun Yodh, PhD, University of Pennsylvania, University Park, Pennsylvania
- Barbara Frisken, PhD, Simon Fraser University, Burnaby, British Columbia
- David A. Weitz, PhD, Harvard University, Cambridge, Massachusetts
- Matthew Lynch, PhD, Procter and Gamble, Cincinnati, Ohio
- Paul M. Chaikin, PhD, New York University, New York, New York

Research Objectives

Binary Colloidal Allot Test-5 (BCAT-5) is a suite of 4 investigations that will photograph randomized colloidal samples aboard the International Space Station (ISS) to determine their resulting structure over time. Scientists will be able to capture the kinetics (evolution) of their samples, as well as the final equilibrium state of each sample.

ISS025-E-008239 (Oct. 19, 2010) – NASA astronaut Shannon Walker, Expedition 25 flight engineer, uses a digital still camera to photograph Binary Colloidal Alloy Test-5 experiment samples in the Kibo Laboratory of the International Space Station.

Earth Benefits

BCAT-5 takes advantage of the microgravity environment on the ISS to prevent the colloidal particles in these samples from encountering sedimentation, convection, and gravitational jamming. These samples will provide important data that is not available on Earth; data that can guide our understanding of phase separation (eg, shelf-life, product collapse), and how it competes with crystallization to impact production (eg, when making plastics).

Space Benefits

BCAT-5 will ultimately impact our understanding of the strength and thermal conductivity of materials by providing insight into the effects of size variation in dense suspensions of particles. For example, the careful selection of crystallization promoters for controlling the crystallite size and size distribution may lead to improvement in materials fabrication processes.

Results

Data analysis of the samples are ongoing, and results are pending publication.

This investigation is ongoing and additional results are pending publication.

Binary Colloidal Alloy Test - 5: Compete (BCAT-5-Compete)

Research Area: Complex Fluids

Expedition(s): 19-26

Principal Investigator(s):
- Barbara Frisken, PhD, Simon Fraser University, Burnaby, British Columbia, Canada

Research Objectives

For the Binary Colloidal Alloy Test - 5: Compete (BCAT-5-Compete) investigation, a crew member photographs microscopic particles (colloids) suspended in a liquid over time. This experiment investigates the competition between crystallization and the separation of solids from liquids. An improved understanding of these processes leads to improved manufacturing methods and commercial products.

ISS025E008239 – NASA astronaut Shannon Walker, Expedition 25 flight engineer, uses a digital still camera to photograph Binary Colloidal Alloy Test-5 experiment samples in the Kibo laboratory of the International Space Station.

Earth Benefits

These samples provide important data that are not available on Earth, data that can guide our understanding of crystallization, which impacts production (eg, when making plastics). Production processes often have defects introduced when there is a competition between processes like phase separation and crystallization. Studying this competition in the absence of gravitational settling provides insights into how to control it.

Space Benefits

Microgravity is essential for colloid crystallization research because gravity greatly interferes with crystal formation. The experiment looks to answer basic physics questions that could be applied to colloidal products used in the space program, including food and consumable products.

Results

Using samples containing 3 equilibrium phases, the BCAT-5-Compete project studied the interplay between phase separation and crystallization in a colloid-polymer mixture along one kinetic pathway. In analogy with atomic systems, the range of the effective attractive interaction between colloids was sufficiently long to allow for a stable liquid phase. On the International Space Station, direct imaging obtained in microgravity allowed the observation of a unique “crystal gel” that occurs when gas-liquid phase separation arrests due to crystallites within the liquid portion spanning the cell. From the initial onset of spinodal decomposition until arrest caused by the crystal gel structure, the kinetics of phase separation remained largely unaffected by the formation of the third phase. This dynamic arrest appeared to result from the stiffness of the crystalline strands exceeding the liquid-gas interfacial tension. Experimentation in microgravity has revealed the fundamental behavior of this system. The kinetic pathway was confirmed, but the small surface forces that were overwhelmed in Earth's gravity played a major role and led to the formation of a unique crystal gel structure. The phases observed reached their final concentrations, but macroscopic phase separation was not achieved because the interfacial energy between the 2 lower-density phases was insufficient to overcome the stiffness of the crystalline strands. This effect may occur in any 3-phase system whose interfacial and elastic energies result from a single dominant system energy scale.

Image of Binary Colloidal Alloy Test - 5: Compete sample 7 being used to study the competition between phase separation and crystallization in colloidal samples. This photo shows distinct phase separation arrested by crystal growth. NASA image.

PUBLICATION(S)

Sabin J, Bailey AE, Espinosa G, Frisken B. Crystal-arrested phase separation. *Physical Review Letters.* November 9, 2012;109(19):195701. doi: 10.1103/PhysRevLett.109.195701.

This investigation is complete; however additional results are pending publication.

Binary Colloidal Alloy Test (BCAT-6), Four Investigations

Research Area: Complex Fluids

Expedition(s): 25-ongoing

Principal Investigator(s):

- Arjun Yodh, PhD, University of Pennsylvania, University Park, Pennsylvania
- David A. Weitz, PhD, Harvard University, Cambridge, Massachusetts
- Matthew Lynch, PhD, Procter and Gamble, Cincinnati, Ohio
- Paul M. Chaikin, PhD, New York University, New York, New York

Research Objectives

Binary Colloidal Allot Test-6 (BCAT-6) is a suite of 4 investigations that photograph randomized colloidal samples in microgravity to determine their resulting structure over time. Results will help scientists develop fundamental physics concepts previously hindered by the effects of gravity. Data may lead to improvements in supercritical fluids used in rocket propellants biotechnology applications, and advancements in fiber optics technology.

Earth Benefits

These samples will provide important data that is not available on Earth. The data may guide our understanding of phase separation. Additionally, product shelf-life may be dependent upon bi-nodal decomposition and possibly upon Ostwald ripening in the emulsion samples.

Space Benefits

This experiment addresses basic physics questions, but some of the areas may eventually have applications for self-assembly of nanoparticles in space.

Results

Data analysis of the samples are ongoing.

This investigation is complete; however additional results are pending publication.

DEVICE FOR THE STUDY OF CRITICAL LIQUIDS AND CRYSTALLIZATION - ALICE LIKE INSERT (DECLIC-ALI)

Research Area: Complex Fluids

Expedition(s): 23-ongoing

Principal Investigator(s):
- Daniel Beysens, PhD, French Atomic Energy Commission (CEA), Grenoble, France
- Yves Garrabos, PhD, Institut de Chimie de la Matière Condensée de Bordeaux, Bordeaux, France

RESEARCH OBJECTIVES

Device for the study of Critical Liquids and Crystallization – Alice Like Insert (DECLIC-ALI) studies liquids at the verge of boiling. The flow of heat during boiling events is different in microgravity than it is on Earth. Understanding how heat flows in fluids at the verge of boiling will help scientists develop cooling systems for use in microgravity.

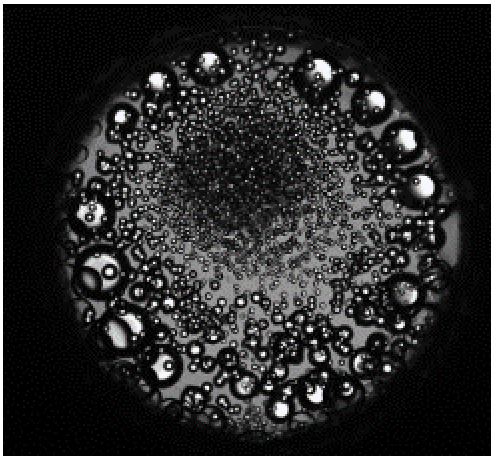


Image shows the state of water in microgravity at the determined supercritical temperature within 0.099 degree Celsius accuracy. Centre National d'Etudes Spatiales, Toulouse, France image.

EARTH BENEFITS

The use of near-critical fluids allows important parameters (eg, compressibility of supercritical fluids, density of gas and liquid phases, surface tension) to be easily varied in a scaled way by using small changes in temperature. The readily variable properties of near-critical fluids makes them appealing candidates for studying numerous interesting phenomena valid for all fluids, which will ultimately lead to the development of improved solvents for chemistry and the environment.

SPACE BENEFITS

The DECLIC facility provides power, communications, command/control, data storage, and multiple, flexible optical capabilities in support of each experiment. The knowledge gained will assist in the understanding of the behavior of cryogenic (of or relating to very low temperatures) rocket propellants for the study of dynamics regarding near-ambient temperature critical fluids. DECLIC is designed for telescience from the ground and will offer scientists the capability to remotely control experiment conditions aboard the ISS provided by DECLIC lockers.

RESULTS

DECLIC-ALI data collection is ongoing.

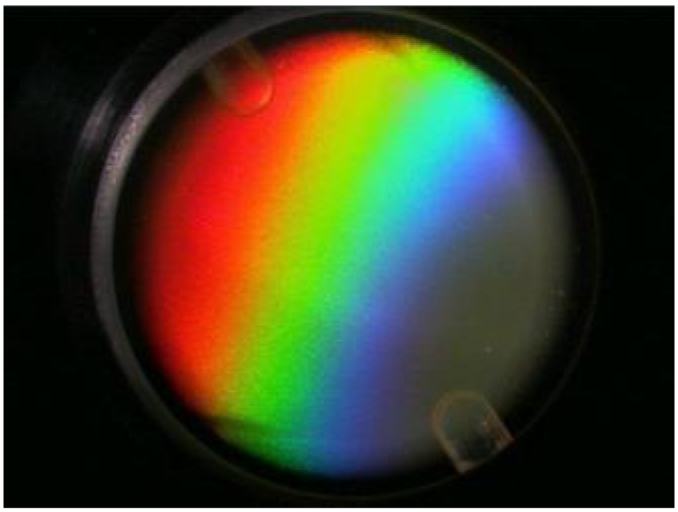
This investigation is ongoing and additional results are pending publication.

EXPRESS PHYSICS OF COLLOIDS IN SPACE (EXPPCS)

Research Area: Complex Fluids
Expedition(s): 2-4
Principal Investigator(s):
- David A. Weitz, PhD, Harvard University, Cambridge, Massachusetts

RESEARCH OBJECTIVES

EXPRESS Physics of Colloids in Space (EXPPCS) studies the kinetics of colloidal (fine particles suspended in a fluid) crystal formation and growth. These experiments provide the critical information necessary to use colloidal precursors to fabricate novel materials in the new field of colloidal engineering. Industries using semiconductors, electro-optics, ceramics, and composites might benefit from this investigation.



This is one of the first images from the EXPRESS Physics of Colloids in Space on the International Space Station. During Expedition 2, sample AB_6 was illuminated with white light to produce the image. The colored regions result from refraction of the white light by the sample and sample cell, splitting it up into its component colors. NASA Glenn Research Center image.

EARTH BENEFITS

EXPPCS will improve such colloids as paints, food products, drug delivery systems and ceramics by providing a better understanding of colloidal behavior. The EXPPCS investigation has contributed to Earth-based investigations of cataracts, which are caused by the buildup of damaged proteins within the eye lens and are the single largest cause of blindness. Diagnosis of cataracts is normally carried out by looking for protein buildup via a standard ophthalmological device known as a slit-lamp microscope, which can only detect cataracts once they have formed. Fortunately, a new laser probe originally developed for the US space program to study protein crystal formation on the International Space Station (ISS), has been shown to detect cataracts before they are symptomatic. This new technique uses dynamic light scattering (DLS) to detect small proteins called alpha-crystalline in the eye's lens, which is a reliable biomarker for cataracts. Laser light is shone into the lens of the eye while a highly sensitive photon detector is used to measure light backscattered at specific wavelengths. If the amount of alpha-crystalline proteins has lessened, this is an indication that cataracts are developing. If cataracts are detected early by this new technique, it may be possible to slow or stop the accumulation of damaged proteins by reducing relevant factors.

SPACE BENEFITS

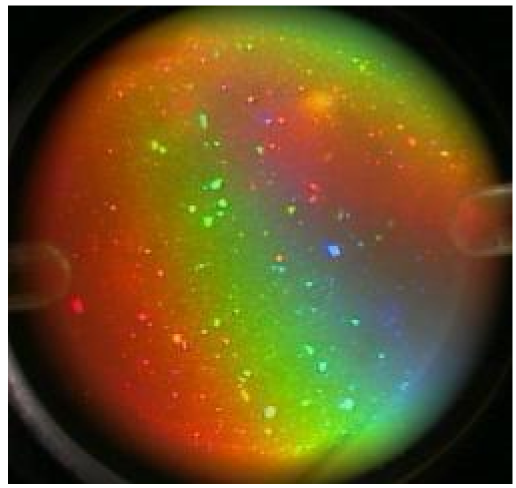
The colloidal engineering process will play a fundamental role in the creation of new materials and products in space, such as optical switches and lasers for communications and displays.

RESULTS

Results are discussed by class of colloid material studied.

Binary colloidal crystals: These alloy samples are dispersions of 2 differently sized particles in an index-matching fluid. Two samples were studied: an AB_{13} crystal structure and an AB_6 crystal structure. Due to a hardware failure late in Expedition 4, the AB_6 experiment was not completed. Unexpected "power law" growth behavior that is still under investigation was observed in the AB_{13} crystal structure sample.

Colloid-polymer mixtures: These mixtures induce a weak attractive interaction that allows precise tuning of the phase behavior of the mixtures, and approximate the phase separation below the critical point of a gas-liquid mixture. The phase behavior is controlled by the concentration of the colloid, the concentration of the polymer, and the relative size of the colloid and the polymer. The results from the ISS experiments studied the spinodal decomposition, or phase separation near the critical point, unencumbered by density differences of the phases. The growth of the phase separation was studied using both light scattering and imaging. Without gravity, the phase separation took 30 times longer than on Earth. The sample was mixed, then phase separation began, gradually coarsening until the container walls interacted with the mixture (at 42 hours) and the colloid-rich phase wet the container wall, completely coating it after 60 hours. Because the results follow very similar time evolution as a shallow quench of a binary liquid, they provide insight into the importance of the length scale of colloidal gels; separation depends more on coarsening rates than initial colloid size (Bailey 2007).



This photo was taken with the 1X color camera of the AB_6 sample after crystallization had occurred. The different colors are the result of different wavelengths of the white light illumination satisfying the Bragg condition at different angles relative to the lights. Bright spots are large crystallites. Diffuse color occurs are due to small crystallites. This image was taken prior to launch. The circular outline is the 2 cm outside diameter of the sample cell. NASA's Glenn Research Center image.

Colloid-polymer gels**:** This sample was expected to be in a fluid-cluster state, but unexpectedly formed a solid gel. The elastic modulus, which was estimated using the experiment's rheology capabilities, will be compared to ground samples. Aging characteristics of this gel were found to be similar to those formed on Earth.

Colloid-polymer critical point**:** Immediately after mixing, the colloid-polymer critical point sample began to separate into 2 phases—1 that resembled a gas and 1 that resembled a liquid, except that the particles were colloids and not atoms. The colloid-poor regions (the colloidal "gas" phase) grew bigger until, finally, complete phase separation was achieved and there was just 1 region of each—a colloid-rich phase and a colloid-poor phase. None of this behavior can be observed in the sample on Earth, because sedimentation would cause the colloids to fall to the bottom of the cell faster than the de-mixing process could occur. Knowledge gained from these runs was used to develop the BCAT-3 later operated on ISS.

Fractal gels: Fractal gels may form when charged colloids have their electrostatic repulsions screened out by the addition of a salt solution, permitting aggregation. These can be formed at very low volume fractions and form highly tenuous aggregates that exhibit a remarkable scaling property—their structure appears the same on all length scales up to a cluster size, and so can be described as a fractal. It was thought that the samples studied (colloidal polystyrene and silica gel) would, in the absence of sedimentation effects, ultimately form a continuous network of fractal aggregate; the polystyrene fractal sample never fully gelled as expected. Initial indications are that the volume fraction tested was too low. Large fractal clusters did grow (larger than they do on Earth), allowing measurement of the internal vibration modes of these structures. The silica gel is thought to have gelled, and is currently being evaluated.

Colloidal glass: These samples are still under evaluation. Comparison to samples formed in one-g in the laboratory were needed to understand whether the crystallization observed was due to poor mixing or was a true microgravity phenomena.

PUBLICATION(S)

Bailey AE, Poon WC, Christianson RJ, et al. Spinodal decomposition in a model colloid-polymer mixture in microgravity. Physical Review Letters. 2007;99(20):205701. doi: 10.1103/PhysRevLett.99.205701.

Manley S, Davidovitch B, Davies NR, et al. Time-dependent strength of colloidal gels. American Physical Society - Physical Review Letters. 2005;95(4):048302(4). doi: 10.1103/PhysRevLett.95.048302.

Manley S, Cipelletti L, Trappe V, et al. Limits to gelation in colloidal aggregation. Physical Review Letters. 2004;93(10):108302-1 - 108302-4. doi: 10.1103/PhysRevLett.93.108302.

Doherty MP, Bailey AE, Jankovsky AL, Lorik T. Physics of colloids in space: Flight hardware operations on ISS. AIAA 2002-0762, *40th Aerospace Sciences meeting*, Reno, NV; January 14-17, 2002.

Weitz DA, Bailey A, Manley S, et al. Results from the physics of colloids experiment on ISS. *NASA Technical Publication*; 2002.

Sankaran S, Gasser U, Manly S, et al. Physics of colloids in Space-2 (PCS-2). *Conference and Exhibit on International Space Station Utilization*, Cape Canaveral, FL; October 2001.

This investigation is complete and all results are published.

Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (InSPACE, InSPACE-2, and -3), Three Investigations

Research Area: Complex Fluids

Expedition(s): 6, 7, 12, 13, 16, 18-20, 27-ongoing

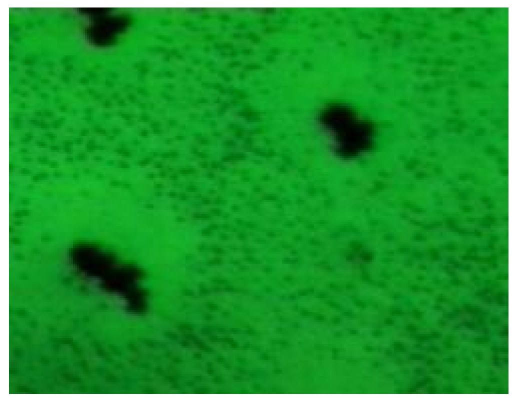
Principal Investigator(s):
- Alice P. Gast, PhD, Massachusetts Institute of Technology, Cambridge, Massachusetts
- Eric M. Furst, PhD, University of Delaware, Newark, Delaware

Research Objectives

The Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (InSPACE) suite of investigations studies the particle dynamics of magnetorheological (MR) fluids (fluids that change properties in response to magnetic fields) to help understand adaptable new fluids for use in such applications as brake systems and robotics.

Earth Benefits

The study of MR fluids on Earth is difficult because the small magnetic particles remain suspended while the sediments (large particles) sink. The low-gravity environment that is provided on the International Space Station (ISS) will eliminate the effects of sinking sedimentation. After the magnetic field is applied to a MR fluid, the microstructures form a rigid lattice that causes the suspension to stiffen. The rapid transformation of these fluids without the iron oxide grains clumping have many possible technological applications on Earth, especially for actuator-type devices. This technology has promise to improve the ability to design structures, such as bridges and buildings, to better withstand earthquake damage.



Video screen shot of the magnetic field that causes paramagnetic particles suspended in the fluid to collect into long chains. These long chains of clumps can interfere with the emulsions ability to stiffen as it should when magnetized. This image shows an end view of the larger aggregates that form during exposure to a pulsed magnetic field. Without the settling effects of gravity, the aggregates grow into complex low-energy structures. NASA's Johnson Space Center, Houston, Texas video.

Space Benefits

At the practical level, these fluids are used in electromechanical interfaces and devices in which the fluid is operationally exposed to similar fields that can affect their operation. Current commercial MR fluid products include tunable dampers and brakes, while future applications in robotics, clutches, and a host of vibration-control systems are envisioned.

Results

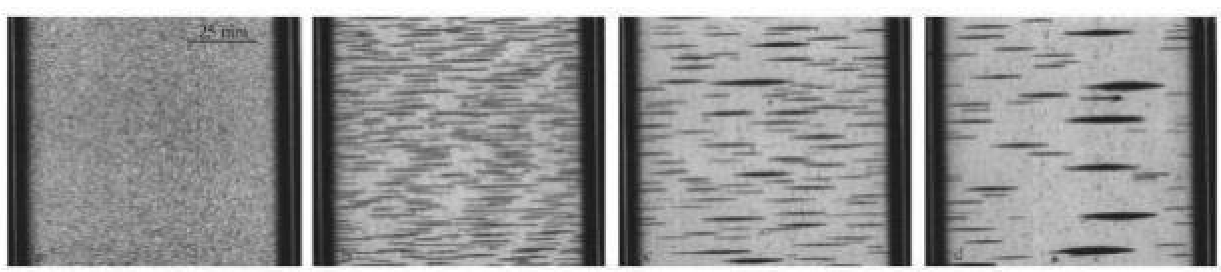
InSPACE (Gast)

Magnetorheological fluids are colloidal suspensions that can form solid-like gels when they are exposed to a steady, uniform magnetic field. Unique gel structures such as colloid-rich cylindrical columns can form within the fluid and be maintained by changing the field strength to relieve any structural stress (Furst 2009).

The collected data was processed, enabling a quantitative assessment of the structural data, including aggregate sizes and shapes. These are key parameters for defining the aggregate kinetics and are used to test theoretical models of the microstructures. Furthermore, understanding the complex properties of the fluids and the interaction of the microparticles will enable the development of more sophisticated methods for controlling and use of these fluids. Results suggest that InSPACE runs did not achieve steady-state structures. However, intriguing data suggesting the onset of instability at low frequency was collected. Both of these phenomena will be further addressed in InSPACE-2 (Vasquez 2008).

InSPACE-2 (Furst)

For the InSPACE-2 experiment, 2 distinct particle growth processes were observed: one where particle-rich and particle-poor regions form and become "trapped," and the other where the system-spanning structure suddenly collapses and particle columns form. These 2 processes are separated by a distinct boundary that depends on the magnetic field strength and magnetic frequency, and results demonstrate how energy barriers preventing colloidal phase transition can be overcome by changing the magnetic driving frequency and forces. As with other experimental studies of colloids in microgravity, the results of the InSPACE-2 experiments show that in these gel systems, gravity plays a dominant role and would slowly compress and deform the gel structures when similar experiments are performed on Earth, whereas in space these structures can be maintained as long as the magnetic forces are applied. Through better understanding of the stable and unstable phase behavior in the absence of gravitational stresses, these results demonstrate how colloidal suspensions may be harnessed in the creation of unique materials and electro-mechanical devices by manipulating the magnetic forces holding them intact (Swan 2012).



Structure evolution in an MR fluid over time while an alternating magnetic field is applied. The far left image shows the fluid after 1 second of exposure to a high-frequency-pulsed magnetic field. The suspended particles form a strong network. The images to the right show the fluid after 3 minutes, 15 minutes, and 1 hour of exposure. The particles have formed aggregates that offer little structural support and are in the lowest energy state. NASA Glenn Research Center, Cleveland, Ohio image.

Publication(s)

Swan JW, Vasquez PA, Furst EM. Buckling instability of self-assembled colloidal columns. *Physical Review Letters*. September 23, 2014;113:138301. doi: 10.1103/PhysRevLett.113.138301.

Swan JW, Vasquez PA, Whitson PA, et al. Multi-scale kinetics of a field-directed colloidal phase transition. *Proceedings of the National Academy of Sciences of the United States of America*. October 2012;109(40):16023-16028. doi: 10.1073/pnas.1206915109.

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This investigation is complete; however additional results are pending publication.

SHEAR HISTORY EXTENSIONAL RHEOLOGY EXPERIMENT (SHERE)

Research Area: Complex Fluids
Expedition(s): 17-18
Principal Investigator(s):
- Gareth H. McKinley, PhD, Massachusetts Institute of Technology, Cambridge, Massachusetts

RESEARCH OBJECTIVES

Shear History Extensional Rheology Experiment (SHERE) is designed to investigate the effect of preshearing (rotation) on the stress and strain response of a polymer fluid (a complex fluid containing long chains of polymer molecules) being stretched in microgravity. The fundamental understanding and measurement of the extensional rheology of complex fluids is important for understanding containerless processing, an important operation for fabrication of parts (such as adhesives or fillers) using elastomeric materials on future exploration missions.

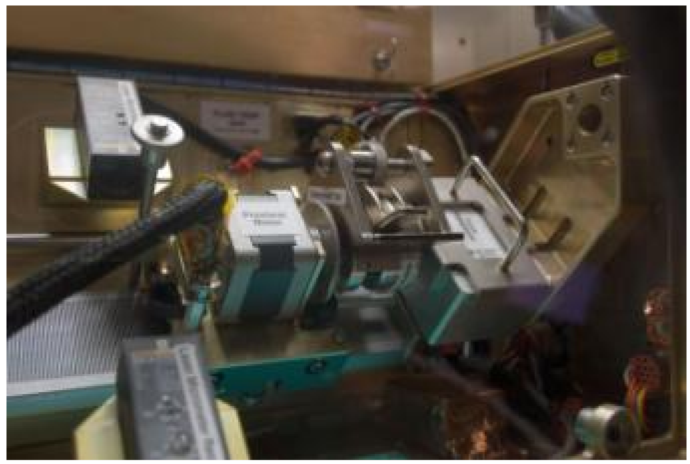
EARTH BENEFITS

Fundamental understanding and measurement of the extensional rheology of complex fluids also allows Earth-based manufacturing processes to be controlled and improved. Ground-based work using variants of the Filament Stretching Rheometer includes studies of spinnability and the investigations of cohesive and adhesive instabilities that manifests themselves in adhesion and tackiness of materials. It has lead to the development of a Resin-spinning technology that allows the formation of ultra-fine elastic threads analogous to spider-silks. Control of the fluid shear history and extensional rheology of test fluid is essential to optimizing the ultimate web properties. Extensional rheology is of critical importance in optimization of polymer processing operations that involve complex flows, ie, flows that contain both shearing (rotation) and elongation (stretching) components.

The Shear History Extensional Rheology Experiment (SHERE) operations team monitoring the progress of the experiment from the NASA Glenn Research Center Telescience Support Center in Cleveland, Ohio. NASA Glenn Research Center image.

SPACE BENEFITS

Understanding the extensional rheology of a complex fluid such as a liquid polymer is key for containerless processing because the absence of the bounding walls of a container or vessel removes the shearing component of the deformation that typically dominates Earth-based processing operations. The resulting flow is thus shear-free or extensional in character. Containerless processing is a central component in the development of *in-situ* fabrication technology, such as a means of producing new parts on demand or replacing existing parts or tools. This represents a critical element in the evolution of an autonomous exploration capability. *In-situ* fabricated parts, which may include both new and recycled materials, will be composed of plastics, filled polymers, metals, ceramics and composites. SHERE plays a role in this area by measuring, in microgravity conditions, a material property that has a direct connection to *in-situ* manufacturing and fabrication of polymeric parts. In-situ manufacturing operations can occur in microgravity or reduced gravity levels (eg, on the moon or Mars) and may include, for example, the extrusion and processing of thermoplastic elastomer films, which are very resilient and can be made thin and lightweight. These elastomeric materials may form the basis of adhesives and fillers utilized in a wide variety of repair applications, especially under a reduced gravity environment, such as the repair of space suits or other similar materials. Understanding and exploiting the ability to fabricate new parts *in-situ* from a limited number of precursor components is critical in future space missions where weight plays a critical role in the overall cost of a mission. Additionally, *in-situ* repair provides a means of maintaining systems during transport and while on long-duration expeditions beyond low-Earth orbit.



ISS017E012296 – View of the Laser Micrometer,Deployment Tool,Preshear Motor,and Force Transducer on the Shear History Extensional Rheology Experiment rheometer within the Microgravity Science Glovebox. Photo was taken in the European Laboratory/Columbus during Expedition 17.

Results

Data analysis continues for the test points performed. This analysis involves the computation of the time evolution in the cross-sectional area of the filament from the radius data, a temperature correction for the relaxation time and the zero-shear rate viscosity to correct for thermal fluctuations in the ISS Glovebox environment, and the computation of the extensional viscosity together with the Trouton ratio (Hall 2009, 2010).

Publication(s)

Soulages J, McKinley GH, Hall NR, Magee KS, Chamitoff GE, Fincke EM. Extensional properties of a dilute polymer solution following preshear in microgravity. *48th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; 2010.

Hall NR, McKinley GH, Erni P, Soulages J, Magee KS. Preliminary findings from the SHERE ISS Experiment. *47th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; 2009.

This investigation is complete and all results are published.

Shear History Extensional Rheology Experiment – II (SHERE-II)

Research Area: Complex Fluids
Expedition(s): 27-ongoing
Principal Investigator(s):
- Gareth H. McKinley, PhD, Massachusetts Institute of Technology, Cambridge, Massachusetts

Research Objectives

The Shear History Extensional Rheology Experiment-II (SHERE-II) investigation involves a non-Newtonian fluid that will undergo preshearing (rotation) for a specified period of time, followed by stretching. This combination of shearing and extensional deformations is common in many Earth-based polymer processing and manufacturing operations such as extrusion, blow-molding, and fiber spinning. However, in order to accurately predict the flow behavior of polymeric fluids under such deformation histories, an accurate knowledge of the extensional viscosity of a polymer system and its variation with strain rate is critical and will be measured during this experiment. The fundamental understanding and measurement of these complex fluids is important for containerless processing, a key operation for fabrication of parts, such as adhesives or fillers, using elastomeric materials on future exploration missions.

The SHERE main hardware (Rheometer, Interface Box, Tool Box, Cables & Keyboard) along the SHERE II fluid modules and stowage tray are scheduled to come down from ISS on the Space-X Demo flight which successfully launch on May 22, 2012. NASA Glenn Research Center, Cleveland, Ohio image.

Earth Benefits

A fundamental understanding and measurement of the extensional rheology of complex fluids also allows Earth-based manufacturing processes to be controlled and improved. Ground-based work using variants of the Filament Stretching Rheometer includes studies of spinnability and the investigations of cohesive and adhesive instabilities that manifests themselves in adhesion and tackiness of materials. It has led to the development of a Resin-spinning technology that allows the formation of ultra-fine elastic threads analogous to spider-silks. Control of the fluid shear history and extensional rheology of test fluid is essential to optimizing the ultimate web properties. Extensional rheology is of critical importance in optimization of polymer processing operations that involve complex flows, ie, flows that contain both shearing (rotation) and elongation (stretching) components. Suspensions of particles in viscoelastic liquids are used in many terrestrial processing operations: polymer melts with fillers, ceramic pastes, biomedical materials, food, cosmetics, or detergents. The final properties of the suspensions are greatly determined by the shape, concentration, and size of the filler. In particular, the fillers can range from nanoscopic to microscopic characteristic dimensions, and this leads to very different types of flow behaviors, filler/matrix interactions, and dynamics.

SPACE BENEFITS

SHERE experimental hardware assembled in the Microgravity Science Glovebox (MSG) on the International Space Station (ISS). NASA's Glenn Research Center, Cleveland, Ohio image.

Understanding the extensional rheology of a complex fluid such as a liquid polymer is key for containerless processing because the absence of the bounding walls of a container or vessel removes the shearing component of the deformation, which typically dominates Earth-based processing operations. The resulting flow is thus shear-free or extensional in character. Containerless processing is a central component in the development of in-situ fabrication technology, such as a means of producing new parts on demand or replacing existing parts or tools. This represents a critical element in the evolution of an autonomous exploration capability. In-situ fabricated parts, which may include both new and recycled materials, will be composed of plastics, filled polymers, metals, ceramics, and composites. SHERE plays a role in this area by measuring, in microgravity conditions, a material property that has a direct connection to in-situ manufacturing and fabrication of polymeric parts. In-situ manufacturing operations can occur in microgravity or reduced gravity levels (eg, on the moon or Mars) and may include, for example, the extrusion and processing of thermoplastic elastomer films, which are very resilient and can be made thin and lightweight. These elastomeric materials may form the basis of adhesives and fillers utilized in a wide variety of repair applications, especially under a reduced gravity environment, such as the repair of space suits or other similar materials. Understanding and exploiting the ability to fabricate new parts in-situ from a limited number of precursor components is critical in future space missions where weight plays a critical role in the overall cost of a mission. Additionally, in-situ repair provides a means of maintaining systems during transport and during future exploration missions.

RESULTS

Results will be published upon completion of data analysis.

This investigation is ongoing and additional results are pending publication.

Selectable Optical Diagnostics Instrument - Aggregation of Colloidal Solutions (SODI-Colloid/SODI-Colloid-2) , Two Investigations

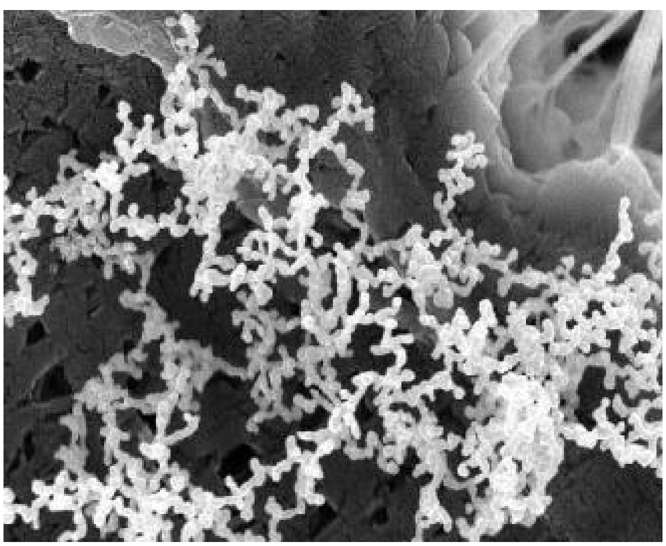
Research Area: Complex Fluids
Expedition(s): 23-26, 29 and 30
Principle Investigator(s):
- Gerard Wegdam, University of Amsterdam, Netherlands
- Roberto Piazza, PhD, Politecnico di Milano, Italy

Research Objectives

The Selectable Optical Diagnostics Instrument - Aggregation of Colloidal Suspensions (SODI-Colloid) investigation studies the growth, mixing, and ordering effects during microgravity aggregation from solutions of colloids (ie, mixtures of particles made of materials and that have the characteristic of remaining evenly distributed within a material medium without settling out). The primary focus is on the use of binary fluid solvent mixture as a growth medium, which may enable the development of fine-scale, tunable crystals resulting in an optically purer product. By examining the three-dimensional ordering and crystallization of colloids, this study intends to directly examine the mechanisms that could advance the development of photonic materials, which are useful in developing devices that confine and direct the optical propagation of electromagnetic waves and signals.

Earth Benefits

SODI-Colloid results potentially could improve such colloids as paints, food products, drug delivery systems and ceramics by providing a better understanding of the properties, and designing of colloidal products.



Metal nanoparticles produced in microgravity. The SODI-Colloid experiment is studying the growth and properties of advanced photonic materials, core elements of the super-fast optical computers to come. ESA image.

Space Benefits

Colloidal engineering processes have the potential to contribute to the creation of new materials and products that may enhance electronic communication hardware within various space architectures.

Results

The original concept of this experiment was that the strength of interactions between the colloidal particles could be tuned by using a binary mixture as solvent and increasing the temperature towards its spinodal decomposition. The critical Casimir effect resulting from the varying length scale of the fluctuations in the solvent then increased the strength of attraction between particles and could be easily and continuously tuned over a significant range without changing the composition of the system. While the strength of the attractive force between particles was being increased, the growth rate of aggregates and the average feature of their structure were quantified by way of Near Field Scattering measurements.

In microgravity, fractal structures formed by diffusion limited aggregation are always obtained, even at the lowest strength of inter-particle attraction, with a fractal dimension that decreases continuously with increasing attraction. This could not be ascribed to a change in a cluster-cluster aggregation regime. Simultaneously, ground experiments with the same samples showed only one type of aggregate with a constant fractal dimension, formed by a reaction-limited process. The experiment demonstrated the possibility of investigating aggregation mechanisms and the resulting structure of colloidal solids by tuning interaction forces in a colloid suspension by changing the temperature of the mixture.

PUBLICATION(S)

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Veen SJ, Antoniuk O, Weber B, et al. Colloidal aggregation in microgravity by critical Casimir forces. *Physical Review Letters 109*. 2012. doi:10.1103/PhysRevLett.109.248302.

This investigation is complete and all results are published.

Capillary Channel Flow (CCF)

Research Area: Fluid Physics
Expedition(s): 25-ongoing
Principal Investigator(s): ● Michael Dreyer, PhD, University of Bremen, Bremen, Germany

Research Objectives

Data from the Capillary Channel Flow (CCF) experiment will help to innovate solutions to transporting liquids (such as fuels, low temperature liquids like liquid nitrogen and water) in microgravity. By understanding capillary fluid flow rates in microgravity, hardware can be developed for "pumping" liquids from one reservoir to another without the need for a pump with moving parts. The reduced cost, weight, and improved reliability of such equipment make this a particularly attractive technology for NASA.

Earth Benefits

Technologies for liquid management in space use capillary forces to position and transport liquids, since the hydrostatic pressure is absent which gives the liquid a defined surface and enables easy withdrawal from the tank bottom. But the effect of capillary forces is limited on Earth to a few millimeters. In space these forces affect free surfaces that extend over meters. For the application of open channels in propellant tanks of spacecraft, design knowledge of these limitations are a requirement, predicated with a bubble free liquid restriction prior to entering the thrusters.

ISS040E088856 - NASA astronaut Reid Wiseman installs CCF hardware in the Microgravity Science Glovebox (MSG).

Space Benefits

CCF will significantly reduce cost and weight, while improving reliability of spacecraft tank designs that can supply gas-free propellant to spacecraft thrusters using capillary vanes.
Technologies for liquid management in space use capillary forces to position and transport liquids, since the hydrostatic pressure is absent that gives the liquid a defined surface and enables easy withdrawal from the tank bottom. But the effect of capillary forces is limited on Earth to a few millimeters. In space these forces affect free surfaces that extend over meters. For the application of open channels in propellant tanks of spacecraft, design knowledge of these limitations are a requirement, predicated with a bubble-free liquid restriction prior to entering the thrusters.

Results

CCF investigates forced liquid flow through partially open capillary channels aboard the International Space Station (ISS). The flow channel is made up of either two parallel plates or an open wedge conduit. Results collected show favorable agreement with predictions of critical flow rates and bubble separation rates. The results also indicate the nature of desabilizations and the myriad outcomes of gas liquid flows in the microgravity environment. Regarding critical

ISS040E088847 - NASA astronaut Reid Wiseman installs CCF hardware in MSG.

flow rate limitations, in general, steady uninterrupted flow is possible as long as it is below the bubble-ingestion speed. However right at this “critical” point, the flow speed of the fluid is counteracted equally by resisting waves going the opposite direction and quickly gives rise to the instability, called choking, which causes ingestion of bubbles into the moving fluid. At this point, the maximum flow rate is achieved briefly before the free fluid surface collapses and ingests air. The results suggest that these limitations are primarily governed by flow velocity, intrinsic properties of the liquid (i.e., surface tension, density, viscosity, wetting condition), and the steady balance of directional forces exerted on the moving fluid. For passive bubble separations in wedge sectioned conduits the studies have suggest devices that can be applied directly to perform such task beyond such fundamental investigations. Researchers are continuing to experiment with different capillary channel designs, fluids, and flow velocities to study and improve computational models for predicting capillary channel flow behavior in space which can translate into fabricating efficient fluid transport systems for fuel, life support, and energy systems for space exploration.

PUBLICATION(S)

Bronowicki PM, Canfield P, Grah A, Dreyer ME. Free surfaces in open capillary channels—Parallel plates. *Physics of Fluids*. January 2015;27:012106. doi: 10.1063/1.4906154.

Grah A, Canfield P, Bronowicki PM, Dreyer ME, Chen Y, Weislogel MM. Transient capillary channel flow stability: Experiments on the International Space Station. *Microgravity Science and Technology*. December 2014;26:385-396. doi: 10.1007/s12217-014-9403-z.

Jenson RM, Wollman AP, Weislogel MM, et al. Passive phase separation of microgravity bubbly flows using conduit geometry. *International Journal of Multiphase Flow*. June 2014;65:68-81. doi: 10.1016/j.ijmultiphaseflow.2014.05.011.

Canfield P, Bronowicki PM, Chen Y, et al. The capillary channel flow experiments on the International Space Station: Experiment set-up and first results. *Experiments in Fluids*. May 8, 2013;54(5):1519. doi: 10.1007/s00348-013-1519-1.

Conrath M, Canfield P, Bronowicki PM, Dreyer ME, Weislogel MM, Grah A. Capillary channel flow experiments aboard the International Space Station. *Physical Review E*. 2013;88:063009. doi: 10.1103/PhysRevE.88.063009.

This investigation is ongoing, and results are pending publication.

Capillary Flow Experiment (CFE)

Research Area: Fluid Physics
Expedition(s): 9, 12-16
Principal Investigator(s):
- Mark Milton Weislogel, PhD, Portland State University, Portland, Oregon

Research Objectives

Capillary Flow Experiment (CFE) is a suite of fluid physics experiments that investigate capillary flows and phenomena in low gravity and consists of 3 investigations: Vane Gap (VG), Interior Corner Flow (ICF), and Contact Line (CL). Results will improve current computer models that are used by designers of low-gravity fluid systems and may improve fluid transfer systems on future spacecraft.

Earth Benefits

The results of the flight experiments are also expected to provide insights into terrestrial interfacial phenomena and may lead to models predicting fluid flows in porous media (i.e., ground water transport), complex capillary structures (i.e., high-performance wicks for heat pipes employed in electronics cooling), and Lab-On-Chip technologies (i.e., microscale biofluids processing).

Space Benefits

The knowledge gained from this payload has the potential to be instrumental in the design of future fluid systems for spacecraft-impacting fluid-bearing containers such as propellant and cryogenic fluids tanks, thermal control system coolant reservoirs, water storage and management systems, liquid state low-gravity materials processing equipment, and biofluids handling instruments for inflight, human health systems. By performing this experiment, researchers will gain information that will lead to improvements in system reliability with reductions in system mass and complexity. These applications of CFE are in direct support of NASA's mission to develop safe, reliable, and affordable spacecraft to pursue the greater exploration of our solar system and universe.

Results

Vanes are structures built along propellant tank walls or inside the tanks that liquid clings to and is “wicked” away from its source. They are used as a form of passive fluid control in very low gravity to transfer wetting (ability of a liquid to maintain contact with a solid surface) fuels to resupply rocket engines. In space, acceleration forces can pool liquid propellant anywhere in the tank so the vanes, by having corners (such as the corner formed by the side vanes and the tank wall), serve to create a flow path to the outlet.

The CFE Vane Gap (VG) experiments identified the angles, known as critical wetting angles where a perfectly or partially wetting fluid is drawn up large or small corner gaps between the vane and cylinder wall and “wets” the entire length of the vane. Results showed critical angles were in close agreement with predictions for the perfectly wetting fluid, whereas these angles deviate substantially from predictions for a partially wetting fluid. Also, a bulk shifting (transferring large amount of liquid) phenomenon was observed only for the highly wetting fluid at these critical junctions, which might be due to small irregularities in geometry and/or container surfaces, showing even small contact irregularities can influence fluid behavior in a significant way (Chen 2009).

CFE Interior Corner Flow (ICF) experiments studied capillary flows in interior corners of 2 tapered containers. The migration rates of 4 different flows (dry, wet, open loop, and bubbly) in the units were observed and compared. Flow rates were in good agreement with predictions for the dry tests, but faster than predicted for previously wetted surfaces and bubbly flow tests. In many cases, the bubbles were separated during the bubble tests of ICF but small bubbles were unhindered.

The CFE Contact Line (CL) study observed the contact line (where the liquid and solid surface make contact) effect on fluid flow over a surface with and without pinning (a cut surface grove to disrupt smooth fluid movement). Results showed pinning produced more rapid wave motions and less fluid damping in a container than the smooth free surface. Larger contact angles (angle between the liquid and the container surface) also produced the same trend as pinning with respect to frequencies and damping rates. Fluid depth in the container was found to have little effect on the fluid's response to disturbances except in cases where shallow depth tests were involved. In general, modeled and observed results were in best agreement for the more predictable and confined movement with pinned contact line (Weislogel 2008).

CFE experiments were highly successful in uncovering microgravity fluid dynamics and the complex interaction of geometry, contact angle, asymmetry, and gap wetting in static and dynamic modes. Subsequent VG tests determined critical wetting conditions for perforated sheets with perfectly wetting fluids. This combination is common in storage tanks and can serve as models for screens and perforated sheets, plates, or vanes. Characterizing porous wicking structures will help in designing passive systems to manage highly wetting fuels, cryogens, thermal fluids, and contaminated aqueous solutions such as urine recyclers.

Publication(s)

Jenson RM, Weislogel MM, Klatte J, Dreyer ME. Dynamic fluid interface experiments aboard the International Space Station: Model benchmarking dataset. *Journal of Spacecraft and Rockets*. July-August, 2010; 47(4):670-679. doi: 10.2514/1.47343.

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Weislogel MM, Jenson RM, Tavan NT, Bunnell CT. Capillary flow experiments aboard ISS. *47th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; 2009.

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Weislogel MM, Chen Y, Collicott SH, Jenson RM. Capillary wetting analysis of the CFE-Vane Gap geometry. *46th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2008.[a]

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Weislogel MM, Jenson RM, Chen Y, Collicott SH, Klatte J, Dreyer ME. Postflight summary of the Capillary Flow Experiments aboard the International Space Station. *59th International Astronautical Congress*, Glasgow, Scotland; 2008. IAC-08-A2.6.A8.

Weislogel MM, Jenson RM, Collicott SH, Williams SL. Geometry pumping on spacecraft (The CFE-Vane Gap Experiments on ISS). *Japan Society of Microgravity Application*. 2008;25(3): 291-295. [e]

Weislogel MM, Jenson RM, Dreyer M, Klatte J. The Capillary Flow Experiments aboard ISS: Moving contact line experiments and numerical analysis. *46th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2008. [b]

Weislogel MM, Jenson RM, Dreyer M, Klatte J. Interim results from the capillary flow experiment aboard ISS; The moving contact line boundary condition. *45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2007.

Weislogel MM, Golliher EL, Hickman M, Green RD, Bunnell CT, Kurta CE. Preliminary results from the Capillary Flow Experiment Aboard ISS: The moving contact line boundary condition. *Proceedings of the 43rd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2005.

This investigation is complete; however additional results are pending publication.

Capillary Flow Experiment-2 (CFE-2)

Research Area: Fluid Physics

Expedition(s): 25-ongoing

Principal Investigator(s):
- Mark Milton Weislogel, PhD, Portland State University, Portland, Oregon

Research Objectives

Capillary Flow Experiments - 2 (CFE-2) is a suite of fluid physics experiments that investigates how fluids move up surfaces in microgravity. The results aim to improve current computer models that are used by designers of low-gravity fluid systems and may improve fluid transfer systems for water on future spacecraft.

Earth Benefits

Results of this study will improve the understanding of fluid flow in miniaturized biological devices used for health screening and analysis; this class of devices is often referred to as lab-on-a-chip.

Space Benefits

Capillary resulting phenomena include critical wetting in discontinuous structures, and capillary flow in complex containers. Specific applications of these results center on particular fluid challenges concerning the storage, transport, and processing of liquids in space. The knowledge assists spacecraft fluid systems designers in increasing system reliability, decreasing system mass, and reducing overall complexity.

The primary science goal for the Vane Gap experiments is to find the critical wetting angles at which fluid wicks up the edges of a perforated vane. An unexpected phenomenon (seen left) occurs when the perforations are filled prior to the running of the experiment. A bulk shift of the fluid is easily identified when the perforations are filled, and stands out distinctly when compared to the relative symmetry of a test run with un-filled perforations. Mark Weislogel image.

Results

The Vane Gap (VG) experiment identifies a fundamental wetting condition akin to the critical corner wetting condition identified by Concus and Finn (1969), but for interior corners formed by walls that possess a gap at the virtual axis of intersection of the two planar walls(i.e., vanes). Such a "wall-vane gap" is common in spacecraft systems, but is treated as an ideal corner. The Capillary Flow Experiment (CFE) involves many studies centered around a phenomenon called wetting. Wetting describes the ability for a liquid to spread across a surface. The original CFE tests were highly successful at uncovering the dynamics of wetting in microgravity. Capillary Flow Experiments -2 (CFE-2) determines the critical wetting conditions for screens and perforated plates for perfectly wetting fluids. The impact of such porous substrateshas immediate implications to the design of passive geometries to manage highly wetting fuels, cryogens, thermal fluids, and contaminated aqueous solutions for urine processing. The unique vane gap critical wetting phenomena is greatly complicated by the presence of three-dimensional (3-D) porous walls.

The Interior Corner Flow (ICF) experiment determines the rates of 3-D inhibition of wetting fluids in complex containers, the dependence of the dynamical boundary conditions as a function of geometry, and the performance of such devices as passive phase (i.e., bubble) separators. The ICF experiments are designed to benchmark the analytical technique developed to predict such flows. The benchmark theory aids in the design and analysis of capillary devices for positioning liquids passively in containers in microgravity environments by controlling the container geometry. The devices are useful in passive phase separation operations such as in the case of tapered screen galleries for bubble-free collection and positioning of fuels for satellites, to address propellant management aboard spacecraft. Spontaneous capillary flows in containers of increasing complexity such as ICF determine critical transients for low-g propellant management.

The objective of the Capillary Structure (CS) experiment is to add another critical dimension of complexity, interconnectivity, to the ICF experiments. Liquid bearing containers can easily be interconnected by capillary structures. The crew studies the time dependent flows as functions of unit cell dimensions and geometry, unit cell interconnectivity, overall structure dimensions and taper. They also investigate passive phase separation characteristics of such construct. Capillary Structures studies full 3-D wicking at micro-scales. The flows incorporate 3-D capillary driven corner flow networks consisting of a matrix of interconnected pores (Weislogel 2009).

Publication(s)

Weislogel MM, Chen Y, Collicott SH, Bunnell CT, Green RD, Bohman D. More Handheld Fluid Interface Experiments for the International Space Station (CFE-2). 47th Aerospace Sciences Meeting and Exhibit, Orlando, FL; January 5-8, 2009.

This investigation is ongoing and additional results are pending publication.

Constrained Vapor Bubble (CVB)

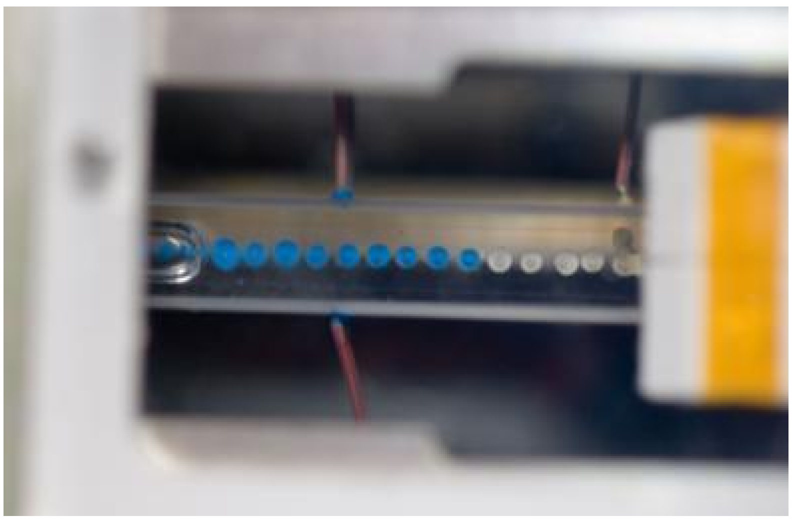
Research Area: Fluid Physics
Expedition(s): 23-28
Principal Investigator(s):
- Peter C. Wayner, Jr, PhD, Rensselaer Polytechnic Institute, Troy, New York

Research Objectives

Constrained Vapor Bubble (CVB) aims to achieve a better understanding of the physics of evaporation and condensation and how they affect cooling processes in microgravity using a remotely controlled microscope and a small cooling device.

Earth Benefits

The project aims to achieve an improved understanding of microscale heat transfer, improved designs for wickless heat pipes, and an increased efficiency in heat transfer devices for cooling critical components. Targeted users are existing microelectronics industry and perhaps military applications. New designs should be able to be developed several months following the analysis and presentation of the results from the experiment.



ISS020E042647 – Photograph taken during the inspection of the Constrained Vapor Bubble module with the science sample on the Fluids Integrated Rack.

Space Benefits

CVB has performed ground-based studies in a thermal vacuum chamber to determine the efficiency of the heater and cooler configuration. Large thermal response times that have been experimentally observed in space-based experiments cannot be obtained from these ground-based studies. Space-based experimentation is the only method available to ascertain internal low-gravity fluid mechanics within a heat pipe.

Results

CVB was specifically designed to look at the performance of a wickless heat pipe and to image the liquid/vapor distribution inside a heat pipe as it operated in microgravity.

An unanticipated nucleate boiling phenomenon was observed in the microgravity environment on the International Space Station (ISS) during operation of the experiment. Surveillance images of constant volume, microgravity boiling dynamics over a 20-hour time period show that nucleation (bubble formation) episodes occurred in a non-periodic but non-random way. Each nucleation event originated at the heater surface and new bubble growth was accompanied by a shock wave that passed through the heat pipe and partially collapsed the original vapor bubble. The maximum heat input to the heat pipe closely followed the timing of the nucleation event. The maximum heat loss, due to thermal radiation from the walls of the device, followed the timing of bubble motion and bubble coalescence. The whole process resulted in about a 10% increase in the overall heat transfer rate. Aided by these results, researchers developed simple models to describe the effect of main bubble location on the nucleation probability in the CVB and to determine the effect of intermolecular forces on the liquid film thickness needed to support nucleate boiling (Plawsky 2012).

Precise control and timing of explosive boiling has already proven its use in inkjet printer technology. This behavior can also be used to produce mechanical work such as moving micro membranes. For NASA, long-term storage of rocket propellants in space is one of the key requirements for planetary space exploration missions. Bubble formation and explosive boiling due to localized heat leaks in storage tanks under microgravity over a long period can be a serious and potentially dangerous condition for space-based fuel depots (Chatterjee 2011). Results of CVB will help with fuel storage tank design for future microgravity missions.

PUBLICATION(S)

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Kundan A, Plawsky JL, Wayner, Jr PC. Thermocapillary phenomena and performance limitations of a wickless heat pipe in microgravity. *Physical Review Letters*. April 7, 2015;114:146105. doi: 10.1103/PhysRevLett.114.146105.

Kundan A, Plawsky JL, Wayner, Jr PC. Thermophysical characteristics of a wickless heat pipe in microgravity – Constrained vapor bubble experiment. *International Journal of Heat and Mass Transfer*. November 2014;78:1105-1113. doi: 10.1016/j.ijheatmasstransfer.2014.07.044.

Chatterjee A, Plawsky JL, Wayner Jr PC, et al. Constrained Vapor Bubble heat pipe experiment aboard the International Space Station. *Journal of Thermophysics and Heat Transfer*. March 27, 2013;27(2):309-319. doi: 10.2514/1.T3792.

Plawsky JL, Wayner Jr PC. Explosive nucleation in microgravity: The Constrained Vapor Bubble experiment. *International Journal of Heat and Mass Transfer*. 2012;55(23-24):6473-6484. doi: 10.1016/j.ijheatmasstransfer.2012.06.047.

Chatterjee A, Plawsky JL, Wayner Jr PC, et al. The Constrained Vapor Bubble (CVB) experiment in the microgravity environment of the International Space Station. *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Orlando, FL; January 4-7, 2011.

Chatterjee A, Plawsky JL, Wayner Jr PC, et al. The Constrained Vapor Bubble Experiment for ISS - Earth's gravity. *Results Journal of Thermophysics and Heat Transfer*. 2010;24(4):400-410. doi: 10.2514/1.47522.

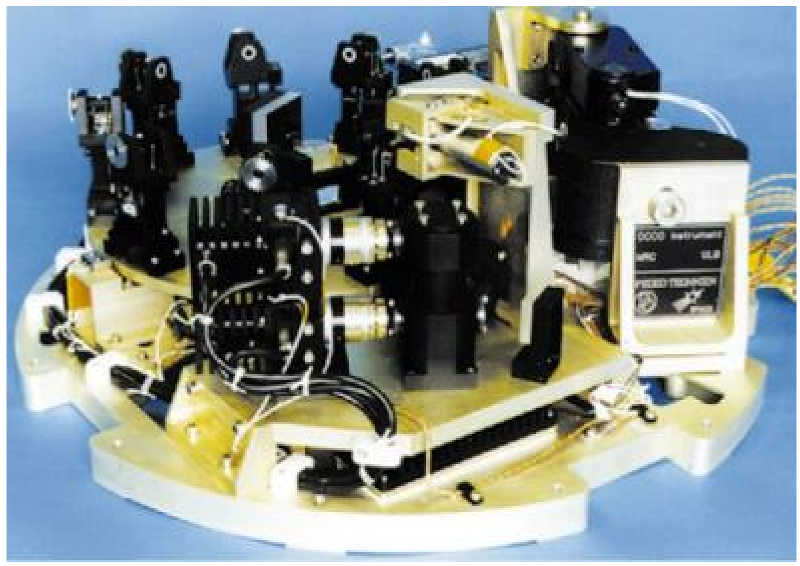
This investigation is complete and all results are published.

Diffusion Coefficient in Crude Oils (DCCO)

Research Area: Fluid Physics
Expedition(s): 5
Principal Investigator(s):
- Jean-Claude Legros, Université Libre de Bruxelles, Brussels, Belgium
- Stefan Van Vaerenbergh, PhD, University of Brussels, Belgium
- Frank Dubois, University of Brussels, Brussels, Belgium

Research Objectives

Diffusion Coefficient in Crude Oils (DCCO) looks to improve the understanding of mass transport phenomena in 3 components hydrocarbon mixtures and the determination of diffusion coefficients. The measurement of diffusion properties in crude oils improves numerical models used by industries to characterize oil fields. Expected benefits are the reduction of the number of required drillings, and therefore reducing exploration costs, especially for deep off-shore exploration. Diffusion coefficients are studied in a model fluid representing typical crude oils.



Experimental hardware of Diffusion Coefficient in Crude Oils. ESA image.

Results

Telemetry data for the DCCO showed the presence of gas bubbles in the diffusion region of the cell. Therefore, valid results from the experiment could not be obtained. The origin of the gas bubbles was not definitive but probably due to permeation of at least 1 of the components through the O-rings of the hardware. Research into diffusion coefficients continues with the SODI-IVIDIL and SODI-DSC/DCMIX investigations.

This investigation is complete; however no publications are expected.

DEVICE FOR THE STUDY OF CRITICAL LIQUIDS AND CRYSTALLIZATION - DIRECTIONAL SOLIDIFICATION INSERT (DECLIC-DSI)

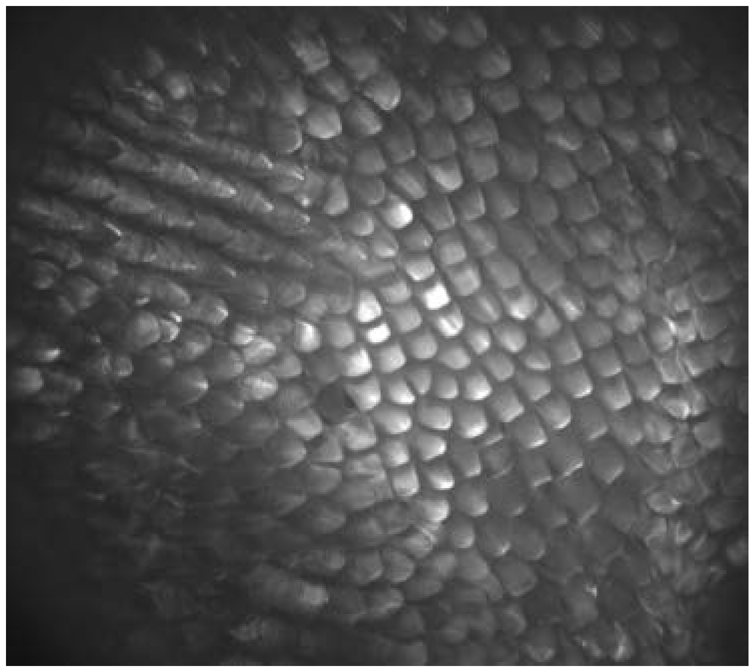
Research Area: Fluid Physics
Expedition(s): 21-ongoing
Principal Investigator(s):
- Nathalie Bergeon, PhD, Université Paul Cézanne, Marseille, France

RESEARCH OBJECTIVES

Device for the Study of Critical Liquids and Crystallization – Directional Solidification Insert (DECLIC-DSI) studies a series of benchmark experiments on transparent alloys that freeze like metals under microgravity aboard the International Space Station (ISS) using succinonitrile (SCN) based alloys. SCN is a transparent organic substance in the liquid state that is used to study the phenomena related to solidification processes.

EARTH BENEFITS

DECLIC-DSI will establish the fundamental physics that govern the formation and selection of solidification patterns. This will provide an opportunity to gain an insight into the general problem of pattern formation, as solidification patterns are recognized to be similar to those forming in many other branches of science.



5C19CFD0 – SCN camphor of reduced concentration obtained by very slow solidification (nominal : 0.24 wt% camphor) – G = 12°C/cm. Marshall Space Flight Center image.

SPACE BENEFITS

DECLIC-DSI involves investigating the birth and growth of morphological instabilities and the effects of coupling between the solidifying interface and the convection. By observing these phenomena in a microgravity environment, it will be possible to refine the theoretical models and numerical simulation predictions, which will ultimately result in the improvement of the industrial ground-based material development processes.

RESULTS

DECLIC-DSI is dedicated to the study of solidification to improve the understanding of metallurgical processes. It uses an organic alloy that freezes like metals but that is transparent to visible light so that the whole process of solidification is visible.

DECLIC-DSI completed four successful solidifications by the end of November 2010. The research team captured 7,000 images during the final session meeting all scientific objectives. DECLIC-DSI contains a crucible filled with a dilute succinonitrile-camphor alloy of a well-defined concentration, which is solidified by motion from a hot zone to a cold zone at a constant pulling rate. In these runs, a large range of experimental conditions were explored to vary the resulting microstructure. Both long solidifications and solidifications with jumps in pulling rates had been performed to get the whole dynamics and mechanisms of microstructure formation or change, spacing adjustment, and pattern ordering. During 2 solidification runs at very low speeds, 2 types of exotic cellular patterns became evident. Latest data are currently under treatment (Bergeon 2011).

The study of solidification microstructure formation is very important in the design and processing of new material. The interface patterns formed by solidification largely govern mechanical and physical properties, thus materials and processing conditions can be designed to obtain specific patterns which give optimum properties and better reliability of the finished product. Experiments such as DECLIC provide a better understanding of the relationship between micro- and macrostructure formation during solidification processes. The experiment ultimately could result in new and better materials for use in manufacturing on Earth (Ramirez 2011).

PUBLICATION(S)

Mota FL, Bergeon N, Tourret D, Karma A, Trivedi R, Billia B. Initial transient behavior in directional solidification of a bulk transparent model alloy in a cylinder. *Acta Materialia*. February 2015;85:362-377. doi: 10.1016/j.actamat.2014.11.024.

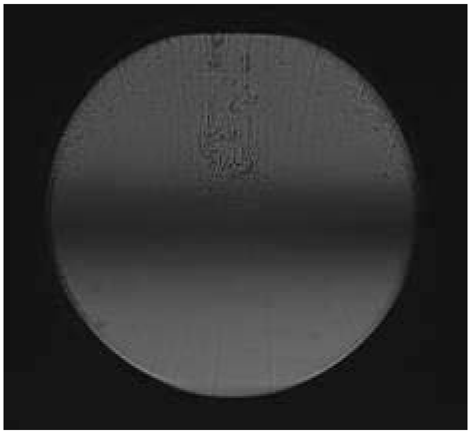
Bergeon N, Ramirez A, Chen L, Billia B, Gu J, Trivedi R. Dynamics of interface pattern formation in 3D alloy solidification: First results from experiments in the DECLIC directional solidification insert on the International Space Station. *Journal of Materials Science*. 2011;46:6191-6202. doi: 10.1007/s10853-011-5382-2.

Ramirez A, Chen L, Bergeon N, Billia B, Gu J, Trivedi R. In situ and real time characterization of interface microstructure in 3D alloy solidification: Benchmark microgravity experiments in the DECLIC-Directional Solidification Insert on ISS. *IOP Conference Series: Material Science and Engineering*. 2011;27(1). doi: 10.1088/1757-899X/27/1/012087.

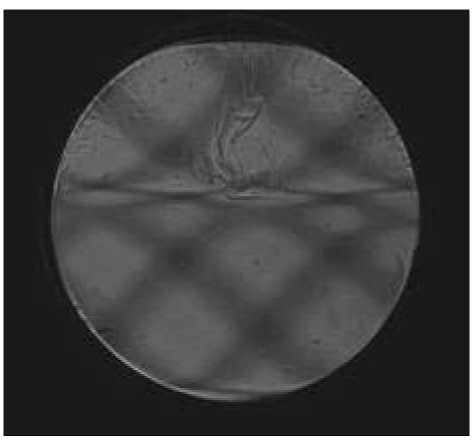
This investigation is ongoing and additional results are pending publication.

DEVICE FOR THE STUDY OF CRITICAL LIQUIDS AND CRYSTALLIZATION - HIGH TEMPERATURE INSERT (DECLIC-HTI)

Research Area: Fluid Physics
Expedition(S): 21-ongoing
Principal Investigator(s):
- Daniel Beysens, PhD, French Atomic Energy Commission (CEA), Grenoble, France
- Yves Garrabos, PhD, Institut de Chimie de la Matière Condensée de Bordeaux, Bordeaux, France



Pure water above the critical point observed in wide field transmission during ground tests of the DEvice for the Study of Critical LIquids and Crystallization - High Temperature Insert. CNES image.



The deformation of the shadow of a grid evidences some density gradients inside the cell. CNES image.

RESEARCH OBJECTIVES

DEvice for the study of Critical LIquids and Crystallization - High Temperature Insert (DECLIC-HTI) studies the transfer of heat and mass in near-critical water and measurement of its physical properties. The DECLIC-HTI design is intended to be later compatible with the use of possible toxic samples. The main functions of HTI are: to isolate a sample from the shuttle atmosphere; to provide an adequate thermal environment to the sample material; to enable optical observation of the sample; and to enable temperature measurements for the control and safety of the experiment.

EARTH BENEFITS

DECLIC-HTI will enable the development of supercritical water reactors to be developed to treat waste as part of applications on Earth (treatment of household waste, nuclear waste, and extraction of oil fuels). This research will lead to spin-offs in the field of clean technologies for producing energy and treating waste.

SPACE BENEFITS

The results obtained with the DECLIC-HTI scientific program should benefit fluid management in space, and potentially the organic waste treatment considering the combustion in supercritical water processes, for future expeditions beyond low-Earth orbit.

RESULTS

The DECLIC-HTI Investigation is ongoing and pending publication of results.

This investigation is ongoing, and results are pending publication.

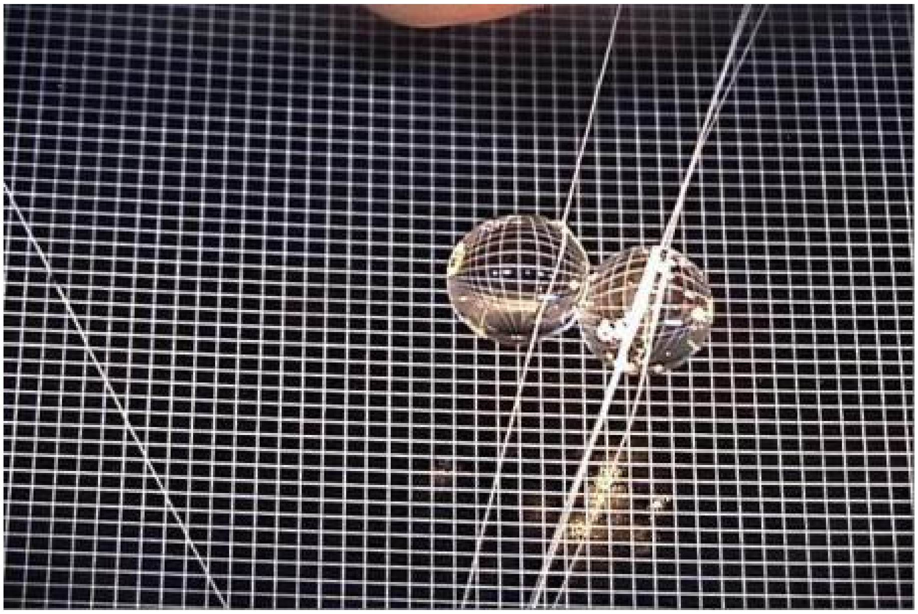
Fluid Merging Viscosity Measurement (FMVM)

Research Area: Fluid Physics
Expedition(s): 9 and 11
Principal Investigator(s):
- Edwin C. Ethridge, PhD, NASA's Marshall Space Flight Center, Huntsville, Alabama

Research Objectives

Fluid Merging Viscosity Measurement (FMVM) is designed to test a new method for measuring the viscosity of high-viscosity materials by measuring the time it takes 3 nearly free-floating drops of a liquid to merge. The materials used are of known viscosities (corn syrup, glycerin, and silicone oil) so that the accuracy of the fluid merging test can be compared to the methods used on Earth. The FMVM experiment can lead to a greater understanding of glass formation from melted lunar soil. It will also lead to a better understanding of liquid phase sintering processes for in-space fabrication methods that can be used for constructing surface habitat structures.

Earth Benefits


This image shows two 4 ml silicone oil viscosity standard liquid drops in the process of coalescing to a single spherical drop. Marshall Space Flight Center image.

This new viscosity measuring process is ideally suited for use with difficult glass forming liquids. It can be used to make measurements that are impossible by other methods. The droplet merging method of viscosity measurement might be applied to small glass samples melted in terrestrial containerless levitation processing facilities. It will also be possible to measure the viscosity of undercooled liquids much more rapidly than with other viscosity methods. Methods being developed by the FMVM experiment will make it possible to determine the viscosity of highly undercooled viscous glassy liquids at temperatures impossible with current methods. New methods to measure viscosity at very low shear rates also has technological significance. This method should permit the investigation of the non-Newtonian viscosity behavior of glasses at very low shear rates. Such viscosity data will be very useful for the modeling of crystallization behavior of materials of scientific interest. Examination of the droplet shape changes with time can also lead to a better understanding of terrestrial industrial and in-space processes. The coalescence of drops has direct application to the science of liquid phase sintering. It should be possible to test models for liquid drop coalescence used to understand liquid phase sintering. Insight into the materials deposition processes is also important to the industrial process of rapid prototyping.

Space Benefits

Understanding the viscosity of molten materials and coalescence of liquid drops is important for everything from glass formation laboratory experiments to industrial materials processes such as sintering (a method of fusing together particles of material at lower temperatures and without melting). Viscosity is one of the key parameters that materials scientists must measure to create accurate models predicting the best methods for materials production. Understanding and controlling viscosity can even enable researchers to make new materials or improve existing ones. Microgravity advantageously eliminates the gravitational distortion of liquid drops, permitting liquids to be suspended in a free-floating condition. Scientists can measure the viscosity of low-viscosity liquids such as molten metal in low-gravity levitators, by measuring vibrations of liquid drops. However, the oscillation method cannot be used on more viscous liquids like molten glass, since they will not oscillate. The FMVM experiment can ultimately lead to a greater understanding of glass formation from melted lunar soil. It will also lead to a better understanding of liquid phase sintering processes for in-space fabrication methods that can be used for constructing surface habitat structures from sintered lunar soil and vehicle components for longer-term space missions.

Results

FMVM tests a new method for measuring the viscosity of high-viscosity materials by measuring the time it takes 2 nearly free-floating drops of a liquid to merge. Preliminary results from data analysis indicate agreement with the predicted coalescence time (Ethridge 2006).

The experiments demonstrate that when the surface tension of a liquid is known, the coefficient of viscosity for that liquid can be determined by the contact radius speed. This data can be fit to numerical results to calculate the viscosity, thus validating the model for this new viscosity measurement method (Antar 2007).

The original data tapes for the FMVM investigation were returned to Earth on space shuttle flight STS-114/LF-1 in August 2005; later experiments were carried out aboard the International Space Station (ISS) in July of 2004 and May of 2005. The behavior of two coalescing drops in microgravity was examined; calculations were run on 7 different conditions to determine the theoretical coalescence half time (time at which the neck diameter of the converging drops was half the original drop diameter) for each condition. These results were then compared with the observed times from experiments conducted aboard ISS and were found to be in close agreement, with the exception of the high-viscosity silicone oil condition (which may have been due to invalid initial conditions input to the analytical model). The results of this experiment validate this numeric model used to calculate the viscosity of a liquid from measured half time coalescence and known surface tension (Ethridge 2009).

PUBLICATION(S)

Ethridge EC, Kaukler WF, Antar BN. Modeling of the Fluid Merging Viscosity Measurement (FMVM) International Space Station experiment with Comsol MultiPhysics. *47th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; 2009.

Antar BN, Ethridge EC, Lehman D. Fluid Merging Viscosity Measurement (FMVM) experiment on the International Space Station. *45th Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2007.

Ethridge EC, Kaukler WF, Antar BN. Preliminary results of the Fluid Merging Viscosity Measurement Space Station experiment. *44th Aerospace Sciences Meeting and Exhibit*. Reno, NV; 2006.

This investigation is complete and all results are published.

Foam Optics and Mechanics - Stability (FOAM-Stability)

Research Area: Fluid Physics
Expedition(s): 19-22
Principal Investigator(s):
- Nicolas Vandewalle, Université de Liège, Liège, Belgium

Research Objectives

Foam Optics and Mechanics - Stability (FOAM-Stability) studies the behavior of wet foams in microgravity conditions. Foamability is an important property of liquids. Most liquids do not stabilize into foam structures because liquid films are drained by gravity until the liquid films break. Amphiphilic (surfactant) molecules are commonly used to prevent rupture of the liquid films. These additives stabilize the films by forming layers of electrostatic charges at the molecular level along the liquid/air interfaces.


ESA astronaut Frank De Winne pictured near the Foam Optics and Mechanics - Stability experiment in the Columbus laboratory of the International Space Station in September 2009. NASA image.

Results

The main process that controls the stability of foam on Earth is the gravity drainage, which eventually causes film thinning of the bubbles toward a critical thickness at which they become unstable and burst. This process is not a factor in microgravity, and foams containing large amounts of liquid can be studied for a longer time. Foam experiments in space allow researchers to explore a new sort of very “wet” foam with liquid fractions around 30%. The high liquid fraction enables bubbles to keep their spherical shape. On Earth, such materials are unstable and most of the time not called foams but bubbly liquid. In space, drainage is suppressed, such that liquid films remain thick, but bubble coalescence events are nevertheless seen. However, after some time, bubble motions become rare events such that the foam is more stable even when shaken. In most cases, the foamability (the volume fraction occupied by the foam only) is almost two times larger on the International Space Station than on Earth. A striking and unexpected result is that a non-foaming solution on Earth makes significant foam in space.

It was discovered that super stable aqueous foams can be created in microgravity conditions. On Earth, coarsening and film ruptures are always present for a solution even with foaming agents. In microgravity, the foam still evolves but the amount of foam does not appear to change significantly. Surprisingly, antifoaming agents have a reduced effect in microgravity, and the resulting foam appears to be stable. This behavior was completely unexpected since anti-foaming agents are meant to avoid foam creation and stabilization. These observations raise new fundamental questions that should be investigated in future works.

Publication(s)

Vandewalle N, Caps H, et al. Foam stability in microgravity. *J Phys Conf Ser*. 327 012024; 2011. doi:10.1088/1742-6596/327/1/012024.

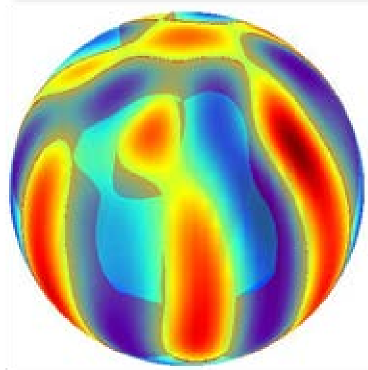
This investigation is complete and all results are published.

Simulation of Geophysical Fluid Flow under Microgravity-I (Geoflow-I)

Research Area: Fluid Physics
Expedition(s): 16 and 17
Principal Investigator(s):
- Christoph Egbers, PhD, Brandenburg University of Technology, Cottbus, Germany

Research Objectives

Physical mechanisms of heat driven rotating fluids are important for a large number of geophysical problems such as explaining the convection of the Earth's liquid outer core. The main objective of the Geoflow investigation is to study the stability, pattern formation, and transition to chaos of thermal convection in fluid-filled rotating spheres. Understanding how Earth's mantle flows is a major interest for geophysics because it could help to explain earthquakes or volcanic eruptions. The results, for example, could also benefit by improving spherical gyroscopes, bearings, and centrifugal pumps.



Geoflow-I: Experimental fringe pattern images projected on a spherical surface indicating column-like thermal flow (top) and agreement with numerical simulated flow field (bottom). ESA image.

Results

In geophysical and astrophysical research, the setup of rapid rotating spherical shell convection, as part of dynamic flow, is of basic interest. Data analysis identifies first subcritical and supercritical fluid flow patterns. In addition, the fully developed supercritical states turn out to have buoyancy-driven polar exchange and complex drift behavior. If these convective flow patterns can be reconstructed, numerical simulations could show details on other properties of the fluid flow beyond the limits of what is available with in-orbit measurement techniques. Quality of the images is excellent and classifying of patterns into space and time is possible. Overall analysis will be done when the set of experiments is completed, including the ongoing GeoFlow II.

Publication(s)

Futterer B, Egbers C, Dahley N, Koch S, Jehring L. First identification of sub- and supercritical convection patterns from 'GeoFlow,' the geophysical flow simulation experiment integrated in Fluid Science Laboratory. *Acta Astronautica*. 2010;66(1-2):193-200. doi: 10.1016/j.actaastro.2009.05.027.

Jehring L, Egbers C, Beltrame P, et al. Geoflow: First results from geophysical motivated experiments inside the fluid science laboratory of Columbus. *47th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; 2009.

This investigation is complete and all results are published.

Simulation of Geophysical Fluid Flow under Microgravity-II (Geoflow-II)

Research Area: Fluid Physics
Expedition(s): 25-ongoing
Principal Investigator(s):
- Christoph Egbers, Brandenburg University of Technology, Cottbus- Senftenberg, Germany

Research Objectives

Simulation of Geophysical Fluid Flow under Microgravity-II (Geoflow-II) studies heat and fluid flow currents within the Earth's mantle. Geoflow-II aims to improve computational methods that scientists and engineers use to understand and predict the processes in the Earth's mantle that lead to volcanic eruptions, plate tectonics, and earthquakes.

Earth Benefits

Understanding how the mantle flows is a major interest for geophysics because it could help to explain earthquakes or volcanic eruptions.

Space Benefits

A better understanding of this type of fluid flow could benefit the manufacturing methods of spherical gyroscopes, bearings, and centrifugal pumps for Earth and space applications.

Geoflow-II image showing plume-like thermal upwellings. ESA image.

Results

Using a spherical geometry set-up, experiments on electro-hydrodynamic driven fluid convection have been performed for both temperature-independent (GeoFlow-I) and temperature-dependent fluid viscosity properties (GeoFlow-II) with a measured viscosity contrast ratio of up to 1.5. Numerical simulations in three-dimensional spherical geometry were also carried out to reproduce the results obtained in the GeoFlow experiments. Observed flow patterns were distinctly different between these 2 experiments. A sheet-like thermal flow was seen in GeoFlow-I. For this case, convection patterns have been successfully reproduced by three-dimensional numerical simulations using 2 different and independently developed simulation programs. By contrast, plume-like structures were observed with GeoFlow-II. Interestingly, numerical simulations do not yield this type of plume for the low-viscosity contrast. However, using a viscosity contrast of 2 orders of magnitude (or higher) in the numerical modelling, the science team could reproduce the patterns seen in GeoFlow-II. Based on this result, it is concluded that nonlinear effects shifted the effective viscosity ratio.

PUBLICATION(S)

Futterer B, Krebs A, Plesa AC, et al. Sheet-like and plume-like thermal flow in a spherical convection experiment performed under microgravity. *J Fluid Mech.* 2013.

Futterer B, Dahley N, Koch S, Scurtu N, Egbers C. From isoviscous convective experiment 'GeoFlow I' to temperature-dependent viscosity in 'GeoFlow II'—Fluid physics experiments on-board ISS for the capture of convection phenomena in Earth's outer core and mantle. *Acta Astronautica*. 2012;71:11-19.

This investigation is complete and all results are published.

Microheater Array Boiling Experiment (MABE)

Research Area: Fluid Physics

Expedition(s): 25-28

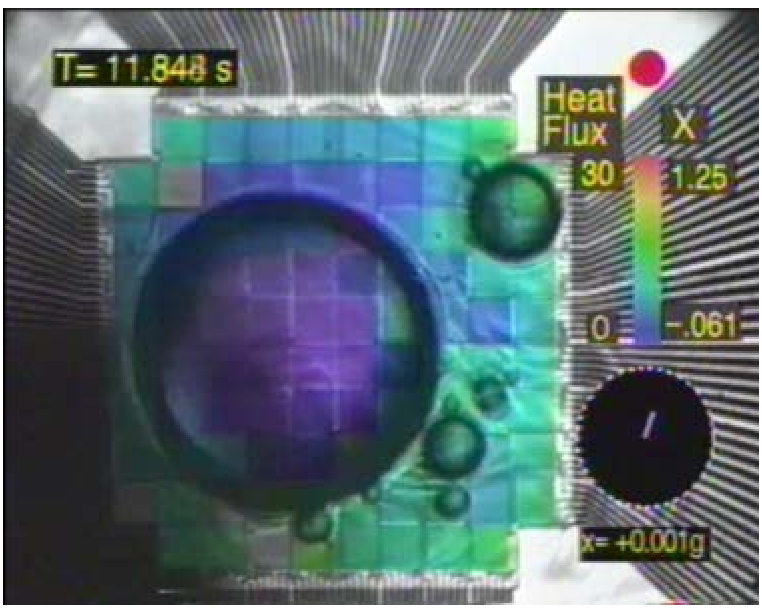
Principal Investigator(s):
- Jungho Kim, PhD, University of Maryland, College Park, Maryland

Research Objectives

Boiling efficiently removes large amounts of heat by generating vapor from liquid; this process is currently being used in many power plants to generate electricity. An upper limit, called the critical heat flux, exists where the heater is covered with so much vapor that liquid supply to the heater begins to decrease, potentially destroying the heater. Microheater Array Boiling Experiment (MABE) determines the critical heat flux during boiling in microgravity to design optimal cooling systems for future space exploration vehicles as well as on Earth.

Earth Benefits

The proposed research has shown that transient conduction is the dominant heat transfer mechanism in boiling of refrigerants-like fluids. This research will provide insight into creating more efficient cooling systems on Earth.



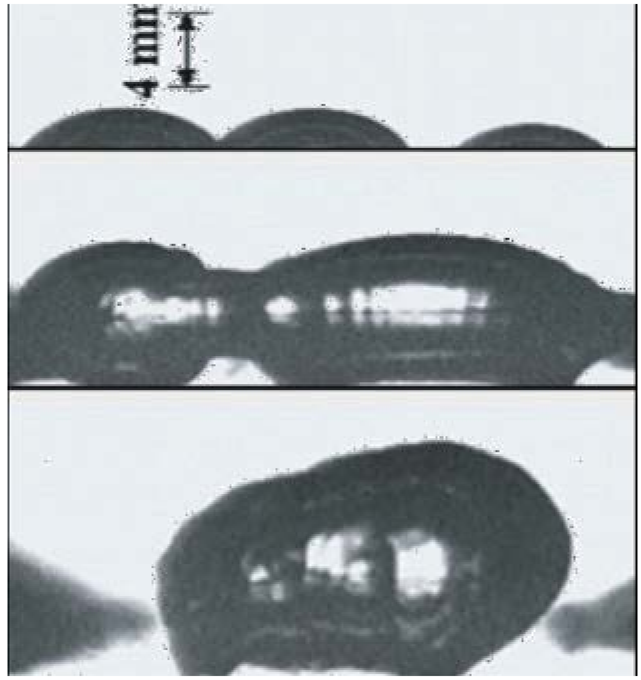
Microheater Array Boiling Experiment Image: High-speed video image that is colorized with heater power data. Correlating the position of the vapor and liquid positions with the heater power data provides insight into the heat transfer and phase change mechanisms. University of Maryland image.

Space Benefits

In microgravity, a bubble can cover an entire heater array instead of just a small area, resulting in burnout of components if local hot spots are present. The increased spatial resolution of these measurements will enable the extent of the dry spot to be measured along with the heat transfer from the liquid surrounding the dry spot. This technique can be applied to other areas including spray cooling, turbulence measurements and flow boiling.

Results

MABE completed over 2 hundred pool boiling tests aboard the ISS between March and April 2011. In the ISS microgravity environment, the heat transfer mechanisms during bubble formation can be determined more accurately since the level of g-jitter (ie, vibrations from the spacecraft, aboard machinery, and crew) is much less than with short-duration experiments using sounding rockets or drop towers. Surface tension dominated boiling (SDB), characterized by the formation of a non-departing coalesced bubble, occurs on small heaters in microgravity. It is found that once a stationary, coalesced bubble covers the heater, a small change in the gravity level would only change the bubble shape without significantly affecting the steady state value of heat transfer. By comparison, if the gravity levels continuously fluctuate as is the case in parabolic flights where the g-jitter values are relatively large, the resulting continuous adjustments in bubble shape can produce flow around the bubble increasing the heat transfer. In essence, the fluctuation in acceleration (g-jitter) affects heat transfer more than the absolute value of acceleration in the SDB case. Microgravity heat transfer predictions based on modified scaling law and taking into account g-jitter effects were shown to be in excellent agreement with experimental data. This is one of the most significant findings of the current work performed under space microgravity environments and may address the widely discussed problem of the effect of g-jitter on pool boiling studies (Rishi 2012).



Microheater Array Boiling Experiment Image: High-speed, time-lapse imagery documenting nucleation of three separate vapor bubbles (top image), coalescence of the middle and right bubble (middle image), and finally after all the vapor bubbles have merged. NASA image.

Publication(s)

Raj R, Kim J, McQuillen J. Pool boiling heat transfer on the International Space Station: Experimental results and model verification. *Journal of Heat Transfer*. 2012;134(10). doi: 10.1115/1.4006846.

This investigation is complete and all results are published.

CHAOS, TURBULENCE AND ITS TRANSITION PROCESS IN MARANGONI CONVECTION (MARANGONI-EXP)

Research Area: Fluid Physics
Expedition(s): 17-34
Principal Investigator(s):
- Hiroshi Kawamura, Tokyo University of Science, Suwa, Japan
- Koichi Nishino, Yokohama National University, Yokohama, Japan

RESEARCH OBJECTIVES

Chaos, Turbulence and its Transition Process in Marangoni Convection (Marangoni-Exp) is the flow driven by the presence of a surface tension gradient, which can be produced by temperature difference at a liquid/gas interface. The convection in liquid bridge of silicone oil is generated by heating the one disc higher than the other. Scientists are observing flow patterns of how fluids move to learn more about how heat is transferred in microgravity.

EARTH BENEFIT

The obtained knowledge on the Marangoni convection is vital for the production of high-quality crystal growth such as semiconductors, optical crystal, and so on. Since the surface tension is dominant not only under the microgravity but also in the micro-scale, the results obtained on the nature of the Marangoni convection will significantly contribute to various micro-fluid handling techniques in micro-TAS (Micro total analysis system) such as DNA examination and clinical diagnostics.

ISS020E048792 – Canadian Space Agency astronaut Robert Thirsk, Expedition 20/21 flight engineer, holds Fluid Physics Experiment Facility/Marangoni Surface (FPEF MS) Core hardware in the Kibo laboratory of the International Space Station. JAXA image.

SPACE BENEFIT

The valuable knowledge from Marangoni space experiment is also applicable to the high-performance heat exchanger and heat pipe both in space and on the Earth. For future space development, it should be necessary to design a more efficient and compact thermal management system, no doubt to help its development.

RESULTS

Five series of experiments, Marangoni Experiment in Space was carried out from 2008 to 2013 in the Fluid Physics Experiment Facility (FPEF) in the Kibo laboratory aboard the International Space Station (ISS).

A set of new data on the transition to oscillatory flow was obtained by observing the traveling of the hydrothermal wave in several runs within the liquid bridges created between 2 plates at different temperature settings. Several flow visualization techniques have been applied to liquid bridge, and 3-Dimensional Particle Tracking Velocimetry (3-D PTV) was used to reveal highly 3-D flow patterns that appear after the transition. Conventional 3-D PTV and multi-frame particle tracking were combined to obtain a better understanding of unsteady, 3-D flow fields in a (standing or traveling wave) oscillatory state. As the result, it was observed that the flow patterns change from a 2-D axisymmetric steady flow to a 3-D non-axisymmetric unsteady flow, when the temperature difference exceeds a certain level. Temperature difference along the free (unbound) surface produces surface tension gradient, so that warmer material will move toward a cooler along the surface, which process is known as thermocapillary convection. Depending upon surface boundary conditions, the fluid movement may be uniform and steady or become wobbly and unstable. The MEIS hardware setup is designed to identify these critical conditions. In microgravity, it is possible to form floating silicone oil columns many times larger than on Earth allowing for a highly detailed study of convection and instability within these "liquid bridges" (LBs).

PUBLICATION(S)

Yano T, Nishino K, Kawamura H, Ueno I, Matsumoto S. Instability and associated roll structure of Marangoni convection in high Prandtl number liquid bridge with large aspect ratio. *Physics of Fluids*. 2015;27(2)024108. doi: 10.1063/1.4908042.

Sato F, Ueno I, Kawamura H, et al. Hydrothermal wave instability in a high-aspect-ratio liquid bridge of Pr > 200. *Microgravity Science and Technology*. 2013;25(1):43-58. doi: 10.1007/s12217-012-9332-7.

Kawamura H, Nishino K, Matsumoto S, Ueno I. Report on microgravity experiments of Marangoni convection aboard International Space Station. *Journal of Heat Transfer*. 2012;134(3):031005-1-031005-13. doi: 10.1115/1.4005145.

Goto M, Sakagami K, Matsumoto S, Ohkuma H. Entering "A NEW REALM" of KIBO Payload Operations - Continuous efforts for microgravity experiment environment and lessons learned from real time experiment operations in KIBO. *Journal of Physics: Conference Series*. 2011;327(012054):1-13. doi: 10.1088/1742-6596/327/1/012054.

Yano T, Nishino K, Kawamura H, et al. Space experiment on the instability of Marangoni convection in large liquid bridge-MEIS-4: Effect of Prandtl number. *Journal of Physics: Conference Series*. 2011;327. doi: 10.1088/1742-6596/327/1/012029.

Yano T, Nishino K, Kawamura H, et al. Three-D flow measurement of oscillatory thermocapillary convection in liquid bridge in MEIS. *Japan Society of Microgravity Application*. 2011;28(2):126-132.

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Abe Y, Ueno I, Kawamura H. Effect of shape of HZ liquid bridge on particle accumulation structure (PAS). *Microgravity Science and Technology*. October 2007;19(3/4):84-86. doi: 10.1007/BF02915760.

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Ueno I, Tanaka S, Kawamura H. Various flow patterns in thermocapillary convection in half-zone liquid bridge of high prandtl number fluid. *Advances in Space Research*. July 2003;32(2):143-148. doi: 10.1016/S0273-1177(03)90244-4.

These investigations are ongoing and additional results are pending publication.

SPATIO-TEMPORAL FLOW STRUCTURE IN MARANGONI CONVECTION (MARAGONI-UVP)

Research Area: Fluid Physics
Expedition(s): 22-24, 26-27, 35-ongoing
Principal Investigator(s):
- Shinichi Yoda, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

The Spatio-temporal Flow Structure in Marangoni Convection (Marangoni-UVP) investigation is another of several investigations being carried out by JAXA to investigate Marangoni convection, a process driven by the presence of a surface tension gradient as produced by temperature differences occurring at a liquid/gas interface. Oscillatory convection, three-dimensional (3-D) flow and particle accumulation structure (PAS) formation are all ideally observed using the Fluid Physics Experiment Facility (FPEF) and the ideal convection characteristics afforded by the microgravity environment. Continued research and understanding of liquid flow characteristics may lead to the development of highly efficient industrial process and products involving semiconductors, optical materials, bio materials, and thermal transport devices.

EARTH BENEFIT

The obtained knowledge on the Marangoni convection is vital for the production of high-quality crystal growth such as semiconductors, optical crystal, and so on. Since the surface tension is dominant not only under the microgravity but also in the micro-scale, the results obtained on the nature of the Marangoni convection will significantly contribute to various micro-fluid handling techniques in micro-TAS (Micro total analysis system) such as DNA examination and clinical diagnostics.

SPACE BENEFIT

The valuable knowledge from Marangoni space experiment is also applicable to the high-performance heat exchanger and heat pipe both in space and on the Earth. For future space development, it should be necessary to design more efficient and compact thermal management system, no doubt to help its development.

RESULTS

The Marangoni Ultrasonic Velocity Profiler (UVP) produced data to advance the field of fluid physics and obtain knowledge concerning the aspect ratio effect on the onset of flow transition over a wide range of conditions. Marangoni UVP-2 was terminated after the eleventh experiment run when the experiment cell was damaged during a sample exchange operation. Marangoni UVP-2R (UVP-2R) provided experimental data showing a strong convection regime could not be accumulated because the experiment cell was re-damaged. The damaged experiment cell will be refurbished on the ground. UVP-2RR will be manifested on a later increment in order to continue the runs not performed during the UVP-2R experiment runs.

This Investigation is ongoing and additional results are pending publication.

Miscible Fluids in Microgravity (MFMG)

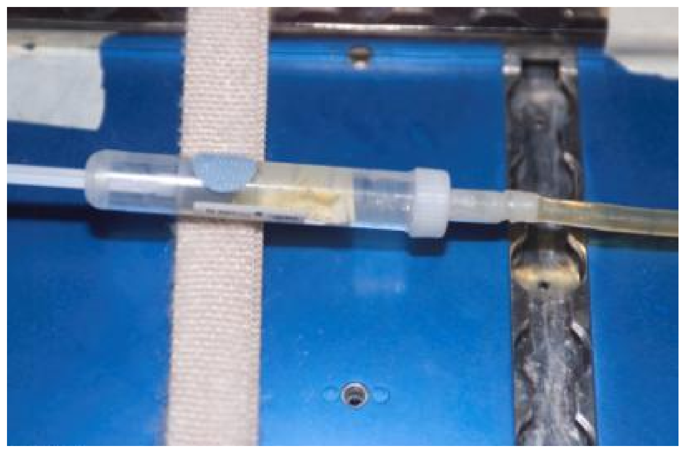
Research Area: Fluid Physics
Expedition(s): 8-11 and 29-ongoing
Principal Investigator(s):
- John A. Pojman, PhD, Louisiana State University, Baton Rouge, Louisiana

Research Objectives

Honey and water are miscible fluids, that it, fluids that dissolve completely in each other. Miscible Fluids in Microgravity (MFMG) involves having water injected into honey to test if it will act like an immiscible fluid, such as water being injected into oil, and spontaneously form a spherical drop. The experiment needs to be performed in weightlessness.

Earth Benefits

The experiment may have relevance to microfluidics.



ISS008E18731 – View of a syringe connected to a drinking straw containing a mixture of honey and water for the Miscible Fluids in Microgravity.

Space Benefits

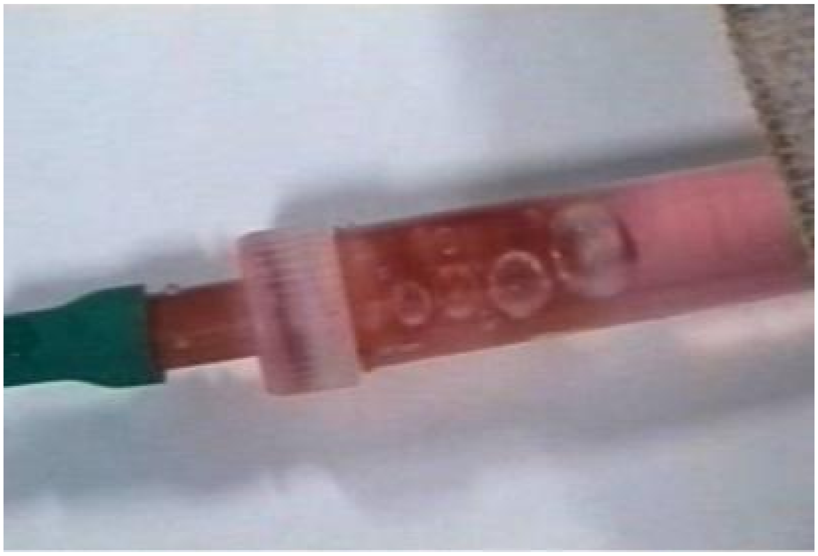
If we show that convection can be caused by an effective interfacial tension between miscible fluids, then this fact might be important for materials processing and fluid handling in weightlessness.

Results

The goal of MFMG was to determine if interfacial phenomena seen with immiscible fluids could be seen with miscible fluids. The experiments had to be performed with existing materials on the International Space Station (ISS). Honey and water were chosen as the fluids, and urine collection syringes were used as the vessels in which the experiments were performed. Four experiments were performed under isothermal conditions to determine: if a stream of honey injected into water would exhibit the Rayleigh-Tomotika instability and break into small drops or if an aspherical drop of water in honey would spontaneously assume a spherical shape. Two sessions in which a stream of honey was injected into water while the syringe was attached to the surface of the Commercial Generic Bioprocessing Apparatus (CGBA) at approximately 31°C. No change in the stream shape was observed. No behavior beyond simple diffusion was observed. We performed simulations with the Navier-Stokes equations plus a Korteweg stress term. We estimated that the maximum possible value of the square gradient parameter was 10-12 N for the honey-water system (Pojman 2005).

Publication(s)

Pramanik S, Mishra M. Linear stability analysis of Korteweg stresses effect on miscible viscous fingering in porous media. *Physics of Fluids*. 2013;25:074104. doi: 10.1063/1.4813403.



ISS011m031541830 - Video image capture of a close-up view of the Miscible Fluids Microgravity (MFMG) experiment at the Maintence Work Area (MWA) in the US Lab. Bubbles are visible in a syringe filled with a red fluid.

Pojman JA, Bessonov N, Volpert V, Paley MS. Miscible Fluids in Microgravity (MFMG): A zero-upmass experiment on the International Space Station. *43rd Aerospace Sciences Meeting and Exhibit*, Reno, NV; January 10-13, 2005.

This investigation is ongoing and additional results are pending publication.

NanoRacks – The Ohio State University Zeolite Crystal (NanoRacks-OSU-Zeolite)

Research Area: Fluid Physics

Expedition(s): 25/26

Principal Investigator(s):
- Michael Snyder, Ohio State University, Columbus, Ohio, United States

Research Objectives

NanoRacks-The Ohio State University Zeolite Crystal Growth (NanoRacks-OSU-Zeolite) processes materials science samples in microgravity. The science goals for NanoRacks-OSU-Zeolite are proprietary.

NanoRacks- The Ohio State University Zeolite Crystal Growth (NanoRacks-OSU-Zeolite) is an experiment designed to mix compounds used for a microgravity crystal growth experiment. Image courtesy of NanoRacks, LLC.

Earth Benefits

The long-term goal of this project is to enhance technological, industrial, and educational growth for the benefit of people on Earth.

Space Benefits

This investigation is a part of a series of investigations to be conducted aboard the International Space Station (ISS) to provide the foundation for use of the ISS as a National Laboratory following assembly complete.

This investigation is complete, and additional results are pending publication.

NUCLEATE POOL BOILING EXPERIMENT (NPBX)

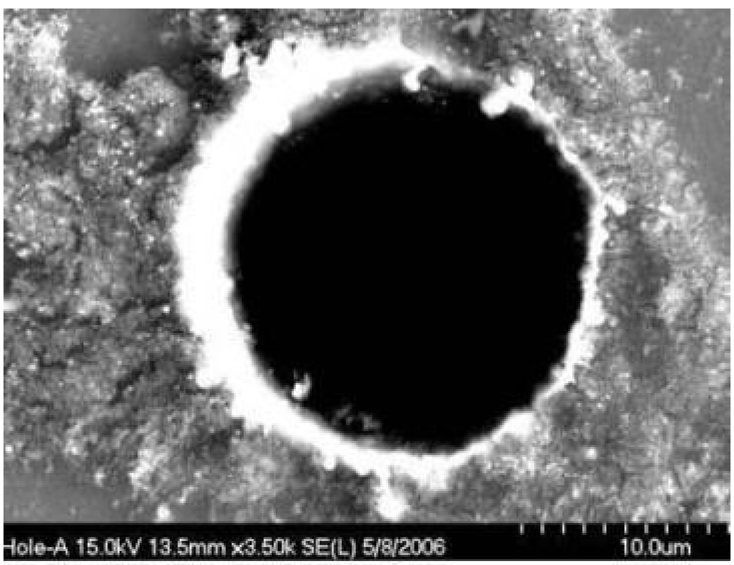
Research Area: Fluid Physics
Expedition(s): 27 and 28
Principal Investigator(s):
- Vijay K. Dhir, PhD, University of California, Los Angeles, Los Angeles, California

RESEARCH OBJECTIVES

Nucleate boiling is bubble growth from a heated surface and the subsequent detachment of the bubble to a cooler surrounding liquid (bubbles in microgravity grow to different sizes than on Earth). As a result, these bubbles can transfer energy through fluid flow; the Nucleate Pool Boiling Experiment (NPBX) investigation provides an understanding of heat transfer and vapor removal processes that take place during nucleate boiling in microgravity. This understanding is needed for optimum design and safe operation of heat exchange equipment that uses nucleate boiling as a way to transfer heat in extreme environments of the deep ocean (submarines) and microgravity.

EARTH BENEFITS

The proposed research provides a fundamental understanding of bubble dynamics and heat transfer during nucleate boiling in extreme conditions. Such an understanding optimizes the design and safe operation of heat exchange equipment employing phase change for transfer of heat in the environments of the deep ocean, extreme cold, and high altitudes.



Nucleate Pool Boiling eXperiment heater wafer. Polished aluminum wafer (reflecting a black background) that was manufactured with 5 nucleation cavities (~20 microns in diameter) to initiate boiling at specific locations. NASA's Glenn Research Center image.

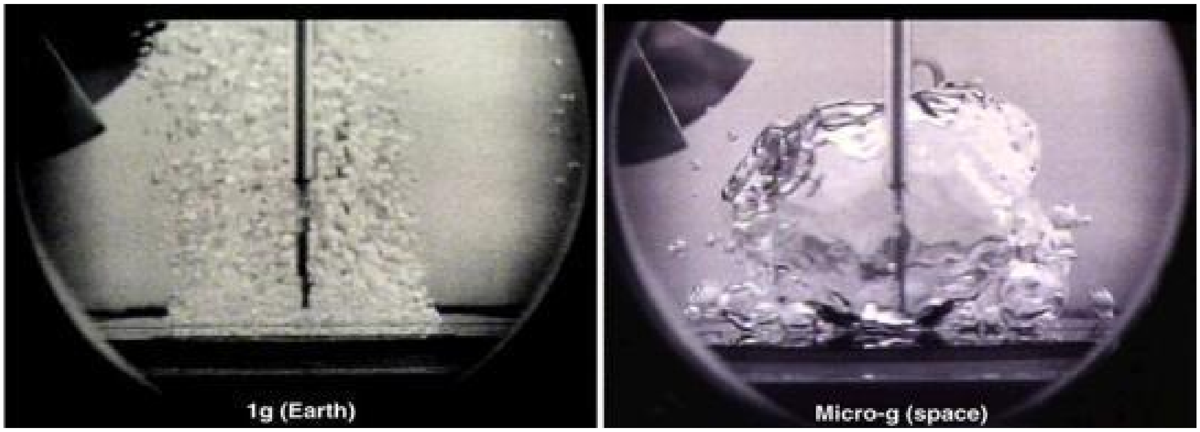
SPACE BENEFITS

The experiments will give engineers the capability to achieve cooling of various components and systems used in space in an efficient manner and thereby lead to smaller and lighter space exploration systems.

RESULTS

In the Nucleate Pool Boiling Experiment (NPBX) single bubble dynamics (eg, inception and growth), multiple bubble dynamics (lateral merger and departure, if any), nucleate pool boiling heat transfer, and critical heat flux using Perfluoro-n-hexane as the test liquid are investigated.

The results of the experiments show that a single bubble continues to grow to occupy the size of the chamber without departing from the heater surface. During lateral merger of bubbles, at high superheats (heating the surface beyond the boiling point) a large bubble may lift off from the surface but continue to hover near the surface while pulling smaller neighboring bubbles into it and growing in size consistent with predictions from numerical simulations. At low superheats, bubbles at neighboring sites simply merge to yield a larger bubble. The larger bubble mostly locates in the middle of the heated surface and serves as a sink for vapor generated on the heated surface. The latter mode continues to persist when boiling is occurring



In Earth's gravity (image on the left) the action of buoyancy allows the bubbles to overcome surface tension forces. The bubbles rise upward away from the heater surface. In microgravity (image on the right) the buoyancy force is very weak. Consequently, the bubbles often remain attached to the heater because of surface tension and become large as more vapor is produced due to the continuous input of energy from the heater. University of California image.

all over the heater surface. This behavior of vapor removal is very different from that at Earth normal gravity where single or merged bubbles rapidly lift off from the surface. Heat fluxes for steady state nucleate boiling and critical heat fluxes are found to be much lower than those obtained under Earth's normal gravity conditions and also lower than previous data obtained on space shuttles, but higher than that predicted by the hydrodynamic theory extrapolated to microgravity. Aside from experimental conditions, rate of nucleate boiling heat transfer will be dependent on relative heater size and fluid confinement. This data is useful for calibration of results of numerical simulations with the condition that correlations that are developed for nucleate boiling heat transfer under microgravity conditions must account for the existence of vapor escape path (sink) from the heater, size of the heater, and the size and geometry of the chamber (Dhir 2012).

Publication(s)

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Aktinol E, Warrier GR, Dhir VK. Single bubble dynamics under microgravity conditions in the presence of dissolved gas in the liquid. *International Journal of Heat and Mass Transfer*. December 2014;79:251-268. doi: 10.1016/j.ijheatmasstransfer.2014.08.014.

Dhir VK, Warrier GR, Aktinol E, et al. Nucleate Pool Boiling Experiments (NPBX) on the International Space Station. *Microgravity Science and Technology*. 2012;24(5):307-325. doi: 10.1007/s12217-012-9315-8.

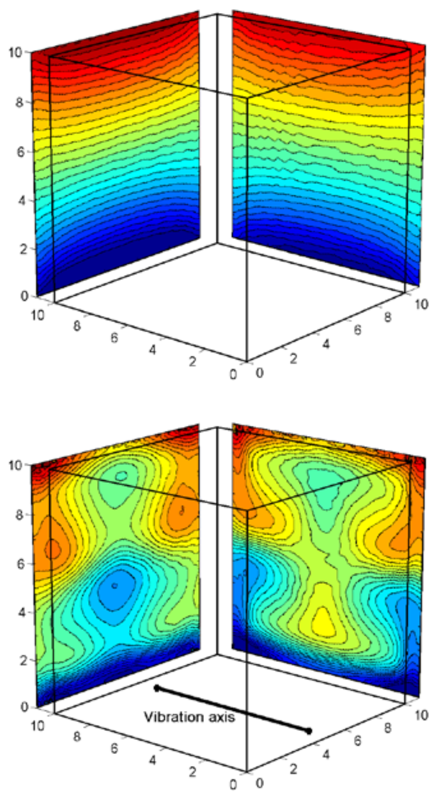
This investigation is complete and all results are published.

Selectable Optical Diagnostics Instrument - Influence of VIbrations on DIffusion of Liquids (SODI-IVIDIL)

Research Area: Fluid Physics
Expedition(s): 19-22
Principle Investigator(s):
- Valentina Shevtsova, University of Brussels, Brussels, Belgium

Research Objectives

The Selectable Optical Diagnostics Instrument - Influence of VIbrations on DIffusion of Liquids (SODI-IVIDIL) investigation studies the influence of controlled vibrations on diffusion in liquids in the absence of buoyant convection (transfer of heat by movement) in microgravity. These studies represent part of a series of investigations on the International Space Station (ISS) on how heat and particles move through liquids in microgravity. SODI-IVIDIL investigates the effects of residual vibrations (g-jitter) on experiments involving diffusion in liquids. Researchers plan to characterize the spectral influence of g-jitter to increase the understanding of the kinetic mechanisms influencing diffusion effects in the presence of vibrations, therefore allowing for more successful science to be operated aboard ISS.



Comparison between the convection flow without vibration (top) and with strong vibration (bottom) from IVIDIL. ESA image.

Earth Benefits

Based on previous studies, scientists have developed numerical simulations to help understand oil behaviors in a drilled well. The SODI-IVIDIL experiment allows scientists to confirm and refine the parameters of their models, leading to more accurate predictions about oil wells being considered for extraction. This investigation also data for applications to fields in mineralogy and geophysics for predictions about the locations of natural resources beneath the Earth's surface.

Space Benefits

The SODI-IVIDIL experiment investigates the effects of residual vibrations (g-jitter) on experiments involving diffusion in liquids. Researchers plan to characterize the spectral influence of g-jitter to increase the understanding of the kinetic mechanisms influencing diffusion effects in the presence of vibrations, therefore allowing for more successful science to be operated aboard ISS.

RESULTS

View of the Selectable Optical Diagnostics Instrument - Influence of Vibrations on Diffusion of Liquids investigation in the Microgravity Science Glovebox in the Columbus module of the International Space Station. NASA image.

Experimental runs focused on the evolution of the liquid's concentration field both with and without imposed vibrations. In the absence of vibration, there was no movement in the system and the concentration field mirrors the structure of the temperature field. However, in the presence of external vibration, more sophisticated flow patterns emerged. When vibration-free experimental data from the concentration profiles were compared with numerical predictions, the concentration profile was linear and in agreement with the predicted profile, which suggested that g-jitter (residual vibration) had little effect on diffusion. However, high-frequency imposed vibrations did affect diffusion, as seen when the concentration profile deviated from the linear profile under the influence of relatively weak fabricated vibrations.

A closer look at the effect of g-jitter on diffusion processes after the conclusion of each experiment revealed that during the nominal (or quasi-steady) vibration period of the ISS, g-jitter did not affect diffusion in experiments run without imposed vibrations. These results were duplicated when the experiments were repeated with large time lags and different temperature gradients. Furthermore, the experimental results were in agreement with numeric simulations. However, perturbations were evident in experiments without imposed vibrations that ran during periods with abnormal transient movements of the ISS such as orbit correction, docking, or undocking. SODI-IVIDIL was the first successful in-orbit experiment to characterize the effect of onboard g-jitter. The results from IVIDIL shed light on the complex mechanisms behind vibration-induced convection and provide useful insight on how to control fluids in space to support future physical and life science experiments.

PUBLICATION(S)

Sechenyh V, Legros JC, Shevtsova V. Measurements Of Optical Properties In Binary And Ternary Mixtures Containing Cyclohexane, Toluene, And Methanol. *J. Chem. Engineering Data, Vol. 57* (4), pp. 1036–1043. (2012) DOI: 10.1021/je201277d.

Shevtsova V, Melnikov D, Lyubimova T, Legros JC, Gaponenko Y, Saghir Z, Sechenyh V, Mialdun A. IVIDIL: on-board g-jitters and diffusion controlled phenomena. *J. Phys.: Conf. Ser, vol. 327*, pp. 1-10. (2011) DOI: 10.1088/1742-6596/327/1/012031

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Shevtsova V, Sechenyh V, Nepomnyashchy A, Legros JC. Analysis Of The Application Of Optical Two Wavelength Techniques To Measurement Of The Soret Coefficients In Ternary Mixtures. *Philosophical Magazine, Vol. 91* (26), pp. 3498 – 3518. (2011) DOI: 0.1080/14786435.2011.586376.

Mazzoni S, Shevtsova V, Melnikov D, Lyubimova T, Gaponenko Y, Saghir Z, Mialdun A. Vibrating liquids in Space. *Europhysics News vol. 41*(6): 14-16. (2010) DOI: 10.1051/epn/2010601.

This investigation is complete, and all results are published.

European Technology Exposure Facility- Plasma Electron Gun Payload (EuTEF-PLEGPAY)

Research Area: Fundamental Physics
Expedition(s): 16-20
Principal Investigator(s):
- Giovanni Noci, Thales Alenia Space, Florence, Italy

Research Objectives

The European Technology Exposure Facility-Plasma Electron Gun Payload (EuTEF-PLEGPAY) experiment is electrostatic charging and discharging of gases in low-Earth orbit on large space structures, identifying a potentially fatal problem for spacecraft electronics. In order to perform controlled experiments, PLEGPAY provides a pressurized gas tank with dose controller and timer, such that the inert gas xenon can be released into the chamber where it becomes ionized by electrons emitted by an insert for ignition.


Plasma Electron Gun Payload instrument located on the outside of the International Space Station. ESA image.

Results

The first runs of the first PLEGPAY experiment demonstrated the capability of the plasma contactor device to control the potential of a very large spacecraft such as the International Space Station (ISS) through the biasing of the plasma contactor. Furthermore, experiment 2 demonstrated the capability to lock the ISS potential around zero by small current emission, and the PLEGPAY Langmuir Probe measurements were found to match the independent floating potential measurements made by the NASA Floating Potential Measurement Unit.

This investigation is complete; however additional results are pending publication.

PLASMA CRYSTAL RESEARCH ON THE ISS (PK-3 PLUS)

Research Area: Fundamental Physics
Expedition(s): 12-40
Principle Investigator(s):
- Gregor Morfill, Max Planck Institute for Extraterrestrial Physics, Garching, Germany
- Vladimir E. Fortov, the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

Plasma crystals form under certain conditions in complex (dusty) plasma when electrically charged dust particles arrange themselves in a regular macroscopic crystal lattice under favorable parameters. This structure allows for an investigation of the properties of condensed matter on the kinetic level. This means that basic processes, such as melting and movement, can be followed by observing the motion of individual particles. Plasma Crystal Research on the ISS (PK-3) gives researchers a better understanding of plasma in space and helps to determine the critical points where crystalline structures appear in the plasma.

German ESA astronaut Thomas Reiter aboard the International Space Station with the PK-3 Plus laboratory. The Experiment Container is mounted in the Service Module. NASA image.

EARTH BENEFITS

Plasma studies in outer space could provide answers to our questions about terrestrial plasmas such as lightning.

SPACE BENEFITS

Learning more about the space environment helps us better explore it. We can work safer, understand better, and ultimately travel further if we know more about the plasmas of space.

RESULTS

The PK-3 Plus experiments were dedicated to observe basic, complex plasma conditions and provide much better insights into the properties of complex plasmas. The difference between using argon or neon as the neutral gas was clear to see. Argon plasma showed a brighter glow, corresponding to a higher ionization rate close to the electrodes. The neon plasma showed a homogeneous distribution of the glow between the 2 electrodes. Although one could imagine that a homogeneous plasma distribution would cause a similar distribution in a complex plasma, the experiments showed the opposite. The argon distribution gives the best conditions for homogeneous, void-free complex plasma, while the neon glow distribution unexpectedly resulted in a big void for identical gas and electrical parameters. The physical reason for this difference was not clear. There are a number of important differences between complex plasma parameters in neon and argon, eg, different ion mass and mean free path, different plasma density, different electron temperature, etc.

PK-3 Plus showed that the “void” in the center of the complex plasma cloud could be easily closed under certain conditions, thus providing a much better homogeneity of the complex plasma, a feature that was hardly achievable before. This is very promising as it is essential for many precision studies and enables new manipulation possibilities for future experiments. Instabilities in the plasma (eg, heartbeat instability that causes continuous contraction and expansion of the void, which the microparticles follow) appeared at high microparticle densities and were strongly related to changes in the plasma glow. However, even though homogeneous and void-free plasma is advantageous for modelling solid (crystalline), fluid and gas phases and transitions between different phases, the reason for the void appearance in the neon distribution, has created an interesting field of study for the future by itself.

PUBLICATION(S)

Petrov OF, Fortov VE. Collective phenomena in strongly coupled dissipative systems of charged dust: From ground to microgravity experiments. *Contributions to Plasma Physics.* December 2013;53(10):767-777. doi: 10.1002/ctpp.201310052.

Worner L, Ivlev AV, Couëdel L, et al. The effect of a direct current field on the microparticle charge in the plasma afterglow. *Physics of Plasmas.* 2013;20(12):123702. doi: 10.1063/1.4843855.

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Zhukhovitskii DI, Fortov VE, Molotkov VI, et al. Nonviscous motion of a slow particle in a dust crystal under microgravity conditions. *Physical Review E.* 2012;86(1-2):016401.

Schwabe M, Jiang K, Zhdanov SK, et al. Direct measurement of the speed of sound in a complex plasma under microgravity conditions. *EPL (Europhysics Letters).* December 2011;96(5):55001. doi: 10.1209/0295-5075/96/55001.

Kretschmer M, Konopka U, Zhdanov SK, et al. Particles inside the void of a complex plasma. *IEEE Transactions on Plasma Science.* November 2011;39(11):2758-2759. doi: 10.1109/TPS.2011.2135383.

Molotkov VI, Lipaev AM, Naumkin VN, et al. Phase transitions in dust plasma in microgravity. *Conference on Low Temperature Plasma Physics*, Petrozavodsk, Russia; June 21-27, 2011. 146-151.

Heidemann RJ, Couëdel L, Zhdanov SK, et al. Comprehensive experimental study of heartbeat oscillations observed under microgravity conditions in the PK-3 Plus laboratory on board the International Space Station. *Physics of Plasmas.* May 16, 2011;18:053701. doi: 10.1063/1.3574905.

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Klumov BA, Joyce G, Rath C, et al. Structural properties of 3D complex plasmas under microgravity conditions. *EPL (Europhysics Letters).* October 2010;92(1):15003. doi: 10.1209/0295-5075/92/15003.

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Ivlev AV, Brandt PC, Morfill GE, et al. Electrorheological complex plasmas. *IEEE Transactions on Plasma Science*. April 2010;38(4):733-740. doi: 10.1109/TPS.2009.2037716.

Liu B, Goree JA, Fortov VE, et al. Dusty plasma diagnostics methods for charge, electron temperature, and ion density. *Physics of Plasmas*. 2010;17(5):053701. doi: 10.1063/1.3400225.

Sutterlin KR, Thomas HM, Ivlev AV, et al. Lane formation in driven binary complex plasmas on the International Space Station. *IEEE Transactions on Plasma Science*. April 2010;38(4):861-868. doi: 10.1109/TPS.2009.2035504.

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Jiang K, Nosenko V, LI YF, et al. Mach cones in a three-dimensional complex plasma. *EPL (Europhysics Letters).* February 2009;85(4):45002. doi: 10.1209/0295-5075/85/45002.

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Sutterlin KR, Wysocki A, Ivlev AV, et al. Dynamics of lane formation in driven binary complex plasmas. *Physical Review Letters*. February 2009;102(8):085003. doi: 10.1103/PhysRevLett.102.085003.

Takahashi K, Thomas HM, Morfill GE, Ivlev AV, Hayashi Y, Adachi S. Diagnosis in complex plasmas for microgravity experiments (PK-3 plus). *Fifth International Conference on the Physics of Dusty Plasmas*, Ponta Degada, Azores, Portugal; May 18-23, 2008.

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This investigation is complete; however additional results are pending publication.

PRODUCTION OF TWO-DIMENSIONAL NANOTEMPLATE IN MICROGRAVITY (2D-NANOTEMPLATE)

Research Area: Materials Science

Expedition(s): 23, 24, 27-30

Principal Investigator(s):
- Takatoshi Kinoshita, PhD, Nagoya Institute of Technology, Nagoya, Japan

RESEARCH OBJECTIVES

Production of Two-Dimensional Nanotemplate in Microgravity (2D-Nanotemplate) fabricates large and highly oriented nanoscale 2-D arranged peptide arrays, by suppressing convection and sedimentation.

EARTH BENEFIT

There is an ongoing trend toward miniaturization and functionalization in the semiconductor industry. The technique demonstrated in space can be applied to the production of high performance semiconductor elements.

SPACE BENEFIT

It is expected that the nanotemplate produced in space will tend to have higher quality. The semiconductor material made of the space-produced nanotemplate should have higher quality and performance. Therefore, the experiment will lead to development of high-performance computers, application to the blue LED lights, and realization of cost reduction in manufacturing of semiconductor products.

ISS024E007811 – View of Doug Wheelock as he retrieves 2-D Nanotemplate sample bags from the Minus Eighty Laboratory Freezer for ISS (MELFI) in U.S Destiny laboratory during Expedition 24. JAXA image.

RESULTS

Amino acid chains (peptide particles) were flown aboard the International Space Station (ISS) and were subjected to concentrated sodium hydroxide (NaOH) solution and allowed to create peptide arrangements for 1 week in a microgravity environment. All samples were successfully retrieved and analyzed.

The peptides formed in orbit in a microgravity environment showed similar nanoscaled patterns with typical structures obtained on the ground in a 1G environment. It indicates that the motion of the peptide is not influenced by microgravity in this experimental system. However, the suppression effect of convection in the microgravity environment was apparent. The formed nanopatterns were sophisticated by keeping away from adsorption of unexpected aggregates.

PUBLICATION(S)

Tanaka M, Abiko S, Himeiwa T, Nakamura M, Koshikawa N, Kinoshita T. Two-dimensional self-assembly of amphiphilic peptide at the solid/water interface toward a facile method for metal nanoparticle alignment. *Chemistry Letters*. 2012;41(10):1221-1222. doi: 10.1246/cl.2012.1221.

Cai R, Zhao Y, Ogura K, Tanaka M, Kinoshita T, Cai Q. Self-assembled gels of amphiphilic sequential peptide in water and organic solvents. *Chemistry Letters*. 2011;40(6):617-619. doi: 10.1246/cl.2011.617.

Nonoyama T, Tanaka M, Kinoshita T, Nagata F, Sato K, Kato K. Morphology control of calcium phosphate by mineralization on the β-sheet peptide template. *Chemical Communications*. 2010;46(37):6983-6985. doi: 10.1039/c0cc02012e.

This investigation is complete; however additional results are pending publication.

JAXA THREE-DIMENSIONAL PHOTONIC CRYSTAL EXPERIMENT (3DPC)

Research Area: Materials Science
Expedition(s): 12, 16
Principal Investigator(s):
- Kensaku Ito, University of Toyama, Toyama, Japan
- Junpei Yamanaka, Nagoya City University, Nagoya, Japan
- Yoshihiro Takiguchi, Hamamatsu Photonics KK, Hamamatsu, Japan

RESEARCH OBJECTIVES

This experiment is aimed at developing technology to make 3-D photonic crystals (3DPC) by self-arrangement of colloidal nanoparticles in space. The photonic crystal will be widely used for optical devices such as optical spectral analyzers or pulse compression/extension devices. This study also demonstrates the effectiveness of the microgravity environment for industrial application.

EARTH BENEFIT

The findings of this experiment, including numerous patents, led to industrial applications such as the research and development of a pen-shaped micro spectroscope that uses a millimeter-sized photonic crystal and the manufacturing of uniform-sized silica microparticles. Moreover, the findings also led to the development of a new colloid crystallization method, which in turn helped start several related venture companies.

Photonic Crystal made in space. JAXA image.

SPACE BENEFIT

This investigation is applied to new knowledge, and not specifically to advances in space exploration.

RESULTS

The 3DPC Experiment was flown aboard the International Space Station (ISS). Millimeter-sized photonic crystals made with silica particles were obtained. As a result of reflectance spectrometry, improvement in uniformity of grid interval was observed. It was confirmed that uniform photonic crystal made with 200 nm-sized silica particles was achieved for the first time in human history due to the micro-gravity environment. Generation of centimeter-sized uniform photonic crystals made with heavier particles than silica was not obtained in this experiment.

Publication(s)

Murai M, Okuzono T, Yamamoto M, Toyotama A, Yamanaka J. Gravitational compression dynamics of charged colloidal crystals*. Journal of Colloid and Interf*ace Science. 2012;370:39-45.

Ohki Y, Ikeda T, Itoh A, et al. Space experiment on 3-dimensional photonic crystal growth and its apparatus. *Journal of the Japan Society for Aeronautical and Space Sciences. Space Tech*. 2009;7(26):Th21-Th26.

Takiguchi Y. Industrial application of three-dimensional colloidal photonic crystals made in space*. Journal of Physics, Conference Series.* 2008;109:012004.

Yamada H, Sawada T, Yamanaka J, Yonese M, Uchida F. Structural characterizations of charged colloidal silica crystals formed by base diffusion*. Chemistry Lett*ers. 2008;37(2):172-173.

Murai M, Yamada H, Yamanaka J, et al. Unidirectional crystallization of charged colloidal silica due to the diffusion of a base. *Langmuir*. 2007;23(14):7510–7517.

Wakabayashi N, Yamanaka J, Murai M, Ito K, Sawada T, Yonese M. Three-dimensional centimeter-sized colloidal silica crystals formed by addition of base. *Langmuir*. 2006;22(18):7936–7941.

This investigation is complete and all results are published.

COLUMNAR-TO-EQUIAXED TRANSITION IN SOLIDIFICATION PROCESSING (CETSOL)

Research Area: Materials Science

Expedition(s): 21-30

Principal Investigator(s):

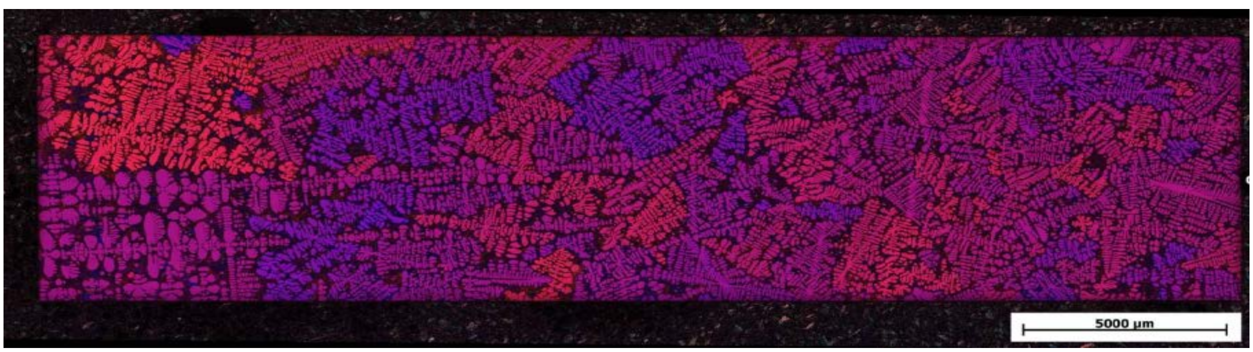
- Charles-Andre Gandin, MINES ParisTech CEMEF, Sophia Antipolis, France
- Bernard Billia, Aix-Marseille Universite´, Marseille, France
- Gerhard Zimmermann, ACCESS e.V., Aachen, Germany
- Yves Fautrelle, Centre National de la Recherche Scientifique, Grenoble, France
- David Browne, National University of Ireland, Dublin, Ireland
- David Poirier, University of Arizona, Tucson, Arizona

RESEARCH OBJECTIVES

Columnar-to-Equiaxed Transition in Solidification (CETSOL) investigates the transition from one structure to the other in a weightlessness environment to alleviate buoyancy-driven melt flow and the sedimentation of the equiaxed grains. This provides the benchmark samples to validate numerical models that attempt to predict and describe this transition that is of high relevance to industrial alloys as the properties of a casting depend on the grain structure.

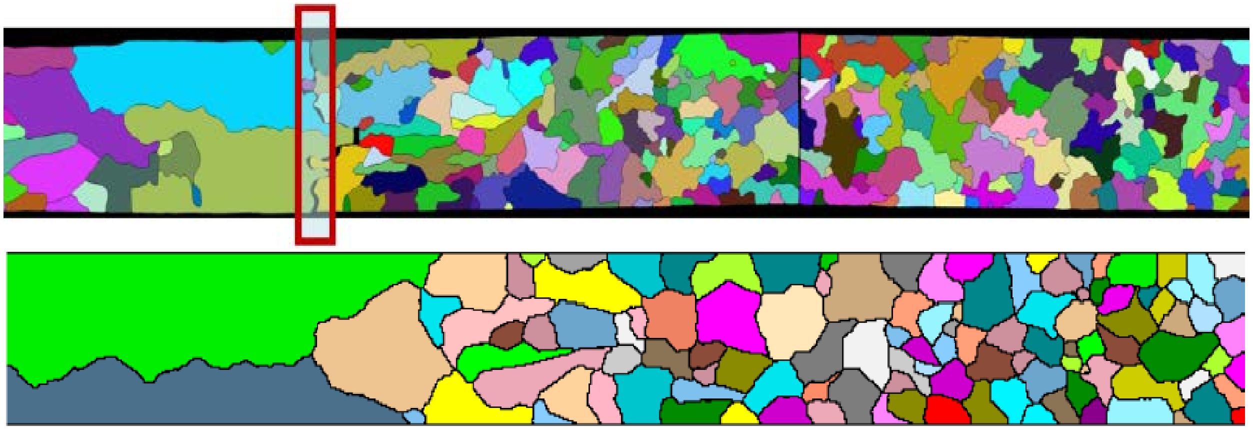
RESULTS

Experimental results are obtained in space using Aluminum-Silicon alloys with, or without, a grain refining suspension directionally solidified under different conditions in the Materials



A typical microstructure obtained in a sample containing grain refiner is featured in the picture below. ESA Image.

Science Laboratory (MSL) on-board the International Space Station (ISS). The analysis of the space samples confirms the occurrence of a columnar-to-equiaxed transition, especially in the refined alloy. Temperature evolution and grain structure analysis provide critical values for the position, the temperature gradient, and the solidification velocity at the columnar to equiaxed transition. A sharp transition is detected when the rate of solidification is increased in contrast to the progressive transition seen when lowering the temperature gradient. Triggering the transition appears to be more difficult in the absence of grain refiner since none of the corresponding samples showed it whereas it was found in sample processed on the ground under similar conditions. This effect is potentially due to the detachment of fragment of dendrites that are less dense than the melt and float up due to gravity towards regions where they serve as nucleation sites for equiaxed grains. Such interpretation appears to be supported by parallel experiments performed under X-ray diagnostics on sounding rocket flights. This unique data are used to improve modelling of solidification microstructures and grain structure on different lengths scales. An example of such a model prediction is depicted in the following picture that can be qualitatively compared with the experimental results presented above.



A detailed analysis of the image and of the crystallographic orientation of the grains enables the scientist to produce the following representation of the sample where the transition from the growth of large columnar dendrites to smaller equiaxed grain is clearly visible (red rectangle). ESA Image.

PUBLICATION(S)

Liu DR, Mangelinck-Noel N, Gandin C, et al. Structures in directionally solidified Al–7wt.% Si alloys: Benchmark experiments under microgravity. *Acta Materialia*. February 2014;64:256-265. doi: 10.1016/j.actamat.2013.10.038.

Mirihanage WU, Browne DJ, Sturz L, Zimmermann G. Numerical modelling of the Material Science Lab - Low Gradient Furnace (MSL-LGF) Microgravity Directional Solidification Experiments on the columnar to equiaxed transition. *IOP Conferene Series: Material Science and Engineering*. January 12, 2012;27(1):012010. doi: 10.1088/1757-899X/27/1/012010.

Sturz L, Zimmermann G, Gandin C, et al. ISS experiments of columnar-to-equiaxed transition in solidification processing. *141st TMS 2012 Annual Meeting and Exhibition*, Orlando, FL; 2012.

Zimmermann G, Sturz L, Billia B, et al. Investigation of columnar-to-equiaxed transition in solidification processing of AlSi alloys in microgravity – The CETSOL project. *Journal of Physics: Conference Series*. December 6, 2011;327(1):012003-12014. doi: 10.1088/1742-6596/327/1/012003.

This investigation is ongoing and additional results are pending publication.

Columnar-to-Equiaxed Transition in Solidification Processing-2 (CETSOL-2)

Research Area: Materials Science

Expedition(s): 27-ongoing

Principal Investigator(s):

- Gerhard Zimmermann, RWTH Aachen University, ACCESS, Aachen, Germany
- Charles-Andre Gandin, (FR), Ecole de Mines de Paris, Sophia Antipolis, France
- Bernard Billia, Aix-Marseille Universite´, Marseille, France
- Yves Fautrelle, Grenoble Institute of Technology, Grenoble, France
- David Browne, National University of Ireland, Dublin, Ireland
- David Poirier, University of Arizona, Tucson, Arizona
- Christoph Beckermann, University of Iowa, Iowa

Research Objectives

Columnar-to-Equiaxed Transition in Solidification Processing-2 (CETSOL-2) investigation aims to deepen the understanding of the physical principles that govern solidification processes in metal alloys. The patterns of the crystals resulting from transitions of liquids to solids is of substantial importance to processes in producing materials such as solar cells, thermoelectrics, and metal alloys.

Earth Benefits

The transport industry is keen to use data from CETSOL-2 to reduce weight and increase strength of aircraft and road vehicles.

Space Benefits

Metal foams are already being used in cars and cranes and research on the International Space Station and is helping to develop newer alloys which can also be used for spacecraft materials and constructions.

This investigation is ongoing and additional results are pending publication.

COARSENING IN SOLID LIQUID MIXTURES-2 (CSLM-2)

Research Area: Materials Science

Expedition(s): 7, 15-17, 23/24

Principal Investigator(s):
- Peter W. Voorhees, PhD, Northwestern University, Evanston, Ill, United States

RESEARCH OBJECTIVES

Coarsening in Solid Liquid Mixtures-2 (CSLM-2) investigates the rates of coarsening of solid particles embedded in a liquid matrix. During this process, small particles shrink by losing atoms to larger particles, causing the larger particles to grow (coarsen) within a liquid lead/tin matrix. This study defines the mechanisms and rates of coarsening that govern similar processes that occur in materials such as turbine blades, dental amalgam fillings, aluminum alloys, etc.

EARTH BENEFITS

On Earth, materials that contain pores created and trapped during solidification degrade properties and cause a distinct weakening in the overall structure of the cast product. Determining what causes these problems will lead to the development of improved manufacturing processes for materials.

ISS007E10467 – Side view of the sample chamber portion of the Coarsening in Solid/Liquid Mixtures-2 experiment installed in the Microgravity Science Glovebox (MSG) of the Destiny Laboratory module. Also visible are cables attaching the hardware to the MSG and a vacuum valve knob.

SPACE BENEFITS

In any mixture that contains particles of different sizes, the large particles tend to grow while the smaller particles shrink in a process called coarsening. Tiny oil droplets coalescing into a large blob are one illustration, but the process occurs in solids as well. Coarsening occurs on Earth during the processing of any metal alloy, and thus, the coarsening process affects products from dental fillings to turbine blades. Since the properties of an alloy are linked to the size of the particles within the solid, coarsening can be used to strengthen materials. This is the case with the majority of aluminum alloys used commercially today. Conversely, if the coarsening process proceeds too long the material can weaken. This occurs in jet turbine blades and is one of the reasons why turbine blades must be replaced after a certain number of hours of service. Thus developing accurate models of the coarsening process is central to creating a wide range of new materials from those used in automobiles to those used in space applications. The results of previous experiments performed on the shuttle have done just that. These models have been incorporated into a computer code that is being used to design many new materials, including materials of importance to NASA's spaceflight program. Solid-liquid systems are ideal systems to study this coarsening process. However, gravity can induce particle sedimentation and thus hamper the studies of coarsening in these mixtures on Earth. The microgravity environment of the space station allows scientists to study the process of coarsening with reduced interference from the sedimentation that occurs on Earth.

RESULTS

Samples from CSLM-2 that were processed during Increment 7 were not able to be returned to Earth in time for evaluating the results. Although the data was lost, engineering data collected on equipment function can benefit subsequent experiments. The CSLM-2 high volume fraction and CSLM-2R low-volume fraction samples were successfully processed and are currently under analysis at Northwestern University. Preliminary analysis of the low-volume fraction samples indicates that the furnaces performed as planned. Recent results show that the particle size distributions for a 30% volume fraction of coarsening phase is very close to that predicted by theory. The particle distribution appears different, perhaps due to the nonspherical shape of the particles that are present at this high volume fraction. Analysis of both the low and high volume fraction samples is continuing.

ISS016E036416 – Expedition 17 Flight Engineer Garrett Reisman works with the Coarsening in Solid Liquid Mixtures-2 (CSLM-2) experiment in the Microgravity Sciences Glovebox. Image was taken in the European Laboratory/Columbus Module during Expedition 16 / Expedition 17 joint operations.

PUBLICATION(S)

Duval WM, Hawersaat RW, Lorik T, Thompson J, Gulsoy EB, Voorhees PW. Coarsening in Solid-liquid Mixtures: Overview of Experiments on Shuttle and ISS. 2013 Materials Science and Technology Conference and Exhibition, Montreal, Quebec, Canada. October 27, 2013.

This investigation is complete, and results are pending publication.

Investigation of Mechanism of Faceted Cellular Array Growth (Facet)

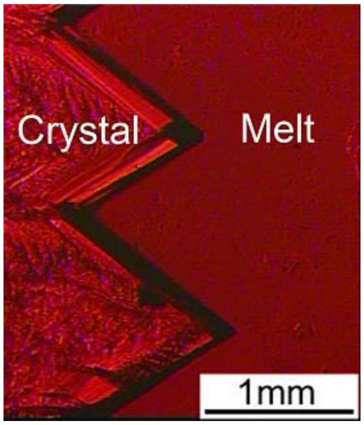
Research Area: Material Science

Expedition(s): 19, 20, 25, 26

Principal Investigator(s):
- Yuko Inatomi, Japan Aerospace Exploration Agency, Tsukuba, Japan

Research Objectives

The goal of the Investigation of Mechanism of Faceted Cellular Array Growth (Facet) is to investigate the phenomena at the solid-liquid interface for crystallization, especially for facet-like (flat faces on geometric shapes) crystallization, which are considered to be strongly influenced by the temperature and concentration distributions in the liquid phase.



Faceted cellular array growth (salol/*t*-butyl alcohol alloy). JAXA image.

Earth Benefit

It is well known that crystals tend to develop structural defects and capture impurities when a new facet is generated. Because of this, it is necessary to examine the mechanism of the facet crystal growth process. The results will provide valuable data on creating high-quality materials for industrial use, such as solar cells or superconducting magnets.

Space Benefit

This investigation is applied to new knowledge of the facet crystal growth process and not specifically to advances in space exploration.

ISS018E044461 – Koichi Wakata installs a FACET cell in the Solution Crystallization Observation Facility (SCOF) during Expedition 18 aboard the International Space Station. JAXA image.

Results

Facet Growth experiments were conducted aboard the International Space Station (ISS) in a micro-G environment. A brief summary of the obtained results at this point is as follows: (1) High-resolution Temperature and Concentration distributions in the vicinity of the solid/liquid (S/L) interface were successfully obtained. (2) The relationship between the growth rate and a kinetics undercooling at the S/L interface, which is known as a driving force of crystal growth, was obtained. (3) Breakdown of the growth interface occurred at the point with maximum kinetics undercooling. Splitting of the S/L interface was caused by the dense *t*-butyl alcohol, which decreased the melting point. (4) Numerical simulations based on a phase-field model validated the observed effect of latent heat of fusion on the change of the S/L change.

If the factors affecting faceted cellular array growth are revealed by this experiment, it may be possible to theoretically explain the process of the growth, and its application to actual material manufacturing processes can be expected. This would also deepen the understanding of the formation process of natural minerals with similar facets such as rock crystal and agate.

PUBLICATION(S)

Inatomi Y, Ashida M, Sakata K, Okutani T. Simultaneous measurement of temperature and concentration during faceted cellular array growth under microgravity. *World Journal of Engineering*. 2014:11(1)41-48. doi: 10.1260/1708-5284.11.1.41.

Inatomi Y, Yoshizaki I, Sakata K, et al. Investigation on mechanism of faceted cellular array growth in International Space Station. *Defect and Diffusion Forum*. April 2012;323-325:533-537. doi: 10.4028/www.scientific.net/DDF.323-325.533.

Wang J, Inatomi Y. Three-dimensional phase field modeling of the faceted cellular growth. *ISIJ International*. 2012;50(12):1901-1907. doi: 10.2355/isijinternational.50.1901.

This investigation is complete; however additional results are pending publication.

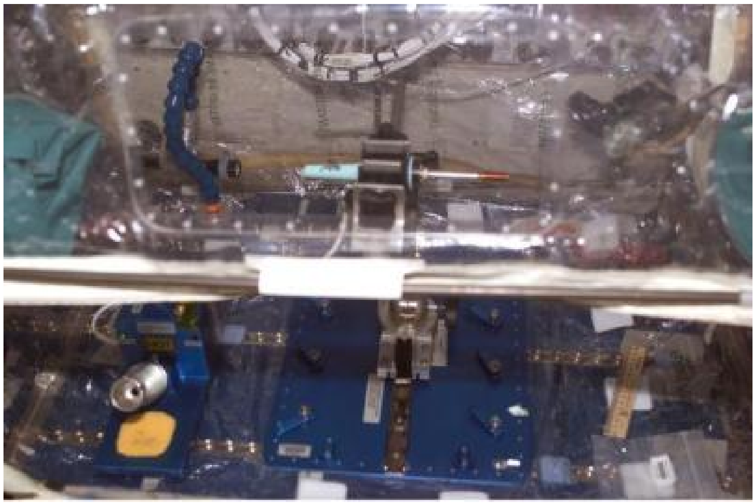
Viscous Liquid Foam - Bulk Metallic Glass (Foam)

Research Area: Materials Science
Expedition(s): 9
Principal Investigator(s):
- William L. Johnson, PhD, California Institute of Technology, Pasadena, Calif, United States

Research Objectives

The Viscous Liquid Foam - Bulk Metallic Glass (Foam) investigation tests and produces hardened foam from bulk metallic glass. The absence of gravity facilitates the creation of a more uniform metallic glass foam, a material with an extremely high strength to weight ratio. Developing lighter and stronger materials can lead to a more durable spacecraft that will require less propellant to travel long distances.

Earth Benefits

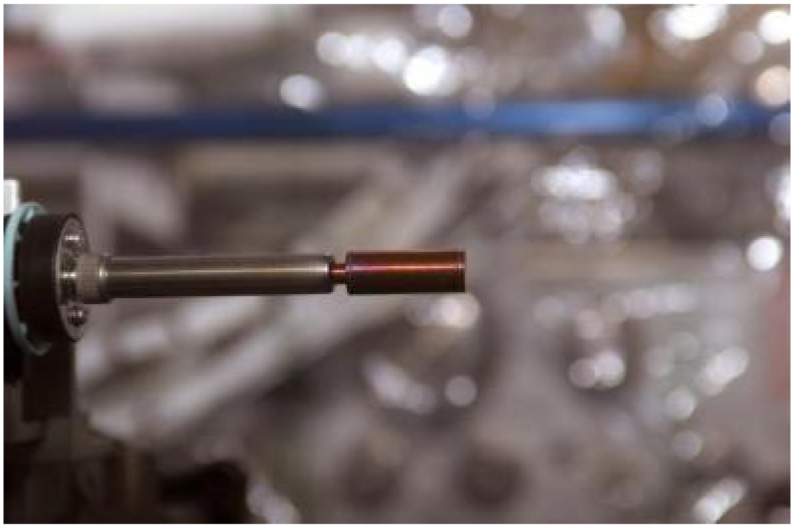


ISS009E14583 – Foam investigation setup in the Maintenance Work Area on the International Space Station during Expedition 9.

Bulk metallic glasses are extremely strong materials (2-3 times stronger than conventional metals) that, when molten, are viscous enough to make well-constructed solid foam. While bulk metallic glass is strong, it is also brittle. A bulk metallic glass foam is very resilient, however, much like spongy human bone. Solid foams are the best materials to make large, stiff structures due to their high strength to mass ratio. Foaming also considerably increases a material's ability to act as a temperature insulator. Foam can be difficult to study on Earth because gravity can interfere with bubble formation, causing the bubbles to rise and the liquid to sink. This is especially true when conventional metal liquid (like aluminum or titanium) is foamed. A better understanding of foaming will help investigators improve a variety of materials used in everything from medical supplies to industrial processing, sports equipment and military vehicles.

Space Benefits

Hardened bulk metallic glass foam may be very useful as a material for building future spacecraft for long-term spaceflight. The foams can also be used to build permanent structures on the moon or Mars. Buildings and spacecraft fuselages made from bulk metallic glass foams can be extremely tough and light at the same time, thereby reducing costs while increasing the protection they provide to explorers.



ISS009E14593 – Close up image of the Foam investigation on the International Space Station, Expedition 9.

RESULTS

The experiment was designed to test the hypothesis that amorphous metals exhibit foam-making qualities on the ground that mimic metallic foam textures made in microgravity conditions. The amorphous metals, when softened or melted, have a super-cooled state that has a very high viscosity—ideal conditions for foam processing. Foam made from a $Pd_{40}Ni_{40}P_{20}$ glass-forming metallic liquid, was made both on the ground and aboard the International Space Station (ISS). Pellets of the material that contained 1-atmosphere bubbles, were sealed in ampoules. The ampoules were made to thread into a soldering iron tip for heating aboard the ISS. The samples were heated at 360°C for 5 minutes, enabling foam creation, then allowed to cool. The ground samples contained textures that were similar to those produced in microgravity—equally distributed bubbles dominated by surface tension forces; the bubbles did not experience sedimentation (floating). These types of foams have great potential for future exploration applications because of their great strength and light weight. In particular, such foams may make very effective shields against micrometeorite and orbital debris strikes.

PUBLICATION(S)

Hofmann DC, Roberts SN. Microgravity metal processing: From undercooled liquids to bulk metallic glasses. *npj Microgravity*. May 27, 2015;1:15003. doi: 10.1038/npjmgrav.2015.3.

Veazey C, Demetriou MD, Schroers J, et al. Foaming of amorphous metals approaches the limit of microgravity foaming. *Journal of Advanced Materials*. 2008;40(1):7-11.

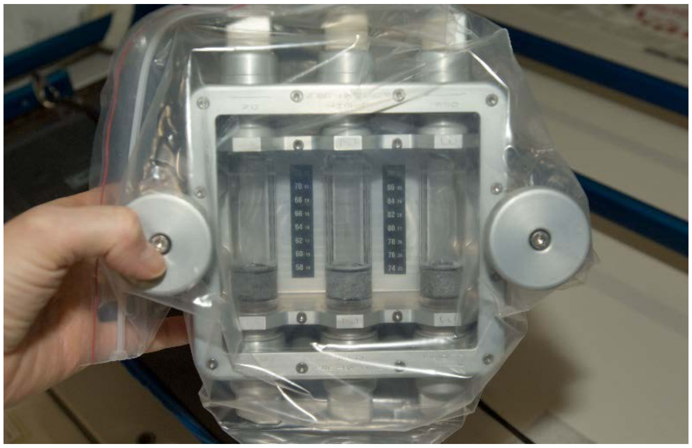
This investigation is complete and all results are published.

FOAM CASTING AND UTILIZATION IN SPACE (FOCUS)

Research Area: Materials Science
Expedition(s): 21/22
Principal Investigator(s):
- PalBárczy, Admatis Ltd, Miskolc, Hungary
- Bela M. Somosvári, Admatis Ltd, Miskolc, Hungary
- Janos Szőke, Admatis Ltd, Miskolc, Hungary

RESEARCH OBJECTIVES

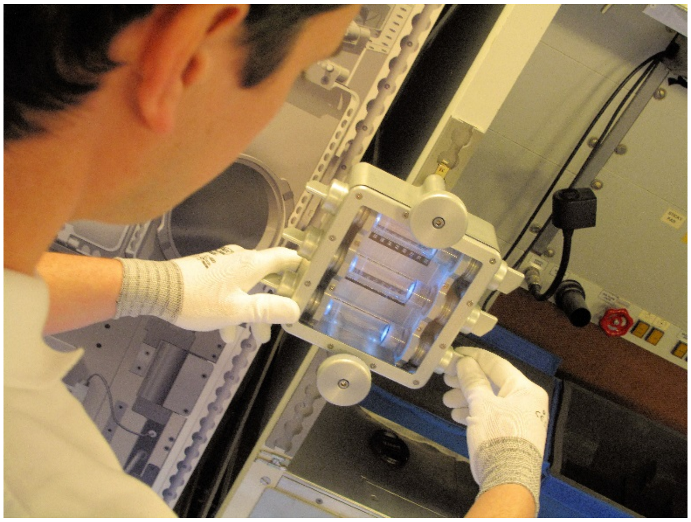
FOam Casting and Utilization in Space (FOCUS) is an industrial materials experiment to investigate foam formation and stability in microgravity. The main objective is a technological demonstration that the new technology is capable of producing particle stabilized aqueous foams under microgravity. The project focuses on the development of a multi-capillary foam generator that has already been successfully tested under normal and elevated gravity conditions. Results are utilized in the development of an alternative foam production technology for metallic and other foamable systems.



View of European Space Agency (ESA) hardware used for foam experiment. Image courtesy of ESA.

RESULTS

Successful microgravity foaming experiment has been carried out aboard of the International Space Station (ISS) using a fully stand-alone equipment. The multi-capillary foam generators were pre-infiltrated with aqueous suspension using controlled gas flow produce foams under microgravity. On the basis of the comparison with terrestrial reference experiments, researchers noted that minimal foam structure differences were found at 0.08 l/min gas flow rate. At higher flow rates, foams blown in microgravity had the largest average bubble sizes. Gravity-insensitive foaming procedure can be important at those technologies that use various foaming directions measured to gravity vector. Foam stability was not improved by eliminating gravity. Similar phenomenon has been found in previous macrogravity measurements using the same suspension. Foam decay in the case of this experiment's suspension was therefore not connected with gravity induced drainage. Foam volumes were increased during microgravity conditions. It was concluded that using the foam generators infiltrated with FOCUS Suspension, foam volumes depended on the gravity level as less gravity level gave more foam. This supports former results in increased gravity conditions.



Flight model of FOam Casting and Utilization in Space tested in Columbus mockup. ESA image

PUBLICATION(S)

Somosvári BM, Bárczy P, Szőke J, Szirovicza P, Bárczy T. FOCUS: Foam evolution and stability in microgravity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2011;382*: 58-63.

These investigations are complete; however, additional results are pending publication.

Pattern Formation during Ice Crystal Growth (Ice Crystal)

Research Area: Material Science
Expedition(s): 18
Principal Investigator(s):
- Yoshinori Furukawa, Hokkaido University, Sapporo, Japan

Research Objectives

The Pattern Formation during Ice Crystal Growth (Ice Crystal) investigation examines the effect of microgravity on the pattern formation of ice crystals by a method of in-situ observation.

Earth Benefit

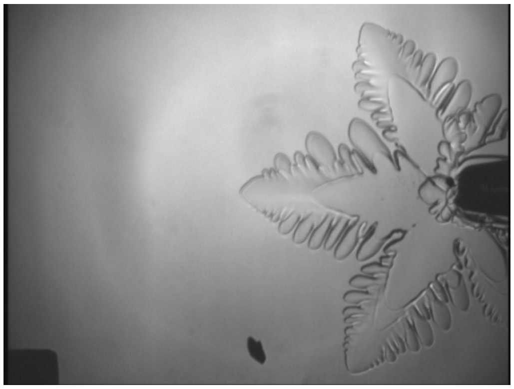
The formation process of ice crystals (the crystal growth process) is complex, and the detailed formation mechanism remains unknown. Understanding how ice crystals grow can lead to additional knowledge in understanding the growth of a wide variety of crystals for use in pharmaceuticals, or in the development of new materials.

Space Benefit

This investigation is applied to new knowledge of the ice crystal growth process and not specifically to advances in space exploration.

Results

Ice crystal growth experiments were carried out 134 times from December 2008 to February 2009 in the Japanese Experiment Module Kibo of the International Space Station (ISS). Images taken during the experiments were analyzed to measure the growth rates of the tip of a dendrite (the branch-like arm) and thickness between the basal faces (the flat front and back surfaces) of an ice crystal growing from heavy water (D_2O) in the range of 0.03 to 2.0 Kelvin (K) super-cooling.



Ice Crystal formation on the International Space Station during Expedition 18. JAXA image.

Observed tip growth velocities were higher than theoretical values at very low super-cooling of below 0.1 K. Tip velocities were in agreement with theoretical values for larger amounts of super-cooling. Researchers concluded that the tip growth velocity is significantly influenced by kinetics of basal face growth rather than by the tip’s asymmetric shape. Researchers also observed that the growth rate of the thickness changed suddenly with time, which indicates that the growth rates of the 2 basal faces are not identical to one another. This is a significant observation since the difference between the growth rates of the 2 basal faces has been proposed as a possible cause of the distortion (morphological instability) that leads to the growth of an ice crystal from a round disk initially into the familiar hexagonal dendrite. There have been no reports to date on this time dependence of the basal face growth rate in experiments conducted under full gravity.

PUBLICATION(S)

Adachi S, Yoshizaki I, Ishikawa T, Shimaoka T. Stable growth of ice crystals under microgravity. *Transactions of the Japan Society for Aeronautical and Space Sciences*. Vol. 12, No. ists29. p.Ph_1-Ph_5.

Yoshizaki I, Ishikawa T, Adachi S, Yokoyama E, Furukawa Y. Precise measurements of dendrite growth of ice crystals in microgravity. *Microgravity Science and Technology*. 2012;24(4):245-253. doi: 10.1007/s12217-012-9306-9.

Adachi S, Yoshizaki I, Ishikawa T, Yokoyama E, Furukawa Y, Shimaoka T. Stable growth mechanisms of ice disk crystals in heavy water. *Physical Review E*. November 2011;84(5):051605. doi: 10.1103/PhysRevE.84.051605.

Yokoyama E, Yoshizaki I, Shimaoka T, Sone T, Kiyota T, Furukawa Y. Measurements of growth rates of an ice crystal from supercooled heavy water under microgravity conditions: Basal face growth rate and tip velocity of a dendrite. *Journal of Physical Chemistry B.* 2011;115(27):8739-8745. doi: 10.1021/jp110634t.

Yokoyama E, Sekerka R, Furukawa Y. Growth of an ice disk: Dependence of critical thickness for disk instability on supercooling of water. *Journal of Physical Chemistry B*. April 9, 2009; 113(14):4733-4738. doi: 10.1021/jp809808r.

This investigation is complete; however additional results are pending publication.

Italian-Foam (I-Foam)

Research Area: Materials Science
Expedition(s): 27/28
Principal Investigator(s):
- Loredana Santo, University of Rome Tor Vergata, Rome, Italy

Research Objectives

The Italian-Foam (I-FOAM) experiment will evaluate the recovery of shape memory epoxy foam in microgravity obtained by solid-state foaming on ground consisting of various geometric complexities shaped on ground. This investigation is expected to study the shape memory properties required to manufacture a new concept actuator (a device that transforms energy to other forms of energy).

Earth Benefits

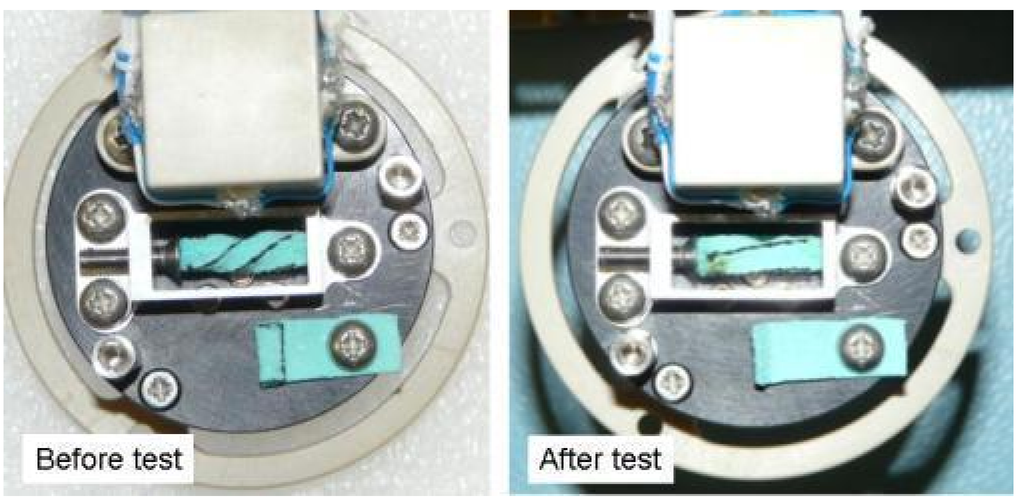
Italian-Foam can be used as energy absorbers (panels and bumpers) and self expandable/deployable structures. Forms of foam are widely used in medical bedding and seating applications because of its unique attributes which can help aid comfort and sleep.

Space Benefits

Italian-Foam can be used in the aerospace industry for different applications from light actuators to structural parts with reduced size during shipping. This type of foam may be very useful as a material utilized for building future spacecrafts for long-term space flight missions.

Results

Experimental results aboard the International Space Station (ISS), along with results obtained on the ground, highlight the complexity in developing foams in microgravity for structural actuators. Foam heating system can behave very differently in space and heat fluctuation is greatly amplified by microgravity. In future experiments, the maximum temperature will increase (at least up to 120°C) if a heating plate will be used again. In the current experiment the maximum temperature was strongly reduced for



Comparison of foam shape recovery in the International Space Station (ISS) experiment after the torsion test to the ground experiment (series of video captured images) that clearly show the same results have been obtained in the ground and ISS experiments. University of Rome Tor Vergata images.

safety reasons. Overall, good results were obtained and important information were acquired for defining a multi-functional composite structure for future experiments. Foam actuator made in space can be tested for compression, torsion, and flexure, but in the case of compression, attention has to be made to have a continuous contact between the foam walls and the heating walls during recovery. As a general conclusion, microgravity does not have much effect on the ability of the foams to recover the initial shape but strongly influences the behavior of the heating devices and, therefore, the efficiency of the foam recovery.

PUBLICATION(S)

Santo L. Recent developments in the field of shape memory epoxy foams. *Materials Science Forum*. May 2014;783-786:2523-2530. doi: 10.4028/www.scientific.net/MSF.783-786.2523.

Santo L, Quadrini F, Mascetti G, Dolce F, Zolesi V. Mission STS-134: Results of shape memory foam experiment. *Acta Astronautica*. October 2013; 91: 333-340. doi: 10.1016/j.actaastro.2013.06.017.

Santo L, Quadrini F, Squeo EA, et al. Behavior of shape memory epoxy foams in microgravity: Experimental results of STS-134 Mission. *Microgravity Science and Technology*. September 2012;24(4):287-296. doi: 10.1007/s12217-012-9313-x.

This investigation is complete, and all results are published.

MICROSTRUCTURE FORMATION IN CASTING OF TECHNICAL ALLOYS UNDER DIFFUSIVE AND MAGNETICALLY CONTROLLED CONVECTIVE CONDITIONS (MICAST)

Research Area: Materials Science

Expedition(s): 21 - 26

Principal Investigator(s):

- Lorenz Ratke, German Aerospace Center, Cologne, Germany
- Eckhard Müller, German Aerospace Center, Cologne, Germany
- Yves Fautrelle, Centre National de la Recherche Scientifique, Grenoble, France
- Andras Roosz, University of Miskolc, Miskolc, Hungary
- Gerhard Zimmermann, ACCESS e.V., Aachen, Germany
- Jacques Lacaze, Centre National de la Recherche Scientifique (CNRS), Cirimat, Toulouse, France
- Sadik Dost, University of Victoria, Victoria, British Columbia, Canada
- David Poirier, University of Arizona, Tucson, Arizona,

RESEARCH OBJECTIVES

MICAST identifies and controls experimentally the fluid-flow patterns that affect microstructure evolution during casting processes, and to develop analytical and advanced numerical models. The microgravity environment of the International Space Station (ISS) is of special importance to this project because only there are all gravity-induced convections eliminated and well-defined conditions for solidification prevail that can be disturbed by artificial fluid flow being under full control of the experimenters. Design solutions that make it possible to improve casting processes and especially aluminum alloys with well-defined properties will be provided.

These 2 pictures resulting from the treatment of images of the cross-section of samples processed in space, provide the sought for quantitative evidence of the influence of convection on the distribution of the precipitates in the solidified alloy.

RESULTS

Preliminary data indicates the samples are homogeneously distributed under purely diffusive conditions, the longer precipitates appear clearly accumulated in the center of the sample when a rotating magnetic field is applied. The size and distribution of the precipitates as a function of the solidification velocity and the controlled flow of melt imposed by the magnetic field are produced by 3D tomographic reconstruction. The enrichment in Si and Fe resulting from the convective flows in the central part of the sample clearly lead to the formation of larger precipitates.

PUBLICATION(S)

Budenkova O, Baltaretu F, Steinbach S, et al. Modelling of Al-7%wtSi-1wt%Fe ternary alloy: Application to space experiments with a rotating magnetic field. *Materials Science Forum.* 2014.

Zimmermann G, Schaberger-Zimmermann E, Steinbach S, Ratke L, Formation of intermetallic phases in AlSi7Fe1 alloy processed on board the ISS. *Materials Science Forum.* 2014.

This investigation is complete and all results are published.

THE MICROSTRUCTURE FORMATION IN CASTING OF TECHNICAL ALLOYS UNDER DIFFUSIVE AND MAGNETICALLY CONTROLLED CONVECTIVE CONDITIONS-2 (MICAST-2)

Research Area: Materials Science
Expedition(s): 27-30, 33-42
Principal Investigator(s):

- Lorenz Ratke, German Aerospace Center (DLR) · Institute of Materials Research, Cologne, Germany
- Yves Fautrelle, Centre National de la Recherche Scientifique, Grenoble, France
- Andras Roosz, University of Miskolc, Miskolc, Hungary
- Gerhard Zimmermann G., ACCESS e.V., Aachen, Germany
- Jacques Lacaze, Centre National de la Recherche Scientifique (CNRS), Cirimat, Toulouse, France
- Sadik Dost, University of Victoria, Victoria, Canada
- David Poirier, University of Arizona, Tucson, Arizona,

RESEARCH OBJECTIVES

Microgravity offers a unique way to study the solidification of metal mixtures, or alloys. The Microstructure Formation in Casting of Technical Alloys under Diffusive and Magnetically Controlled Convective Conditions-2 (MICAST-2) investigation will study a magnetic field's influence on the solidification of alloys containing aluminum-silicon (AlSi) and aluminum-silicon-iron (AlSiFe). The experiment will also inform computer models of metal casting, which could help the metals industry design better mixtures and processes.

EARTH BENEFITS

The microgravity environment of the International Space Station is key for alloy research because gravity-induced actions are eliminated, and turbulence or convection can be carefully manipulated by the researchers. The experiments could improve ground-based development of new lightweight, high-performance materials that can be used in future space missions.

Frank De Winne works with Materials Science Laboratory hardware in the Destiny laboratory. NASA Image.

SPACE BENEFITS

The MICAST experiments produces data that enhances computer models simulating metal solidification on Earth. Knowledge gained from the MICAST experiments helps to improve ground-based metal casting processes, leading to new stronger, lightweight materials.

This investigation is ongoing and additional results are pending publication.

Materials Science Laboratory - Columnar-to-Equiaxed Transition in Solidification Processing and Microstructure Formation in Casting of Technical Alloys under Diffusive and Magnetically Controlled Convective Conditions (MSL-CETSOL and MICAST), Two Investigations

Research Area: Materials Science

Expedition(s): 21-24, 27-ongoing

Principal Investigator(s):

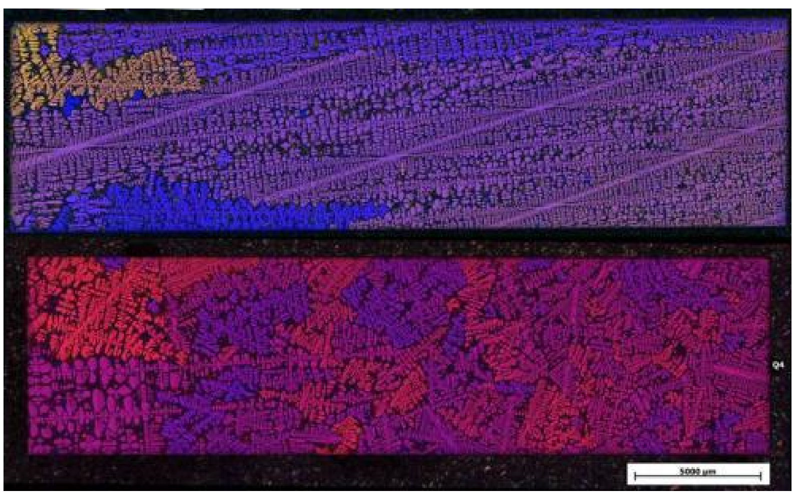
- David Poirier, Sc.D., University of Arizona, Tucson, Arizona
- Gerhard Zimmermann, PhD, ACCESS e.V., Aachen, Germany, Lorenz Ratke, Institute for Space Simulation, Cologne, Germany

Research Objectives

MSL-CETSOL and MICAST are 2 investigations that support research into metallurgical solidification, semiconductor crystal growth (Bridgman and zone melting), and measurement of thermo-physical properties of materials. This is a cooperative investigation with the European Space Agency and NASA for accommodation and operation aboard the International Space Station (ISS).

Earth Benefits

These linked experiments aim to improve our understanding of the solidification processes of metallic alloys. As the mechanical properties, and therefore potential Earth-based applications, are directly related to solidification conditions, it is crucial to validate the predictions of numerical models that describe solidification processes. Additionally, this research improves knowledge of casting processes, so that future tailored metallic alloys can be created for several applications of our daily life.



Microstructure and grain structure in longitudinal cross-sections of flight samples showing columnar growth (top) and transition to equiaxed grain growth (bottom). ACCESS Technology, Aachen, Germany image.

Space Benefits

The MSL-CETSOL and MICAST investigations will provide a unique insight into microgravity solidification processes of cast alloys under well controlled conditions.

Results

When a molten metal or alloy cools and crystallizes, the resulting solid generally has 2 competing types of grain structures. At first, fast cooling of the melt normally forms columns of long branching grains growing inward from the side walls. Then as internal heat is shed from the remaining liquid fraction, the cooling rate decreases, which often leads to seeding and growth of equiaxed (having axes of about the same length) grains. This effect is described as a columnar-to-equiaxed transition (CET) and is very important, and highly studied, in metal forming processes and metallurgy since it greatly affects the physical properties and behavior of virtually all metallic products, including high-value parts such as single crystal turbine blades in aircraft engines. CET experiments to study and control this transitional process have been successfully performed in the Materials Science Laboratory (MSL) with the Low-Gradient Furnace (LGF) module onboard the ISS from November 2009 until April 2010.

Turbulent melt flow is minimized in space, which enables growth of equiaxed grains free of sedimentation and buoyancy effects. The critical phases of each microgravity experiment, i.e. the homogenization and solidification phases, were performed during sleep periods of the astronauts to reduce, as well, vibrational disturbances. Gravity sensors data close to the MSL confirm that a gravity level below ±0.0005 g was achieved during all experiments, g = 9.8m/s² on Earth. Aluminium-silicon (AlSi) alloys with and without grain refiners (particles added to limit crystal grain branching) were processed successfully in the LGF. First analysis shows that in the non-grain-refined samples columnar dendritic growth exists, whereas CET is observed in the grain refined samples. Critical parameters for the temperature gradient and the cooling rate describing CET are determined from analysis of the thermal data and the grain structure. These data are used for initial numerical simulations to predict the position of the columnar-to-equiaxed transition and will form a unique database for calibration and further development of numerical CET-modeling (Zimmermann 2011).

ISS026E014918 – NASA astronaut Catherine (Cady) Coleman, Expedition 26 flight engineer, removes the Low Gradient Furnace and installs the Solidification and Quench Furnace in the Material Science Laboratory in the Destiny laboratory of the International Space Station.

Preliminary results of an AlSi mixture with grain refiners show that, during solidification, the columnar crystallization front advances forward and an undercooled liquid zone develops ahead the front, thus facilitating equiaxed crystal formation. Equiaxed nucleation with grain refiners follows the free growth model in simulation. In most castings, grain refiner particles may be engulfed or pushed by the growing solid liquid interface. So, these grain refiner particles cannot initiate grains and normally end up in the grain boundaries, thus general grain refiner efficiency is very low. It was found that the efficiency of the grain refiners is at a maximum when addition level is low. Experimental CET, in this case, is at a distance of ~128 ± 2 mm versus the simulation distance of 127.5 mm. Hence, the agreement between model simulation and experiment is reasonably strong. The columnar length is approximately equal to the distance the furnace is moving at a slower velocity and, therefore, it is possible to suggest that CET is related to the velocity jump and resulting temperature change. More studies of alloy systems without grain refiners are being conducted, and the influences of grain refiners need to be evaluated further (Mirihanage 2011).

Publication(s)

Mirihanage WU, Browne DJ, Sturz L, Zimmermann G. Numerical modelling of the Material Science lab - Low Gradient Furnace (MSL-LGF) microgravity directional solidification experiments on the columnar to equiaxed transition. *IOP Conference Series: Material Science and Engineering*. January 12, 2012;27(1):012010. doi: 10.1088/1757-899X/27/1/012010.

Zimmermann G, Sturz L, Billia B, et al. Investigation of columnar-to-equiaxed transition in solidification processing of AlSi alloys in microgravity – The CETSOL project. *Journal of Physics: Conference Series*. December 6, 2011;327(1):012003-12014. doi: 10.1088/1742-6596/327/1/012003.

These investigations are ongoing and additional results are pending publication.

PRODUCTION OF HIGH PERFORMANCE NANOMATERIALS IN MICROGRAVITY (NANOSKELETON)

Research Area: Materials Science
Expedition(s): 21-24
Principal Investigator(s):
- Masahiko Abe, PhD, Tokyo University of Science, Tokyo, Japan

RESEARCH OBJECTIVES

The Production of High Performance Nanomaterials in Microgravity (Nanoskeleton) investigation aims to clarify the effect of gravity on oil flotation, sedimentation, and convection on crystals generated in microgravity. Nanoskeleton data will be added into a computational chemistry simulation for Nanoskeleton synthesis, and the simulation will be used for the prediction of the proper parameters for synthesis on the ground.

EARTH BENEFIT

Nanoskeleton will lead to the development of the new Titanium Dioxide (TiO_2) photocatalyst. The experiment data will be input into the computational chemistry simulation for Nanoskeleton synthesis, and the simulation will be applied for the prediction of the proper parameter for Nanoskeleton synthesis on the ground.

RESULTS

Samples were flown aboard the International Space Station (ISS), whereupon polyethylene based films were immersed in a solution to create the TiO_2 crystalline-based nanoskeleton samples. Some of the samples were infused with Trimethylbenzene (TMB) and Triethylbenzene(TEB) oil in order to increase the size of the pores of the nanoskeleton. All samples were successfully retrieved from the ISS and analyzed. The appearance of the ISS samples subjected to microgravity was almost the same with that of the Earth bound control samples. However, the microgravity environment samples revealed a significant effect on the distance between pores of the nanoskeletons prepared with oil (TMB and TEB), while uniformity and regularity of the pores was improved for the samples prepared without TMB. It was also noted that samples with more ordered structures had improved photo catalytic activity.

PUBLICATION(S)

Onodera M, Nagumo R, Miura R, et al. Multiscale simulation of dye-sensitized solar cells considering Schottky barrier effect at photoelectrode. *Japanese Journal of Applied Physics*. April 20, 2011; 50(4):04DP06. doi: 10.1143/JJAP.50.04DP06.

Shibata H, Ohshika S, Ogura T, et al. Preparation and photocatalytic activity under visible light irradiation of mesostructured titania particles modified with phthalocyanine in the pores. *Journal of Photochemistry and Photobiology A: Chemistry*. January 2011; 217(1):136-140. doi: 10.1016/j.jphotochem.2010.09.029.

Dai S, Wu Y, Sakai T, Du Z, Sakai H, Abe M. Preparation of highly crystalline TiO2 nanostructures by acid - assisted hydrothermal treatment of hexagonal-structured nanocrystalline titania/ cetyltrimethyammonium bromide nanoskeleton. *Nanoscale Research Letters*. August 11, 2010;5(11):1829-1835. doi: 10.1007/s11671-010-9720-0.

Sakai T, Yano H, Shibata H, et al. Pore-size expansion of hexagonal-structured nanocrystalline titania/CTAB Nanoskeleton using cosolvent organic molecules. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. November 2010;371(1-3):29-39. doi: 10.1016/j.colsurfa.2010.08.054.

This investigation is complete; however additional results are pending publication.

Study of Aggegation Mechanism and Kinetics of ZSM-5 and Silicate-1 Nanoslabs into ZSM-5/Silicate-1 Hybird Phases Under Near-2 Weightless Conditions (Nanoslab-1 and Nanoslab-2), Two Investigations

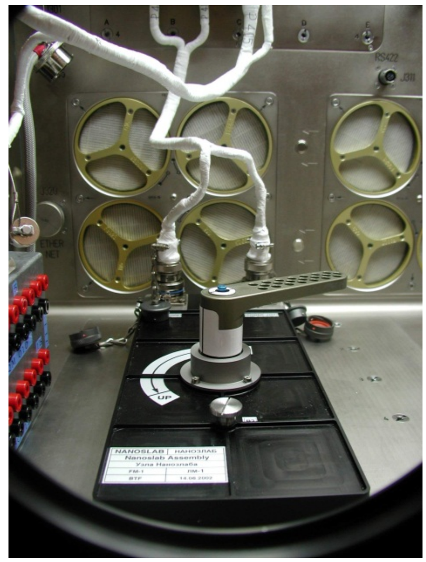
Research Area Material Science

Expeditions: 5 and 8

Principal Investigator(s):
- Johan A. Martens, Katholieke Universiteit, Leuven, Leuven, Belgium

Research Objectives

Silicalite-1 and Zeolite Socony Mobil-5 (ZSM-5) are important materials in industrial applications. Understanding the effects of convection and sedimentation during bulk-zeolite formation are necessary for optimization of existing syntheses. The investigation studies the aggregation mechanism and kinetics of: ZSM-5 nanoslabs (SiO_2 phase, doped with aluminium), Silicalite-1 nanoslabs (pure SiO_2 phase) and ZSM-5 / Silicalite-1 hybrid mixture phases under weightless conditions.



Closeup of Nanoslab in the Microgravity Science Glovebox. ESA image.

Results

Microgravity significantly slowed particle aggregation, confirming the sensitivity of the process to convection and shear forces. Microgravity also considerably enhanced the effect on aggregation of reduced temperatures and charge. Only the formation and presence of Ordered Liquid Phases (OLPs) before aggregation can account for these observations, and an on-ground study confirmed OLP occurrence. The strong effect of convection and shear forces in microgravity indicates the important role OLPs play, and their discovery is useful for optimizing zeolite synthesis and design of hierarchical, functional materials. No results were obtained for the Nanoslab investigations due to a failure.

This investigation is complete; however no publications are expected.

Toward Understanding Pore Formation and Mobility During Controlled Directional Solidification in a Microgravity Environment (PFMI)

Research Area: Materials Science
Expedition(s): 5, 7, 8, 13
Principal Investigator(s):
- Richard N. Grugel, PhD, Marshall Space Flight Center, Huntsville, Alabama

Research Objectives

Using a transparent model material, this experiment studies the fundamental phenomena responsible for the formation of certain classes of defects in metal castings. Investigators examine the physical principles that control the occurrence of defects in manufacturing on Earth in order to develop methods to reduce flaws, defects, or wasted material.

Earth Benefits

On Earth, materials that contain pores created and trapped during solidification degrade properties and cause a distinct weakening in the overall structure of the cast product. Examples of these materials include semiconductors and aircraft turbine blades.

Space Benefits

PFMI provides insight on how materials solidify in the space environment. Once this process is understood and improvements are made, future manufacturing processes can take place in the microgravity environment providing robust products.

Results

Observed bubble migration up through the liquid column indicates that thermocapillary forces do play a role in bubble removal during solidification in microgravity, thereby providing a potential mechanism for avoiding porosity in space processing. Direct comparison between the ground-based thin (2-D) samples and the flight bulk (3-D) samples showed significant differences in the interface texture. The flight samples achieved planar growth, an emergence of dendrites (crystallizes in the shape of a tree or branch), in less time than ground-based samples. When comparing the planar interface recoil, the flight sample was steeper than the ground-based sample. Additionally, the dendrite spacing in the flight bulk samples were closer together than the ground-based thin samples. The use of 2-D (thin) samples in one-g for comparison with theoretical models is not adequate, therefore solidification of bulk samples in a microgravity environment and in the lab setting is necessary for a suitable comparison. The bulk solidification samples, which were filled with succinonitrile (SCN), were melted and re-solidified to observe the bubbles that formed. During controlled re-solidification, aligned tubes of gas were seen to be growing perpendicular to the planar solid/liquid interface, inferring that the nitrogen previously dissolved into the liquid SCN was now coming out at the solid/liquid interface and forming the little-studied liquid=solid+gas type reaction. Researchers expects that the results will be directly applicable to understanding solidification for materials processing by providing insights into fundamental behavior of bubbles.

PUBLICATION(S)

Grugel RN, Luz PL, Smith GP, et al. Materials research conducted aboard the International Space Station: Facilities overview, operational procedures, and experimental outcomes. *Acta Astronautica*. 2008;62:491-498. doi: 10.1016/j.actaastro.2008.01.013.

Grugel RN, Luz PL, Smith GP, et al. Experiments conducted aboard the International Space Station: The Pore Formation and Mobility Investigation (PFMI) and the In-Space Soldering Investigation (ISSI): A current summary of results. *57th International Astronautical Congress*, Valencia, Spain; October 2-6, 2006;IAC-06-A2.2.10:10. doi: 10.2514/6.IAC-06-A2.2.10.

Grugel RN, Anilkumar AV, Cox MC. Observation of an aligned gas - Solid eutectic during controlled directional solidification aboard the International Space Station - Comparison with ground-based Studies*. 42nd Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2005.

Strutzenberg LL, Grugel RN, Trivedi R. Morphological evolution of directional solidification interface in microgravity: An analysis of model experiments performed on the International Space Station. *43rd Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2005.

Grugel RN, Anilkumar AV. Bubble formation and transport during microgravity materials processing: Model experiments on the Space Station. *42nd Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2004.

Grugel RN, Anilkumar AV, Lee CP. Direct observation of pore formation and bubble mobility during controlled melting and re-solidification in microgravity, solidification processes, and microstructures. *A Symposium in Honor of Wilfried Kurz, The Metallurgical Society*, Warrendale, PA; 2004:111-116.

This investigation is complete and all results are published.

SOLIDIFICATION ALONG A EUTECTIC PATH IN TERNARY ALLOYS-2 (SETA-2)

Research Area: Materials Science

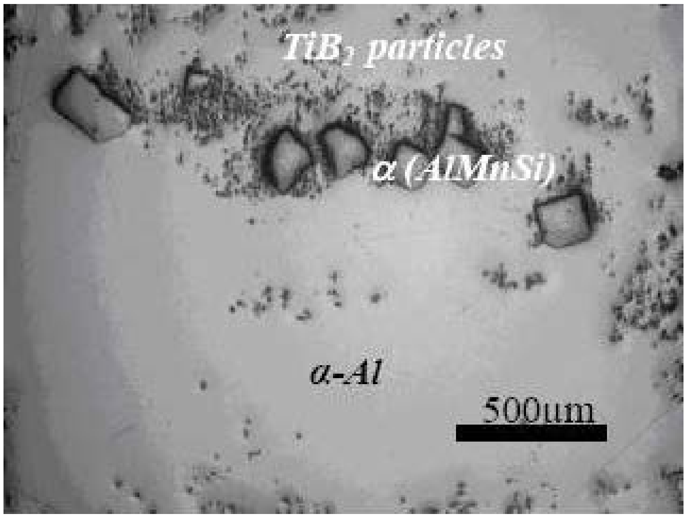
Expedition(s): 29-ongoing

Principal Investigator(s):

- Stephan Rex, ACCESS e.V., Aachen, Germany
- Ulrike Hecht, ACCESS e.V., Aachen, Germany
- Gabriel Faivre, French National Centre for Scientific Research, Paris, France
- Ludo Froyen, Katholieke Universiteit, Leuven, Leuven, Belgium
- Lorenz Ratke L., Institute for Space Simulation, Cologne, Germany
- Ralph Napolitano, Iowa State University and The Ames Laboratory, Ames, Iowa

RESEARCH OBJECTIVES

Solidification along a Eutectic path in Ternary Alloys - 2 (SETA-2) studies the process of solidification in various alloy materials in microgravity; focusing on the microscale structural patterns formed in these materials when they transition from liquids to solids. Specifically this investigation studies the effect of different processing velocities on the microstructure evolution; while examining the influence of elimination of the gravity component on force balance, which maintains the pushing/engulfment configurations; and determining the influence and behaviour of foreign particles added to the alloy.



SETA 2a. Symbiotic univariant eutectic growth in ternary aluminium alloys. ESA Image.

RESULTS

No results are currently available as the research is on-going.

This investigation is ongoing and additional results are pending publication.

Space Dynamically Responding Ultrasonic Matrix System (SpaceDRUMS)

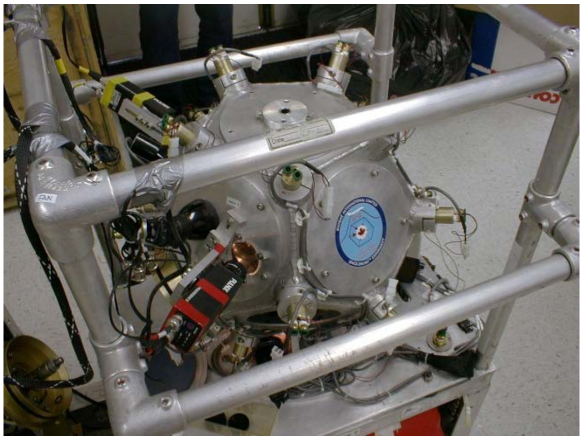
Research Area: Materials Science
Expedition(s): 21-24, 27-30
Principal Investigator(s):
- Jacques Guigne, PhD, Guigne Space Systems, Incorporated, Paradise, Newfoundland, Canada

Research Objectives

The goal of Space Dynamically Responding Ultrasonic Matrix System (SpaceDRUMS) is to provide a suite of hardware capable of facilitating containerless advanced materials science, including combustion synthesis and fluid physics. That is, inside SpaceDRUMS® samples of experimental materials can be processed without ever touching a container wall.

Earth Benefits

An already demonstrated capability of the combustion synthesis facilitated by SpaceDRUMS® is the production of advanced porous and glass ceramics for which patents have been awarded. New innovations from this hardware can include a very light and strong new class of porous glass ceramic material, exhibiting high temperature tolerance, controlled porosity, functionally graded and acoustic absorption, and high wear resistance. These materials are ideal for a wide range of potential applications, from dental and bone replacement, noise reduction in engines, filters, cutting tools and drill bits.



The dodecahedron combustion chamber shown above is the central part of the Processing Module. It has 20 acoustic transducers attached on the corners and three cameras for providing sample position feedback and for viewing and recording the action. The Processing Module is the quad-locker portion of SpaceDRUMS.

Space Benefits

Any new materials developed using the SpaceDRUMS® technology may have significant applications in space as well as on Earth. Some of the advanced ceramics, lighter and more durable, may have applications in new spacecraft or extraterrestrial outposts, such as bases on the moon. Advances in fluid physics stemming from SpaceDRUMS® may also have applications in future spacecraft propulsion systems.

This investigation is complete; however no publications are expected.

SOLIDIFICATION USING A BAFFLE IN SEALED AMPOULES (SUBSA)

Research Area: Materials Science
Expedition(s): 5
Principal Investigator(s):
- Aleksander G. Ostrogorsky, PhD, Rensselaer Polytechnic Institute, Troy, New York

RESEARCH OBJECTIVES

Solidification Using a Baffle in Sealed Ampoules (SUBSA) provides experimental methods of crystallizing melts in microgravity are expected to result in reduced fluid motion in the melt, leading to better distribution of subcomponents and the potential for improved technology used in producing semiconductor crystals.

EARTH BENEFITS

Semiconductor materials can conduct, stop or modify a wide range of electrical and optical signals. Therefore, all computer chips, sensors, and wireless communication devices, etc. are built from tiny chips cut from large semiconductor crystals. Improved semiconductor quality, well-formed crystals with few or no imperfections, are the key reason that the electronic devices today are so much smaller and more powerful than their predecessors.

One of the first materials science experiments on the International Space Station - the Solidification Using a Baffle in Sealed Ampoules (SUBSA)—will be conducted during Expedition 5 inside the Microgravity Science Glovebox. Dr. Aleksandar Ostrogorsky, a materials scientist from the Rensselaer Polytechnic Institute, Troy, NY, and the principal investigator for the SUBSA experiment, uses the gloves to examine an ampoule like the ones used for his experiment inside the glovebox's work area. The Microgravity Science Glovebox and the SUBSA experiment are managed by NASA's Marshall Space Flight Center in Huntsville, Alabama. NASA/MSFC image.

SPACE BENEFITS

The SUBSA furnace, with its capability to control and visualize melting and solidification of semiconductor crystals, has increased our understanding of solidification phenomena. The transparent furnace coupled with the video downlink and real-time commanding capability provides a powerful tool for scientists and engineers. The scientists were able to watch the motion of the crystal-melt interface as semiconductor crystals were formed. The design of the SUBSA ampoule that includes a baffle and a system that prevents de-wetting resulted in crystals whose properties have not been disrupted by micro-accelerations at the Station, making it possible for future researchers to produce the high-quality semiconductor crystals that are in demand on Earth.

Results

Eight single crystals of indium antimonide (InSb), doped with tellurium and zinc, were directionally solidified in microgravity. The molten semiconductor material solidified as expected, without separating from the ampoule walls or releasing the undesirable bubbles that have been reported in several previous microgravity investigations. Semiconductor crystals with reproducible, nearly identical composition were obtained for the first time in space.

Publication(s)

Churilov AV, Ostrogorsky AG. Solidification of Te and Zn doped InSb in space. *Journal of Thermophysics and Heat Transfer*. 2005;19(4):547-547.

Ostrogorsky AG, Churilov AV. Model of Tellurium- and Zinc-Doped Indium Antimonide solidification in space. *Journal of Thermophysics and Heat Transfer*. 2005;19(4):542-547.

Ostrogorsky AG, Marin C, Churilov AV, et al. Solidification using the baffle in sealed ampoules. *41st Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2003.

Spivey RA, Gilley S, Ostrogorsky AG, et al. SUBSA and PFMI transparent furnace systems currently in use in the International Space Station microgravity science glovebox. *41st Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2003.

This investigation is complete and all results are published.

Self-Propagating High-Temperature Synthesis in Space (SVS), Six Investigations

Research Area: Materials Science
Expedition(s): 11, 13, 16, 18, 19-22
Principal Investigator(s):
- Alexander G. Merzhanov, Institute of Structural Macrokinetics and Materials of the Russian Academy of Sciences, Chernogolovka, Moscow region, Russia

Research Objectives

The Self-Propagating High Temperature Synthesis in Space (SVS) suite of investigations establish a mechanism for combustion and structural formation in self-propagating, high-temperature synthesis systems under conditions of weightlessness. SVS consists of 6 distinct investigations.

SVS-1

Study the effect of weightlessness on the mechanism of combustion and structural formation in self-propagating, high-temperature synthesis systems (powder mixtures and compressed samples).

Crew member performs a session of the Self-Propagating High Temperature Synthesis in Space investigation on the International Space Station. Roscosmos image.

SVS-2

Continue studying the effect of weightlessness on the mechanism of combustion and structural formation in self-propagating, high-temperature synthesis systems (compressed samples and powder mixtures) and to obtain materials with a foam structure and granular frameworks during the experiment based on new samples.

SVS-3

Obtain porous foam materials and to weld and seal under space conditions.

SVS-4

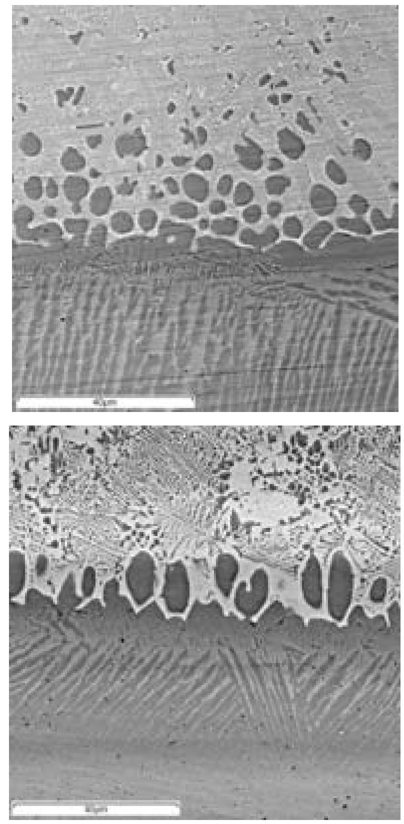
Study the effect of microgravity on the processes of self-propagating, high-temperature synthesis welds (weld of 2 layers of titanium foil using an exothermic combustion reaction of a powder mixture of titanium and carbon black) and the synthesis of porous functional gradient materials (with porosity or chemical component gradients).

SVS-5

Study the effect of long-term microgravity throughout the processes of self-propagating, high-temperature synthesis reactions, to create self-propagating, high-temperature synthesis coatings, and to obtain porous functional materials in long-term microgravity. Also, study the effect of long-term weightlessness on the interaction between melted self-propagating, high-temperature synthesis products and metal bases.

SVS-6

Study the mechanism of combustion and formation of macro and microstructures in condensed reaction products, the structure of pore volumes, and transitional areas at joints (welds) in samples with varying porosity and chemical composition, the mechanism and kinetics of the formation of intermetallics and high-melting inorganic compounds at the borders of metals with self-propagating, high-temperature synthesis system components. Completing these tasks will make it possible to develop technologies for the formation of materials and compounds with given properties necessary for further space exploration.



Microstructure of a base at the border of the base and the self-propagating high-temperature synthesis product, obtained in laboratory (top), and space (bottom) conditions. Roscosmos image.

Space Benefits

Establishing the mechanism of combustion and structural formation in self-propagating, high-temperature synthesis systems in weightlessness will make it possible to obtain high-melting materials with unique foam structures or granular frameworks, which are efficient heat insulating materials for use in space technology. Investigating the materials obtained through self-propagating, high-temperature synthesis in long-term microgravity demonstrated the potential for obtaining highly porous foam materials and coatings for use in the aerospace industry in weightlessness.

Results

In the framework of the experiments conducted, the mechanisms of combustion and structural formation in self-propagating, high-temperature synthesis systems in microgravity were established, and methods of synthesizing highly porous, high-melting, heat-insulating materials with unique properties were developed. Materials with granular structures and foam materials based on self-propagating, high-temperature synthesis systems were obtained, and experiments were conducted to obtain coatings and connections via self-propagating high-temperature synthesis, SHS welding, and SHS soldering in space conditions.

The results of the studies [SVS-1] and [SVS-2] showed the high gravitational sensitivity of the processes taking place in the combustion waves and high temperature transformation liquid phase products. Unique macro and microstructures of cast combustion products and porous materials were obtained in microgravity. The interaction of the metal and oxide phases that formed during synthesis was investigated.

The results of [SVS-5] demonstrated the potential for using thermal explosion processes to synthesize gradient materials, connections, and coatings based on intermetallics in microgravity. The mechanism of formation of coatings based on titanium aluminides and nickelides on titanium bases via self-propagating, high-temperature synthesis in NiO-Al thermite systems was studied.

PUBLICATION(S)

Shcherbakov VA, Sytschev AE, Sachkova NV. Interaction of SHS-produced melt with Ti surface in microgravity conditions. *International Journal of Self-Propogating High Temperature Synthesis.* July 2, 2010;19(2):141-149. doi: 10.3103/S106138621002010X.

Sanin VN, Yukhvid VI, Sytschev AE, Sachkova NV, Shiryaeva MY. The effect of microgravity on the composition of SHS products of the mixture NiO + Ni + Al + WC. *Inorganic Materials*. June 7, 2009;45(6):635-344. doi: 10.1134/S0020168509060119. [Original Russian Text © Sanin VN, Yukhvid VI, Sychev AE, Sachkova NV, Shiryaeva MY. *Neorganicheskie Materialy.* 2009;45(6):694-703.].

Vadchenko SG, Sytschev AE. SHS in microgravity: The Ti-Si-Al-C system. I*nternational Journal of Self-Propogating High Temperature Synthesis*. August 12, 2008;17(2):149-153. doi: 10.3103/S1061386208020118.

These investigations are complete and all results are published.

Zeolite Crystal Growth (ZCG)

Research Area: Materials Science
Expedition(s): 4-6
Principal Investigator(s): ● Albert Sacco, Jr, PhD, Texas Tech University, Lubbock, Texas

Research Objectives

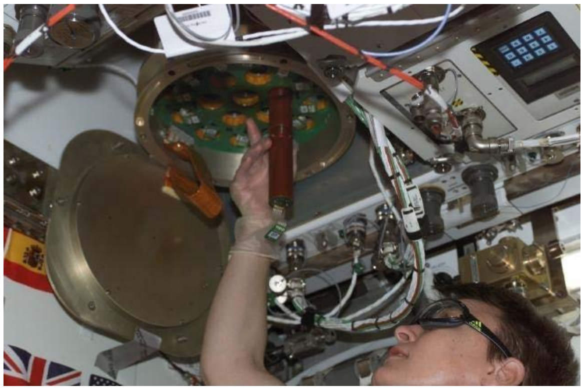
The ZCG investigations examined how subtle changes in the chemical formulation affected nucleation and growth of zeolite crystals. The microgravity environment allowed researchers to grow higher-quality crystals. These crystals have a number of useful commercial applications as catalysts and absorbents.

Earth Benefits

The 3-dimensional structure of a zeolite crystal allows it to act as a sieve to selectively filter certain chemicals in applications such as petroleum processing. Larger crystals allow researchers to better define the structure and understand how it works, with a goal of producing improved crystals on Earth. Improved zeolites may have applications in storing hydrogen fuel, reduction of hazardous by-products from chemical processing, and more efficient techniques for petroleum processing.

Space Benefits

Multifunctional Titanosilicates may be used for Absorbtion/Separation of Carbon Dioxide and Water for Portable Life Support System (PLSS) A lightweight fully regenerative water/carbon dioxide separator is a necessity for long duration, deep space exploration. One critical component is a regenerative water/carbon dioxide separator that can capture the water for recovery, and either capture and recover the carbon dioxide or vent it to a low pressure environment (i.e., Mars). Titanosilicates can be adjusted both with respect to size and shape, and with respect to pore size. These have been used commercially to separate water and carbon dioxide. By varying size and shape the pressure drop is minimized, while variations in the pore size for a given structure allows the customization of these high surface area (~500 m2/g) adsorbents. As a potential added benefit, the constituents to make titanosilicates can be obtained on the lunar surface from ilmenite (iron titanium oxide which crystallizes in igneous rocks out of magma in the bottom layers) reduction and silicates (compound of silicon and oxygen).



NASA Image: ISS005E19055 - View of Astronaut Peggy Whitson, Expedition Five Flight Engineer, as she places a cartridge into the Zeolite Crystal Growth (ZCG) experiment located in the U.S. Laboratory/Destiny on ISS.

Results

ZCG produced zeolite crystals with a high degree of crystalline perfection in microgravity. During ISS Expedition 6, 19 zeolite samples were mixed and incubated. These samples were returned to Earth at the conclusion of Expedition 6 and sent back to the principal investigator for analysis.

Results from the samples mixed on ISS suggest that the Lewis acid catalytic sites are altered in microgravity, as indicated by lower catalytic activity in the MPV probe reaction compared to Earth-grown zeolite. This further suggests that the control of fluid dynamics during crystallization may be important in making better industrial catalysts. Although space-grown zeolites had the same particle morphology and identical surface framework as zeolites grown on Earth, the average zeolite size of the space-grown crystals was 10% larger than crystals grown on Earth (Akata 2004).

Larger zeolite crystals allow researchers to better define the structure and understand how they work, with a goal of producing improved crystals on Earth. Improved zeolites may have applications in storing hydrogen fuel, reduction of hazardous byproducts from chemical processing, and more efficient techniques for petroleum processing (Akata 2009).

PUBLICATION(S)

Akata B, Goodrich TL, Ziemer KS, Sacco, Jr A. The catalytic activity of space versus terrestrial synthesized zeolite Beta catalysts in the Meerwein Ponndorf Verley Reactions: Support for PFAL as the Lewis active site for cis-alcohol selectivity. *Microgravity Science and Technology*. June 2007;19(2):5-11. doi: 10.1007/BF02911862.

Akata B, Yilmaz B, Jirapongphan SS, Warzywoda J, Sacco Jr A. Characterization of zeolite Beta grown in microgravity. *Microporous and Mesoporous Materials*. June 2004;71(1-3):1-9. doi: 10.1016/j.micromeso.2004.03.012.

This investigation is complete, and all results are published.

Study of the Structure and Morphology of Zeogrids Obtained Under Microgravity Conditions (Zeogrid)

Research Area: Material Science
Expedition(s): 4
Principal Investigator(s):
- Johan Martens, Katholieke Universiteit, Leuven, Belgium
- Christine Kirschhock, Katholieke Universiteit, Leuven, Belgium
- Sebastian Kremer, Katholieke Universiteit, Leuven, Belgium

Research Objectives

Zeogrids are unique materials for a wide range of applications because they combine zeolitic microporous and mesoporous properties. The steps of zeogrid formation have to be understood in detail to allow the design of specialized zeogrids. Structure and morphology of the obtained products are expected to be influenced by a weightless environment. Zeogrid studies the self-organization of nanoscopic zeolite slabs (nanoslabs). Structure directing agents (templates) are used to promote the organization of zeolitic nanoparticles (Silicalite-1 nanoslabs) into superstructures (Zeogrids).

Zeogrid assembly. Including working chamber with 21 cells with samples. ESA image.

Results

This experiment provided strong evidence for the self-organization of nanoslabs into ordered phases under microgravity conditions. In weightless conditions, millimeter-sized solid particles were formed that clearly showed orientational order when measured by small angle X-ray scattering. The discovery of correlated "domains" and its influence on the kinetics in microgravity was very attractive from a scientific point of view. Furthermore, the improved understanding of the self-organization of zeolitic building units in ordered liquid phases had significant impact on the development of new application-oriented materials. Through mastering of the formation of orientational order, designer zeolites appeared to be within reach. The form and structure of zeogrids and zeotiles were highly sensitive to the mixing conditions, suggesting a strong impact of convection on the nanoslab ordering process upon surfactant addition. It was observed that the samples obtained under microgravity conditions were larger in size, monolithic, and better ordered internally. These observations indicated that shear flow and convection effects have a major role in arranging the elementary building units before solidification occurs. A closer analysis of the rules governing the complex phase behavior can lead to new synthesis strategies to modify the aggregation product from within those phases.

PUBLICATION(S)

Kirschhock CEA, Kremer SPB, Vermant J, Tendeloo GVan, Jacobs PA, Martens JA. Design and synthesis of hierarchical materials from ordered zeolitic building units. *Chemistry - A Euopean Journal.* 2005;11:4306-4313. doi: 10.1002/chem.200401329

Kremer SP, Kirschhock C, Aerts A, Villani K, Martens JA, Lebedev OI, Van Tendeloo G. Tiling Silicalite-1 Nanoslabs into 3D Mosaics. *Advanced Materials.* 2003;15(20):1705-1707. doi: 10.1002/adma.200305266.

This investigation is complete, and all results are published.

PLASMA CRYSTAL EXPERIMENT – NEFEDOV (PKE-NEFEDOV)

Research Area: Plasma Physics

Expedition(s): 1-11

Principal Investigator(s):
- Gregor Morfill, Max Planck Institute for Extraterrestrial Physics, Garching, Germany
- Vladimir E. Fortov, the Russian Academy of Sciences, Moscow, Russia

Arrival of PKE-Nefedov aboard the International Space Station. NASA image.

RESEARCH OBJECTIVES

PKE-Nefedov is designed for long-term investigations of complex plasmas in weightlessness. Complex plasmas contain ions, electrons, neutral atoms (or molecules), and small solid particles normally in the micrometer range. These microparticles attract thousands of elementary charges in the plasma and interact with each other via a screened Coulomb potential. Complex plasmas are of special interest because they can behave as liquid and crystalline states and are observable at the kinetic level. Thus, they form a new model system for strongly coupled states.

RESULTS

During the 4.5 years of operation of the PKE-Nefedov laboratory on the International Space Station, 45 successful complex plasma experiment sessions in microgravity (typically 90 min each) were completed. The scientific outcome was very broad and fundamental. It covered many aspects of physics, like solid state and fluid physics, wave phenomena, physics of binary systems, particle growth, decharging of particles in the afterglow plasma, coagulation of charged particles in a neutral gas, additional to pure complex plasma phenomena like the study of the ion drag force and the void formation. The scientific yield counts more than 30 publications in international journals.

Side view of a plasma crystal in the laboratory. Dust particles are suspended in an argon plasma above a high-frequency electrode (bottom). The horizontal field of view is 2 cm. *Max Planck Institute for Extraterrestrial Physics image.*

PUBLICATION(S)

Ivlev AV, Kretschmer M, Rubin-Zuzic M, et al. Decharging of complex plasmas: First kinetic observations. *Physical Review Letters.* February 2003;90(5):055003. doi: 10.1103/PhysRevLett.90.055003.

Mikikian M, Boufendi L, Bouchoule A, et al. Dust particles growth and behavior under microgravity conditions. *Dusty Plasmas in the New Millennium: Third Conference on the Physics of Dusty Plasmas*, Durban, South Africa; May 20-24, 2002.

Morfill GE, Thomas HM, Annaratone BM, et al. Complex plasmas under microgravity conditions: First results from PKE-Nefedov. *Dusty Plasmas in the New Millennium: Third Conference on the Physics of Dusty Plasmas*, Durban, South Africa; May 20-24, 2002.

This investigation is complete and all results are published.

Studying Plasma Dust Crystals and Liquids in Microgravity on the ISS RS (Plazmenniy Kristall), Thirty Investigations

Research Area: Plasma Physics
Expedition(s): 1, 3, and 5-ongoing
Principal Investigator(s):
- Vladimir E. Fortov, Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

Studying Plasma Dust Crystals and Liquids in Microgravity on the ISS RS (Plazmenniy Kristall) is comprised of 30 distinct investigations. It is conducted within a framework of international cooperation with the German Space Agency (DLR), the Max Planck Institute for Extraterrestrial Physics, the European Space Agency, and Roscosmos. Several of the investigations are detailed below:

Mach Cones-PK

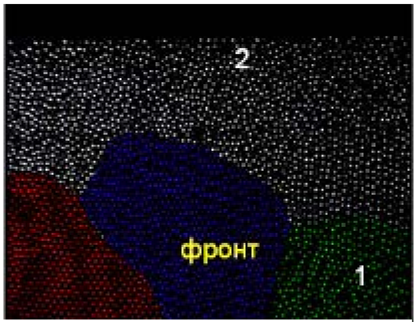
Mach Cones-PK space investigates the interaction of individual particles moving at a speed that exceeds Mach 3 (the speed of sound of dust) in a large three-dimensional plasma dust system.

Projectile-PK

Projectile-PK studies the interaction between a strongly charged dust particle and a dust crystal.

Phase Transitions-PK-1

Phase Transitions-PK-1 studies structural phase transitions in dust plasma when exposed to an external alternating electrical field. During this investigation a new state of dust plasma was studied: electrorheological (ER) plasma, when a transition occurs from an isotropic plasma dust fluid to an anisotropic state.



Crystal domains with varying orientations (1, 2, 3). The number of dust particles in the system exceeds 10^6. Roscosmos image.

Phase Transitions-PK-2

Phase Transitions-PK-2 studies non-equilibrium transitions in binary dust plasma. The interpenetration of particles 3.4 microns in diameter in a plasma dust system formed by large-diameter dust particles was studied under varying conditions.

Phase Transitions-PK-3

Phase Transitions-PK-3 studies the phase transition from a plasma liquid to a plasma crystal in a large three-dimensional plasma dust system.

Crystallization Front-PK

Crystallization Front-PK studies the possibility of discovering a crystallization front in a three-dimensional plasma dust system.

Search-PK-3-2

Search-PK-3-2 conducts baseline experiments in the Plazmenniy Kristall 3 Plus science unit in which the parameters for plasma containing particles vary throughout virtually the entire range.

Earth Benefits

The experiment has great importance for fundamental science, because microgravity opens up possibilities for discovering entirely new effects in plasma with charged solid macroparticles.

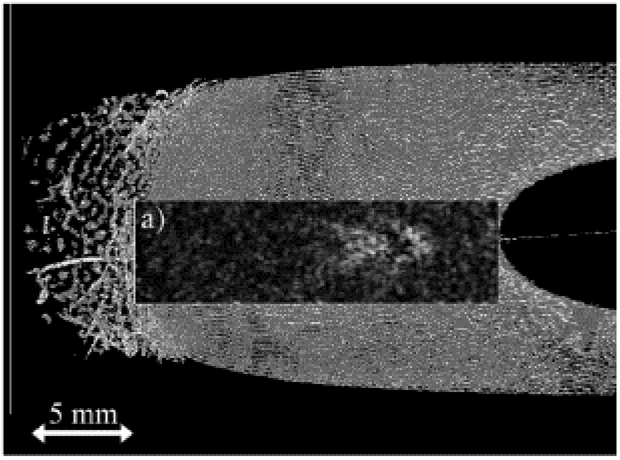
Results

Mach Cones-PK

The effectiveness of directly measuring the speed of sound in a 3-D plasma dust system was demonstrated by measuring the mach angle that comprises the half-angle of the mach cone solution. The speed of the large particle exceeded 35 mm/s. The speed of sound measured was 20-30 mm/s, ie, the large particle traveled in supersonic mode at a mach number ranging from 2.8-1.3.

Projectile-PK

Trajectories of small particles were studied in detail and a theory of their motion was developed based on hydrodynamic approximation. A comparison of the particle trajectories calculated on the basis of a classical solution with those obtained in the experiment demonstrates that motion of dust particles corresponds to the case of their non-viscous flow of a spherical Wigner-Seitz cell around a large particle in which the transfer of impulse moment between the environment and the outflowing medium did not occur. This situation explained the effect of drag force disappearing from the dust crystal.



Photograph of the dust particle cloud obtained with a quadrant camera with a field of view of 35.7x26.0 mm. On the left, a short path is observed in the large particle's leading edge section in the dust cloud. As can be seen in the photograph, the movement of the particle is accompanied by the appearance of a Mach cone. The cones shown in the figure were obtained by superimposing two sequential video footage frames. It is clear that the projection of the double cone on the plane deviates somewhat from the straight lines. Roscosmos image.

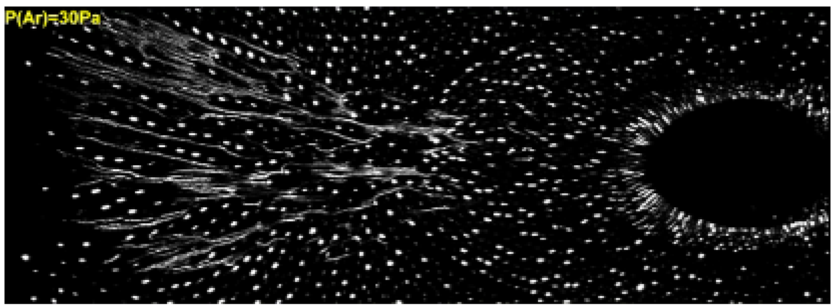
Phase Transitions-PK-1

The phase transition isotropic medium-chain structure in ER plasma was studied in microgravity. Particles remained in a disordered liquid phase while the amplitude of the alternating field applied was lower than a given threshold. The subsequent increase of the field led to a reorganization of the particles. The particles became more and more ordered until well-defined chains along the field were formed. The transition between isotropic and chain liquid states was entirely reversible; a decrease in the field returned the particles back to an isotropic state.

Phase Transitions-PK-2

For Phase Transitions-PK-2, 3.4-micron particles penetrated the stable structure of large particles and traveled to the center of the plasma chamber. During observations, it was established that in the external area, when the speed of the penetrating particles was fairly high, the penetration of the small particles resulted in the formation of chains. The large particles also structured into chains and formed lanes. The formation of such structures is observed in nature, when 2 streams of particles move towards each other under the impact of a certain force. The phenomenon observed was a non-equilibrium transition, and was dependent upon the specific characteristics and dynamics of the particle interaction. It is of interest for various fields of physics. With experiments involving dust plasma in microgravity, it is possible to enable the movement of individual particles and study the dynamics of the transition.

Phase Transition-PK-3



Penetration of dust particles 3.4 microns in diameter into a structure of particles 9.2 microns in diameter in an argon plasma at a pressure of 30 Pa. The formation of chains and lanes is visible. Frames were obtained by superimposing sequential images: small particles are identified in the form of long bands, and large particles appear as points. Roscosmos image.

The increase in distance between particles (ie, the decrease in density of the dust component) was the main factor responsible for the fusion of the plasma dust system with the increase in pressure of the inert gas. Similarly, the decrease in pressure resulted in compression of the dust system and stimulated crystallization. The interaction energy as a function of pressure was maximal with the lowest pressure p ≈ 11 Pa for both of the plasma dust systems studied. The increase in inert gas pressure resulted in the decrease in interaction energy between dust particles, as well as the decrease in pressure of the gas causing an increase in interaction. An analysis of the phase state of the plasma dust system observed (based on assessing the phase trajectories of the system in an equilibrium phase diagram) showed that when pressure increases both systems move in the direction of the fusion curve. The plasma dust system of small-size particles crossed the phase border at high pressures.

Crystallization Front-PK

The formations of a crystallization front and domains with varying orientations were discovered.

Search-PK-3-2

In the PK-3 Plus unit, three ways of closing off an area free of microparticles were successfully demonstrated, decreasing high frequency discharge power to the minimum possible level, using a symmetrical flow of gas and effect of an external low-frequency electrical field.

PUBLICATION(S)

D'yachkov LG, Savin SF, Myasnikov MI, et al. Coulomb clusters in a cusp magnetic trap under microgravity condition. *ESCAMPIG XXI*, Viana do Castelo, Portugal; July 10-14, 2012.

Khrapak SA, Klumov BA, Huber P, et al. Fluid-solid phase transitions in three-dimensional complex plasmas under microgravity conditions. *Physical Review E*. June 2012;85(6-2):066407.

Ivlev AV, Thoma MH, Rath C, Joyce G, Morfill GE. Complex plasmas in external fields: The role of non-hamiltonian interactions. *Physical Review Letters*. April 15, 2011;106(15):155001. doi: 10.1103/PhysRevLett.106.155001.

Thomas HM, Morfill GE, Ivlev AV, et al. New directions of research in complex plasmas on the International Space Station. *Fifth International Conference on the Physics of Dusty Plasmas*, Ponta Degada, Azores, Portugal; 2008 May 18-23, 2008.

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Lipaev AM, Khrapak SA, Molotkov VI, et al. Void closure in complex plasmas under microgravity conditions. *Physical Review Letters*. June 2007;98(26):265006. doi: 10.1103/PhysRevLett.98.265006.

Ivlev AV, Thomas HM, Morfill GE, et al. Coalescence of complex plasma clouds. *New Journal of Physics*. February 15, 2006;8(2):25. doi: 10.1088/1367-2630/8/2/025.

Kretschmer M, Khrapak SA, Zhdanov SK, et al. Force field inside the void in complex plasmas under microgravity conditions. *Physical Review* E. May 2005;71(5):056401. doi: 10.1103/PhysRevE.71.056401.

Fortov VE, Vaulina OS, Petrov OF, et al. Dynamics and structural properties of dusty plasma liquid in microgravity: Experiments onboard the International Space Station. *Plasma Physics and Controlled Fusion*. December 1, 2004;46(12B):B359-B366. doi: 10.1088/0741-3335/46/12B/031.

Yaroshenko VV, Annaratone BM, Khrapak SA, et al. Electrostatic modes in collisional complex plasmas under microgravity conditions. *Physical Review E*. June 2004;69(6):066401. doi: 10.1103/PhysRevE.69.066401.

Fortov VE, Vaulina OS, Petrov OF, et al. Dynamics of macroparticles in a dusty plasma under microgravity conditions (First experiments on board the ISS). *Journal of Experimental and Theoretical Physics*. April 2003;96(4):704-718. doi: 10.1134/1.1574544.

Nefedov AP, Morfill GE, Fortov VE, et al. Pke-Nefedov: Plasma crystal experiments on the International Space Station. *New Journal of Physics*. April 22, 2003;5(3):33.1-33.10. doi: 10.1088/1367-2630/5/1/333.

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Samsonov D, Morfill GE, Thomas HM, et al. Kinetic measurements of shock wave propagation in a three-dimensional complex (dusty) plasma. *Physical Review E*. 2003 March 2003;67(3):036404. doi: 10.1103/PhysRevE.67.036404.

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Annaratone BM, Khrapak SA, Bryant P, et al. Complex-plasma boundaries. *Physical Review E*. November 2002;66(5):056411. doi: 10.1103/PhysRevE.66.056411.

Mikikian M, Boufendi L, Bouchoule A, et al. Dust particles growth and behavior under microgravity conditions. *Dusty Plasmas in the New Millennium: Third Conference on the Physics of Dusty Plasmas*, Durban, South Africa; May 20-24, 2002.

Morfill GE, Thomas HM, Annaratone BM, et al. Complex plasmas under microgravity conditions: First results from PKE-Nefedov. *Dusty Plasmas in the New Millennium: Third Conference on the Physics of Dusty Plasmas*, Durban, South Africa; May 20-24, 2002.

This investigation is ongoing and additional results are pending publication.

TECHNOLOGY DEVELOPMENT AND DEMONSTRATION

Future exploration—the return to the moon and human exploration of Mars—presents many technological challenges. Studies on the ISS can test a variety of technologies, systems, and materials that will be needed for future Exploration missions. Some of the technology development experiments have been so successful that the hardware has been transitioned to operational status. Other experimental results feed new technology developments.

Amine Swingbed

Research Area: Air, Water and Surface Monitoring
Expedition(s): 27-ongoing
Principal Investigator(s):
- Jeffrey Sweterlitsch, Johnson Space Center, Houston, Texas
- John Graf, PhD, Johnson Space Center, Houston, Texas

Research Objectives

The Amine Swingbed investigation determines if a vacuum-regenerated amine system can effectively remove carbon dioxide (CO_2) from the International Space Station (ISS) atmosphere using a smaller, more efficient vacuum regeneration system.

Earth Benefits

Although designed for human spaceflight missions where ample access to the vacuum of space is available, the technology can be used in Earth applications if access to a clean-purge gas supply is available.

Expedition 30 Commander Dan Burbank assembles the Amine Swingbed Hardware Assembly in the US Laboratory/Destiny.

Space Benefits

This technology and hardware provides environmental control of the spacecraft's habitable volume by removing metabolically produced CO_2, a requirement of all human spaceflight missions, and minimizing losses of ullage air and humidity. This payload is capable of removing the amount of CO_2 produced by 6 crew members and so is directly applicable to the ISS. Because of air save and water save, it is also applicable for longer-duration human spaceflight missions.

Results

Data is still being collected from this investigation, and analysis is ongoing.

Patent(s)

Dean, II WC, inventor; Swing bed canister with heat transfer features. US patent 7,637,988; 29. December 2009.

This investigation is ongoing and additional results are pending publication.

Analyzing Interferometer for Ambient Air (ANITA)

Research Area: Air, Water and Surface Monitoring
Expedition(s): 15-17
Principal Investigator(s):
- Gijsbert Tan, European Space Research and Technology Research Centre, Noordwijk, Netherlands

Research Objectives

ANITA monitors 32 potential gaseous contaminants, including formaldehyde, ammonia and carbon monoxide, in the atmosphere aboard the International Space Station (ISS). The experiment tests the accuracy and reliability of this technology as a potential next-generation atmosphere trace-gas monitoring system for the station.

ISS015E29193 - Expedition 15 Flight Engineer Clayton Anderson beside the ANITA equipment in the US Laboratory/Destiny.

Earth Benefits

ANITA provides an improved multi-component gas measurement system for various purposes, such as workplace monitoring (including airplanes and submarines), environmental monitoring, and control of industrial processes.

Space Benefits

ANITA will lead to new atmospheric monitoring systems for future spaceflight.

Results

ANITA was a flight experiment precursor for a permanent continuous air quality monitoring system on the ISS, developed to help ensure crew health and safety. Because ANITA was an experimental system, ANITA's air analyses were compared to results from other sources of analyses, including archival samples captured in grab sample containers and analyzed on ground, and real-time instruments aboard ISS, such as the Volatile Organic Analyzer and the Carbon Dioxide Monitor. For the first time, many gases in the ISS air were measured with high-time resolution. The observed results showed effects from spacecraft visits to the ISS, crew activities, the number of crew members present, and the functioning of the air revitalization systems. Of the 13 gas compounds quantified by ANITA and the 12 gases detected and quantified by the archival samplers, only 4 were in common. ANITA measurements of carbon

ISS015E32200 - Clay Anderson using the sampling pump and 2.5 liter gas sample bag for the ANITA experiment in the Node 1/Unity.

dioxide, methanol, ethanol, and perfluoro propane (PFP) were in close agreement with grab sample readings. After extensive cross-checking and analyses, ANITA's estimates for carbon monoxide, methane, and sulphur hexafluoride (SF_6) showed from small to large differences from the grab sample analyses; however, the origin of these differences are unknown. Freon 11 and Halon 1301 were both measured at low levels by ANITA and the grab samples but with higher values from ANITA. Designed to detect and quantify 33 gas compounds in the air, ANITA's first measurements on ISS gave warnings for gas compounds the system was not calibrated for since significant concentrations were not expected. The previously unknown presence of the gas SF_6, a chemical used in certain medical investigations, was discovered by ANITA in the ISS atmosphere. ANITA also detected a leak of Freon 218, also known as PFP, from the Russian air conditioner and was used to monitor the timeline of PFP concentrations in relation to Carbon Dioxide Removal Assembly (CDRA) operations and shuttle docking. The ANITA data helped to determine that the zeolite bed in the CDRA was not effective in scrubbing the PFP leak from the air, but that dilution of the ISS air after shuttle docking did substantially reduce the level of PFP. Prior to ANITA, PFP levels in the ISS atmosphere had only been estimated (Honne 2008, 2009, 2011; Stuffler 2009).

Publication(s)

Honne A, Schumann-Olsen H, Kaspersen K, Mosebach H, Kampf D. ANITA – an FTIR-based continuous air quality monitoring system on the ISS (International Space Station). *Applied Industrial Optics: Spectroscopy, Imaging and Metrology*, Toronto, Canada; 2011.

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Honne A, Schumann-Olsen H, Kaspersen K, et al. Evaluation of ANITA air monitoring on the International Space Station. *SAE International Journal of Aerospace*. 2009;4(1):451-466. doi: 10.4271/2009-01-2520.

Stuffler T, Mosebach H, Kampf D, et al. Advanced ISS air monitoring – The ANITA and ANITA2 Missions. *SAE International Journal of Aerospace*. July 12, 2009;2009-01-2523. doi: 10.4271/2009-01-2523.

Stuffler T, Mosebach H, Kampf D, et al. ANITA air monitoring on the International Space Station part 1: The mission. *SAE Technical Paper*. June 29, 2008;2008-01-2042. doi: 10.4271/2008-01-2042.

This investigation is complete and all results are published.

Jet Propulsion Laboratory Electronic Nose (ENose)

Research Area: Air, Water and Surface Monitoring
Expedition(s): 18-20
Principal Investigator(s):
- Margaret A. Ryan, PhD, Jet Propulsion Laboratory, Pasadena, California

Research Objectives

The JPL Electronic Nose (ENose) is a full-time, continuously operating event monitor designed to detect air contamination from spills and leaks in the crew habitat in the International Space Station (ISS). It fills the long-standing gap between onboard alarms and complex analytical instruments. ENose provides rapid, early identification and quantification of atmospheric changes caused by chemicals to which it has been trained. ENose can also be used to monitor cleanup processes after a leak or a spill.

Earth Benefits

Many important and diverse Earth-based applications exist for ENose technology. One major driver is the current need for advanced detection devices for security (both civilian and military) and health safety applications, such as the detection of explosives and infection monitoring. This technology can also be integrated with other devices, such as analytical instruments and environmental monitoring and control systems, to monitor enclosed environments.

Images of JPL Electronic Nose taken during testing with Express Rack 7 at the SPACEHAB Payload Processing Facility.

Expedition 34 Flight Engineer (FE) Roman Romanenko working with the ENose and Nose Target Book hardware in the Service Module (SM).

Space Benefits

The ENose is envisioned to be one part of a distributed system for automated monitoring and control of the breathing atmosphere in inhabited spacecraft in microgravity. It is designed as an event or incident monitor, capable of providing rapid, early identification and quantification of changes in the atmosphere caused by leaks or spills of compounds targeted by the device. The flexibility of the device includes the ability to be programmed to detect new compounds, the possibility of providing sensor sets for particular analyte suites, and a wide dynamic range from fractional parts per million (ppm) to 10,000 ppm, making ENose a valuable part of an air quality monitoring and control system comprised of several types of instruments. Such a system can be included in an environmental control system, which actuates remediation of anomalous events.

RESULTS

Analysis of ENose monitoring data showed regular, periodic rise and fall of humidity. Occasional releases of Freon 218 (Perfluoropropane), used in ISS cooling systems, were detected by ENose and the Analyzing Interferometer for Ambient Air (ANITA) payload, another air quality monitoring instrument. Formaldehyde, which is not detectable by any other instrument in the US Lab, was frequently detected by ENose at low concentrations and may result from off-gassing of polymeric seals or o-rings heated by operating equipment. Similarly, the presence of methanol was detected by ENose but could not be correlated to any specific activities aboard. ENose and ANITA detected the unexpected presence of sulfur hexafluoride (SF_6). Sulfur hexafluoride was not on the JPL ENose target list of compounds, so it was reported as an "unknown" event for the in-flight analysis. In postflight, based on sensor response modeling inputs and experimental verification, it was determined these unknown events could be related to SF_6 (Shevade 2010). Each detected event lasted from 20 to 100 minutes, which is consistent with the air replacement time in the US Lab (Ryan 2009, 2010a).

PATENT(S)

Homer ML, Jan DL, Jewell AD, Kisor AK, Manatt KS, Manfreda AM, Ryan MA, Shevade AV, Taylor C, Tran TA, Yen SS, Zhou H, inventors; System for detecting and estimating concentrations of gas or liquid analytes. US patent 8,024,133. September 20, 2011.

PUBLICATION(S)

Ryan MA, Manatt KS, Gluck SE, et al. The JPL electronic nose: Monitoring air in the US lab on the International Space Station. *2010 IEEE Sensors*, Kona, HI; November 1-4, 2010.

Shevade AV, Ryan MA, Homer ML, et al. Characterization of unknown events observed by the third generation JPL electronic nose using sensor response models. *40th International Conference on Environmental Systems*, Barcelona, Spain; July 11-15, 2010.

Kateb B, Ryan MA, Homer ML, et al. Sniffing out cancer using the JPL electronic nose: A pilot study of a novel approach to detection and differentiation of brain cancer. *NeuroImage*. 2009;47(Supp 2):T5-T9. doi: 10.1016/j.neuroimage.2009.04.015.

Ryan MA, Manatt KS, Gluck SE, et al. Operation of third generation JPL electronic nose on the International Space Station. *SAE International Journal of Aerospace*. 2009;2009-01-2522.

Shevade AV, Ryan MA, Homer ML, Kisor AK, Manatt KS, Lara LM. Monitoring pre-combustion event markers by heating electrical wires. *SAE International Journal of Aerospace*. 2009; 2009-01-2543.

This investigation is complete and all results are published.

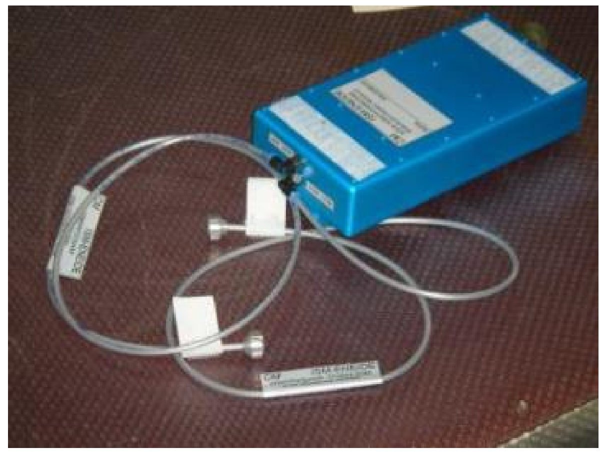
ELECTRONIC NOSE MONITORING (E-NOSE)

Research Area: Air, Water, and Surface Monitoring
Expedition(s): 10 and 11
Principal Investigator(s):

- Eugenio Martinelli, University of Rome Tor Vergata, Rome, Italy
- Carlos D'Amico, University of Rome Tor Vergata, Rome, Italy
- Corrado Di Natale, University of Rome Tor Vergata, Rome, Italy

RESEARCH OBJECTIVES

The objective of the Electronic Nose Monitoring (E-Nose) experiment is to test the technology of this system under microgravity conditions and to verify its suitability to space applications.



Electronic Nose Monitoring electronic module and probes. ESA image.

EARTH BENEFITS

Many important and diverse Earth-based applications exist for E-Nose technology, including the current need for advanced detection devices for security (both civilian and military) and health safety applications, such as the detection of explosives and infection monitoring.

SPACE BENEFITS

The Jet Propulsion Lab (JPL) E-Nose is envisioned to be one part of a distributed system for automated monitoring and control of the breathing atmosphere in inhabited spacecraft in microgravity. Such a system can be included in an environmental control system, which actuates remediation of anomalous events.

RESULTS

Onboard tests of the prototype included a simple experiment aimed at measuring the air in the close environment of the instrument. This verified functionality and sensor stability in the experimental sessions with the device in different positions. During the 3 runs, the temperature remained in the range of 21-26°C and the relative humidity between 65% and 85%. The temperature of the sensors chamber was maintained in the range of 25-29°C. In each run the sampling tube was moved around in a circular path sampling the air. As temperatures varied slowly and little in absolute value, this did not influence the responses of the sensors. The presence of a unique cluster of data indicated a substantial constancy of the air quality during the 3 runs and the same good reproducibility of the “ground version” electronic nose. This is because the in-orbit prototype differs from the “ground version” of the instrument only for the packaging and the electronic circuit design. Functionality and sensors are the same for both prototypes.

This investigation is complete; however additional results are pending publication.

ITALIAN-ELECTRONIC NOSE FOR SPACE EXPLORATION (I-ENOS)

Research Area: Air, Water and Surface Monitoring
Expedition(s): 27 and 28
Principal Investigator(s):
- Arnaldo D'Amico, University of Rome Tor Vergata, Rome, Italy
- Corrado Di Natale, University of Rome Tor Vergata, Rome, Italy
- Eugenio Martinelli, University of Rome Tor Vergata, Rome, Italy

RESEARCH OBJECTIVES

Italian-Electronic NOse for Space exploration (I-ENOS) is a study involving air quality monitoring and the search for possible anomalies in the internal in-orbit atmosphere utilizing a network of 3 sensorial I-ENOS units.

View of an I-ENOS bag and 3 I-ENOS sensors mounted to the Combustion Integrated Rack (CIR) in the US Laboratory/Destiny.

EARTH BENEFITS

Earth-based applications include the detection of dangerous gases emitted from substances like pesticides, paints, glues, and other hazardous building materials.

SPACE BENEFITS

The ability to monitor the International Space Station (ISS) air quality provides the opportunity to improve the ISS cabin air conditions and to identify potential real-time anomalies that may occur in the ISS air quality.

RESULTS

The I-ENOSE experiment was performed on ISS in May 2011. No anomalies in air quality were observed. However, analysis of I-ENOSE data showed that responses of the I-ENOSE sensors could be correlated to certain crew activities performed in close proximity to the sensors. Analysis of data are complete and results are pending publication.

PUBLICATION(S)

Martinelli E, Pennazza G, Sintonico M, et al. Chemical drift counteraction based on pulsed measurements strategy. *12th International Meeting on Chemical Sensors*, Columbus, OH; July 13-16, 2008.

Martinelli E, Zampetti E, Pantalei S, et al. Design and test of an electronic nose for monitoring the air quality in the International Space Station. *Microgravity Science and Technology*. 2008;19: 60-64.

Fortezza R, Pontetti G, Martinelli E, Lo Castro F, Di Natale C, D'Amico A. Soyuz missions and taxi flights: New opportunities for technology development. An example: The ENEIDE mission. *Acta Astronautica*. 2006;59(1-5):351-357. doi: 10.1016/j.actaastro.2006.02.025.

STS-134 Mission Specialist (MS-2) Roberto Vittori holding an I-ENOS bag on the International Space Station.

D'Amico A, Di Natale C, Martinelli E, Sandro L, Baccarani G. Sensors small and numerous: Always a winning strategy?. *Sensors and Actuators B: Chemical*. April 29, 2005;106(1):144-152. doi: 10.1016/j.snb.2004.05.046.

Di Natale C, Paolesse R, D'Arcangelo G, et al. Identification of schizophrenic patients by examination of body odor using gas chromatography-mass spectrometry and a cross-selective gas sensor array. *Medical Science Monitor*. 2005;11(8):366-375.

Di Natale C, Paolesse R, Macagnano A, et al. Sensitivity-selectivity balance in mass sensors: The case of metalloporphyrins. *Journal of Materials Chemistry*. 2004;14:1281-1287. doi: 10.1039/B313250A.

Martinelli E, Pennazza G, Di Natale C, D'Amico A. Chemical sensors clustering with the dynamic moments approach. *Sensors and Actuators B: Chemical*. 2004;101(3):346-352. doi: 10.1016/j.snb.2004.04.010.

Martinelli E, Pennazza G, Paolesse R, et al. Monitoring of biofiltration efficiency of bioreactor exhaust air by an electronic nose. *2004 IEEE Sensors Conference*, Vienna, Austria; 2004.

Willers H, de Gijsel P, Ogink N, et al. Monitoring of biological odour filtration in closed environments with olfactometry and an electronic nose. *Water Science and technology: A Journal of the International Association on Water Pollution Research*. 2004;50(4):93-100.

This investigation is complete and all results are published.

Lab-on-a-Chip Application Development-Portable Test System (LOCAD-PTS)

Research Area: Air, Water and Surface Monitoring
Expedition(s): 14-20
Principal Investigator(s):
- Norman R. Wainwright, PhD, Charles River Laboratories, Charleston, South Carolina

Research Objectives

Lab-on-a-Chip Application Development-Portable Test System (LOCAD-PTS) is a handheld device used for rapid detection of biological and chemical substances on surfaces aboard the International Space Station (ISS). Astronauts swab surfaces with a specialized swabbing unit, which dissolves the sample in water and dispenses it into the LOCAD-PTS. Within 15 minutes, results are displayed on the screen. The study's purpose is to effectively provide a rapid indication of biological cleanliness to help crew monitor microorganisms in the ISS cabin environment.

Astronaut Suni Williams, Expedition 14 flight engineer, works with the LOCAD-PTS. Williams is placing the sample mixed with water from the swabbing unit into the LOCAD-PTS cartridge.

Earth Benefits

Currently, the technology is being used to assess fluids used in pharmaceutical processing. The technology has been used to swab the Mars Exploration Rovers (MER), for planetary protection, and to assess microbial contamination in the NASA Extreme Environment Mission Operations (NEEMO) project. This technology will provide quick medical diagnostics in clinical applications. It will also provide environmental testing capabilities that may serve homeland security.

Space Benefits

This commercial, off-the-shelf technology is applicable in many areas related to microbial detection, crew health diagnostics, and environmental monitoring. The drastic reduction in time for detection (minutes versus days) will provide a capability on ISS that does not currently exist and may help risk mitigation in the event that some type of microbial build-up is observed. Eventually, it is planned that LOCAD-PTS be used to assess water, air, and food supplies in addition to surfaces. Other cartridges are being developed to perform limited crew health diagnostics and monitor other biological molecules, such as protein and peptidoglycan, and specific chemicals that pose a potential hazard to the crew, such as hydrazine and ammonia.

RESULTS

The testing of ISS cabin surfaces occurred in 2 phases using various combinations of Contact Slides and LOCAD-PTS with Gram-negative bacteria (LAL), fungi (beta-glucan), and Gram-positive bacteria (LTA) cartridges. The first phase involved extensive swabbing and sampling of limited sites with both cartridges and contact slides (like Petri dishes). When LAL cartridges were used with contact slides, low levels of endotoxin were found at 5 sites with the cartridges and at 3 sites with the contact slides. When beta-glucan and LTA cartridges were used with contact slides, low levels of fungi were detected on the beta-glucan cartridges, no bacteria or fungi colonies grew on the contact slides, and very low levels of endotoxin were on the LTA cartridges. The very low values were expected because the cartridges produced for this study had a lower sensitivity to its targeted microbial cells than the other 2 cartridges. The results for this phase were not expected to correlate because the cartridges measure the presence of both live and dead microbes, and the slides measure live microorganisms; more so, results were expected to generate a bigger picture of microorganisms present at different sites. The second phase involved a single swab using cartridges only of various crew-selected sites expected to have high microbial growth. Moderate to high levels of endotoxin were observed at sites mostly associated with exercise, hygiene and dining facilities, where microbial nutrients such as sweat, food remnants, and water were generally present. A surprising observation from both phases was that endotoxin was distributed throughout the ISS, despite previous indications that most bacteria on ISS surfaces were Gram-positive. Lastly, parallel analysis of at least 1 site with all 3 cartridges and contact slides was performed. Although the values from all 3 cartridges were different from each other, the majority of the results were still low or very low. Analysis of all the data collected from the LOCAD-PTS experiments showed 31 samples had low or absent levels of endotoxin, and 11 samples had moderate to high levels at sites with frequent crew contact, demonstrating that most surfaces on the ISS are relatively free of microbial molecules (Maule 2009; Morris 2012).


Expedition 14 Flight Engineer Suni Williams uses the swabbing unit to collect samples that will be placed into the cartridges to be analyzed by the Lab-on-a-Chip Application Development reader.

PUBLICATION(S)

Morris HC, Damon M, Maule JG, Monaco LA, Wainwright NR. Rapid culture-independent microbial analysis aboard the International Space Station (ISS) stage 2: Quantifying 3 Microbial Biomarkers. *Astrobiology*. September 2012;12(9):830-840. doi: 10.1089/ast.2012.0863.

Maule JG, Wainwright NR, Steele A, Gunter DL, Morris H, Monaco L. Rapid monitoring of bacteria and fungi aboard the International Space Station. *47th Aerospace Sciences Meeting and Exhibit*, Orlando, FL; 2009.

Maule JG, Wainwright NR, Steele A, et al. Rapid culture-independent microbial analysis aboard the International Space Station (ISS). *Astrobiology*. 2009;9(8):759-775. doi: 10.1089/ast.2008.0319.

Maule JG, Wainwright NR, Steele A, et al. Operation of a new system for microbial monitoring aboard the International Space Station. *AIAA Space 2008 Conference and Exposition*, San Diego, CA; 2008.

This investigation is complete; however additional results are pending publication.

LAB-ON-A-CHIP APPLICATION DEVELOPMENT-PORTABLE TEST SYSTEM – EXPLORATION (LOCAD-PTS-EXPLORATION)

Research Area: Air, Water and Surface Monitoring
Expedition(s): 18
Principal Investigator(s):
- Jake G. Maule, PhD, Carnegie Institution of Washington, Washington, DC

RESEARCH OBJECTIVES

Lab-on-a-Chip Application Development-Portable Test System - Exploration (LOCAD-PTS-Exploration) is a handheld device for rapid detection and quantification of biological substances aboard the International Space Station (ISS). LOCAD-PTS-Exploration tested procedures aboard the ISS that will ultimately support scientific activities during the human exploration of other planets. For the first time, external surfaces of a spacecraft were sampled for biological material during extra-vehicular activity (EVA or spacewalk), followed by analysis within the cabin environment.

Lab-on-a-Chip Application Development-Portable Test System-Exploration principal investigator Jake Maule swabs a handrail of the S6 Truss.

EARTH BENEFITS

The procedures used in this study to detect biological material in the hostile environment of space have many other applications for similar tests performed in extreme environments on Earth. These include the investigation of hyperthermophiles (organism that thrives in extremely hot environments from 60°C and higher) in active volcanic craters and fumeroles (opening in Earth's crust that emits steam and gases such as carbon dioxide, sulfur dioxide, hydrochloric acid, and hydrogen sulfide); the detection of lethal viral outbreaks; the exploration of deep sea flora and fauna by deep divers on the ocean floor; and the evaluation of biological attacks in a military or civilian situation.

SPACE BENEFITS

The extent to which human space exploration transfers biological material to other planets is currently unknown. The data obtained with LOCAD-PTS-Exploration serves as a foundation for planetary protection procedures that will be performed during future human exploration of other planets.

RESULTS

LOCAD-PTS analysis of 15 sites on the S6 Truss prior to launch detected no endotoxin at any test site. However, the fungal marker glucan was found at some sites, especially on gap spanners (fabric straps that span the gap between handrails to assist movement of extra-vehicular crew). After the launch and installation of the S6 Truss on ISS, swabs were performed on the right-hand gloves of both EVA suits before and after the first spacewalk. LOCAD-PTS analysis showed that the absolute level of glucan on the spacesuit gloves was low, especially when compared with other surfaces within the station. Interestingly, there was a 50% decrease in glucan on the gloves from pre-EVA to post-EVA, despite the EV crew's contact with many sites on the S6 Truss that tested high for glucan preflight. This might be because of glucan on the S6 Truss being destroyed after a few days in space and to glucan on the spacesuit glove (detected pre-EVA) detaching during a spacewalk. These insights will help design contamination control strategies for the human exploration of other planets.

Video screen shot of ISS Expedition 18 Flight Engineer Sandy Magnus, as she swabs the glove of EVA crew member Richard Arnold following EVA 1 on Flight Day 5 of STS-119.

PUBLICATION(S)

Eigenbrode J, Benning LG, Maule JG, Wainwright NR, Steele A, Amundsen HE. A field-based cleaning protocol for sampling devices used in life-detection studies. *Astrobiology*. 2009;9(5):455-465. doi: 10.1089/ast.2008.0275.

This investigation is complete; however additional results are pending publication.

Supervision of Autonomous and Teleoperated Satellites – Interact (SATS-Interact)

Research Area: Air, Water and Surface Monitoring
Expedition(s): 29-ongoing
Principal Investigator(s):
- Randy Stiles, Lockheed Martin Space Systems Company, Sunnyvale, California
- Vadim Slavin, Lockheed Martin Space Systems Company, Sunnyvale, California

Research Objectives

Supervision of Autonomous and Teleoperated Satellites (SATS) is a research effort aimed at drastically improving remote operation of space assets by enabling a single user to control multiple maneuvering small satellites. SATS is achieving this by developing software called Interact, which allows a single, ground-based operator to command a team of remote nanosatellites working on a common mission.

Earth Benefits

The research performed under SATS applies to a broad range of remote autonomous robotic agents, such as remote underwater vehicles and remote ground vehicles operating in hazardous conditions.

Space Benefits

Results from SATS, specifically the Interact software, enable a more efficient method of controlling a group of nanosatellites that can be tasked to perform services such as satellite servicing, spacecraft assembly, and emergency repairs.

Results

Data collection for SATS-Interact is ongoing.

This investigation is ongoing and additional results are pending publication.

Experimental Studies of the Possible Development of Microscopic Deterioration of ISS RS Module Structural Elements when Impacted by the Components of the Station's External Atmosphere and Conditions Promoting the Life of Microflora on Pressure Hull Surfaces under MLI (Test)

Research Area: Air, Water, and Surface Monitoring
Expedition(s): 25, 26 and 29-ongoing
Principal Investigator(s):
- Oleg A. Saprykin, PhD, Central Research Institute for Machine Building, Korolev, Russia
- Elena V. Shubralova, Central Research Institute for Machine Building, Korolev, Russia

Research Objectives

Experimental Studies of the Possible Development of Microscopic Deterioration of ISS RS Module Structural Elements when Impacted by the Components of the Station's External Atmosphere and Conditions Promoting the Life of Microflora on Pressure Hull Surfaces under MLI (Test) examines the chemical, toxicological, and microbiological samples taken from the exterior surface of the pressure hull on and underneath MLI in deposition areas of corrosive life support system products and components of the station's external atmosphere.

Sampling underneath a flap. Roscosmos image.

Space Benefits

Information obtained on anomalous processes that reduce the life specifications of pressure hulls will be applied to spacecraft with extended lifetimes and high autonomy, such as a system for a mission to Mars or on the surface of the moon or Mars.

Results

Viable spore-forming *Bacillus licheniformis* bacteria was discovered in a sample taken near a Vozdukh system valve. This demonstrates that on a space station using a system that vents out air environment components after cleaning it, microorganisms contained in the living compartment air can be transferred to the surface of the station. This important factor should be taken into consideration when conducting planetary quarantine measures in Martian and other far-away missions. The experiment enabled direct proof confirming that viable spores of microorganisms, whose resilience to unfavorable environmental factors is extremely high, and can be present on the exteriors of unmanned and manned space stations.

PATENT(S)

Tsygankov OS, Shubralova EV, Deshevaja EA, Tsygankova ZV, Makarov AV, inventors; Device for sampling of outer surface of space object by astronaut. *Federal Service for Intellectual Property of Russian Federation*. Patent Number 2536746. February 14, 2013.

This investigation is ongoing and additional results are pending publication.

Vehicle Cabin Atmosphere Monitor (VCAM)

Research Area: Air, Water and Surface Monitoring
Expedition(s): 19-28
Principal Investigator(s):
- Ara Chutjian, PhD, California Institute of Technology, NASA's Jet Propulsion Laboratory, California

Research Objectives

Vehicle Cabin Atmosphere Monitor (VCAM) identifies gases that are present in minute quantities in the International Space Station (ISS) air that could harm the crew's health. Experience in monitoring the ISS environment provides a new understanding of the closed environment and will be applied to operations of future spacecraft and long-duration human exploration missions.

View of VCAM during gas supply change-out during Expedition 30.

Earth Benefits

Instruments larger than VCAM monitor the air in enclosed systems on Earth, such as onboard submarines. Small portable units are used in the field to monitor the environment.

Space Benefits

VCAM will protect crew members by informing them of the slow buildup of potentially harmful chemicals in their breathing air. While VCAM's library contains species that are known to be present in the various life-support systems, VCAM can provide data that allow ground scientists to identify compounds that were not expected. These same functions of detection, identification, and quantification can be used in the event of a chemical spill or release.

Results

VCAM's performance was sufficient to detect and identify 90% of the target compounds at their 180-day Spacecraft Maximum Allowable Concentration levels. About 1 month into operations, VCAM suffered a mass spectrometer heater failure. VCAM was recalibrated to operate without the heater and returned to nominal operations after a patch cable, delivered on STS-134/ULF6, was installed to power a backup heater. VCAM and Grab Sample Container (GSC) analytical results were in good agreement for 10 compounds: 1,2-dichloroethane, acetone, benzene, carbonyl sulfide, dichloromethane, ethanol, isoprene, limonene, toluene, and the xylenes. While VCAM could not quantize 6 compounds (1-butanol, 2-butanone, 2-propanol, ethyl acetate, hexamethylcyclotrisilazane, and octamethylcyclotetrasiloxane) prior to the heater

NASA astronaut Ron Garan prepares to install a Gas Supply Orbital Replacement Unit into the VCAM.

repair, post repair measurements of these compounds by VCAM and GSC yielded concentrations at least 20 times less than VCAM requirements. VCAM also did not report any “false positives” for the 17 chemicals detected by GSC measurements that were below the quantification limit of 0.05 mg/m^3. Measurements of the compound perfluoropropane showed only fair agreement between VCAM and GSC data. VCAM also detected a large number of unknown chemical species not part of the original VCAM requirements list, which were later identified during ground analysis. Additionally, VCAM performed autonomous measurements of the major constituents of the ISS atmosphere. VCAM’s measurements of N_2 and O_2 were in excellent agreement with measurements taken by the Major Constituents Analyzer (MCA) of the same constituents. CO_2 measurements were in agreement as well through February 2011, but thereafter, VCAM measurements diverged and the instrument error increased, likely because of instrument contamination (Darrach 2011, 2012).

PUBLICATION(S)

Darrach MR, Chutjian A, Bornstein BJ, et al. Trace chemical and major constituents measurements of the International Space Station atmosphere by the vehicle cabin atmosphere monitor. *42nd International Conference on Environmental Systems*, San Diego, CA; July 15-19, 2012.

Darrach MR, Chutjian A, Bornstein BJ, et al. On-orbit measurements of the ISS Atmosphere by the vehicle cabin atmosphere monitor. *41st International Conference on Environmental Systems*, Portland, OR; July 17-21, 2011.

PATENT(S)

Schaefer RT, Mojarradi M, Chutjian A, Darrach MR, MacAskill J, Tran TA, Burke GR, Madzunkov SM, Blaes BR, Thomas JL, Stern R, Zhu DQ, inventors; Electronic drive and acquisition system for mass spectrometry. US patent. 7,772,550. August 10, 2010.

This investigation is complete and all results are published.

Disruption Tolerant Networking for Space Operations (DTN)

Research Area: Avionics and Software
Expedition(s): 19-ongoing
Principal Investigator(s):
- Kevin Gifford, PhD, University of Boulder, Boulder, Colorado

Research Objectives

Disruption Tolerant Networking (DTN) research is concerned with establishing communications with and between extreme and performance-challenged environments, even if continuous, end-to-end connectivity is not available. The DTN program establishes a long-term, readily accessible communication test-bed aboard the International Space Station (ISS). Two Commercial Generic Bioprocessing Apparatus (CGBA), CGBA-4 and CGBA-5, serve as communications test computers that transmit messages between the ISS and ground Mission Control Centers. All data is monitored and controlled at the BioServe remote Payload Operations Control Center (POCC) located on the Engineering Center premises at the University of Colorado - Boulder.

Expedition 28 Flight Engineer Ron Garan is seen during periodic servicing of the CGBA-5 with its CSI (Science Insert).

Earth Benefits

DTN Earth-based applications include sensor networks, mobile devices, use of data mules, and military communications that involve stressed, disconnected, and disrupted networks.

Space Benefits

For Exploration, DTN enables network communications using multiple communication assets and network paths that increases the robustness of the communication network. DTN also improves the timeliness of data return from operating spacecraft, which reduces risk, reduces cost, increases crew safety, improves operational awareness, and improves science return.

RESULTS

The first experiment, which occurred on July 10, 2009, involved downlinking images of a previous CGBA-5 experiment over a planned Tracking and Data Relay Satellite System (TDRSS) handover, during which the space-to-ground and ground-to-space links were interrupted for several minutes. The CBGA-5, which had no feedback regarding the state of the space-to-ground link, responded to the disruption as designed, by custodial retransmission of the data after a configurable timeout. This initial deployment of the DTN-on-ISS network demonstrated the success of the bundle protocol in handling disruptions. The next test involved using DTN for unattended operations. The CGBA-5 downlinked its status telemetry files via the non-DTN transmit-in-the-blind configuration as well as via a DTN configuration. During a 3-day period in which 14 files were generated per hour, the non-DTN scheme resulted in an average of 3 504 redundant receptions per file. The DTN scheme performed much better at an average of 0.06 redundant receptions per file. During the next phase of investigation, the DTN-on-ISS network will be extended to include a second payload, CGBA-4, which will expand the network to 2 space nodes and 2 ground nodes and enable experimentation with cross-node routing and 1-way custody transfer (Jenkins 2010).


Expedition 29 Flight Engineer Satoshi Furukawa works on the CGBA-5/CSI-5 experiment in the Columbus Laboratory.

PUBLICATION(S)

Jenkins A, Kuzminsky S, Gifford K, Pitts RL, Nichols K. Delay/Disruption-tolerant networking: Flight test results from the International Space Station. *2010 IEEE Aerospace Conference*, Big Sky, MT; March 6-13, 2010.

This investigation is ongoing and additional results are pending publication.

ELECTRONICS SPACE TEST (EST)

Research Area: Avionics and Software
Expedition(s): 10 and 11
Principal Investigator(s):
- Giorgia Pontetti, G & A Engineering, Oricola, Italy

RESEARCH OBJECTIVES

The Electronics Space Test (EST) experiment is an analysis and test campaign to demonstrate that standard industrial components that are adequately protected and used correctly can be implemented in space. The EST is a technology demonstrator validating an electronic high-density power system, new generation batteries, advanced calculus devices for real-time computing, programmable and re-programmable devices for microsatellite and picosatellite subsystems and different kinds of sensors typically found aboard spacecraft.


ESA astronaut Roberto Vittori works with Electronics Space Test equipment on the International Space Station in 2005. ESA image.

RESULTS

The experiment results were very positive as no failures of the commercial components were recorded during the mission. No failures were logged by the Italian astronaut Roberto Vittori during the 10 days aboard mission (Soyuz 10S/Soyuz 9S exchange), and all the scheduled data were recorded by EST components. Once back on ground, the EST stored data were analyzed and verified the success of the experiment.

PUBLICATION(S)

Fortezza R, Pontetti G, Martinelli E, Lo Castro F, Di Natale C, D'Amico A. Soyuz missions and taxi flights. New opportunities for technology development. An example: The ENEIDE mission. *Acta Astronautica*. 2006 July; 59(1-5): 351-357. doi: 10.1016/j.actaastro.2006.02.025.

This investigation is complete, and all results are published.

EXPRESS PAYLOAD SIMULATOR

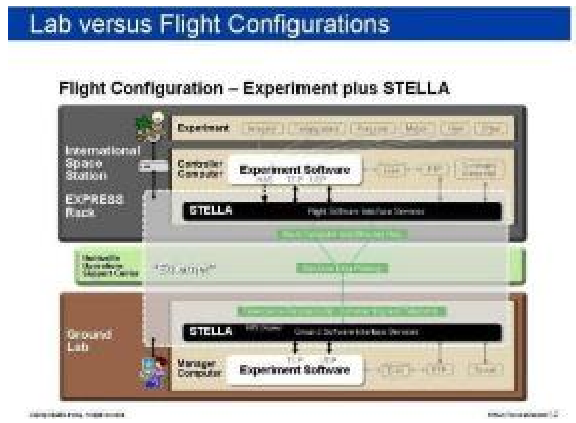
Research Area: Avionics and Software

Expedition(s): 19-ongoing

Principal Investigator(s):
- Kevin Gifford, PhD, University of Boulder, Boulder, Colorado

RESEARCH OBJECTIVES

ExPRESS Payload Simulator is a flight demonstration of the Software Toolkit for Ethernet Lab-Like Architecture (STELLA) integrated with LabVIEW provided to International Space Station (ISS) Expedite the Processing of Experiments to Space Station (ExPRESS) Rack payload developers to significantly aid in the development of the payload software interface to the ISS Command and Data Handling system.



For flight operations, Ethernet data transmitted via standard protocols are transparently redirected by STELLA through the NASA systems so the in-orbit "Controller Computer" and ground-based "Manager Computer" operate unchanged, as if the experiment software is still operating in the ground laboratory.

EARTH BENEFITS

The STELLA software simplifies payload development for the ISS by providing an off-the-shelf software interface between the payload and the ExPRESS rack.

SPACE BENEFITS

STELLA integrates with payload flight and ground software to correctly format and package commands and data for uplink from the ground to ISS and telemetry from a payload for downlink from ISS to the ground.

RESULTS

There are no published results at this time.

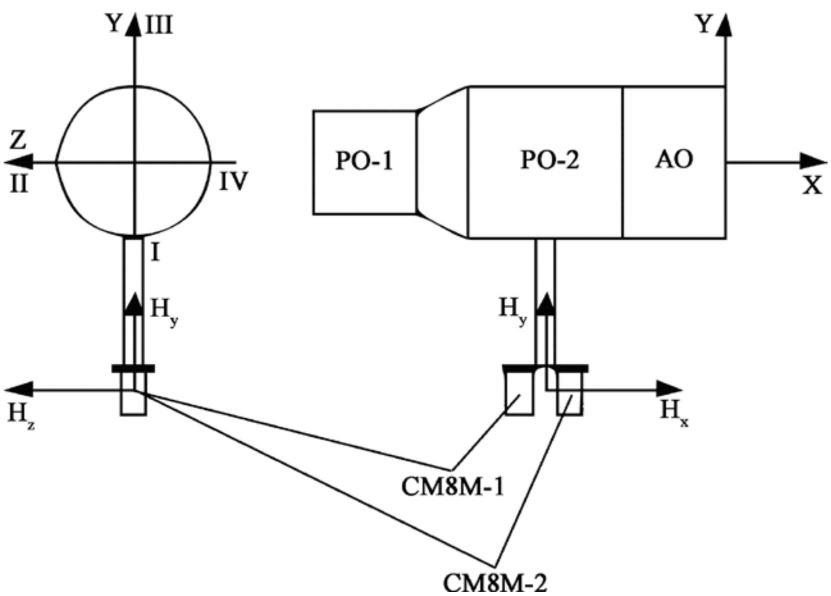
This investigation is complete; however additional results are pending publication.

Determining and Analyzing the Magnetic Interference on the ISS (Iskazheniye)

Research Area: Technical Research and Experimentation
Expedition(s): 1-9
Principal Investigator(s):
- Mikhail Y. Belyaev, PhD, S.P. Korolev Rocket and Space Corporation Energia, Korolev, Russia

Research Objectives

The Determing and Analyzing the Magnetic Interference on the ISS (Iskazheniye) investigation determines and analyzes the magnetic interference on the ISS to improve the accuracy of determining orientation using magnetic measurements sensors and to support the high-quality analysis of scientific experiments, in which Earth's magnetic field (EFM) is used, or accounted for.



Location of magnetometers on the Service Module of the ISS RS. Roscosmos image.

Space Benefits

The mathematical model created and updated based on the ISS magnetic interference data obtained in the Iskazheniye experiment during various equipment operating modes will make it possible, in the stage of nominal station operations, with an accuracy acceptable for flight control, to adjust station orientation using sensors that require minimal energy consumption. In addition, this model will make it possible not only to account for the impact of interference on some scientific research devices, but also to support optimal planning of operations with them. The results of this space experiment may be used to design and control other spacecraft and to conduct research on them.

Results

During Iskazheniye, information was obtained on the actual magnetic interference during the operation of station service and scientific equipment, and the contribution of ISS RS systems and equipment to the distortion of magnetometer readings with regards to orientation errors was determined.

Based on the experiment results, mathematical models were developed that describe the magnetic interference occurring on the ISS in flight, the Earth's magnetic field, and methods for processing the obtained measurements [data] accounting for disturbances from magnetically hard materials, magnetically soft materials, and current loops.

Based on the obtained data, the mathematical model was created and updated to account for the ISS own magnetic field during various operating modes of its equipment and systems, which facilitated the increase of the station orientation control accuracy.

To date, based on the considerations of the ISS own magnetic field, according to specially developed methods and mathematical models for the current station configuration, the accuracy of orientation control using magnetometers was increased from 14 - 12° to 2 - 1.5° (according to the results of periodical updates of the deviation vector, which increases as the assembly of the ISS goes forward).

Therefore**,** the results obtained in the Iskazheniye provide additional capabilities for solving flight control issues, experiment planning, and analysis of obtained research results.

This investigation is complete; however additional results are pending publication.

Serial Network Flow Monitor (SNFM)

Research Area: Avionics and Software
Expedition(s): 9-ongoing
Principal Investigator(s):
- Carl Konkel, The Boeing Company, Houston, Texas

Research Objectives

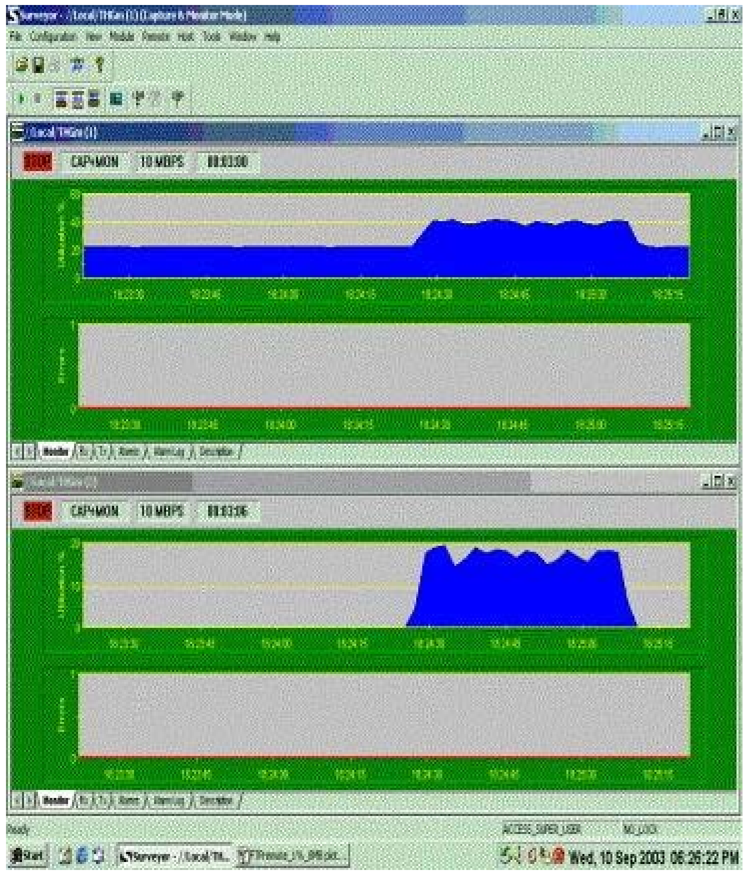
Serial Network Flow Monitor (SNFM), using a commercial software CD, monitors the payload local area network (LAN) to analyze and troubleshoot LAN data traffic. Validating LAN traffic models allows for faster and more reliable computer networks to sustain systems and science on future space missions.

Earth Benefits

Locating and correcting computer network problems alleviates data downlinking issues, which allows scientists on the ground to receive data from their experiments.

Space Benefits

SNFM extends International Space Station (ISS) accommodations to sub-rack payloads, provides a set of standard interfaces and resources for sub-rack payloads, supports the simultaneous and independent operations of multiple payloads within the rack, and accommodates multiple science disciplines. This information will allow monitoring and improvement in the data transfer capabilities of in-orbit computer networks.



Computer screen capture image provides a graphic example of network load monitoring.

Results

Data analysis is ongoing.

This investigation is ongoing and additional results are pending publication.

Preliminary Advanced Colloids Experiment (PACE), Three Investigations

Research Area: Characterizing Experiment Hardware

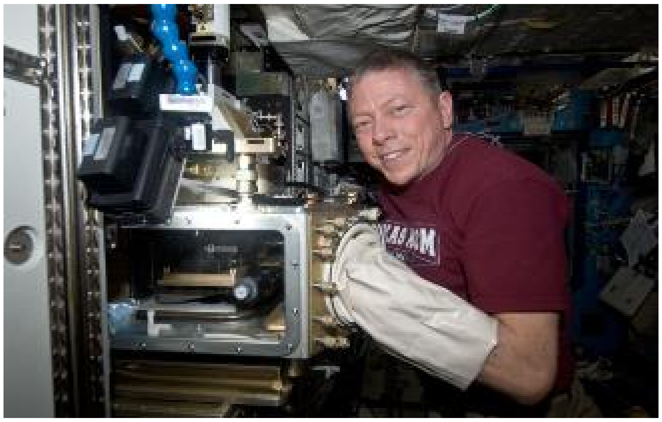
Expedition(s): 25-30

Principal Investigator(s):

- William V. Meyer, PhD, NASA's Glenn Research Center, Cleveland, Ohio
- Jacob N. Cohen, PhD, NASA's Ames Research Center, Moffett Field, California
- Paul M. Chaikin, PhD, New York University, New York, New York

Research Objectives

Preliminary Advanced Colloids Experiment (PACE) is a technology demonstration that sets the stage for the Advanced Colloid Experiment (ACE) by testing the Light Microscopy Module (LMM) in the International Space Station (ISS) environment.



Expedition 29 commander Mike Fossum works on the Fluids Integrated Rack/Fluids and Combustion Facility, conducting a session with Preliminary Advanced Colloids Experiment. Fossum is working at the Light Microscopy Module in the U.S. Laboratory Destiny.

PACE 100X Oil Test Target (Meyer)

PACE 100X Oil Test Target establishes the capabilities of the LMM that are used for high resolution image magnification in ACE.

PACE-2 3D Particle Test (Cohen and Chaikin)

PACE-2 characterizes the resolution of the high-magnification colloid experiments with the LMM to determine the minimum size of the particles that can be resolved by ACE. There is a direct relationship between magnification, particle size, test duration, and in-orbit vibration that is quantified.

PACE-LMM-Bio (Cohen)

PACE-LMM-Bio is a NASA Rapid Turn Around (RTA) engineering proof-of-concept proposal in preparation for ACE. In Bio, crew members image 3-D biological sample particles, tissue samples, and live organisms. The goal of this experiment is to indicate the microscope's capabilities for viewing biological specimens.

Earth Benefits

The PACE investigations set the groundwork for ACE, which will provide data that can advance the understanding of phase separation (eg, shelf-life, product collapse) and how it competes with crystallization to impact production (eg, when making plastics). A better understanding of crystallization and phase-change processes could have an enormous commercial impact in a wide variety of industries. PACE-LMM-Bio may expand our understanding of the effects of the space environment on biological systems. Since all life evolved under the effects of gravity, the absence of gravity may identify novel pathways that are important for a fundamental understanding of life's basic processes on Earth.

View of a Preliminary Advanced Colloids Experiment particle sample to be installed in the FIR/FCF.

Space Benefits

The knowledge from the PACE investigations serve as preparation for the experimentation in ACE, which will fly samples of colloid systems that serve as larger scale models of atomic systems. These samples are used to model the factors that influence phase changes. Researchers anticipate these experiments will have a significant impact upon our understanding of fundamental physics as it pertains to how matter transitions from solid to liquid to gas. An immediate space application for this technology demonstration is in extending the shelf life of consumables on future long-duration missions. PACE-LMM-Bio improves the ability to analyze the effects of microgravity on biological systems. The ability to analyze samples on ISS also removes the effects of return on samples and may eliminate the need for sample return altogether.

Results

There are no published results at this time.

This investigation is complete, and results are pending publication.

Department of Defense Synchronized Position, Hold, Engage, Reorient, Experimental Satellites-Chip Scale Atomic Clock (DOD SPHERES-CSAC)

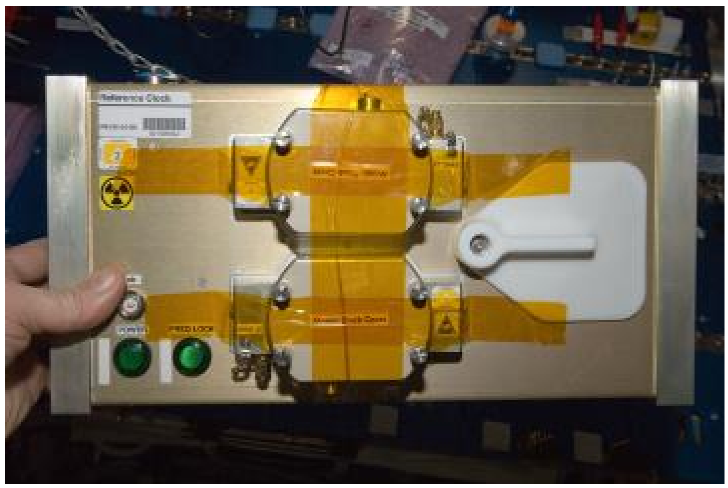
Research Area: Communication and Navigation
Expedition(s): 29-30
Principal Investigator(s):
- Andrei Shkel, Defense Advanced Research Projects Agency, Washington, DC

Research Objectives

Department of Defense Synchronized Position, Hold, Engage, Reorient, Experimental Satellites - Chip Scale Atomic Clock (DOD SPHERES-CSAC) demonstrates the performance of an atomic clock in the sustained microgravity environment of the International Space Station (ISS). An atomic clock is a precision clock that depends on an electrical oscillation regulated by the natural vibration frequencies of an atomic system. Atomic clocks are the most accurate time keepers in the world.

Earth Benefits

DOD SPHERES-CSAC results may aid in the development of small-scale inertial navigation systems (INS) for use on vehicles such as ships, aircraft, and submarines.



Front view of DOD SPHERES-CSAC Reference Clock. The goal of the CSAC program is to create ultra-miniaturized, low-power, atomic time and frequency reference units. Photo was taken during Expedition 30.

Space Benefits

The development of Chip-Scale Atomic Clock enables ultra-miniaturized (wristwatch in size) and ultra-low power time and frequency references for high-security, ultra-high frequency (UHF) communication and jam-resistant global positioning system (GPS) receivers. The use of these ultra-miniature time reference units could greatly improve the mobility and robustness of any system and platform with sophisticated UHF communication and/or navigation requirements. Results from DOD SPHERES-CSAC may also help in the development of small-scale INS for use on small satellites (mass 1-10 kg).

Results

There are no published results at this time.

This investigation is complete; however additional results are pending publication.

Esperimento di Navigazione per Evento Italiano Dimostrativo di EGNOS (ENEIDE)

Research Area: Communications and Navigation
Expedition(s): 10 and 11
Principal Investigator(s): ● Giovanni Fuggetta, Thales Alenia Space, Milan, Italy

Research Objectives

Esperimento di Navigazione per Evento Italiano Dimostrativo di EGNOS (ENEIDE) is an experiment, which will apply advanced navigation techniques based on the European Geostationary Navigation Overlay Service (EGNOS). The objective is to measure and verify in low-Earth orbit, the GPS and EGNOS signals, which will be used in the combined GPS/EGNOS navigation system for spacecraft control and guidance.

Esperimento di Navigazione per Evento Italiano Dimostrativo di EGNOS receiver. ESA image.

Results

The experiment exploited the EGNOS signals with the use of a space-borne Global Navigation Satellite System receiver developed by Thales Alenia Space in 1999. This verified the performance of the GPS/EGNOS receiver aboard the Soyuz spacecraft and compared results from the combined receiver during different phases of the mission with equivalent data received from the spacecraft and the International Space Station (ISS).

All the analyses conducted up to now make it possible to confirm that the ENEIDE experiment was carried out successfully. Being based on a new instrument concept of integrated GPS/EGNOS-WAAS tracking, the possibilities of real-time use of this instrument for critical space operations in which safety is a critical component have been addressed. ENEIDE provided a benchmark for the validation of the TAS-I receivers of LAGRANGE class. The different environmental conditions in which the receiver operated (sun-pointing attitude, orbital attitude, peculiar antenna pointing constraints, etc) make the experiment an important laboratory for different applications like attitude analyses, atmospheric sounding, space weather, real-time navigation and control. In detail, the set-up (receiver + laptop) worked properly and tracking of the WAAS-EGNOS satellites allowed the download of the full GEO navigation message. The tracking of L1 and L2 frequencies proved to be efficient according to the expectation of the predicted link-budget.

Publication(s)

Pugliese M, Bengin V, Casolino M, Roca V, Zanini A, Durante M. Tests of shielding effectiveness of Kevlar and Nextel onboard the International Space Station and the Foton-M3 capsule. *Radiation and Environmental Biophysics*. April 3, 2010;49(3):359-363. doi: 10.1007/s00411-010-0283-3.

Bertucci A, Durante M, Gialanella G, et al. Biological dosimetry in the ENEIDE mission on the International Space Station. *Microgravity Science and Technology*. September 2007;19(5-6):206-209. doi: 10.1007/BF02919483 [Also Biodosimetry results].

Zin A, Landenna S, Conti A, Marradi L, Di Raimondo MS. ENEIDE: An experiment of a spaceborne, L1/L2 integrated GPS/WAAS/EGNOS receiver. *Microgravity Science and Technology*. September 2007;19(5-6):54-59. doi: 10.1007/BF02919453.

Zin A, Landenna S, Conti A, Marradi L, Di Raimondo MS. ENEIDE: An experiment of a space-borne, L1/L2 Integrated GPS/WAAS/EGNOS receiver. *European Navigation Conference* (ENC 2006), Manchester, UK; 2006.

This investigation is complete and all results are published.

ERNOBox

Research Area: Communications and Navigation
Expedition(s): 23-ongoing
Principal Investigator(s):
- Sven Rakers, EADS/Astrium Space Transportation, Bremen, Germany

RESEARCH OBJECTIVES

The primary objective of the ERNOBox control computer, is to assess the in-orbit performance of newly developed components. The secondary objective is to transmit environmental data such as vibration, acoustic noise, and temperature of the computer in order to analyze the computer reliability.

The ERNOBox. ESA image.

RESULTS

The ERNOBox was installed in March 2008 and ran successfully during the planned 6 months, sending its telemetry regularly. In order to correct a software failure and prepare for its future role as data relay hardware for the Vessel Identification System experiment, a new software version had to be loaded. However, the ERNObox suffered a hardware failure, which following analysis, pointed to a defective memory chip, a manufacturer design flaw.

The ERNOBox was returned to Earth on shuttle mission STS-127, repaired, and the new software was installed. The refurbished hardware was returned to the International Space Station on STS-132 in May 2010 and activated in Columbus in May 2010. The research is currently ongoing as part of the Vessel ID System.

This investigation is ongoing and additional results are pending publication.

GLOBAL TRANSMISSION SERVICES-1 AND -2 (GTS-1/-2), TWO INVESTIGATIONS

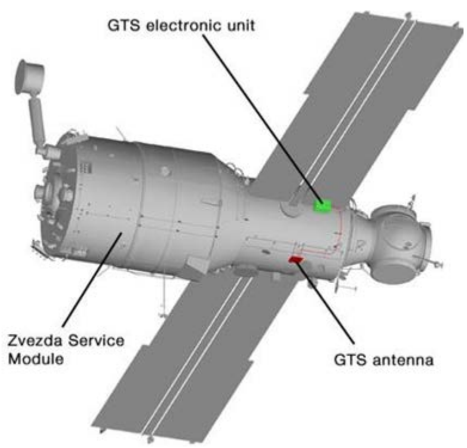
Research Area: Communications and Navigation

Expedition(s): 7-20

Principal Investigator(s):
- Felix Huber, PhD, Steinbeis Transferzentrum Raumfahrt, Gaufelden - Stuttgart, Germany

RESEARCH OBJECTIVES

The Global Transmission Services-1 and -2 (GTS-1, GTS-2) is a technology experiment for the testing, validation and demonstration of radio transmission techniques for the synchronization of earth-based clocks and watches from the International Space Station (ISS). In addition, the GTS data services, based on a unique coding scheme, could ultimately lead to commercial services, such as blocking of stolen cars or lost credit cards, directly from space.



Location of the Global Transmission Services antenna and Electronics Units. ESA image.

RESULTS

Testing showed a lower than expected signal strength traced to interference from the hull of the Russian Service Module on which the GTS antenna was launched to the ISS, as well as additional field of view blockage from the Pirs Docking Module and its attached Soyuz spacecraft (not originally scheduled to be at the ISS during the GTS testing).

This investigation is ongoing and additional results are pending publication.

Testing of the Laser Communications System for Transferring Large Data Files from ISS RS Hardware (SLS)

Research Area: Communication and Navigation
Expedition(s): 27-36
Principal Investigator(s):
- Victor V. Sumerin, Research and Production Corporation Systems of Precision Instrumentation, Moscow, Russia

Research Objectives

Testing of the Laser Communications System for Transferring Large Data Files from ISS RS Hardware, or Laser Communications System (SLS), is a prospective new direction for space communications systems with the development of systems based on transferring information using a laser channel. In the future, such systems could support a large throughput while consuming less energy and have smaller dimensions and mass of transmit/receive equipment than is currently used by radio communications systems.

Space Benefits

Successful tests of the onboard laser communications terminal hardware on the International Space Station (ISS) and a demonstration of the receiving-transmitting technology for transferring information using the space laser communications line will allow us to begin the actual implementation of laser communications technologies in space lines used for information transfer.

Examples of the transmitted digital images that were obtained by the ISS RS crewmembers earlier during Earth observation experiments and the shooting of onboard operations. Roscosmos image.

The use of laser communication links between spacecraft will allow us to decrease the mass, dimensions, and energy consumption as compared to the existing options of its design when using radio channels.

Results

During testing, it was possible to demonstrate the capability of the systems to operate in scattered cloud conditions, both through the clouds (in low density) and with interruptions in communications while passing through high-density clouds. The first session with the transfer of target information (test-image) with a speed of 125 Mb/s took place on October 2, 2012. The test-image was being transmitted continuously throughout the cycle, which allowed for quasi-quantitatively assessing the changes in the quality of the line based on the noise level of the incoming images. The total volume of information transmitted was 2.6 GB. The amount of useful data transmitted was 732 MB. The largest unit received with no errors was 38 998 937 bytes. The probability of error varied between 3.2×10^{-9} and 3×10^{-3} depending on the distance between the ground laser terminal and the ISS. This experiment is ongoing. To date, over 100 test sessions were performed, with the accumulation and processing of statistical data.

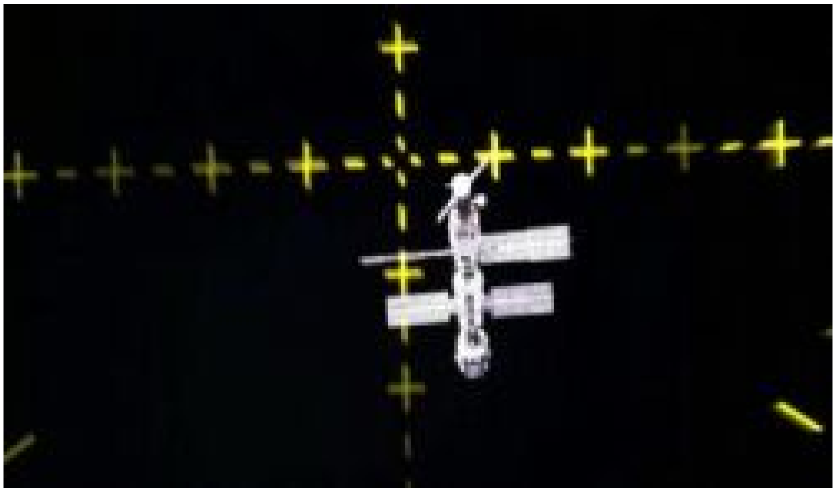
PUBLICATION(S)

Sorokin IV, Grigoriev VN, Ivlev OA, Sumerin VV, Shargorodsky VD. Methods and results of a laser communication experiment aboard the ISS Russian Segment. *30th International Symposium on Space Technology and Science (ISTS-30)*, Kobe, Japan; July 4-10, 2015. 2015-t-20.

This investigation is complete; however additional results are pending publication.

STUDY OF A HIGH-PRECISION SYSTEM FOR PREDICTING ISS MOTION (VEKTOR-T)

Research Area: Communications and Navigation
Expedition(s): 4, 5, 7, 8, 9, 12-30 and 33-ongoing
Investigator(s):
- Mikhail Y. Belyaev, PhD, S.P. Korolev Rocket and Space Corporation Energia, Korolev, Russia



A more detailed caption of this image is needed. Roscosmos image.

RESEARCH OBJECTIVES

The Study of a High-Precision System for Predicting ISS Motion (Vektor-T) verifies the International Space Station (ISS) motion prediction methodology that has been developed for improving the ISS motion determination and prediction accuracy as compared to the nominal orbital determination and prediction system currently in operation. To accomplish this task Vektor-T utilizes navigational measurements of ISS motion using both the ground tracking station radar systems and the Global Position System (GPS) and GLONASS navigation satellite system receivers.

SPACE BENEFITS

As a result of the Vektor-T experiment, a pilot high-precision system for predicting the ISS motion will be developed. Operating this system will improve the ISS motion determination accuracy and will provide precise navigational correlation for the results of the experimental and research activities performed on the ISS, as well as for other station flight control tasks.

RESULTS

The phase of development testing of navigation satellite data processing methodologies to address ISS motion determination tasks has currently been completed, and work has begun on the task of configuring a high-precision system for predicting the ISS motion using the following as a basis: the developed models of perturbations impacting the ISS; the motion determination and prediction methodologies; and the experimentally refined ISS motion prediction model parameters.

This investigation is ongoing and additional results are pending publication.

VESSEL IDENTIFICATION SYSTEM (VESSEL ID SYSTEM)

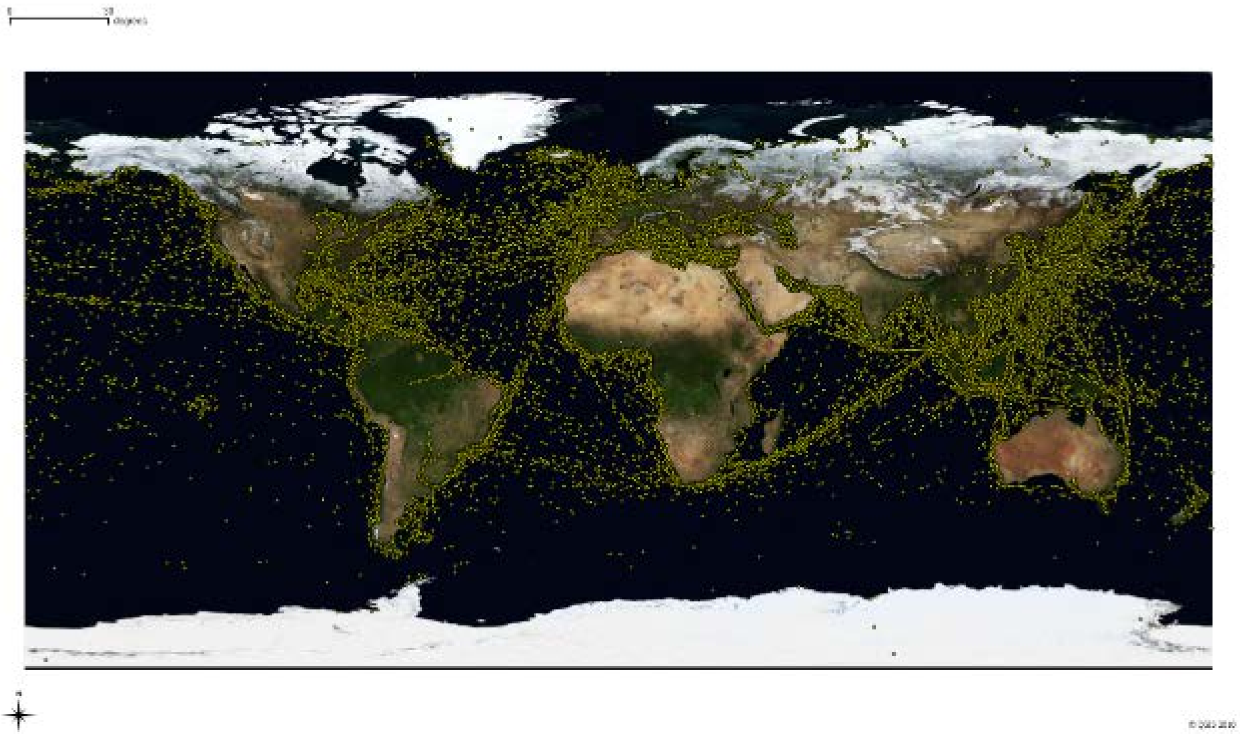
Research Area: Communications and Navigation

Expedition(s): 23-ongoing

Principle Investigator(s):
- Richard B. Olsen, Norwegian Defense Research Establishment, Kjeller, Norway

RESEARCH OBJECTIVES

The Vessel Identification System is testing the means to track global maritime traffic from space by picking up signals from standard Automatic Identification System (AIS) transponders carried by all international ships over 300 tons, cargo vessels over 500 tons, and all types of passenger carriers. Meanwhile various service entities have been asking to get access to the Vessel ID data, which is continuously acquired on the Columbus module.



Positions of all ships being tracked by Norwegian Automatic Identification System using their Automatic Identification System transmissions as of mid-November 2010. Some 60,000 ships were tracked in the 4 months since the experiment started in June 2010. ESA/FFI image.

EARTH BENEFITS

Data from this ship-monitoring device could be combined with data from satellites to provide better surveillance of ships at sea. Current AIS technology is only designed to monitor vessels in coastal waters, but the Vessel Identification System will incorporate ships in open waters.

SPACE BENEFITS

The Vessel ID System tests a new mechanism that can be used to install small passive experimental payloads on the International Space Station's exterior. The Grappling Adaptor to On-Orbit Railing (GATOR) could attach small payloads to International Space Station handrails, which are used by crew members during extravehicular activity. This would provide an additional space on the station to conduct passive experiments or collect data.

Results

The 2 operational phases with the NORAIS receiver, which was operated by FFI/Norway, have been extremely successful, with data telemetry received by the Norwegian User Support Operations Center (N-USOC), in Trondheim, Norway, via ESA's Columbus Control Centre in Germany. Data has been received by NORAIS in almost continuous operation, and all modes of operation have worked extremely well. On a good day, approximately 400,000 ship position reports were received from more than 22,000 different ship identification numbers (Maritime Mobile Service Identity, or MMSI).

The in-orbit data of the NORAIS Receiver v18 has been analyzed since and show very good results.

As of March 2013, the Vessel Identification System acquired an extensive amount of data for nearly 3 years since its installation in and on Columbus. Meanwhile, various service entities have been asking to get access to the Vessel ID data, which is continuously acquired on Columbus.

Publication(s)

Eriksen T, Nordmo Skauen A, Narheim B, Helleren O, Olsen O, Olsen R. Tracking ship traffic with Space-Based AIS: Experience gained in first months of operations. *2010 International Waterside Security Conference (WSS)*, Carrara, Italy; November 3-5, 2010;1-8.

This investigation is ongoing and additional results are pending publication.

Skin Care (Skin)

Research Area: Commercial Demonstrations
Expedition(s): 13, 14
Principal Investigator(s):
- Michael Massow, PhD, ISS Lab Ruhr GmbH, Dortmund, Germany

Research Objectives

Astronauts experience changes in their skin during spaceflight. SkinCare was designed to examine these changes and use the data collected to create a model for skin aging. This model can be used to create countermeasures to protect skin on Earth and in space.

The SkinCare Experiment is uploaded to the ISS during ESA's Astrolab Mission with German ESA astronaut Thomas Reiter. NASA/ESA image.

Results

Apart from itching and dryness of the skin (possibly partly due to the special skin care being used in the ISS), a thinning of the skin and increased sensitivity combined with delayed healing of wounds and also an increased tendency to skin infections have been reported after a long stay in space. A pilot study, involving one subject, applied non-invasive skin testing methods before, during, and after a long-term mission using single measuring parameters of the skin and at the same time examined the effects of a skin protection cream.

Tests concerning the skin hydration, trans-epidermal water loss, and elasticity states were carried out, and ultrasound measurement of the fine structure of the skin was also done. Measurements were made on predetermined different skin areas on both inner forearms with the right forearm being treated daily with a skin care emulsion. The measurements in the ISS, performed by the trained crew member, were done in more or less stable environmental conditions throughout the measuring period. However, before and after measurements, done during the astronauts' stay in different countries showed that local environmental conditions can have extreme influence on the results. All skin elasticity parameters increased postflight, from different to normal ageing of the skin, which indicates a clear loss of elasticity. Elasticity measurements and especially the ultrasound images of the skin showed signs of a decrease of density of the skin fiber system. Epidermal measurements provided evidence of a thinning of the top skin layer and a prolonged molting time of the cells from the base layer toward the top. These results correlated with the reports from astronauts about the state of the skin during their stay in space. Comparison of the mean values of the hydration measurements before, during, and after the mission showed that there were only minor differences between the sides (right versus left). However, there was a clear hydration effect of the applied skin care emulsion. Treatment with the emulsion over the course of the mission led to an improvement in the hydration of the outermost layer as well as in the barrier function (moisture retention) of the epidermis.

Due to logistical and technical reasons and also because the measurements were carried out on only one subject, further tests with more test subjects, using optimized test conditions and additional measuring methods (eg, for the determination of capillary blood flow and oxygen saturation of hemoglobin) are necessary. This way, the general medical risks can be determined via skin physiological parameters and the side effects on the skin due to long-term stay in space can be minimized.

PUBLICATION(S)

Tronnier H, Wiebusch M, Heinrich U. Change in skin physiological parameters in space - Report on and results of the first study on man. *Skin Pharmacology and Physiology*. 2008;21(5):283-292. doi: 10.1159/000148045.

This investigation is complete; however additional results are pending publication.

Dust and Aerosol Measurement Feasibility Test (DAFT)

Research Area: Fire Suppression and Detection
Expedition(s): 10 and 13
Principal Investigator(s):
- David L. Urban, PhD, NASA's Glenn Research Center, Cleveland, Ohio

Research Objectives

The Dust Aerosol Measurement Feasibility Test (DAFT) releases particles in the International Space Station (ISS) atmosphere to test the ability of different equipment to measure the levels of dust and air quality. Accurate fire detection requires being able to distinguish dust particles from soot particles and being able to detect smoke particles of the appropriate size. This experiment will provide the first systematic measurements of the sizes of particles in the air aboard ISS over time and prove the usefulness of the P-Trak Ultrafine Particle Counter (a small handheld, commercial device). If successful, the detector will be used in the Smoke and Aerosol Measuring Experiment (SAME).

Video screen shot of ISS Commander and Science Officer Leroy Chiao performing DAFT operations on station during Expedition 10.

Earth Benefits

The smoke detectors developed from the results of this experiment can also be useful in other extreme environments on Earth, such as submarines or underwater laboratories. Accurate detection of smoke in these environments can save lives.

Space Benefits

Extended duration spaceflight missions with larger vessels will require fire detection systems with increased reliability and sensitivity. DAFT is the first step in the development of an Advance Fire Detection System for use on future space exploration missions. Additionally, the devices in this experiment can be used to provide more detailed information about the character of the particulate in the atmosphere aboard the ISS.

RESULTS

Preliminary DAFT results showed the P-Trak Ultrafine Particle Counter (a device that counts ultra-fine dust particles in a microgravity environment) could be successfully built into the Smoke and Aerosol Measurement Experiment (SAME) payload and established the optimal ranges for particle detection using this instrument. The data collected also indicate very low-particulate levels in the ISS environment relative to that previously measured on the space shuttle. This low particulate level was not surprising due to the small crew size on ISS (2 or 3 vs 7 on space shuttle) and the High-Efficiency Particular Accumulator (HEPA) filtration system on ISS. The particulate level was expected to rise with the larger ISS 6 person crew. In later experiment runs, DAFT showed the average size of the particles was larger on orbit than on Earth. These results could be due to the inefficiency of the large particle filter. Once the average particulate level throughout ISS is known, it can be used to design future smoke detectors that accurately distinguish normal dust from the presence of dangerous smoke particles. A series of events (malfunction of the electronic data transmitted, crew time limits, and an alcohol wick that did not open) shortened the overall experiment, but adequate data was collected to label the demonstration successful (Urban 2005).

Expedition 13 science officer Jeffrey N. Williams works with DAFT in the US Laboratory of the ISS.

PUBLICATION(S)

Ruff GA, Urban DL, King MK. A research plan for fire prevention, detection, and suppression in crewed exploration systems. *43rd Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2005.

Urban D, Griffin D, Ruff G, et al. Detection of smoke from microgravity fires, *SAE International Journal of Aerospace*, 2005-01-2930, 2005.

This investigation is complete; however no publications are expected.

Food Tray in Space

Research Area: Food and Clothing Systems
Expedition(s): 10 and 11
Principal Investigator(s):
- Olindo Temperini, Agenzia Regionale per lo Sviluppo Agricolo del Lazio (ARSIAL), Rome, Italy

Research Objectives

The objective of the Food Tray in Space experiment is to increase the variety and quality of food available to crews in space, more specifically the International Space Station (ISS). The Food Tray in Space experiment was demonstrating that food items, produced from high-quality products, are tasty and nutritious and don't lose their quality under spaceflight conditions.

Results

As part of the experiment, ESA astronaut Roberto Vittori completed a feedback form, which covered 3 questions:

1) Did the products change characteristics (smell, taste, consistency)?
2) Would you change anything in the food tray (quantity, form and type)?
3) Would you include items on the ISS menu?


Food items from the Food Tray in Space experiment. ESA image.

While the first question provided no change in any characteristics of any of the food items, the nougat did prove too crumbly to be easily eaten in response to the second question. Preferences were also provided for the final question.

This investigation is complete; however additional results are pending publication.

Tactile Display-aided Orientation Awareness (SUIT)

Research Area: Food and Clothing Systems
Expedition(s): 8 and 9
Principle Investigator(s):
- Jan B. Van Erp, TNO Human Factors, Soesterberg, Netherlands

Research Objectives

The goal of the Tactile Display-aided Orientation Awareness (SUIT) project is to support astronauts with a vibrotactile suit to help with orientation in space. The technology demonstration consists of a vest with 56 vibrating elements covering the torso of the astronaut. These elements provide cues to the astronaut of a given predefined “downwards” direction within the International Space Station (ISS) by vibrating in that direction. As the vibration of one of these elements is directly mapped to the astronaut’s body position, this makes it a fast and intuitive way to present spatial information.

Results

Data showed that spatial orientation in microgravity differs from that on Earth, possibly facilitating space motion sickness and degrading performance. It was found that artificial touch information in the form of a localized vibration on the torso that indicates downward direction can make orienting in microgravity faster, better, and easier. The importance of the artificial touch information seemed to increase over the initial 7 days of staying in microgravity while the weight of visual information decreased over the same period. The results underlined the capacity of the brain to adapt to unusual environments and to use and integrate artificial cues.

ESA astronaut André Kuipers performs the Tactile Display-aided Orientation Awareness experiment, assisted by his Russian colleague Gennadi Padalka.

The data showed that the support tool results in: a faster completion of the tasks; better task performance; and tasks being subjectively rated as easier than the control conditions in which the support tool was off. It is concluded that the support tool is able to enlarge the astronaut’s orientation awareness and that the experiment was both a successful proof-of-concept as well as a successful technology demonstration. The results also showed that, on average, the astronaut responded faster in microgravity than on Earth.

However, the experiment did reveal that the vest fit could be improved and the tool has more potential in challenging situations, as compared to daily operations. Spin-off to applications can be envisaged for pilots, divers, individuals with a visual or vestibular dysfunction, emergency services, and the automobile and sports industry.

PUBLICATION(S)

van Erp JB, van Veen HA, Ruijsendaal M. More than a feeling: Bringing touch into astronauts' spatial orientation. *Microgravity Science and Technology*. September 2007;19(5-6):108-112. doi: 10.1007/BF02919463.

van Erp JB, van Veen HA. Touch down: The effect of artificial touch cues on orientation in microgravity. *Neuroscience Letters*. August 14, 2006;404(1-2):78-82. doi:10.1016/j.neulet.2006.05.060.

This investigation is complete and all results are published.

THREE DIMENSIONAL CAMERA (3D CAMERA)

Research Area: Imaging Technology
Expedition(s): 7, 8, and 9
Principal Investigator(s):
- Massimo Sabbatini, European Space Research and Technology Centre, Noordwijk, Netherlands

RESEARCH OBJECTIVES

The 3D Camera still photographic camera is tested on the International Space Station (ISS) in its capabilities to take three-dimensional, still images in microgravity, either of the internal facilities, systems structures and daily life of the ISS or of external views outside the ISS windows.

ESA 3D Camera hardware. ESA image.

RESULTS

The 3D Camera performed extremely well during its tests on the ISS, producing an extensive amount of high-quality three dimensional imagery of internal and external views of the ISS and Earth. This has been used as part of public outreach activities with images used as standalone products or embedded within three dimensional ISS simulators.

This investigation is complete; however additional results are pending publication.

Panasonic 3D Camera (3DA1 Camcorder)

Research Area: Imaging Technology
Expedition(s): 27-ongoing
Principal Investigator(s):
- Rodney Grubbs, NASA's Marshall Space Flight Center, Huntsville, Alabama

Research Objectives

The Panasonic 3D Camera (3DA1 Camcorder) can record 3-D high-definition video onto secure digital memory cards, like the type used in many consumer cameras. The camera experiment compares the quality of file-based camcorders, as opposed to videotape recorders, and examines how well the camera's sensors perform in space. The video also provides a unique virtual view of the International Space Station (ISS) in 3-D.

Earth Benefits

High-definition video in 3-D provides a realistic representation of life on the ISS, which could be used for public outreach programs.

3DA1 Camcorder delivered to the ISS by shuttle flight STS-135/ULF7.

Space Benefits

The experiment compares the Panasonic camera's metal-oxide semiconductor (MOS) sensor to other charge-coupled device (CCD) cameras. Historically, cameras with CCD imaging sensors have been susceptible to radiation damage, resulting in damaged pixels noticeable as white dots in the picture. Observing the frequency and decay rate of the MOS sensor allows the determination of whether a MOS-based camera provides a more robust spaceflight imaging system than a CCD-based camera. Additionally, file-based workflows allow more flexibility for managing motion imagery and eliminate the need for returning tapes to Earth, thus lowering costs and increasing efficiency.

This investigation is ongoing; however no publications are expected.

Erasmus Recording Binocular (ERB)

Research Area: Imaging Technology
Expedition(s): 14
Principal Investigator(s):
- Massimo Sabbatini, European Space Research and Technology Centre, Noordwijk, Netherlands

Research Objectives

Erasmus Recording Binocular (ERB) is a three-dimensional (3-D) video camera that is used to take images of the environment aboard the International Space Station (ISS). The images are used to create an accurate map of the interior of the ISS.

Erasmus Recording Binocular (ERB) 3-D video camera for use in the ERB experiment during Astrolab. The camera will be used to accurately map the interior of the International Space Station in its current configuration. These images will be used to improve the models available on the ground. ESA image.

Results

All images were received by mid-January 2007 in the Erasmus Centre and were made available at various venues all over Europe. The use of ERB resulted in the several conclusions.

It was indeed possible to build a demonstrator with relatively reduced resources and prove the validity of the design for space. The ergonometry used proved successful, and astronauts appreciated the ERB unique feature of having onboard stereo viewing capabilities. Radiation was of a transitory nature even though many Single Event Upset (SEU)s where visible. The SEU's were cleared and reset after a reboot of the system.

The potential for outreach achieved by 3-D images was very high, and all audiences from children to professionals have enjoyed them and found them very engaging. It was proven that the sense of presence in an environment not easily reachable is guaranteed even with low-resolution cameras. Astronauts found images useful in assessing the constraints that an environment like the ISS poses to space payload designers and to the people that work in such conditions.

This ambitious goal has not been achieved yet. The images of the whole ISS have been useful to visually map the ISS, but an accurate 3-D model reconstruction is ambitious and began in 2009, in preparation of the high-resolution images coming from the successor of ERB.

The positive feedback received from the astronaut and from the all people who saw the stereo images encouraged the team to develop a new-generation ERB: the ERB2.

PUBLICATION(S)

Sabbatini M, Collon MJ, Visentin G. Stereo images from space. *Stereoscopic Displays and Applications XIX*, San Jose, CA; February 14, 2008: 680315-680315-9.

Sabbatini M, Visentin G, Collon MJ, Ranebo H, Sunderland D, Fortezza R. Stereo cameras on the International Space Station. *Stereoscopic Displays and Virtual Reality Systems XIV*, San Jose, CA; February 15, 2007: 64901P-64901P-6.

This investigation is complete and all results are published.

Erasmus Recording Binocular-2 (ERB-2)

Research Area: Imaging Technology
Expedition(s): 23-ongoing
Principal Investigator(s):
- Massimo Sabbatini, European Space Research and Technology Centre, Noordwijk, Netherlands

Research Objectives

The Erasmus Recording Binocular-2 (ERB-2) is a high-definition three-dimensional (3-D) video camera that has been undergoing testing on the International Space Station (ISS) to determine its ability to function in the challenging environment on a spacecraft. ERB-2 is an upgrade of the ERB device first tested on the ISS in 2006. This new-generation video camera offers improved resolution and sensitivity in low-light conditions as well as the possibility of 3-D live streaming.

Earth Benefits

These technologies are helping to feed into astronaut training programs and improving ISS simulators.

ESA astronaut Paolo Nespoli uses the Erasmus Recording Binocular-2 stereoscopic camera on April 23, 2011, for filming Anomalous Long Term Effects in Astronauts' Central Nervous System - Shield experiment hardware in the US laboratory Destiny. NASA image.

Space Benefits

Three-dimensional cameras proved a popular choice for astronauts to use during their free time in orbit; they act both as a central element of relaxation for astronauts while at the same time producing valuable imagery for use in education and promotion activities.

Results

Commissioning of ERB-2 was successfully finalized on September 10, 2010. Since then, ERB-2 has been successfully filming life and work on the International Space Station, which is proving very useful for education and promotion activities and stimulating the public’s interest in space activities. On August 6, 2011, ERB-2 successfully undertook the first 3-D live streaming from space, transmitted to ESA’s Erasmus User Support and Operations Centre in Noordwijk, the Netherlands. The quality of the high-definition (HD) video material was very convincing.

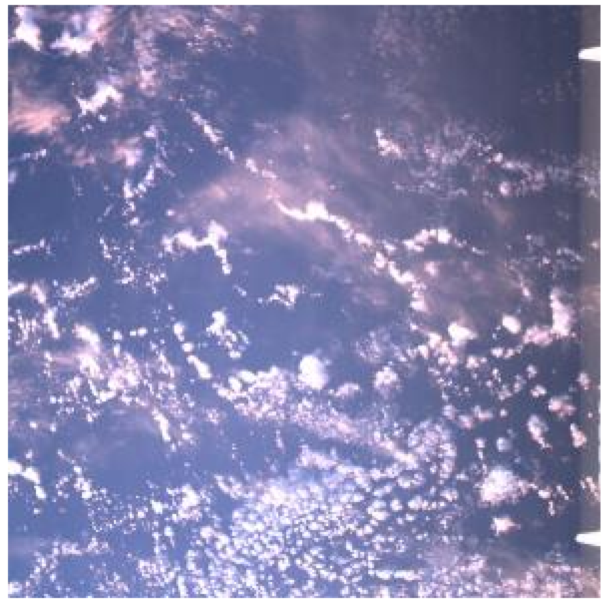
This investigation is complete; however additional results are pending publication.

European Technology Exposure Facility-Earth Viewing Camera (EuTEF-EVC)

Research Area: Imaging Technology
Expedition(s): 16-20
Principal Investigator(s):
- Massimo Sabbatini, European Space Research and Technology Centre, Noordwijk, Netherlands

Research Objectives

The main goal of the The European Technology Exposure Facility-Earth Viewing Camera (EuTEF-EVC) system is to capture color images of the Earth's surface to be used as a tool to increase general public awareness of the International Space Station (ISS) and promote the use of the ISS to the potential user community for observation purposes. The Earth Viewing Camera forms part of an overall program of development and testing of imaging technologies for extreme environments.


Second Image to be generated by the Earth Viewing Camera. ESA image.

Results

Following activation of the Earth Viewing Camera in orbit, the camera experienced some problems of overexposure and lack of resolution in pictures produced that could have been due to mis-alignment of the optics in the integration/launch phase, as well as an unpredictable data link problem. That being said, important data was gathered within the Earth Viewing Camera project that could help with the possible future development of external camera technologies.

This investigation is complete; however no publications are expected.

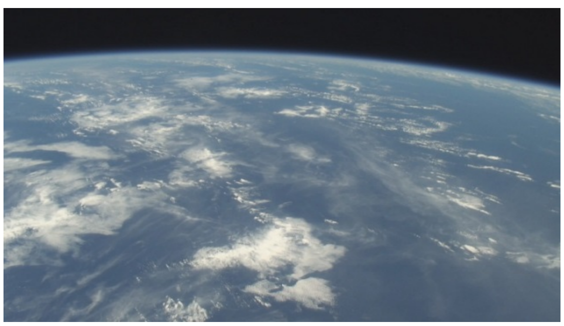
HIGH DEFINITION TELEVISION MULTI-PROTOCOL CONVERTER SYSTEM (HDTV MPC)

Research Area: Imaging Technology
Expedition(s): 17- ongoing
Principal Investigator(s):
- Keiji Murakami, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

The High Definition Television (HDTV) Multi-Protocol Converter (MPC) System transmits an HDTV image, which the ISS crew records on orbit, to the ground. The HDTV image and audio that is transmitted to the ground by MPC is converted to HD-SDI signal, so that a HDTV monitor can display the signal through a commercial HDTV/HD-SDI Decoder in real time; the downlinked images are also able to be watched and edited by commercial software on personal computers.

Report from Kibo with Cabin HDTV Camera. JAXA image.



Blue Earth View with KIBO HDTV-EF Camera JAXA image.

EARTH BENEFIT

The HDTV MPC represents a new way to transmit HDTV and Ethernet signals that record experimental data to be sent back to earth.

SPACE BENEFIT

This investigation is applied to new knowledge, and not specifically to advances in Space Exploration.

RESULTS

In cooperation with NASA, the transmission to the ground of the HDTV image by MPC was successful in October of 2007. After that, MPC capability was evaluated in detail by NASA and became the standard system equipment of ISS. Furthermore, MPC was used during the repair mission of the Hubble space telescope mission, STS-125, in 2009.

From 2007 to the present, most of the HDTV images such as live-broadcast from ISS cabin, reports of ISS missions, and Earth observation images by astronauts, which are broadcast on television and shown in science museums are transmitted to the ground through MPC. The MPC system continues to be used in order to transmit HDTV image of HDV Camcorder from ISS to the ground.

This investigation is ongoing and additional results are pending publication.

HDTV CAMERA UTILIZING THE SERVICE MODULE INTERNATIONAL SPACE STATION (HDTV IN SM)

Research Area: Imaging Technology
Expeditions(s): 3 and 4
Principle Investigator(s):
- Teruhiko Tabuchi, Japan Aerospace Exploration Agency, Tsukuba, Japan

RESEARCH OBJECTIVES

HDTV Camera Utilizing the Service Module International Space Station (HDTV in SM) evaluates the influence of damage by the space radiation to the image sensors in the camera and also by the image sensor samples in the International Space Station (ISS). Image sensor samples are returned to the ground and analyzed for the relation between space radiation and the damage (hot pixel) on the image sensors.

EARTH BENEFIT

New knowledge is expected to be the major benefit of this investigation.

SPACE BENEFIT

This new video recording technology can document future long-duration exploration missions. HDTV can provide improved imagery for spacecraft surveys while inflight.

RESULTS

The HDTV in SM investigation showed that the number of hot pixels (image data caused by cosmic radiation hits) increases in proportion to the quantity of radiation. It was also observed that the number of hot pixels increases in proportion to the storage days in the ISS cabin. However, after the camera was returned to the ground, it was stored at room temperature, then the damage on CCD were recovered, and the hot pixels were shown to have decreased (Nagamatsu 2011).

ISS003E5826 – Cosmonaut Vladimir N. Dezhurov, Expedition 3 flight engineer representing Roscosmos, works with camera equipment in the Zvezda Service Module on the International Space Station. JAXA image.

PUBLICATION(S)

Nagamatsu A, Murakami K, Yokota A, et al. Space radiation damage to HDTV camera CCDs onboard the international space station. *Radiation Measurements*. February 2011;46(2):205-212. doi: 10.1016/j.radmeas.2010.11.016.

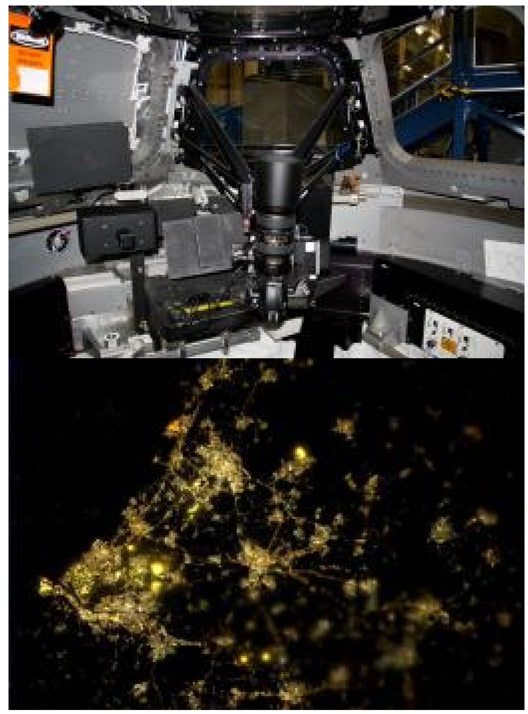
This investigation is complete and all results are published.

NIGHTPOD

Research Area: Imaging Technology
Expedition(s): 29-ongoing
Principal Investigator(s):
- Massimo Sabbatini, European Space Research and Technology Centre, Noordwijk, Netherlands
- Esposito MS, Cosine Science & Computing BV, Leiden, Netherlands

RESEARCH OBJECTIVES

The objective of the NightPod experiment is to verify capability of a new tracking device used to improve digital photography for Earth observation at night by using long exposure time and compensating for the relative motion of the International Space Station (ISS) and Earth. It is a camera support for which position can be adjusted via 3 axes. The in-built tracking mechanism can be programmed with attitude and altitude data of the ISS so that it would follow any target point.



Top: NightPod tracking device situated in the Cupola Module on the International Space Station. Bottom: Image taken on Nikon D3s camera using the NightPod device. ESA image.

EARTH BENEFITS

The imagery of the Earth at night has a large number of potential applications, from the original motivation to build NightPod, ie, taking images of cities at night to create a map of the distribution of the population, to mapping fishing activities, light pollution, and fires.

SPACE BENEFITS

Because a dedicated satellite is not foreseen in the near future, the most likely candidate suppliers of high-resolution, global, nocturnal imagery are the crew aboard the ISS. The NightPod device has been commissioned by ESA to assist the crew in such tasks: tracking visual targets on the Earth and neutralizing the effect of ISS motion, allowing for an increase in exposure time, and therefore the quality of the nocturnal images.

RESULTS

Photographing the Earth with the support of NightPod has resulted in very sharp high-definition photos of the planet’s surface. The quality of photos far exceeded previous missions, and given the added clarity, comparisons of the imagery can start to be made over time. Possible scenarios include: cities at night, vegetation fires at night, visual analysis of maritime traffic/road traffic, volcano activity at night, urban pollution, squid fishing at night, day/night transitions. The system has been designed to be adaptable, and astronauts on the space station have already been thinking of using NightPod to look the other way, into space, taking images of stars and space.

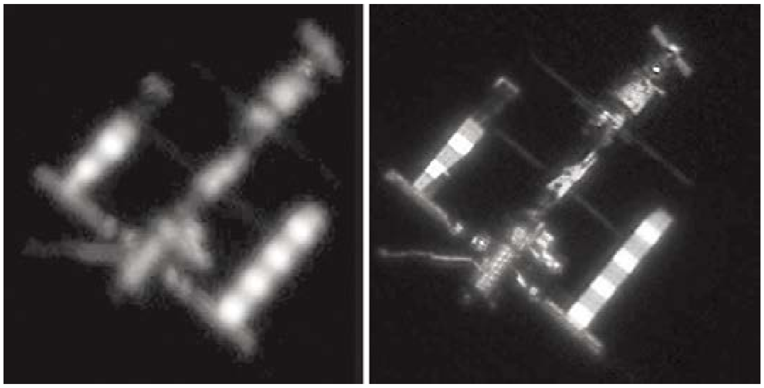
This investigation is complete; however additional results are pending publication.

Specular Point-like Quick Reference (SPQR)

Research Area: Imaging Technology
Expedition(s): 10 and 11
Principle Investigator(s):
- F. Graziani, University of Rome La Sapienza, Rome, Italy

Research Objectives

The objective of the Specular Point-like Quick Reference (SPQR) experiment is to evaluate the possibility of improving the resolution of ground-based telescopic imaging of manned spacecraft in orbit. The concept is to reduce image distortions due to atmospheric turbulence by evaluating the Point Spread Function (PSF) of a point-like light reference. This is provided by a laser beam emitted by the ground station and reflected back to the telescope by a Cube Corner Reflector (CCR) mounted on an International Space Station (ISS) window.



Partially improved image of the International Space Station obtained using a bright feature as a point reference. ESA image.

Results

The experiment was successfully performed from March to May 2005. A beam splitter installed on the 25-inch telescope allowed the incoming light to be divided, filtered, and simultaneously imaged with 2 10-bit high frame rate digital cameras. The first camera used a broad-band filter centered at 532 nm and provided an image of the spacecraft, which was distorted by atmospheric turbulence. The second camera used a notch filter at 532 nm and simultaneously provided a point spread function for processing of the broadband, visible light image. The broadband image was the one to be processed in order to achieve the best possible quality image of the spacecraft, while the narrow band picture was the one need to get the point spread function (PSF) from the laser beam reflection. The actual PSF had to be compared with the theoretical one (the one we would have if no atmosphere disturbances were present). Therefore the distortion affecting the picture could be assessed, hence the deconvolution needed to process the rough image. The figure above shows the result of deconvolution for an ISS pass that occurred on May 3, 2005. On the left, an atmospherically distorted image of the ISS is shown under optimal atmospheric conditions (very stable and clear) and nighttime imaging conditions. On the right is an image that has been obtained by superimposing several frames and deconvolving them with a PSF. It is important to note that no matter the perfect tracking and the excellent atmospheric conditions, the image quality without processing with the PSF would be poor. The SPQR experiment proved for the first time that a powerful laser could be fired towards the ISS without problems for the astronauts or the attitude control sensors of the ISS. Furthermore, the use of the PSF and image processing allowed removing the effect of atmospheric disturbance on the image, allowing a resolution of about 20 cm, ie, at the diffraction limit.

PUBLICATION(S)

Paolozzi A, Porfilio M, Currie DG, Dantowitz RF. The SPQR experiment: Detecting damage to orbiting spacecraft with ground-based telescopes. *Microgravity Science and Technology*. 2007;XIX(5/6):65-69. doi: 10.1007/BF02919455.

This investigation is complete; however additional results are pending publication.

Super Sensitive HDTV Camera System (SS-HDTV)

Research Area: Imaging Technology

Expedition(s): 28-29

Principle Investigator(s):
- Hideaki Tazuke, Japan Broadcasting Corporation (NHK), Tokyo, Japan

Research Objectives

The Super-Sensitive High Definition TV (SS-HDTV) project is a joint research effort between Japan Broadcasting Corporation (NHK) and JAXA. The SS-HDTV camera takes images of Earth at night capturing phenomena like auroras, meteor showers, etc., and broadcasting the images as a TV program.

Earth Benefit

SS-HDTV records the natural phenomena of auroras, lightning, sprites, airglow, meteor showers, and others for additional study and observation.

Space Benefit

This investigation is applied to new knowledge and not specifically to advances in space exploration.

Results

SS-HDTV was flown to the International Space Station (ISS) in April 2011 by Russian cargo ship *Progress* for operations in the ISS pressurized module cabin including JEM and Cupola. The SS-HDTV system was used to take the high-resolution images, such as luminous cloud, lightning, sprite, aurora, atmospheric airglow, meteor shower, the zodiacal light, night view, sunset, and the moon images.

Astronaut Satoshi Furukawa in action ‘SS-HDTV Video in the ISS Cupola. JAXA image.

This investigation is complete and all results are published.

Atomic Densities Measured Radially in Metal Halide Lamps Under Microgravity Conditions with Emission and Absorption Spectroscopy (ARGES)

Research Area: Life Support Systems and Habitation

Expedition(s): 8 and 9

Principal Investigator(s):
- Gerrit Kroesen, Eindhoven University of Technology, Eindhoven, Netherlands

Research Objectives

The Atomic Densities Measured Radially in Metal Halide Lamps Under Microgravity Conditions with Emission and Absorption Spectroscopy (ARGES) experiment investigates the High-Intensity Discharge (HID) lamps (which utilize plasma technology) in weightlessness. The experiment's goal is to understand imperfections that existed in the technology in a similar way to the instabilities from the Plasma Crystal Research (PK) experiment series of experiments. These cause uneven light emission and instabilities that could cause cracks in the burner wall leading to non-functionality.

High Intensity Discharge lamps for the Atomic Densities Measured Radially in Metal Halide Lamps Under Microgravity Conditions with Emission and Absorption Spectroscopy. Pim Kemps image.

Results

The experiment in which electronics company Philips and Eindhoven Technical University were participating, was a 100% success and yielded to very promising results. The instabilities in the lamp were expected to be shaped as a rotating helix, and instead they appeared to be a singly bent curve that was not rotating. This fact is very important in improving the performance of the lamps, especially since the instabilities occurred mainly in the most efficient lamps.

ARGES experiment chamber. Dutch Space image.

Analysis afterwards indicated that the rotation in the metal was caused solely by convection and the curving was caused by self-generated magnetic fields. For one condition, residual gravity caused a very slow rotation. As expected, the axial de-mixing did not occur during the in-orbit mission experiments, so the radial demixing could indeed be studied undisturbed. The first results from the experiment actually concluded that one of the main problems/influences causing flickering in the lamps was gravity.

PUBLICATION(S)

Flikweert AJ, Nimalasuriya T, Kroesen GM, Haverlag M, Stoffels WW. The metal-halide lamp under varying gravity conditions measured by emission and laser absorption spectroscopy. *Microgravity Science and Technology*. January 30, 2009;21(4):319-326. doi: 10.1007/s12217-009-9106-z.

Kroesen GM, Haverlag M, Dekkers E, et al. ARGES: Radial segregation and helical instabilities in metal halide lamps studied under microgravity conditions in the International Space Station. *Microgravity Science and Technology*. March 2005;16(1-4):191-195. doi: 10.1007/BF02945974.

This investigation is complete and all results are published.

Selecting and Testing Procedures and Equipment for Detecting Locations of Module Depressurization on the International Space Station (Bar), Two Investigations

Research Area: Life Support Systems and Habitation
Expedition(s): 16-ongoing
Principal Investigator(s):
- Oleg A. Saprykin, PhD, Central Research Institute for Machine Building, Korolev, Russia
- Elena V. Shubralova, Central Research Institute for Machine Building, Korolev, Russia

Research Objectives

The Selecting and Testing Procedures and Equipment for Detecting Locations of Module Depressurization on the International Space Station (Bar) investigation supports International Space Station (ISS) safety by developing means and methods to detect the location of leaks. One of the causes of leakage can be micro-destruction of the ISS pressure hull.

Bar-1

The goal of the Bar-1 investigation is the experimental verification of the performance and ergonomic properties of the Bar scientific equipment set, as well as the methods of leak locations in full-scale conditions using the database of the background conditions. This set of the Bar scientific equipment is designed to detect leak locations in the ISS Russian Segment (RS) modules, investigate the inner environment, and identify and control potentially hazardous zones of microdestructive growth in the ISS RS module pressure hull.

ISS Crew member Yevgeny Tarelkin operates the ultrasound analyzer during International Space Station Expedition 34. Roscosmos image.

Bar-2

The goal of the Bar-2 investigation is the formation of a database of the background conditions based on the results of monitoring the physical environment parameters and the pressure hull surface microconditions in zones of potential leaks.

Earth Benefits

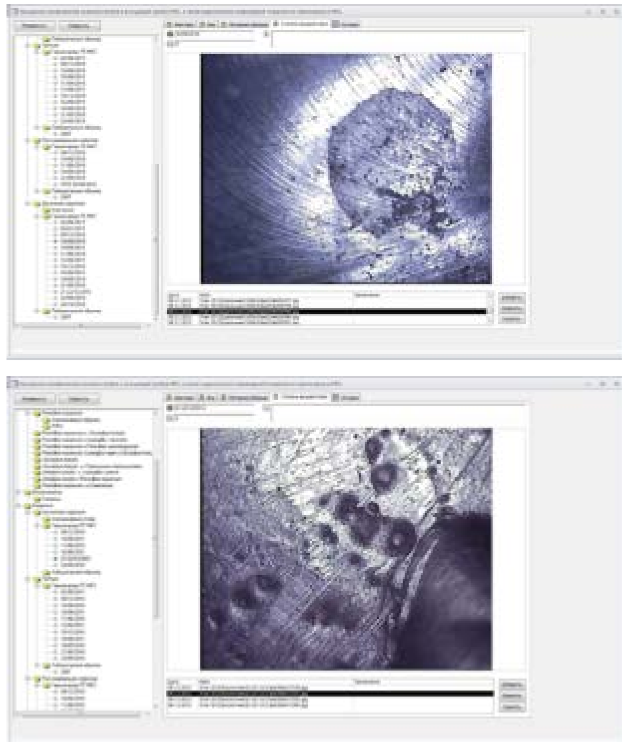
The Bar scientific equipment can be used in civic aviation and shipbuilding as a diagnostic tool to detect ship hull microdestruction, find corrosion growth on structural elements, and assess conformity to permissible acoustic levels.

Space Benefits

The goal of the Bar investigation is to provide safety for the ISS Russian Segment. The Bar equipment can be used as a prototype for detecting leak locations inside the ISS RS modules and, in combination with the database identifying areas of potential leaks, as a system for control of the ISS pressure hull condition.

Results

The performance and ergonomic properties of the Bar equipment were verified, and 56 potentially hazardous zones of leaks were identified and examined. Additional zones of potential micro-destruction growth on the ISS pressure hull were also identified. Several databases were created to track the background physical environmental parameters in the potentially hazardous zones of leak and micro-destruction growth, the current state of the ISS pressure hull (including microbiological and corrosive conditions on the hull), and train cosmonauts to identify surfaces in which microorganism colonies have expanded.



Images of surfaces with corrosion damage of samples taken during the Bar experiment. Roscosmos image.

Publication(s)

Deshevaya EA, Shubralova EV, Novikova ND, Polikarpov NA. Results of intravehicular environment influence on pressure body state studies conducted in space experiments “Bar” and “Expert” on-board ISS in 2008-2011. *Space Forum 2011 Dedicated on 50th Anniversary for Yu A Gagarin Flight*, Moscow, Russia; October 18-21, 2011.

Deshevaya EA, Shubralova EV, Novikova ND, Borisov VV, Kononenko OD, Polikarpov NA. Testing and evaluation of a method for locating potentially hazardous sites of eventual microdestruction and detecting marks of ISS RS hull leakage. *Acta Astronautica*. May-June, 2011;68(9-10):1555-1559. doi: 10.1016/j.actaastro.2010.10.006.

Deshevaya EA, Shubralova EV, Borisov VV, et al. Main outcomes of space experiments “Bar” and “Expert” implementation on-board ISS. *35th Academic Readings on Cosmonautics*, Moscow, Russia; January 2011: 577.

Makov YN, Bychkov VB, Kononenko OD, Shubralova EV. Low-frequency background ultrasonic problematics applied to measurement necessity study of low-frequency background ultrasonic influence on cosmonauts during long-term presence on space vehicles. *35th Academic Readings on Cosmonautics*, Moscow, Russia; 2011, 577-579.

Deshevaya EA, Novikova ND, Polikarpov NA, et al. Results analysis of space experiments “Bar” and “Expert” conducted on-board ISS Russian segment: Perspectives of “Bar” equipment kit application for detection of potentially dangerous areas for ISS pressure body microdistruction processes extension. *6th International Aerospace Congress*, Moscow, Russia; 2010.

Borisov VV, Deshevaya EA, Kononenko OD, Shubralova EV, Novikova ND. Development test of method of leakage spots detection on-board ISS. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering*). 2009(4):144-152.

Deshevaya EA, Borisov VV, Kononenko OD, Shubralova EV. Verification of the method for revealing of potentially dangerous zones of possible development of micro- destruction of the PS ISS pressurized structure (based on the results of the 17-ISS mission). *17th IAA Humans in Space Symposium*, Moscow, Russia; June 7-11, 2009: 32.

Borisov VV, Lukjaschenko VI, Makolkin E, et al. Prospects of applying the remote monitoring devices for detecting the depressurization locations at the International Space Station and for checking its structure. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2007;49(4):174-182.

Shubralova EV, Makolkin E, Deshevaya EA, et al. Ultrasonic vibrations influence on microdistruction process. *2nd International Scientific Technical Conference*, Saransk; 2006: 98-101.

Anfimov NA, Borisov VV, Lukjaschenko VI, et al. Perspectives of bar telemetric means utilization for leakage detection and monitoring of the ISS construction conditions. *55th International Astronautical Congress*, Vancouver, Canada; October 4-8, 2004.

These investigations are ongoing and additional results are pending publication.

Crew Restraint

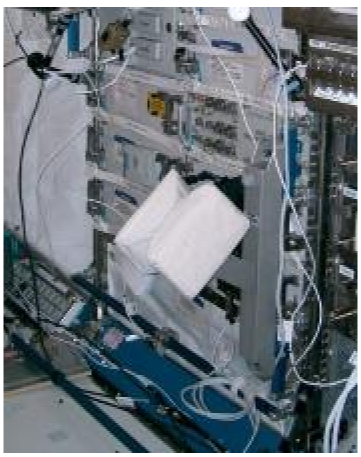
Research Area: Life Support Systems and Habitation

Expedition(s): 7 and 8

Principal Investigator(s):
- Pedro Duque, European Space Agency, Oberpfaffenhofen, Germany
- P. Mitschdoerfer, European Space Research and Technology Centre, Noordwijk, Netherlands

Research Objectives

The objective of the Crew Restraint experiment is to test new equipment that uses astronaut's knees to hold them in position during operational activities. Almost all current restraint devices use the feet to restrain the body, and it is generally perceived that this unnaturally overloads the smaller muscle groups of the feet. Restraining the crew member at the knee level lowers the forces needed since the knees are closer to the center of gravity of the astronaut, and larger muscle groups are relied upon to a greater extent.



Left: Crew Restraint attached to the front of an International Space Station rack. Right: ESA astronaut Pedro Duque works on the Microgravity Science Glovebox while testing the new Crew Restraint device. ESA image.

Results

Attaching the Crew Restraint was one area where improvements to the design could be made. It was designed to attach to seat tracks on the front of station racks. However, due to the width of the restraint at the base, this meant that it didn't fit easily on most racks, especially where covers on racks interfered with the process. The process of reconfiguring equipment to make the restraint's installation possible also meant that there was a risk of disturbing other crew members.

However, Pedro expanded the possibilities for the device by incorporating handrail to seat track adapters that were available in orbit. Using these adapters showed that the crew restraint could be used in many more locations, which made it possible to use equipment available at the site rather than first relocating it (obviously possible with mobile equipment). From a crew perspective, this would not be necessary for using laptop computers as they are able to use them easily without the use of a restraint.

The device itself was comfortable, though quite a lot of effort was needed to perform a pitch (forward) move. It was however quite easy to move from side to side and reach different areas without having to change restraint configuration (being able to reach to racks either side of the rack you are working in front of). For example, Pedro found it easy to undertake procedures using the crew restraint for working on the Microgravity Science Glovebox in orbit. The overall feedback from the test proved it was a good idea in general, though it will need to be evaluated for a longer period of time in order to make design improvements and realize its full potential.

This investigation is complete; however no publications are expected.

Forward Osmosis Bag (FOB)

Research Area: Life Support Systems and Habitation
Expedition(s): 27-ongoing
Principal Investigator(s):
- Howard G. Levine, PhD, NASA's Kennedy Space Center, Cape Canaveral, Florida

Research Objectives

The Forward Osmosis Bag (FOB) system is designed to convert dirty water into a liquid that is safe to drink using a semi-permeable membrane and a concentrated sugar solution. FOB looks at the forward osmosis membrane in a spaceflight environment and compares its performance against ground reference controls.

Earth Benefits

Hydration Technology Innovations (HTI), the manufacturer of the Forward Osmosis membrane, has used the same technology to create a lifesaving water filter for use in disaster relief situations. This product has been successfully used in disaster relief efforts for the 2010 earthquakes in both Haiti and Chile and was tested in the waters from the aftermath of Hurricane Katrina.

Mission specialist Rex Walheim uses the Forward Osmosis Pump Syringe to inject the Challenge Liquid into the FOB during STS-135/ULF7.

Space Benefits

Forward osmosis technology has several potential applications for spaceflight. In the near term this technology extends existing non-potable water resources on the International Space Station (ISS), thus providing a low-mass alternative for the reduction of stockpiled water on the ISS and flexibility during off-nominal situations, such as in the event a resupply vehicle is delayed or the primary water-recycling system becomes nonfunctional. A small forward osmosis device could be incorporated into new long-exposure spacewalk suits in order to recycle metabolic wastewater (ie, sweat and urine) into drinkable fluid. A forward osmosis device product could be incorporated into new return vehicles as a mass and volume-efficient method of providing crews with post-splashdown fluids. The existing lightweight COTS product can be tethered in seawater to produce a drinkable fluid.

Results

A microgravity test of the FOB was completed during shuttle flight STS-135 in July 2011. Postflight analysis showed the ion rejection rates, which are measures of how well a membrane rejects the passage of dissolved ions, in microgravity to be the same as measured during ground testing. However, the flux rates (rates of flow per unit area) declined in microgravity by up to

50%, although the exact amount of reduction remains to be determined due to significant scattering of the flux data. Considerable fluid wicking, which was not seen on the ground, also occurred during the bag filling process in orbit. While it did not affect the experiment results, fluid wicking could be a problem in the future if the bag is not filled completely (Flynn 2012). Results from FOB will be applied in future water recovery methods for both ground and space missions as well as help reduce mission costs by recycling used materials.

PUBLICATION(S)

Flynn MT, Soler MP, Shull S, et al. Forward osmosis cargo transfer bag. *42nd International Conference on Environmental Systems*, San Diego, CA; July 15-19, 2012.

This investigation is ongoing and additional results are pending publication.

INTEGRATED RESEARCH ON LOW-FREQUENCY ACOUSTIC AND ELECTROMAGNETIC FIELDS IN THE ISS HABITATION COMPARTMENTS (INFRAZVUK-M)

Research Area: Life Support Systems and Habitation
Expedition(s): 2, 13 and 15
Investigator(s):
- Mikhail Y. Belyaev, PhD, S.P. Korolev Rocket and Space Corporation Energia, Korolev, Russia

RESEARCH OBJECTIVES

The Integrated Research on Low-Frequency Acoustic and Electromagnetic Fields in the ISS Habitation Compartments (Infrazvuk-M) investigation develops and tests the tools and methods of creating a real-time system for monitoring the spatial-temporal structure and energy spectral parameters of low-frequency physical background fields in the International Space Station (ISS) Service Module (SM) habitation compartments.

SPACE BENEFITS

Based on Infrazvuk-M results, recommendations were provided to introduce improved systems, as part of the nominal acoustic noise control system, into the ISS RS modules, for crew protection from the adverse effects of exposure to the interior physical environment, including the acoustic noise in the ISS RS module habitation compartments.

Onboard Noise Analyzer. Roscosmos image.

RESULTS

The measurements showed that the noise generated by the new fan as installed in the SM ventilation system was significantly lower than that of the nominal fan. The reduction in overall noise level, measured at a distance of 50 cm from the fan with the interior panel open, was 2.8 dB.

The noise reduction values as obtained have demonstrated a satisfactory noise-reduction effect through the use of the low-noise fan, which had previously been identified during the ground-based tests.

This investigation is complete and all results are published.

Investigation of Early Symptoms of Microdestruction of Structures and Instrument Modules in the Russian Segment of ISS (Expert)

Research Area: Microbial Populations in Spacecraft

Expedition(s): 18-22

Investigator(s):

- Oleg A. Saprykin, PhD, Central Research Institute for Machine Building, Korolev, Russia
- Elena V. Shubralova, Central Research Institute for Machine Building, Korolev, Russia

Research Objectives

Investigation of Early Symptoms of Microdestruction of Structures and Instrument Modules in the Russian Segment of ISS (Expert) investigates the early symptoms of the surface microdestruction of the pressurized body and structures in the International Space Station (ISS) modules while monitoring temperature-humidity parameters, acoustic fields of ultrasound band and other spaceflight factors, which can affect the microdestruction processes. Secondly, Expert will lead the development of an onboard system to reveal early symptoms of microdestruction and update methods to prevent microdestruction of the pressurized body and structures in the ISS.

Cosmonaut Oleg Kotov examines the area behind a panel. Roscosmos image.

Earth Benefits

The diagnostic equipment and the method of its usage can be used in civic aviation and shipbuilding**.**

Space Benefits

The results of the Expert provide the long-term ISS safe operation.

Results

Results of Expert included the development of methods for the monitoring of background physical environmental parameters, which can affect the microdestruction processes. These parameters were tracked in a database. Thirty zones of possible microdestruction growth were added to the previously identified potentially hazardous zones of leaks. These zones were subjected to regular inspections. Fifty percent of the test samples taken from the newly identified zones of possible microdestruction growth contained decomposer fungi and bacteria.

Monitoring of air flow in behind-panel areas allowed locating zones with insufficient air cooling in the instrument area. It was proven that circulations of air flow in instrumentation behind-panel areas affected topology of microorganism contamination of the ISS pressure hull. Additionally, conditions of the pressure hull in the potentially hazardous zones were inspected and the surface conditions recorded in a database. Finally, a fungi database was created to store images of the microconditions of the test samples and to be used in training ISS crew members to preliminarily identify microorganisms and assess growth of decomposer microorganisms on the pressure hull surface.

Area behind a panel, the temperature is 11˚C with $2{,}0 \times 10^3$ colony-forming unit (CFU) of *Ulocladium botrytis* and $2{,}0 \times 10^3$ CFU of *Aspergillus sydowii*. Roscosmos image.

PUBLICATION(S)

Deshevaya EA, Shubralova EV, Novikova ND, Polikarpov NA. Results of intravehicular environment influence on pressure body state studies conducted in space experiments “Bar”and “Expert” on-board ISS in 2008-2011. *Space Forum 2011 Dedicated on 50th Anniversary for Yu. A. Gagarin Flight*, Moscow, Russia; October 18-21, 2011.

Deshevaya EA, Shubralova EV, Novikova ND, Borisov VV, Kononenko OD, Polikarpov NA. Testing and evaluation of a method for locating potentially hazardous sites of eventual microdestruction and detecting marks of ISS RS hull leakage. *Acta Astronautica*. May-June, 2011;68(9-10):1555-1559. doi: 10.1016/j.actaastro.2010.10.006.

Deshevaya EA, Novikova ND, Polikarpov NA, et al. Results analysis of space experiments “Bar” and “Expert” conducted on-board ISS Russian segment: Perspectives of “Bar” equipment kit application for detection of potentially dangerous areas for ISS pressure body microdistruction processes extention. *6th International Aerospace Congress*, Moscow, Russia; 2010.

PATENT(S)

Zyablov VA, Deshevaya EA, Novikova ND, Shubralova EV, Scherbakov EV, inventors; The method of destruction of bio-destructor microorganisms on surfaces of the ISS habitable modules. *Federal Service for Intellectual Property*. Patent 2372942. November 20, 2009.

This investigation is complete and all results are published.

Surface, Water, and Air Biocharacterization - A Comprehensive Characterization of Microorganisms and Allergens in Spacecraft Environment (SWAB)

Research Area: Microbial Populations in Spacecraft

Expedition(s): 13-16, 19-22

Principal Investigator(s):
- Duane L. Pierson, PhD, NASA's Johnson Space Center, Houston, Texas

Research Objectives

A Comprehensive Characterization of Microorganisms and Allergens in Spacecraft (SWAB) uses advanced molecular techniques to comprehensively evaluate microbes aboard the International Space Station (ISS) including pathogens (organisms that may cause disease).

ISS0515E07586 - Astronaut Sunita L. Williams, Expeditions 14 and 15 flight engineer, conducts a Surface, Water and Air Biocharacterization (SWAB) air sampling in the Destiny laboratory of the International Space Station.

SWAB also tracks changes in the microbial community as spacecrafts visit the station and new station modules are added. This study assesses the risk of microbes to the crew and the spacecraft. The determination of risk from infectious disease during spaceflight missions is composed of several factors including both the concentration and characteristics of the microorganisms to which the crew are exposed. Thus, having a good understanding of the microbial ecology aboard spacecraft provides the necessary information to mitigate health risks to the crew. While stringent steps are taken to minimize the presence of pathogens on spacecraft, medically significant organisms have been isolated from both the Mir and ISS. Historically, the method for isolation and identification of microorganisms from spacecraft environmental samples depended upon their growth on culture media. Unfortunately, only a fraction of the organisms might grow on a specific culture medium, potentially omitting those microorganisms whose nutritional and physical requirements for growth are not met. To address this bias in our understanding of the ISS environment, the SWAB Flight Experiment was designed to investigate and develop advanced monitoring technology to better characterize the ISS environment.

Earth Benefits

The results of this study provide insight into changes that occur in the microbial ecology of semi-closed systems. The development of specific primers for bacterial enumeration and fungal identification during this study advance the ability of ground-based investigators to diagnose the potential sources of microbial contamination and give insight into the causes of health-related microbial contamination issues such as “sick building syndrome.”

ISS010E11563 - An example of contamination that has developed on one of the interior panels aboard ISS. This image shows how contamination can form on interior ISS surfaces. Crews have weekly sessions to clean ISS surfaces. SWAB will help us understand the microbes involved in contamination and how to deal with them.

Space Benefits

Knowing the microorganisms that the crew encounter is crucial in assessing the health risks of the crew and performance of the spacecraft systems. By studying the types of organisms and the change in this ecosystem over time, preventative and disinfection regiments are developed to mitigate the accumulation of medically significant organisms or microorganisms that foul filters or degrade components of the spacecraft.

Results

For the SWAB flight experiment, it was hypothesized that environmental analysis using non-culture-based technologies would reveal microorganisms, allergens, and microbial toxins not previously reported in spacecraft, allowing for a more complete health assessment. Key findings during this experiment included: Sample analyses using the culture-based and advanced molecular methodology, which provided similar results, indicating the current monitoring methods are not “missing” medically significant bacteria and fungi. Dust samples taken from the HEPA air filters identified 17 different microbial mold species, most commonly *P. chrysogenum* and *A. pullulans*. Other opportunistic pathogens were also detected including a particularly high concentration of *A. flavus* and *A. niger*. Fortunately, to date there have been no known health effects from mold as a result of living aboard the ISS (Vesper 2008). Molecular techniques have tremendous potential for microbial monitoring; however, sample preparation and data analysis present challenges for spaceflight hardware. Results indicate that some molecular techniques, such as denaturing gradient gel electrophoresis (DGGE), can be much less sensitive than culture-based methods, and More sensitive molecular techniques, such as quantitative polymerase chain reaction (QPCR), were able to identify viral DNA from ISS environments, suggesting potential transfer of the organism between crew members.

Publication(s)

Vesper SJ, Wong W, Kuo CM, Pierson DL. Mold species in dust from the International Space Station identified and quantified by mold-specific quantitative PCR. *Research in Microbiology*. July 2008;159(6):432-435. doi: 10.1016/j.resmic.2008.06.001.

This investigation is complete; however additional results are pending publication.

Creation of an Express Water-Toxicity Monitoring System for Spaceflight Conditions (Toksichnost)

Research Area: Microbial Populations in Spacecraft
Expedition(s): 8-10
Principal Investigator(s):
- Tatiana A. Alekhova, PhD, Lomonosov Moscow State University, Moscow, Russia

Research Objectives

Creation of an Express Water-Toxicity Monitoring System for Spaceflight Conditions (Toksichnost') evaluates water toxicity in spaceflight conditions. This investigation was performed on water samples obtained from the ISS condensate water processor (downstream from the purification units, before the addition of preservatives), as well as on water samples delivered from Earth, for comparative analysis.

During International Space Station Expedition 7, Flight Engineer Yu.G. Sharipov performs a session of the experiment. Roscosmos image.

Space Benefits

The results of Toksichnost' (the method for integral evaluation of the toxicity of water and water solutions) will have great practical significance for assuring safety and supporting the health of cosmonauts during long-term spaceflights.

Results

The experiment confirmed the viability of the method of express environmental monitoring designed for an integrated evaluation of the aqueous solutions and water without preservatives in microgravity through measuring the illumination intensity changes of the Ecolyum microbial biosensor as it interacts with substances in the sample test tube, as compared against a standard. The results of the first session of the experiment (ISS-Expedition 8) were used to improve experimental technique with regard to collecting water samples. It was found to be necessary to mechanically mix the solution being studied, which consisted of 2 liquids of nearly identical density, to provide the required homogeneity in microgravity. Analyses of water samples returned to Earth and control samples on the ground produced largely similar results.

Publication(s)

Alekhova TA. Microflora research on a surface of the International Space Station Russian Segment (ISS RS) constructional materials. *3rd Congress of Microbiologists of Uzbekistan*, Tashkent, Uzbekistan; 2005.

This investigation is complete and all results are published.

ACTIVE RACK ISOLATION SYSTEM - ISS CHARACTERIZATION EXPERIMENT (ARIS-ICE)

Research Area: Microgravity Environment Measurement
Expedition(s): 2-4
Principal Investigator(s):
- Glenn S. Bushnell, The Boeing Company, Seattle, Washington

RESEARCH OBJECTIVES

Constant microgravity conditions are essential for many International Space Station (ISS) experiments. Very small changes in acceleration (such as normal crew activity) can cause subtle vibrations to echo through the ISS. Active Rack Isolation System (ARIS) can protect these delicate experiments by absorbing the shock of motion before it can affect an experiment. This capability enables accommodation of future research that is sensitive to vibration disturbances.

EARTH BENEFITS

Experiments ranging from protein crystallization (which can lead to vast advancements in medicine) to the way different fluids behave when mixed are conducted on the ISS. In order for these experiments to lead to improvements in our lives on Earth, they must be conducted as close to undisturbed as possible in space. The ARIS can lead to better science by protecting those experiments from sudden movements and disturbances that can occur aboard the ISS. ARIS-ICE will allow for the ARIS to better perform its function.

Cosmonaut Vladimir Dezhurov performs ARIS-ICE hammer tests in the US Destiny laboratory during Expedition 3.

SPACE BENEFITS

Even though ISS orbits the Earth in relative microgravity, it is subjected to various sources of disruptive movements that can compromise sensitive experiments. Simple daily activities, like crew exercise, can cause enough vibration to potentially interfere with a particular experiment's results. ARIS allows experiments to remain as undisturbed as possible, and the data collected from ARIS-ICE allows for more successful science to be performed aboard the ISS.

RESULTS

ARIS-ICE operations were performed for over a year during Expeditions 2-4. During that period, more than 1 700 test runs were completed, ranging from short 1-second stability tests to 5-hour isolation characterization tests. Station vibrations were isolated to levels well below the science requirements of investigations in EXpedite the PRocessing of Experiments to Space Station (EXPRESS) racks equipped with ARIS. Through a series of acceleration characterization experiments conducted during ARIS-ICE, investigators determined that the ARIS facility provides the ability to predict and prevent the potentially damaging effect of station vibrations. It was also determined that sensitive experiments installed in ARIS would be isolated and protected from both vibrational and acceleration movements. These capabilities are critical to make ISS a unique, world-class research laboratory in microgravity.

PUBLICATION(S)

Fialho IJ, Bushnell GS, Allen JL, Quraishi N. Taking H-infinity to the International Space Station: Design, implementation, and on-orbit evaluation of robust controllers for active microgravity isolation. *AIAA Guidance, Navigation, and Control Conference*, Austin, TX; 2003.

Bushnell GS, Fialho IJ, Allen JL, Quraishi N. Microgravity flight characterization of the International Space Station Active Rack Isolation System. *Proceedings of SPIE 5052, Smart Structures and Materials 2003*, San Diego, CA; 2002.

Bushnell GS, Fialho IJ, McDavid T, Allen JL, Quraishi N. Ground and on-orbit command and data handling architectures for the Active Rack Isolation System microgravity flight experiment. *53rd International Astronautical Congress, The World Space Congress*, Houston, TX; 2002.

This investigation is complete and all results are published.

Identification of Sources of Disturbances During Disruption of microgravity on the International Space Station (Identifikatsiya)

Research Area: Microgravity Environment Measurement
Expedition(s): 1-ongoing
Principal Investigator(s):
- Anatoli I. Likhoded, PhD, Central Research Institute for Machine Building, Korolev, Russia

Research Objectives

Identification of Sources of Disturbances During Disruption of Microgravity on the International Space Station (Identifikatsiya) measures accelerations and microaccelerations performed during dynamic operations: docking, undocking, orbital reboost, and other operations during which the International Space Station (ISS) structures are exposed to force loads. Telemetry analysis is used to determine dynamic characteristics and update the mathematical model of the ISS, taking into account changes to its configuration.

Space Benefits

The results of the experiments will be useful in the creation and use of large-scale structures in space. The performance of Identifikatsiya is the only opportunity to experimentally confirm the reliability of the assessments of actual spectra of cyclical loading (in terms of loading levels and the number of cycles experienced) and for assessment of the conditions of microgravity in various working compartments in the station. These results are the foundation for assessing the degree of reliability and experimental monitoring of the depletion of the lifetime of ISS structure, which is particularly relevant with regard to extending the station's life.

S135E011814 – International Space Station in the early hours of July 19, 2011.

Results

During the course of Identifikatsiya, a large amount of factual material, requiring systematization, was compiled on force loading and acceleration fields, which were recorded by onboard accelerometers that were located on ISS RS modules. Essentially, a database of samples of various external force loads was created. The measurement results obtained made it possible to determine the dynamic characteristics for various ISS configurations and to obtain data on the level and nature of propagation of dynamic disturbances from typical sources of external loads, based on the measurements of acceleration parameters in various modes.

In order to identify sources of micro-gravitational disturbances and other off-nominal dynamic loads on the ISS structure, methodological and software/algorithmic means were developed for mathematically recreating unknown parameters of external force loads, based on analysis of telemetry from onboard microacceleration sensors. Inverse problems of this type are of independent interest and have important applications in various areas of technology. It was established that during dynamic operations, the level of loading on the structures of modules did not exceed design values.

PUBLICATION(S)

Likhoded AI, Vvedenskiy NY, Anisimov AV, Safronov VN, Titov VA. Regulatory structure and mathematical modeling of actual loads and assessment of the depletion of the mechanical lifetime of the structure of the International Space Station's Russian Segment. *Kosmonavtika i Raketostroyeniye*. 2011;1(162):74-79.

Anisimov AV, Likhoded AI. Computational reconstruction of actual docking force loads on the structure of the International Space Station based on processing readings from onboard accelerometers. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2007;49(4):115-119.

Panichkin N, Vvedensky N, Likhoded A, Anisimov A. Identification of unsanctioned external forces on ISS structure in abnormal situations through telemetry data. *55th International Astronautical Congress*, Vancouver, Canada; 2004;IAC-04.T.P.02.

This investigation is ongoing and additional results are pending publication.

A Study of the Effects of Onboard System Operating Modes on ISS Flight Conditions (Izgib)

Research Area: Microgravity Environment Measurement
Expedition(s): 1-30 and 33-ongoing
Principal Investigator(s):
- Mikhail Y. Belyaev, PhD, S. P. Korolev Rocket and Space Corporation Energia, Korolev, Russia

Research Objectives

The A Study of the Effects of Onboard System Operating Modes on ISS Flight Conditions (Izgib) determines the gravitational environment aboard the International Space Station (ISS) by studying both heterogeneous and homogeneous (in terms of density) fluid flows in microgravity using the Dakon-M science equipment.

Space Benefits

The knowledge of microacceleration levels, their spectral composition, and their spatial distribution is a necessary condition for the effective utilization of manned space complexes as a means for achieving scientific and applied objectives, as well as for refining mathematical models and dynamic characteristics of various ISS stack configurations and for monitoring the structure's remaining operating life.

Results

The results obtained during the sessions using this equipment have demonstrated that microaccelerations caused by dynamic station operations can excite convective flows in a heterogeneously heated gas environment. The root causes of convective flow excitation have been validated by comparing the Dakon-M results with angular rate sensor measurements. In particular, the tests have demonstrated that convection can occur as a result of continuous microaccelerations existing aboard the ISS, as well as of the accelerations related to boosting the station's orbit and to docking and undocking with Progress-M and Soyuz vehicles.

External Appearance of the Dakon-M Science Equipment. Roscosmos image.

A study of convective and isothermal flows caused by small inertial forces aboard the ISS RS was completed using the Dakon-M science equipment during the 2011 ISS increments. The performed studies show that the microgravity environment aboard the ISS RS is unfavorable for a number of experiments. To ensure the favorable conditions for microgravity experiments, Progress vehicles are proposed as a platform for such experiments after the spacecraft has fulfilled its primary functions. The performed experiments has shown that the Progress attitude control methods developed for this use can ensure microacceleration levels of at least 10^{-6} g, which is a unique achievement opening up broad possibilities for the implementation of science programs.

The expected scientific and engineering results of the Izgib experiment are related to the ability to obtain the inputs required for the development of both mathematical micro g-load models and a database on hardware-related impacts on micro g-load levels for different science hardware locations.

PUBLICATION(S)

Bryukhanov NA, Tsvetkov VV, Belyaev MY, Babkin EV, Matveeva TV, Sazonov VV. Experimental investigation of the modes of operation of uncontrolled attitude motion of the Progress spacecraft. *Cosmic Research*. January 2006;44(1):48-57. doi: 10.1134/S0010952506010059. [Original Russian Text © Bryukhanov NA, Tsvetkov, Belyaev MY, Babkin EV, Matveeva TV, Sazonov VV. *Kosmicheskie Issledovaniya*. 2006;44(1):52-61.]

Babkin EV, Belyaev MY, Efimov NI, Sazonov VV, Stazhkov VM. Determination of quasi-steady-state components of microaccelerations occurring aboard the International Space Station. *RAS M. V. Keldysh Institute of Applied Mathematics*. 2003.

Babkin EV, Belyaev MY, Efimov NI, Stazhkov VM, Sazonov VV. Residual microaccelerations aboard the ISS Russian segment. *2nd Russian Conference on Space Materials Science*, Kaluga, Russia; July 3-6, 2003:49.

Babkin EV, Belyaev MY, Efimov NI, Obydennikov SS, Sazonov VV, Stazhkov VM. First results of determining microaccelerations aboard the ISS Russian segment. *RAS M. V. Keldysh Institute of Applied Mathematics*. 2001.

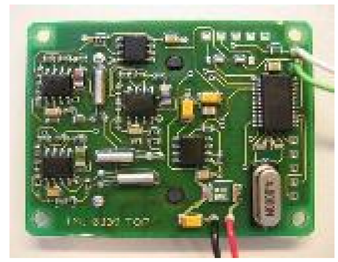
This investigation is ongoing and additional results are pending publication.

MOUSE TELEMETER - CALIBRATION OF STAR ACCELEROMETER

Research Area: Microgravity Environment Measurement
Expedition(s): 8 and 9
Principal Investigator(s):
- G. van Essen, TeleMetronics Biomedical, Wageningen, Netherlands

RESEARCH OBJECTIVES

The main goal of the Mouse Telemeter - Calibration of Star Accelerometer experiment is to test mouse abdomen implanted temperature sensors under weightless conditions with recorded movements of the subject, focusing on autonomous calibration of the accelerometers.



Mouse Telemeter. Image courtesy of ESA.

RESULTS

The right-hand graph shows the experiment's results performed on Earth, the left-hand graph in orbit. Sequentially, the Mouse Telemeter was moved as indicated in 3 orthogonal positions (to test the 3 orthogonal accelerometers). From the graphs, it became clear that the accelerometers acted the same way on Earth as under microgravity conditions. Unfortunately, the X-axis accelerometer did not respond during the space experiment. The only logical conclusion is that a malfunction occurred in the X-axis accelerometer or in the subsequent electronics. Further, the vertical lines at the left side of the space graph do not occur on the terrestrial graph. They may be caused by repeatedly on and off switching before the tests. The conclusion from the experiment was that the piezo electric accelerometers tested are suitable for use in the STAR mouse implant developed for ESA by TeleMetronics Biomedical.

PUBLICATION(S)

van Essen G, Masseling BH, Jansen MB, van Loon JJWA. Monitor activity, temperature, and heart rate with a mouse telemeter to be used for animal research on board the international space station. *Journal of Gravitational Physiology*. 2005;12(1):281-283.

This investigation is complete and all results are published.

Telemetry Data-Based Determination of the Dynamic ISS Characteristics (Tenzor)

Research Area: Microgravity Environment Measurement
Expedition(s): 1-9
Principal Investigator(s):
- Mikhail Y. Belyaev, PhD, S. P. Korolev Rocket and Space Corporation Energia, Korolev, Russia

Research Objectives

The Telemetry Data-Based Determination of the Dynamic ISS Characteristics (Tenzor) investigation was carried out in order to test the methods for determining and updating the ISS dynamic characteristics based on the telemetry data reflecting the motion control system operation. The rationale for initiating Tenzor was the proposed changes in the ISS dynamic characteristics required because of the ISS reconfigurations for Progress or Soyuz vehicle docking/undocking operations, cargo transfer, operating fluids consumption, installation activities aboard the station, etc, which have an indirect impact on the interrelation of the ISS moments of inertia, aerodynamic characteristics, and center of mass position.


Yamal-200 spacecraft. Roscosmos image.

Space Benefits

The method for updating the dynamic spacecraft characteristics developed during Tenzor performance and results review is applicable not only to the ISS, but also for controlling other spacecraft.

Results

The data obtained by Tenzor are used to increase the effectiveness of ISS flight control, since more accurate dynamic parameters entered into the mathematical simulations at the ground complex and into the station computer system increase the reliability and predictability of station behavior when maintaining a specified angular position or changing the ISS attitude.

Based on the data obtained by Tenzor a feasibility study was carried out on controlling the Yamal-200 spacecraft attitude based on the mathematical simulation of its motion. To increase the accuracy of this simulation and of the motion control system operation, the dynamic characteristics of the spacecraft were refined. The study results demonstrated the feasibility of controlling the Yamal-200 spacecraft using the mathematical simulation of angular motion.

Therefore, the results obtained for the ISS (method for updating the mass value based on the mass of the launched satellite) provide additional capabilities to perform flight control tasks, plan experiments, and analyze experiment results obtained.

PUBLICATION(S)

Banit YR, Sevastianov NN, Branez VN, et al. The control of JAMAL 200 attitude using angular motion mathematical model. *7th International Symposium on Reducing the Costs of Spacecraft Ground Systems and Operations*, Moscow, Russia; June 11-15, 2007;648.

Belyaev MY, Bryukhanov NA, Ryabukha SB, Stazhkov VM, Luryashchenko AV, Obydennikov SS. Microperturbations occurring during ISS Russian Segment Operation. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2007;1(46).

Banit YR, Belyaev MY, Dobrinskaya TA, Efimov NI, Sazonov VV, Stazhkov VM. Determination of the inertia tensor of the International Space Station on the basis of telemetry data. C*osmic Research*. March 2005;43(2):131-142. doi: 10.1007/s10604-005-0025-5. [Original Russian text: Banit, Belyaev, Dobrinskaya, Efimov, Sazonov, Staz. *Kosmicheskie Issledovaniya*. 2005;43(2):135-146.

Zavalishin DA, Belyaev MY, Sazonov VV. Applying data from the MAMS accelerometer to assess the dynamic characteristics of the ISS. *RAS M.V. Keldysh Institute of Applied Mathematics*. 2005. [Preprint 101. Also: Zavalishin DA, Belyaev MY, Sazonov VV. Applying data from the MAMS accelerometer to assess the dynamic characteristics of the ISS // Materials of the XXX academic readings on space exploration. *Russian Academy of Sciences commission*, Moscow; 2006.]

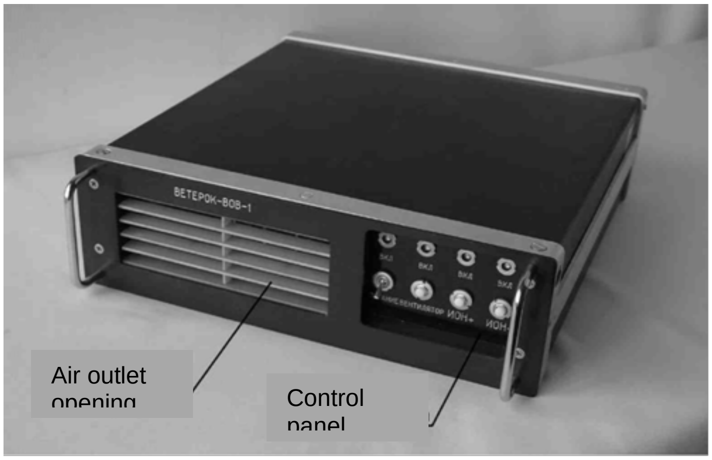
This investigation is complete; however additional results are pending publication.

Developing New Technologies for the Optimization of Gaseous Environment in Living Compartments of the International Space Station Russian Segment (Veterok)

Research Area: Microgravity Environment Measurement
Expedition(s): 21-28
Principal Investigator(s):
- Victor S. Karelin, S.P. Korolev Rocket and Space Corporation Energia, Moscow, Russia

Research Objectives

The Developing New Technologies for the Optimization of Gaseous Environment in Living Compartments of the International Space Station Russian Segment (Veterok) investigation studies the capability of destroying pathogenic microbes, dust, fungi, and odors. By depriving the air of ions, living organisms may die. Veterok ionizes the purified air of the spacecraft to confirm the equipment operational capability and the effectiveness of new technologies for the gas environment parameters optimization under the International Space Station (ISS) orbital flight conditions.



External view of the fan/air purifier. Roscosmos image.

Space Benefits

The use of the fan/purifier as a nominal device will make it possible to essentially decrease the throughput of the main life support system and significantly enhance the parameters of the living environment for crewmembers.

Results

During the experiment, the claimed equipment characteristics were confirmed and experiment data were obtained on ISS gas environment parameters using the developed equipment. The experiment was conducted in three ISS RS modules - the SM, MRM1, and MRM2.

Based on the measurement results, it was established that the concentration and polarity of air ions in the area of equipment operation (at a distance of 1 m from the equipment window) were at the lower threshold of the nominal values range, and under the device, they were below nominal. During the comparison of ion concentrations before and after equipment operation in the mode of pumping air through the equipment's electrostatic filter, it was established that this process does not result in the ionization of the air environment in the pressurized volume of MRM2.

This investigation is complete; however additional results are pending publication.

SPACE RADIATION EFFECTS ON THE CENTRAL NERVOUS SYSTEM (ALTEINO)

Research Area: Radiation Impacts on Humans

Expedition(s): 4

Principal Investigator(s):
- Marco Casolino, PhD, University of Roma Tor Vergata, Rome, Italy
- Livio Narici, PhD, University of Roma Tor Vergata, Rome, Italy

RESEARCH OBJECTIVES

The Space Radiation Effects on the Central Nervous System (Alteino) Sileye-3 device studies the flow of cosmic particles on the International Space Station (ISS) through the extremes of activity of the 11-year solar cycle, building valuable data on solar particle events, secondary particles, and particle showers. A focus of this research is to understand the effect space radiation has on human brain function by combining a silicon particle detector with EEG data for measurements on brain function and astronaut feedback on visual disturbance.

RESULTS

The cosmic-ray detector was placed in the Pirs module. From the particle acquisition rate observed with Sileye-3, it was possible to see the radiation characteristics due to the station's passage between the low-latitude regions (geomagnetic equator), where the rate is lowest and the high-latitude regions, where the geomagnetic cut-off is lower and particle rate is higher. The highest peaks were observed during passage in the South Atlantic Anomaly (SAA). The data showed high energy (E_{kin}>100 MeV) events, obtained requiring that the energy released in the first and the last planes does not differ more than 20% and plotting the total energy released in the telescope. At relativistic energies, the energy lost in the silicon detectors was negligible if compared to the kinetic energy of the particles and therefore the energy loss in the silicon planes was constant and proportional to Z^2 (the square of the electric charge). The highest peak was due to protons and helium, composing more than 90% of observed radiation.

The Alteino apparatus is mounted inside the Pirs module aboard the International Space Station. ESA image

PUBLICATION(S)

Casolino M. Cosmic ray investigations during the marco polo and eneide missions with the sileye-3/alteino experiment. *Microgravity Science and Technology.* September 2007;19(5-6):49-53. doi: 10.1007/BF02919452.

Casolino M, Bidoli V, Minori M, et al. Relative nuclear abundances inside ISS with Sileye-3/Alteino experiment. *Advances in Space Research*. 2006;37(9):1685-1690. doi: 10.1016/j.asr.2006.02.050.

Scrimaglio R, Rantucci E, Segreto E, et al. Analysis of Sileye-3/Alteino data with a neural network technique: Particle discrimination and energy reconstruction. *Advances in Space Research*. 2006;37(9):1697-1703. doi: 10.1016/j.asr.2005.12.004.

Casolino M. Cosmic ray measurements inside ISS with Sileye3/Alteino experiment. *29th International Cosmic Ray Conference,* Pune, India; August 3-10, 2005.

This investigation is complete and all results are published.

ALTEINO LONG TERM COSMIC RAY MEASUREMENTS ON BOARD THE INTERNATIONAL SPACE STATION (ALTCRISS)

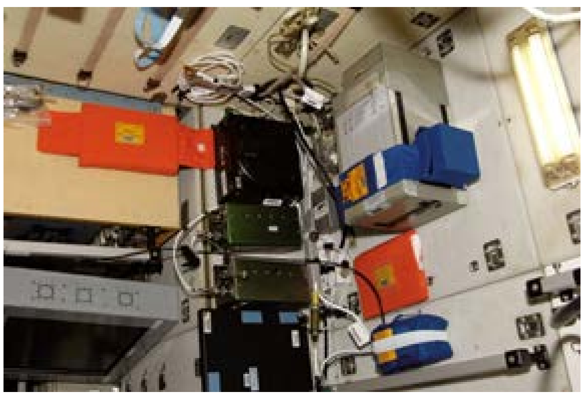
Research Area: Radiation Measurements and Shielding
Expedition(s): 12-16
Principal Investigator(s):
- Marco Casolino, PhD, Universita of Roma Tor Vergata, Rome, Italy

RESEARCH OBJECTIVES

Alteino Long Term Cosmic Ray Measurements on board the International Space Station (ALTCRISS) is dedicated to performing a long-term measurement of the radiation environment at different points inside the International Space Station (ISS). ALTCRISS will also continuously measure the cosmic radiation flow and its changes over time, especially in relation to long- and short-term solar activity, induced respectively by the solar cycle and solar eruptions.

RESULTS

Data collection began in December 2005 during Expedition 12. As part of the preliminary results, data capture by the Sileye-3 experiment hardware in its unshielded configuration during an eleven day period in the Pirs Docking Compartment was used to create an all-particles map that correlates particle flux, the rate of transfer of particles through a unit area, with latitude. The map showed that the highest flux peak occurred in the South Atlantic Anomaly (SAA), the region where the inner Van Allen radiation belt comes nearest to Earth and where the particle flux rate increases more than one order of magnitude. Smaller peaks also occurred at the poles, where geomagnetic shielding is lower than nearer the equator, which also results in higher particle flux rates.



ISS015E11115 – View of a Time Log Table (upper right) and Materials Kits (blue and orange bags) for the Alteino Long Term Cosmic Ray Measurements on board the International Space Station Experiment in the Zvezda Service Module. Photo taken during Expedition 15

Researchers also derived a spectrum of atomic nuclei identifiers with atomic numbers up to and above that of iron from the Pirs Docking Compartment data acquisition session. The spectrum also showed that nuclei with even atomic numbers were more abundant than those with odd atomic numbers, which is characteristic of cosmic rays. Analysis of data is currently ongoing.

The data gathered from the ALTCRISS project will be useful in not only determining the radiation environment aboard ISS but will contribute to the determination of the effectiveness of shielding materials in space (Casolino 2007).

PUBLICATION(S)

Casolino M, Altamura F, Minori M, et al. The Altcriss project on board the International Space Station. *Advances in Space Research*. 2007;40(11):1746-1753. doi: 10.1016/j.asr.2007.04.037.

This investigation is complete; however additional results are pending publication.

ANOMALOUS LONG TERM EFFECTS IN ASTRONAUTS' CENTRAL NERVOUS SYSTEM - SHIELD (ALTEA-SHIELD)

Research Area: Radiation Measurements and Shielding
Expedition(s): 23-ongoing
Principal Investigator(s):
- Livio Narici, PhD, University of Roma Tor Vergata, Rome, Italy

RESEARCH OBJECTIVES

The Anomalous Long Term Effects in Astronauts' Central Nervous System - Shield (ALTEA-Shield) investigation provides an assessment of the radiation environment inside the International Space Station (ISS). ALTEA-Shield monitors the radiation environment around our planet and tested different types of shielding materials against the effects of radiation.

EARTH BENEFITS

This type of research is providing those on Earth with a more detailed picture of the radiation environment in low-Earth orbit, which can help to better understand how this planet works. By comparing this data with data on Earth it could help to determine the impact that Earth's radiation environment may have on climatology and thus help to improve climate models.

Top: ESA astronaut Paolo Nespoli, works with the Anomalous Long Term Effects in Astronauts' Central Nervous System - Shield (ALTEA-Shield, [survey]) equipment on the International Space Station. Bottom: ESA astronaut André Kuipers configures hardware for the ALTEA-Shield (shield) experiment in the Columbus laboratory on June 8, 2012. NASA image.

SPACE BENEFITS

The development of better shielding materials is a necessity for making improvements in future spacecraft and satellite design and essential mission planning. In addition to the positive effect this will have on human exploration missions, this will also help to extend the life of satellites in orbit by reducing the effect caused by solar and galactic radiation, which can damage satellite electronics.

RESULTS

An extensive amount of data was gathered from the survey part of the ALTEA-Shield experiment, which is being used to check radiation/atmospheric models. As seen below, this data included an identification of the spectra of different forms of radiation and nuclear identification. This was followed up in the second half of 2012 by tests of 2 different shielding materials (Polyethylene and Kevlar) at 2 different thicknesses, the first material having collected 54 cumulative days of data, the second 94 days. For data acquisition, a different configuration of the silicon detectors were covered with the tile samples (and one with no shielding for comparative purposes). Polyethylene is a well-known shielding material as it is extremely lightweight and contains a lot of hydrogen (hydrogen atoms are good at absorbing and dispersing radiation).

PUBLICATION(S)

Di Fino L, Zaconte V, Ciccotelli A, Larosa M, Narici L. Fast probabilistic particle identification algorithm using silicon strip detectors. *Advances in Space Research*. 2012;50(3):408-414. doi: 10.1016/j.asr.2012.04.015.

This investigation is complete and all results are published.

BIORADIATION DOSIMETRY IN SPACEFLIGHT (BRADOZ)

Research Area: Radiation Measurements and Shielding
Expedition(s): 1-11
Investigator(s):
- Yury A. Akatov, Institute of Medical and Biological Problems of the Russian Academy of Sciences, Moscow, Russia

RESEARCH OBJECTIVES

Bioradiation Dosimetry in Spaceflight (Bradoz) creates methods of bioradiation dosimetry for more precise assessments of biologically significant dose loads on the human body during long-term spaceflights. During Bradoz, complex studies are performed that make possible the establishment of a stable, reliable correlation between the physical characteristics of ionizing cosmic radiation being measured and the vitally important biological effects of radiation exposure.

Placement of several Bradoz sets within the ISS RS compartments. Roscosmos image.

SPACE BENEFITS

Bradoz results can be used during the creation and operation of a system for accounting of and monitoring individual radiation doses in space explorers during the period of their professional activity.

RESULTS

During the course of research for the Bradoz project, experimental materials were obtained for assessing the biologically significant dose loads on the human body during spaceflight. The results of the Bradoz experiment convincingly showed that dose measurements in International Space Station compartments using only thermo-luminescent detectors gave an absorbed dose error of up to 10% (reduced) and an equivalent dose error of up to ± 30% due to possible variations in the radiation quality factor. This error can be reduced through the use of a combined method, consisting of the joint use of thermo-luminescent and solid-state track detectors.

PUBLICATION(S)

Hajek M, Berger T, Vana N, et al. Convolution of TLD and SSNTD measurements during the BRADOS-1 experiment onboard ISS (2001). *Radiation Measurements*. 2008;43(7):1231-1236. doi: 10.1016/j.radmeas.2008.04.094.

Szabó J, Palfalvi JK, Dudas B, Akatov YA, Eordogh I. Cosmic ray detection on the ISS by a 3 axes track etch detector stack and the complementary calibration studies. *Radiation Measurements*. February 2008;43(2-6):688-693. doi: 10.1016/j.radmeas.2008.02.016.

Hajek M, Berger T, Fugger M, et al. BRADOS - Dose determination in the Russian Segment of the International Space Station (2006). *Advances in Space Research*. 2006 January 2006;37(9):1664-1667. doi: 10.1016/j.asr.2006.01.015.

Hajek M, Berger T, Fugger M, et al. Dose distribution in the Russian Segment of the International Space Station. *Radiation Protection Dosimetry*. 2006;120(1-4):446-449. doi: 10.1093/rpd/nci566.

Tsetlin VV, Akatov YA, Arkhangelsky VV, Mitrikas VG, Bondarenko VA, Makin SA. Results of monitoring radiation conditions inside the ISS RS (2000–2005). *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2006;40(5):21-25.

This investigation is complete and all results are published.

Dosimetry for Biological Experiments in Space (DOBIES)

Research Area: Radiation Measurements and Shielding
Expedition(s): 16-28
Principal Investigator(s):
- Filip van Havere, PhD, Belgium Nuclear Research Centre, Mol, Belgium

Research Objectives

The main goal of the Dosimetry for Biological Experiments in Space (DOBIES) project, along with the Dose Distribution Inside the International Space Station (DOSIS) and Expose-E experiment, is to develop a standard dosimetric method (as a combination of different techniques) to measure the absorbed doses and equivalent doses in biological samples. Knowledge of the absorbed doses and equivalent doses is very important for understanding the observed behavior of biological samples in space.

ISS020E022219 - Documentation of the installation of the Dose Distribution Inside ISS (DOSIS) in the Columbus module by the Expedition 20 crew. View is of the DOSIS Main box - with cables and connectors. NASA image.

Results

The dosimeters were distributed among 64 positions in the EXPOSE-E trays. Thirty-two of them were placed as depth dose samples, close to the biological samples, and the other 32 samples were positioned below the biological samples, as dark samples. So far, only TLD results can be presented. The daily dose (dark samples) in tray 1 is varying from 0.22 to 0.36 mGy/day, depending on the sample position. The higher the position in the tray, the less shielding is present, the higher the daily doses are. The same effect is observed for tray 2, where daily doses varied between 0.21 and 0.37 mGy/day, as well as for the dark samples. Depth doses varied between 0.33 and 0.21 mGy/day.

The results presented here are preliminary results, since data for CR 39 measurements are still missing. Moreover, a detailed comparison of the data obtained by the different groups need to be made. In order to combine doses obtained with TLD's and CR 39 to one single dose, there is need for an algorithm that takes the overlap for both detectors into account (TLD’s “see” a part of the high LET spectrum as well).

Publication(s)

Vanhavere F, Genicot JL, O'Sullivan D, et al. DOsimetry of BIological Experiments in SPace (DOBIES) with luminescence (OSL and TL) and track etch detectors. *Radiation Measurements.* 2008;43(2-6):694-697. doi:10.1016/j.radmeas.2007.12.002.

Goossens O, Vanhavere F, Leys N, et al. Radiation dosimetry for microbial experiments in the International Space Station using different etched track and luminescent detectors. *Radiation Protection Dosimetry*. April 27, 2006;120(1-4):433-437. doi: 10.1093/rpd/nci652.

This investigation is complete; however additional results are pending publication.

DOSE DISTRIBUTION INSIDE THE ISS (DOSIS)

Research Area: Radiation Measurements and Shielding

Expedition(s): 19-28

Principal Investigator(s):
- Günter Reitz, PhD, German Aerospace Center, Cologne, Germany
- Filip Vanhavere, PhD, Belgium Nuclear Research Centre, Mol, Belgium

RESEARCH OBJECTIVES

The aim of the Dose Distribution Inside the ISS (DOSIS) experiment is to measure radiation field parameters such as absorbed dose, particle fluence, and Linear Energy Transfer (LET) spectra as well as dose equivalent at different locations inside the European Columbus module of the International Space Station (ISS) with passive and active radiation measurement devices. The Dosimetry for Biological Experiments in Space (DOBIES) is additionally developing a standard method to measure the absorbed doses in biological samples aboard the ISS.

RESULTS

Data for the experiment was generated through two active DOSTEL detectors and two sets of passive radiation detectors which were located in different locations around the Columbus laboratory from July – November 2009 (set 1) and from November 2009 – May 2010 (set 2). The passive detectors were analyzed on ground following deinstallation and return on Shuttle while monthly data downlinks from the ISS were undertaken for the active detectors between July 2009 and June 2010 with one gap of data from 13 December 2009 to the 5 January 2010.

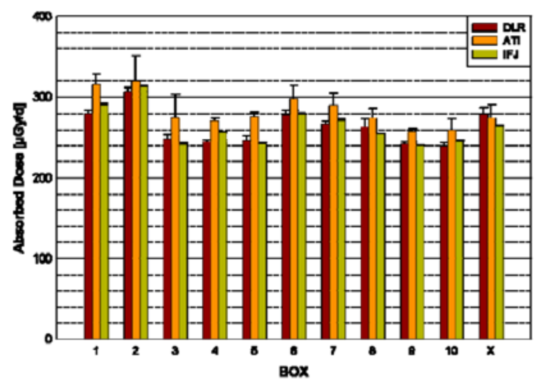


Figure 3-17: DOSIS – I : Data for ^{6}LiF:Mg, Ti Thermoluminescence detectors

As an example of the results from the first set of passive detectors (Thermoluminescence Detectors or TLDs and Nuclear Track Etch detectors) Figure 3-17 shows the daily dose rate measured with neutron sensitive 6LiF: Mg, Ti TLDs for three different groups (DLR, Cologne, ATI, Vienna and IJF, Krakow) while Figure 3-18 shows the daily dose rate measured with non-neutron sensitive 7LiF: Mg, Ti TLDs for three different groups (DLR, Cologne, ATI, Vienna and IJF, Krakow). As is seen in Figure 3-18 the absorbed dose rate inside Columbus can vary up to 50% depending on the location of the detectors.

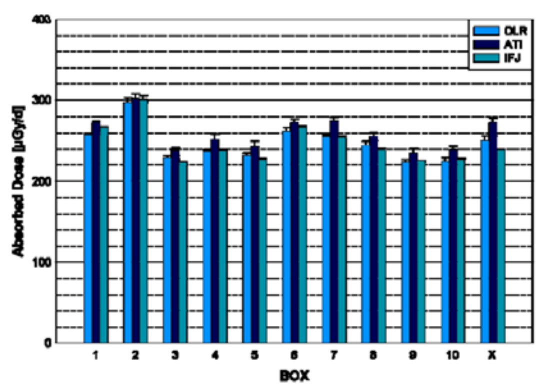


Figure 3-18: DOSIS – I: Data for ^{7}LiF:Mg, Ti Thermoluminescence detectors

This investigation is complete; however additional results are pending publication.

EUROPEAN TECHNOLOGY EXPOSURE FACILITY-DOSIMETRY TELESCOPES (EUTEF-DOSTEL)

Research Area: Radiation Measurements and Shielding

Expedition(s): 16-20

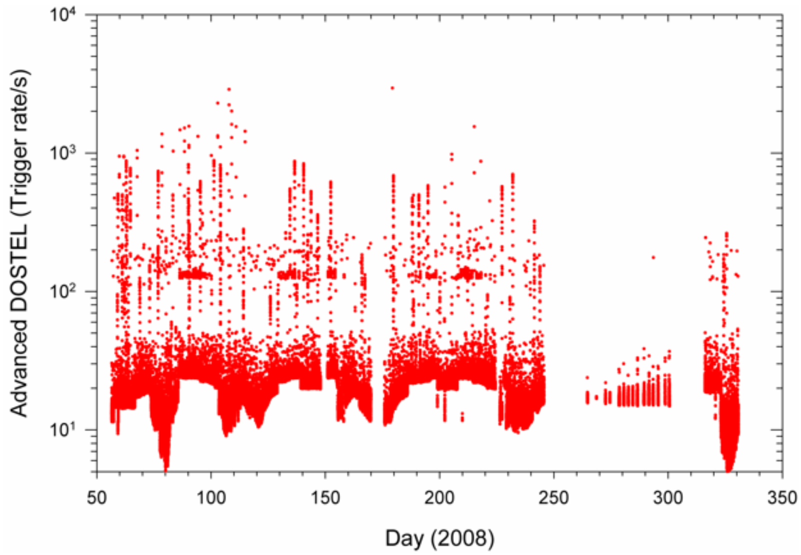
Principal Investigator(s):
- Günter Reitz, PhD, German Aerospace Center, Köln, Germany

RESEARCH OBJECTIVES

The results of the European Technology Exposure Facility-DOSimetry TELescopes (EuTEF-DOSTEL) measurements outside the International Space Station (ISS) will be compared with data obtained with a similar DOSTEL positioned on top of the head of the MATROSHKA facility in the frame of MATROSHKA exposure Phase 2B inside the Russian Zvezda Module. This enables the direct comparison of space radiation data gathered in and outside the ISS with very similar active radiation detectors, taking into account the very different shielding conditions in and outside.

RESULTS

For the time where DOSTEL was switched on, the instrument performed perfectly. As an example, the picture shows the trigger rate of the DOSTEL for the time from February to December 2008 (days 56-330). The trigger profile shows in the lower part the variation of dose due to the galactic cosmic ray environment, while the spikes in the picture were related to passes over the South Atlantic Anomaly as well as due to electrons from the horns of the radiation belts at higher latitudes.



Trigger Rates for the European Technology Exposure Facility-DOSimetry TELescopes experiment. G. Reitz image.

PUBLICATION(S)

Reitz G, Beaujean R, Benton ER, et al. Space radiation measurements on-board ISS - The DOSMAP experiment. *Radiation Protection Dosimetry*. 2005;116(1-4):374-379. doi: 10.1093/rpd/nci262.

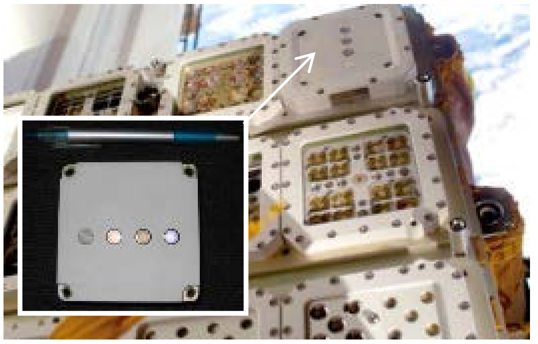
This investigation is complete and all results are published.

EUROPEAN TECHNOLOGY EXPOSURE FACILITY - EXPOSURE EXPERIMENT - RADIATION RISKS RADIOMETER-DOSIMETER (EUTEF-EXPOSE-R3D)

Research Area: Radiation Measurements and Shielding
Expedition(s): 16-20
Principal Investigator(s):
- D.P. Häder, Friedrich-Alexander-Universität, Erlangen, Germany

RESEARCH OBJECTIVES

The European Technology Exposure Facility - Exposure Experiment - Radiation Risks Radiometer-Dosimeter (EuTEF-Expose-R3D) is a device that records, with time resolution, the dose of solar light over 4 wavelength ranges (UV-A, UV-B, UV-C, and photosynthetic active light) as well as the flux of heavy cosmic particles.


The European Technology Exposure Facility - Exposure Experiment - Radiation Risks Radiometer-Dosimeter. ESA image.

RESULTS

Measurement frequency was 0.1 Hz. Due to errors in data transmission or temporary termination of Expose power, not all data could be acquired. Radiation was not constant during the mission. The radiation dose during the mission was 1823.98 MJ m^{-2} for PAR, 269.03MJ m^{-2} for UV-A, 45.73 MJ m^{-2} for UV.B, or 18.28 MJ m^{-2} for UV-C. Registered sunshine duration during the mission was about 152 days (about 27% of mission time).

The time profiles of the REP-generated daily fluences, and the absorbed doses at the orbit of ISS during the period February 2008-August 2010 were analyzed in dependence of the daily Ap index (a measure of the general level of geomagnetic activity over the globe for a given day) and compared with the daily relativistic electron fluence with energies of more than 2 MeV measured.

PUBLICATION(S)

Dachev TP, Tomov BT, Matviichuk YN, et al. Relativistic electron fluxes and dose rate variations observed on the International Space Station. *Journal of Atmospheric and Solar-Terrestrial Physics*. July 2013;99:150-156. doi:10.1016/j.jastp.2012.07.007.

Dachev TP, Tomov BT, Matviichuk YN, et al. Relativistic electron fluxes and dose rate variations during April - May 2010 geomagnetic disturbances in the R3DR data on ISS. *Advances in Space Research*. July 2012;50(2):282-292. doi: 10.1016/j.asr.2012.03.028.

Dachev TP, Horneck G, Häder D, et al. Time profile of cosmic radiation exposure during the EXPOSE-E mission: The R3DE instrument. *Astrobiology*. May 2012;12(5):403-411. doi: 10.1089/ast.2011.0759.

Schuster M, Dachev TP, Richter P, Häder D. R3DE: Radiation risk radiometer-dosimeter on the International Space Station-optical radiation data recorded during 18 months of EXPOSE-E exposure to open space. *Astrobiology*. 2012;12(5):393-402. doi: 10.1089/ast.2011.0743.

This investigation is complete and all results are published.

Low Altitude Zone Ionizing Observatory (LAZIO-SiRAD)

Research Area: Radiation Measurements and Shielding
Expedition(s): 10 and 11
Principal Investigator(s):
- Roberto Battiston, Istituto Nazionale di Fiscica Nucleare- Sezione di Perugia and Universita di Perugia, Perugia, Italy

Research Objectives

Low Altitude Zone Ionizing Observatory (LAZIO-SiRAD) is a technological demonstrator that aims to perform a number of measurements involving cosmic rays in space, their relation to anomalous phosphine (light flash) perception by crew members, the effect of different shielding materials in reducing the radiation environment, and characterization of the magnetic environment inside the International Space Station (ISS). A further topic of research, and probably the most important one regarding this experiment, regards earthquake monitoring from space.

Low Altitude Ionizing Observatory hardware. ESA image.

ISS010E24814 – Low Altitude Ionizing Observatory (LAZIO) in the Service Module 402/Zvezda during International Space Station (ISS) Expedition 10. LAZIO measures cosmic rays in space and their relation to anomalous phosphine (light flash) as perceived by crew members. Also studies the effect of different shielding materials to reducing the radiation environment and characterizes the magnetic environment inside the ISS. Hardware consists of a Main Electronics Box and Voice Recorder.

Results

This technological demonstrator operated for few days. Ionizing particles were detected within the ISS: the first magnetic observations performed by this instrument were promising and demand for a further and deeper analysis based on a longer time series of data. The main expectations from EGLE were the evaluation of its capability in detecting signals up to ULF frequencies, which was successful. There is also an indication that magnetic measurements exhibit the same time period of the ISS rotation around the Earth. As part of the EGLE test there were also successful testing of the system's 1-Wire® data acquisition system, and the signal conditioning and data acquisition board, which produced good quality of signal-to-noise-ratio in all the three frequency bands.

Publication(s)

Casolino M. Cosmic ray investigations during the Marco Polo and Eneide missions with the sileye-3/Alteino experiment. *Microgravity Science and Technology*. September 2007;19(5-6):49-53. doi: 10.1007/BF02919452.

Sgrigna V, Altamura F, Ascani S, et al. First data from the EGLE experiment onboard the ISS. *Microgravity Science and Technology*. September 2007;19(5-6):70-74. doi: 10.1007/BF02919456.

This investigation is complete and all results are published.

RADI-N NEUTRON FIELD STUDY (RADI-N)

Research Area: Radiation Measurements and Shielding
Expedition(s): 19-22
Principal Investigator(s):
- Harry Ing, Bubble Technology Industries, Chalk River, Ontario, Canada
- Vyacheslav A. Shurshakov, Institute of Biomedical Problems, Moscow, Russia

RESEARCH OBJECTIVES

Radi-N Neutron Field Study (RaDI-N) measures neutron radiation levels while aboard the International Space Station (ISS). RaDI-N uses bubble detectors as neutron monitors that have been designed to only detect neutrons and ignore all other radiation.

ISS020E050738 – Canadian Space Agency astronaut Robert Thirsk, Expedition 20/21 flight engineer, works with a Bubble dosimeter detector kit for the Matryoshka-R experiment in Service Module.

EARTH BENEFITS

Data provided from RaDI-N can lead to further understanding of how neutron radiation may damage or mutate Deoxyribonucleic acid (DNA), which may cause cataracts and cancer on Earth as well as in space. While the levels of neutron radiation are much higher in space than on Earth, any understanding into the way radiation may alter DNA function is extremely useful.

SPACE BENEFITS

The RaDI-N team is confident that their findings will provide an invaluable resource for accurate risk assessment of neutron radiation in space. This could help reduce astronauts' exposure to radiation during future missions.

RESULTS

The Radi-N experiment, conducted during ISS-20/21 in 2009, used bubble detectors to characterize the neutron radiation field in three locations in the US Orbital Segment (USOS) of the ISS. The goal of the experiment was to compare the neutron dose and energy distribution in Columbus, the US Laboratory, and the Japanese Experiment Module (JEM). The data collected provided some important conclusions regarding neutron radiation in the ISS (Smith 2013). The measured neutron energy distributions agreed well with previous measurements and did not show a strong dependence on the location in the ISS. These energy distributions showed that approximately 40% of the neutron dose measured was due to high-energy neutrons (> 15 MeV). Measurements with bubble dosimeters showed that the neutron dose received in the sleeping quarters (in the JEM) was less than that received during daily activities around the ISS. Furthermore, experiments with a water shield in the JEM showed that the neutron dose on the inner side of the shield was reduced to 72% of the value on the outer side of the shield. A follow-up experiment, Radi-N2, commenced in 2012 and is ongoing.

Publication(s)

Smith MB, Khulapko S, Andrews HR, Arkhangelsky V, Ing H, et al. Bubble-detector measurements of neutron radiation in the International Space Station: ISS-34 to ISS-37. *Radiation Protection Dosimetry*. 2015. doi:10.1093/rpd/ncv181.

Smith MB, Akatov YA, Andrews HR, et al. Measurements of the neutron dose and energy spectrum on the International Space Station during Expeditions ISS-16 to ISS-21. *Radiation Protection Dosimetry*. 2013;153(4):509-533.

This investigation is complete; however additional results are pending publication.

AUTONOMOUS ROBOTIC OPERATIONS PERFORMED FROM THE ISS (AVATAR EXPLORE)

Research Area: Robotics
Expedition(s): 19-21
Principal Investigator(s):
- Pierre Langlois, Space Technologies, St. Hubert, Quebec, Canada

Red autonomously explores the Mars Emulation Terrain. Canadian Space Agency image.

RESEARCH OBJECTIVES

Autonomous Robotic Operations Performed from the International Space Station (ISS; Avatar Explore) involves a mobile robotic test bed located in the Mars Emulation Terrain at the Canadian Space Agency (CSA) headquarters in St. Hubert, Quebec, which is remotely operated from the ISS.

SPACE BENEFITS

As humans travel further into the solar system, they increasingly rely on robots to access difficult environments. The Avatar Explore Mars simulation will one day become a reality. By contributing Canadian technology and experience now, our ability and capabilities to play a vital and dynamic role in future space exploration is improving.

EARTH BENEFITS

Avatar Explore was intended to encourage aspiring researchers with a vision in remote communications to pursue research opportunities in space robotics, which will inevitably lead to advancements in operational protocols.

This investigation is complete; however additional results are pending publication.

Red uses a laser to scan the terrain and provide 3-D images. Canadian Space Agency image.

Human Exploration Telerobotics - Smartphone (HET-Smartphone)

Research Area: Robotics
Expedition(s): 29-ongoing
Principal Investigator(s):
- Terry Fong, NASA's Ames Research Center, Moffett Field, California

Research Objectives

Human Exploration Telerobotics - Smartphone (HET-Smartphone) demonstrates and assesses intravehicular activity (IVA) free-flyer telerobotic operations using Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) and remote operation of SPHERES by ground control and crew. HET-Smartphone assesses telerobotic operations in order to increase crew efficiency and productivity for future human exploration missions.

Expedition 29 Commander Mike Fossum is performing the HET-Smartphone investigation in the JEM Pressurized Module.

Earth Benefits

HET-Smartphone explores many aspects of human-robot interaction including high-level control of robots over large time delays and limited bandwidth. Findings from these experiments benefit other Earth-based telerobotics tasks such as robot-assisted surgery, bomb squad robots, and remote industrial inspection.

Space Benefits

HET-Smartphone identifies and quantifies requirements, architecture, operations concepts, costs, and risks associated with telerobotic operations of free-flyers for future human exploration missions.

Results

Data are still being collected from this investigation, and analysis is ongoing.

This investigation is ongoing and additional results are pending publication.

Robonaut

Research Area: Robotics
Expedition(s): 27-ongoing
Principal Investigator(s):
- Myron A. Diftler, PhD, NASA's Johnson Space Center, Houston, Texas

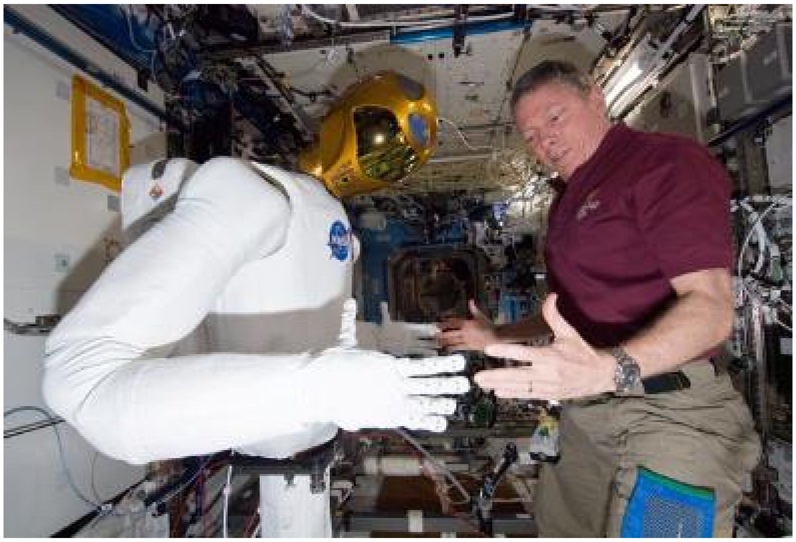
Research Objectives

Robonaut serves as a springboard to help evolve new robotic capabilities in space and demonstrates that a dexterous robot can launch and operate in a space vehicle, manipulate mechanisms in a microgravity environment, operate for an extended duration within the space environment, assist with tasks, and eventually interact with the crew members.

Robonaut 2 is the next generation dexterous robot, developed through a Space Act Agreement by NASA and General Motors.

Earth Benefits

General Motors plans to use technologies from Robonaut in future advanced vehicle safety systems and manufacturing plant applications. Robonaut validates manufacturing technologies that will improve the health and safety of GM team members at manufacturing plants throughout the world.


Expedition 29 commander Mike Fossum works with Robonaut 2 during checkout and operation in the US Laboratory *Destiny*.

Space Benefits

Robonaut is an endeavor between NASA and General Motors (GM) to improve robotic technology and capabilities for future space exploration platforms.

Results

Robonaut 2 (R2) arrived on ISS in February 2011 and underwent testing in preparation to become, initially, an Intra-Vehicular Activity (IVA) tool and then evolve into a system that can perform Extra-Vehicular Activities (EVA or spacewalk). After the completion of a series of system level checks to ensure the robot traveled well aboard the Space Shuttle *Atlantis*, ground control personnel will remotely control the robot to perform free space tasks that will help characterize the differences between Earth and microgravity control. For approximately 1 year, the fixed base R2 will perform a variety of experiments using a reconfigurable task board that was launched with the robot. While working side-by-side with human astronauts, R2 will actuate switches, use standard tools, and manipulate space station interfaces, soft goods, and cables. The results of these experiments will demonstrate the wide range of tasks a dexterous humanoid can perform in space, and they will help refine the methodologies used to control dexterous robots both in space and here on Earth (Diftler 2012).

Publication(s)

Diftler MA, Ahlstrom TD, Ambrose RO, et al. Robonaut 2 - Initial activities on-board the ISS. *2012 IEEE Aerospace Conference*, Big Sky, MT; 2012: pp.1-12. doi: 10.1109/AERO.2012.6187268.

Patent(s)

Sanders AM, Platt RJ, Quillin N, Permenter FN, Pfeiffer J, inventors; Method and system for controlling a dexterous robot execution sequence using state classification. United States Patent and Trademark Office 8,706,299. April 22, 2014.

Abdallah ME, Hargrave B, Platt RJ, inventors; Applying workspace limitations in a velocity-controlled robotic mechanism . United States Patent and Trademark Office 8,676,382. March 18, 2014.

Reiland M, Diftler MA, inventors; System and method for tensioning a robotically actuated tendon. United States Patent and Trademark Office 8,618,762. December 31, 2013.

Ihrke CA, Bridgwater LB, Diftler MA, Linn DM, Platt RJ, Hargrave B, Askew SR, Valvo MC, inventors; Robotic finger assembly. United States Patent and Trademark Office 8,562,049. October 22, 2013.

Abdallah ME, Ihrke CA, Reiland M, Wampler CW, Diftler MA, Platt RJ, Bridgwater LB, inventors; Torque control of underactuated tendon-driven robotic fingers. United States Patent and Trademark Office 8,565,918. October 22, 2013.

Reiland M, Hargrave B, Platt RJ, Abdallah ME, Permenter FN, inventors; Architecture for robust force and impedance control of series elastic actuators. United States Patent and Trademark Office 8,525,460. September 3, 2013.

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Ihrke CA, Bridgwater LB, Platt RJ, inventors; Tendon tension sensor. United States Patent and Trademark Office 8,371,177. February 12, 2013.

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Davis DR, Radford NA, Askew SR, inventors; Connector pin and method. United States Patent and Trademark Office 8,033,876. October 11, 2011.

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This investigation is ongoing and additional results are pending publication.

ROBOTIC REFUELING MISSION (RRM)

Research Area: Robotics
Expedition(s): 27-ongoing
Principal Investigator(s):
- Frank Cepollina, NASA's Goddard Space Flight Center, Greenbelt, Maryland

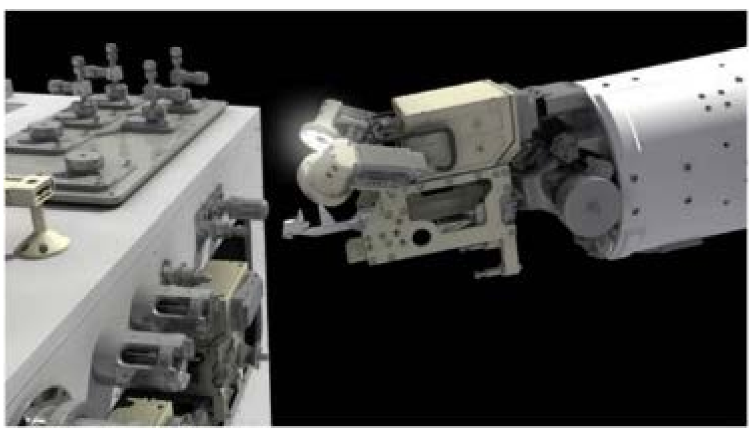
RESEARCH OBJECTIVES

The Robotic Refueling Mission (RRM) investigation demonstrates and tests the tools, technologie,s and techniques needed to robotically service and refuel satellites in space, especially satellites not originally designed to be serviced. RRM will reduce risks and lay the foundation for future robotic servicing missions in microgravity.

The Robotic Refueling Mission module on the International Space Station, temporarily installed on the Dextre robot's Enhanced Orbital Replacement Unit Temporary Platform.

EARTH BENEFITS

Robotic refueling extends the lifetime of satellites, allowing owners and operators years of additional service and revenue, more value from the initial satellite investment, and significant savings in delayed replacement costs. Numerous satellites are in orbit today that could benefit from such a service.



In this artistic representation, the wire cutter and blanket manipulation tool (right) approaches the Robotic Refueling Mission box (left) to cut wire on a sealed cap.

SPACE BENEFITS

Robotic refueling and servicing allow human and robotic explorers to reach distant destinations more efficiently and effectively by eliminating the need for space explorers and satellites to launch with large amounts of fuel aboard, thus freeing up mass for mission-critical equipment and capabilities. As an ISS investigation, RRM reduces the risk associated with performing robotic servicing tasks in-orbit and lays the foundation for a future robotic servicing mission to a free-flying satellite. It also advances space robotic capabilities. It is the first NASA technology demonstration to test and prove technology needed to perform robotic refueling and servicing on spacecraft not originally built for them, and the first use of Dextre beyond robotic maintenance of the space station for technology research and development. One of RRM's secondary goals is to validate a Tool-to-Spacecraft contact dynamics robotics simulation facility developed on the ground in parallel with the RRM flight hardware by using the performance data collected from all RRM operations. This is the first step in the plan to expand the Goddard Satellite Servicing Center's capability to develop and test future space robotic servicing and assembly missions with a higher degree of assurance.

Results

Data are still being collected from this investigation, and analysis is ongoing.

This investigation is ongoing and additional results are pending publication.

DUAL RF ASTRODYNAMIC GPS ORBITAL NAVIGATOR SATELLITE (DRAGONSAT)

Research Area: Small Satellites and Control Technologies
Expedition(s): 19-20
Principal Investigator(s):
- David B. Kanipe, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Dual RF Astrodynamic GPS Orbital Navigator Satellite (DRAGONSat) demonstrates autonomous rendezvous and docking (ARD) in low-Earth orbit and gathers flight data with a global positioning system (GPS) receiver strictly designed for space applications. ARD is the capability of 2 independent spacecraft to rendezvous in orbit and dock without crew intervention. DRAGONSat consists of 2 picosatellites (1 built by the University of Texas and 1 built by Texas A&M University) and the Space Shuttle Payload Launcher (SSPL) is the first mission in the 4-mission Low Earth Orbiting Navigation Experiment for Spacecraft Testing Autonomous Rendezvous and Docking (LONESTAR) program.

EARTH BENEFITS

This investigation enhances student education by engaging the student in a real-world engineering scenario that includes managing requirements, geographic distance, system engineering, project management, and diverse cultures. This project also develops critical skills that are invaluable to NASA in the future as the aerospace workforce continues to mature and retire and exposes NASA to the best and brightest students.

DRAGONSat looks at independent rendezvous of spacecraft in orbit using Global Positioning Satellite data.

SPACE BENEFITS

This investigation demonstrates ARD in space and provides NASA with actual flight data that is directly applicable to the Exploration Systems Architecture Study's Technology Assessment area under Avionics and Software. Data from DRAGONSat has a direct impact on the further development of ARD, which will be used in future exploration missions.

RESULTS

Texas A&M University's AggieSat2 and University of Texas' Bevo-1 launched together from shuttle flight STS-127/2JA on July 30, 2009. The 2 satellites failed to completely separate, which hindered communications through antennas that were partially captive within Bevo-1. Despite this failure, AggieSat2 operated for 230 days in low-Earth orbit until re-entry on March 17, 2010. While mission success requirements to download 2 full orbits of GPS data were not achieved, the NASA-provided DRAGON GPS unit was commanded to operate for one 90-minute period and data samples throughout this period were downlinked that show the GPS unit was operational and tracking GPS satellites. Texas

A&M students also developed a model to predict a satellite's drag coefficient. Undergraduate students managed, implemented, and documented the entire spectrum of the satellite life cycle, and many students obtained real-time spacecraft operations experience as well (Graves 2012).

PUBLICATION(S)

Graves JT, Perez JA, Reed HL, et al. AggieSat2 Student Satellite Mission. *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Nashville, TN; January 9-12, 2012. doi:10.2514/6.2012-434.

This investigation is complete; however additional results are pending publication.

ITALIAN-ASTRONAUT PERSONAL EYE (I-APE)

Research Area: Small Satellites and Control Technologies
Expedition(s): 27-28
Principal Investigator(s): ● Giorgia Pontetti, G & A Engineering, srl, Oricola (AQ), Italy

RESEARCH OBJECTIVES

Italian-Astronaut Personal Eye (I-APE) is a demonstration test created for the development of an autonomous micro-vehicle that will be used to support the International Space Station (ISS) crew IVA (Intra-Vehicular Activity) and EVA (Extra-Vehicular Activity) operations. The micro-vehicle can be powered by lithium ion batteries and controlled by a microprocessor receiving inputs from IMUs (Inertial Measuring Units) based on measurements obtained from gyroscopes.

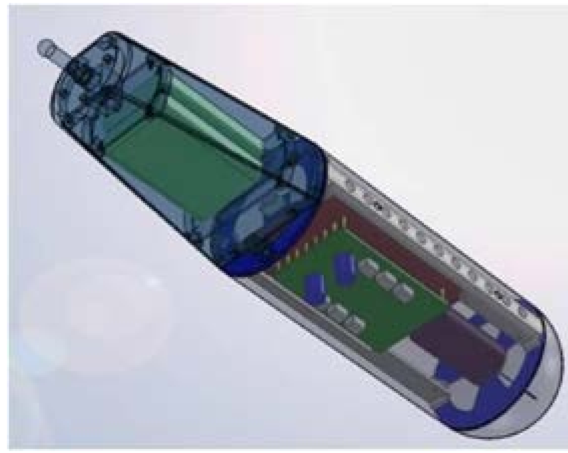


Illustration of the APE hardware. ASI image.

EARTH BENEFITS

This investigation could be used for educational purposes and to inspire future generations to pursue a career in the development of autonomous micro-vehicles.

SPACE BENEFITS

The I-APE investigation provides space micro-aircraft as aid to the astronaut corps during IVA and EVA operations. It also employs company-developed technologies and solutions that use specialized components standard to the market; therefore, it is a low-cost solution for space.

RESULTS

There are no published results.

This investigation is complete; however additional results are pending publication.

Middeck Active Control Experiment-II (MACE-II)

Research Area: Small Satellites and Control Technologies
Expedition(s): 1-2
Principal Investigator(s):
- R. Rory Ninneman, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico

Research Objectives

The Middeck Active Control Experiment-II (MACE-II) allows engineers to design future spacecraft and facilities with lightweight, inexpensive structures and materials without sacrificing the stability demanded by sensitive payloads. MACE-II, the first hands-on experiment aboard the International Space Station (ISS), consists of 2 basic parts that are designed to detect and compensate for vibrations. During experiments, scientists use a gimbal at one end of the multi-body platform (MBP) to create a disturbance that is detected by the experiment support module (ESM), which then calculates the opposing forces to be applied at the opposite gimbal, thereby stabilizing the platform. The set of algorithms used by the ESM are adaptable and can change because of moving parts, variations in temperature, and normal wear and tear on mechanical systems. A collaborating team at the Massachusetts Institute of Technology (MIT) plan to study how control systems such as that used for MACE-II can be applied to hardware and systems that change over time, such as telescopes, antennas, and robotic arms that must be moved to perform specific duties.

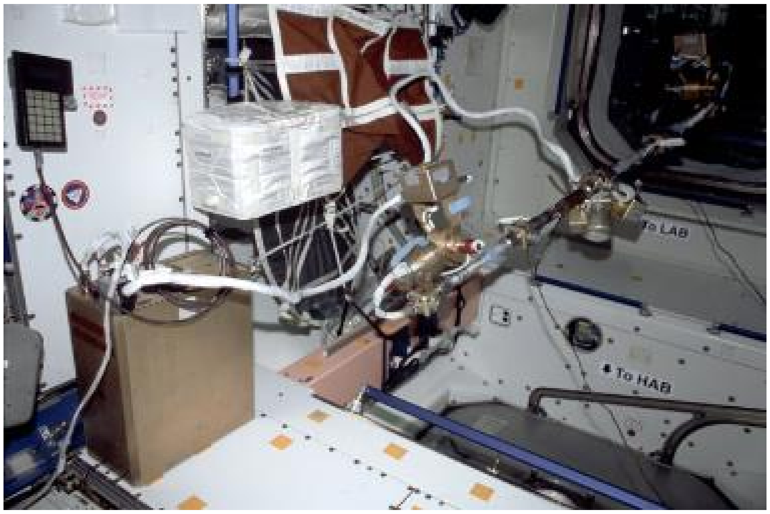
Susan Helms, Expedition 2 flight engineer, works with Middeck Active Control Experiment-II, which is shown "floating" in the microgravity environment of the International Space Station.

Earth Benefits

The autonomous adaptive control technology demonstrated by MACE-II can be used in any vehicle that must negotiate turbulent airstreams and atmospheric changes. It can be used to develop smart, problem-solving auto pilots for commercial jets or better guidance and pointing systems for military aircraft.

Space Benefits

MACE-II tested self-reliant, adaptive technologies that can detect problems with ISS hardware and correct those problems as needed. This reduces the amount of crew and ground-based personnel time required to monitor and repair ISS hardware. This technique is also critical for control of large, flexible structures that must perform precision pointing and tracking.



View of Middeck Active Control Experiment-II hardware floating in the Node 1 Unity module of the International Space Station.

RESULTS

Fourteen test protocols were completed during Expedition 1, and an additional 62 test protocols were completed during Expedition 2. Algorithms were developed to control mechanical systems in real time using only information from onboard sensors and actuators to respond to changes in the system. These algorithms were able to adapt whenever they sensed changes in vibration or the loss of a sensor or actuator. The system was able to reduce unwanted vibrations without human intervention by a factor of 10 while the system was under control. It was also able to decrease vibrations by a factor of 6 after adapting to the failure of a primary actuator. While the Air Force Research Laboratory Science Team successfully completed all of its experiment objectives associated with the MACE-II unit, the MIT Science Team was unable to do the same because of data downlink constraints (Ninneman 2003).

PUBLICATION(S)

Ninneman RR, Founds DB, Davis LD, Greeley S, King J. Middeck Active Control Experiment reflight (MACE II) program: Adventures in space. *AIAA Space 2003 Conference and Exposition*, Long Beach, CA; September 23-25, 2003.

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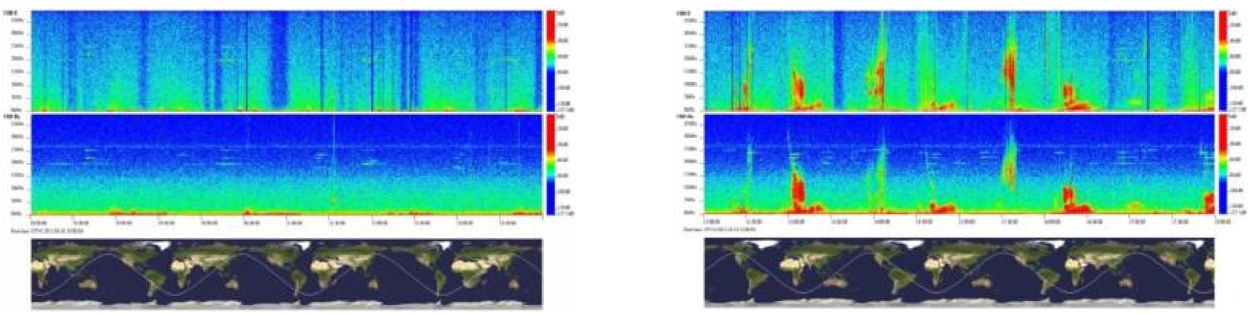
This investigation is complete and all results are published.

Study of Physical Processes Associated with Atmospheric Lightning Discharges Using the Chibis-M Microsatellite and Progress Cargo Vehicle (Mikrosputnik)

Research Area: Small Satellites and Control Technologies
Expedition(s): 29-ongoing
Principal Investigator(s):
- Lev M. Zelenyi, PhD, Institute of Space Research of the Russian Academy of Sciences, Moscow, Russia

Research Objectives

The Study of Physical Processes Associated with Atmospheric Lightning Discharges Using the Chibis-M Microsatellite and Progress Cargo Vehicle (Mikrosputnik) is designed for an in-depth investigation of the physical mechanisms of electrical discharges in the atmosphere in the broadest energy spectrum, specifically from RF to gamma rays. Above all, the extremely powerful gamma radiation at altitudes of 10-20 kilometers is a potential hazard for airline crews and passengers. Gamma radiation, which does in fact reach Earth, covers wide areas, which can be important both from an ecological perspective and in terms of human safety. And finally, single supercharged RF pulses carry high radiation energy in virtually the entire radio wave range used (up to and exceeding 3 GHz) and can serve as a convenient natural radiation source to create a global monitoring system for radio communications.



Monitoring of electromagnetic activity (0.01-40 kHz) by latitude and longitude (data obtained in quiescent geomagnetic conditions as of 10/02/2012 are shown on the left; geomagnetic disturbances as of 10/13/2012 are shown on the right; these panels describe, from top to bottom: the electrical filed component, the magnetic field component, and the microsatellite orbit projection on the Earth's surface; the time interval as shown along the horizontal axis on the left and right pictures is ~6 hours).

Earth Benefits

This research demonstrated the need for providing useful information on space weather to a wide range of users in the science, economics, medicine, and other sectors. Because of the developments in space communication/navigation systems, northern regions exploration and transpolar civil aviation routes exploitation, the dependence on solar and space environment factors will only increase in the future.

Monitoring of electromagnetic activity (0.01-40 kHz) by latitude and longitude (data obtained in quiescent geomagnetic conditions as of 10/02/2012 are shown on the left; geomagnetic disturbances as of 10/13/2012 are shown on the right; these panels describe, from top to bottom: the electrical filed component, the magnetic field component, and the microsatellite orbit projection on the Earth's surface; the time interval as shown along the horizontal axis on the left and right pictures is approximately 6 hours).

RESULTS

Measurements of electrical activity by the RF analyzer from the Groza equipment set have demonstrated that in reality the spatial storm front structure is of multidimensional, or to be more exact, the distribution of charged cells is random and can be described in the terms of a fractal topology, ie, some kind of a self-organization of an electrically charged layer occurs.

The microsatellite flight has facilitated creating a map showing the geographical areas with the highest discharge frequencies. The map is used to generate the Groza equipment operation timelines that allow implementing a pre-programmed activation of the necessary modes of operation for both the microsatellite systems (power supply, attitude control, etc) and the Groza instruments.

For more detailed information on the Chibis-M mission science objectives and technology and information parameters, see the following website: http://chibis.cosmos.ru.

PUBLICATION(S)

Sorokin IV, Markov. Technology development aboard the Russian segment of the ISS. *66th Interantional Astronautical Congress*, Jerusalem, Israel; October 12-16, 2015. IAC-15.B3.3.6.

Klimov SI, Zelenyi LM, Gotlib VM, et al. On-orbit microsatellite “Chibis-M” testing of the trigger from high-altitude atmospheric discharges. *2012 TEPA Conference*, Russia; July 9-11, 2012.

Klimov SI, Garipov GK, Gotlib VM, et al. The method of study in the ionosphere of the physical processes occurring in high altitude atmospheric thunderstorms. *2012 USNC-URSI National Radio Science Meeting*, Boulder, Colorado; January 4-7, 2012.

This investigation is complete; however additional results are pending publication.

Preparing Nanosatellite and Launching it from the Russian Segment of the International Space Station (Nanosputnik), Two Investigations

Research Area: Small Satellites and Control Technologies

Expedition(s): 10

Principal Investigator(s):
- Arnold S. Selivanov, PhD, Russian Corporation for Rocket-Space Instrumentation and Information Systems, Moscow, Russia

Research Objectives

Preparing Nanosatellite and Launching it from the Russian Segment of the International Space Station (Nanosputnik) inserts a nanosatellite into low-Earth orbit and controls it to blaze a trail for future reduction of expenditures on the development and use of space systems based on small spacecraft.

Space Benefits

Nanosputnik results will be used in the following spheres of the aerospace industry: technologies for low-cost creation and launches of spacecraft; technologies for performing technical research and experiments on board manned orbital stations; telecommunications technology; and technologies for global control of the systems of spacecraft.

Results

During Expedition 10 in 2005, the first phase of the Nanosputnik experiment was implemented: nanosatellite [THC]-0 No. 1 was manually launched from the International Space Station during an extravehicular activity. The duration of the satellite's autonomous flight was 4 months (it descended into the dense layers of the atmosphere on August 30, 2005), during which time the program of flight experiments was performed in full, and results were obtained that confirmed the successful achievement of the tasks assigned in the experiment:


Manual launch of nanosatellite [THC]-0 No. 1 by cosmonaut S. Sharipov on March 28, 2005 during International Space Station Expedition 10. Roscosmos image.

- Use of the GLOBALSTAR satellite telecommunications system to control and communicate with the small spacecraft was confirmed.
- Effective monitoring of the spacecraft's functioning using the subscriber set of the international COSPAS-SARSAT system was shown.
- Tests of experimental onboard devices—system monitor, Sun sensors, horizon sensor, lithium battery, passive (magnetic) attitude-control and stabilization system—were successfully performed.

PUBLICATION(S)

Bandel D, Ovchinnikov MY, Tayl S, Khromov OY, Selivanov AS. GREASAT Nanosatellite: General Description. Russian Academy of Science M. V. Keldysh Institute of Applied Mathematics. 2009(21):34.

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Petushkov AM, Sergeyev SA. Experiment to verify new technologies of satellite control (Preliminary results of the flight of nanosatellite [THC]-0 No. 1 of the Federal State Unitary Enterprise Russian Scientific Research Institute of Space Instrumentation). *10th International Conference on Systemic Analysis of Control and Navigation*, Yevpatoriya, Crimea; June 3-10, 2005.

Selivanov AS, Tuchin YM, Urlichich YM, Vishnyakov VM. Preliminary results of flight tests of technological nanosatellite [THC]-0. *10th International Conference on Systemic Analysis of Control and Navigation*, Yevpatoriya, Crimea; June 3-10, 2005.

Kupriyanova NV, Ovchinnikov MY, Penkov VN, Selivanov AS. Passive magnetic attitude-control system for the First Russian Nanosatellite, [THC]-0. Russian Academy of Science M. V. Keldysh Institute of Applied Mathematics. 2005: 23.

Selivanov AS, Urlichich YM, Tuchin YM, Khromov OY, Nikushkin IV. Minimal-assembly technological nanosatellite [THC]-0. *3rd Conference on Microtechnology in Aviation and Space Exploration*, St. Petersburg, Russia June 8-9, 2004:7-8.

Selivanov AS, Urlichich YM, Khromov OY. Family of technological nanosatellites for experimental research. *4th International Conference and Exhibition Small Satellites, New Technologies, Miniaturization*, Korolev, Russia; May 31 - June 4, 2004: 34-35.

Selivanov AS, Urlichich YM, Tuchin YM. Design of technological nanosatellite [THC]-1 for remote earth sensing. *2nd Conference on Aerospace Systems Based on Microtechnologies: Creation and Primary Areas of Use*, St Petersburg, Russia; June 9-11, 2003: 34-35.

Selivanov AS, Urlichich YM, Popov GA, Lukyaschenko VI. On creating an experimental small spacecraft for development-testing microtechnologies. *Issues in Developing and Using Microtechnologies in Aviation and Space Exploration*, St Petersburg, Russia; 2002.

This investigation is complete; however additional results are pending publication.

Pico-Satellite Solar Cell Experiment (PSSC)

Research Area: Small Satellites and Control Technologies
Expedition(s): 18, 27-28
Principal Investigator(s):
- Henry Yoo, PhD, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico

Research Objectives

View of the Picosat for the Pico-Satellite Solar Cell Experiment experiment during its deployment from the starboard side of the payload bay of the orbiter Endeavour.

The purpose of the Pico-Satellite Solar Cell Experiment (PSSC) is to demonstrate a responsive spaceflight capability for testing new solar cell technology within the introduction cycle of the new technology. Production has begun on a new generation of High Efficiency Solar Cells that are committed to fly on major Department of Defense (DOD) space assets. In the past, flying new solar cell technology for the first time on a major satellite program has resulted in unexpected interactions with the space environment, which caused either failure of the solar arrays or significant degradation of performance limiting ultimate useful life in orbit. The PSSC Testbed flight experiment is designed to obtain space environment degradation data for these advanced solar cells. This capability will allow for gathering spaceflight performance data before the launch of new satellites with the new solar cell technology as the primary power source.

Earth Benefits

The new advanced materials and components demonstrated on PSSC will improve the performance, increase the useful life, and reduce the operational costs of commercial weather, communications, and Earth observation satellites.

Space Benefits

Results from PSSC will provide a better understanding of the durability of various solar cell materials when exposed to the space environment. Many of these materials might be used in the design of future spacecraft.

This investigation is complete; however additional results are pending publication.

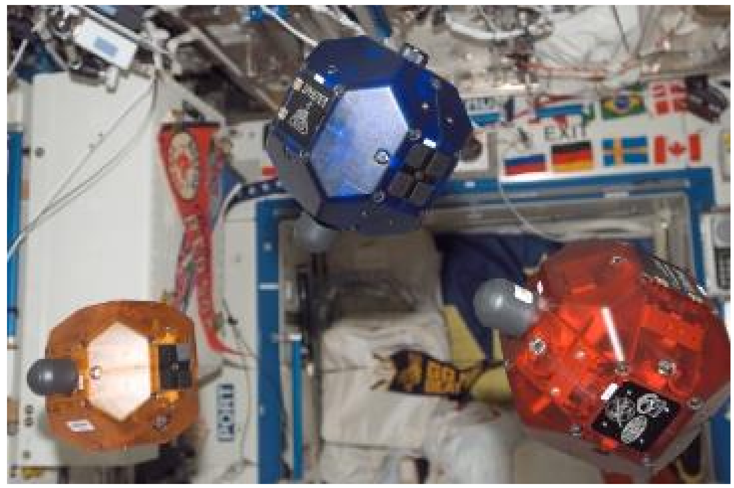
Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES)

Research Area: Small Satellites and Control Technologies

Expedition(s): 8, 13-30, ongoing

Principal Investigator(s):
- David W. Miller, PhD, Massachusetts Institute of Technology, Cambridge, Massachusetts

Research Objectives



Three satellites fly in formation as part of the Synchronized Position Hold, Engage, Reorient, Experimental Satellites investigation during Expedition 14 in the US Laboratory module.

The Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) experiment is a testbed for formation flying by satellites. SPHERES consists of 3 self-contained satellites, each of which measures 0.2 meter in diameter and weighs 3.5 kg. Each satellite contains internal propulsion, power, avionics, software, communications, and metrology systems. The SPHERES experiment tests relative attitude control and station-keeping between satellites, re-targeting and image plane-filling maneuvers, collision avoidance, and fuel-balancing algorithms, and an array of geometry estimators that are used in various missions. SPHERES is an ongoing demonstration. Each session tests progressively more complex 2- and 3-body maneuvers that include docking, formation flying, and searching for “lost” satellites.

Earth Benefits

The technologies for formation flight of small satellites influence Earth-based applications of current satellite technologies including surveillance, mapping, communications, and navigation.

Space Benefits

Results from SPHERES support the development of autonomous spacecraft to carry out a variety of tasks in the space environment and the simplification of autonomous docking allowing for servicing, re-supplying, reconfiguring, and upgrading of space systems. Smaller autonomous spacecraft can perform tasks too complicated or too expensive for larger spacecraft to execute. The algorithms developed during this investigation eliminate the complicated spacecraft maneuvers that require ground teams to coordinate and execute. Examples of the use of small autonomous spacecraft include a Separated-Spacecraft Interferometer in which light from 2 or more spacecraft telescopes combine to provide a high-resolution image, and a satellite cluster, a collection of microsatellites that operate cooperatively to perform the function of a single large satellite.

RESULTS

Testing in the risk-tolerant environment of the ISS has allowed SPHERES researchers to push the limits of their algorithms. The initial test sessions showed the hardware operated correctly and the software programs uploaded successfully to the satellites. The SPHERES team identified and corrected many of the operational and programmatic difficulties encountered by lengthening session frequency, using real-time audio and video, and allowing the crew to run tests sequentially. All data collected has been used to continually improve formation flight and docking procedures, creating many space firsts such as the first free-flyer to operate aboard the ISS, the first to demonstrate docking to a tumbling target in a microgravity environment, and docking using on-line path-planning. The final integrated tests of the autonomous docking algorithms culminated with the successful demonstration of docking to fixed and tumbling targets, with and without obstacles or failures. Various flight maneuvers (such as 2-stage reconfiguration, scatter, and imaging) were successfully performed with 2 and 3 satellite formations. In addition, several algorithms for collision avoidance and formations starting from random positions have been developed, tested, and validated on the ISS. Several tests included robotic experiments where the satellites were controlled by astronauts on the ISS. Results showed that including assisting elements, like autonomous collision avoidance, enhanced the operator's performance by allowing the operator to concentrate on the assigned task rather than worry about collision avoidance.

PUBLICATION(S)

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ISS020E018324 - NASA astronaut Michael Barratt (left) and Japan Aerospace Exploration Agency (JAXA) astronaut Koichi Wakata, both Expedition 20 flight engineers, perform a check of the Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) Beacon / Beacon Tester in the Destiny laboratory of the International Space Station.

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This investigation is ongoing and additional results are pending publication.

Space Test Program-Houston 2 (STP-H2), Three Investigations

Research Area: Small Satellites and Control Technologies

Expedition(s): 14

Principal Investigator(s):

- Robert E. Bruniga, United States Naval Academy, Annapolis, Maryland
- James Keeney, PhD, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico

Research Objectives

The complement of Space Test Program-H2 (STP-H2) investigations was deployed from STS-116/12A.1 on December 20, 2006.

S116E07836 - Shown is one of the ANDE satellites floating free from Internal Cargo Unit (ICU) after deployment. The second satellite did not leave its half of the ICU until 4 hours after launch from the shuttle cargo bay.

ANDE (Bruniga)

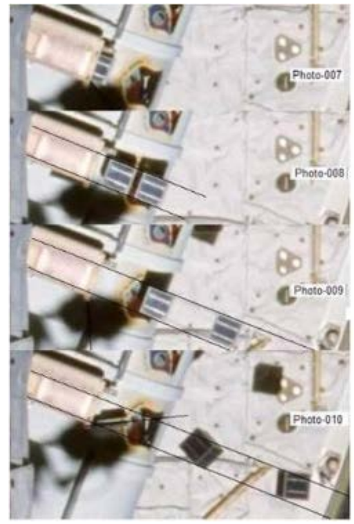
The Atmospheric Neutral Density Experiment (ANDE) consists of 2 spherical microsatellites: the Mock ANDE Active (MAA) spacecraft and the Fence Calibration (FCal) spacecraft. These satellites were launched from the space shuttle cargo bay into a circular orbit just below the International Space Station (ISS) altitude. The main objective of the ANDE mission is to measure the total atmospheric density and composition between 100 and 400 kilometers.

RAFT (Bruniga)

Radar Fence Transponder (RAFT) is a student experiment from the U.S. Naval Academy that used picosatellites to test the Space Surveillance Radar Fence and experimental communications transponders. More specifically, RAFT was designed to provide the Navy Space Surveillance System (NSSS) radar fence with a means by which to determine the limits of a constellation of picosatellites that would be otherwise undetectable to the radar fence and to enable NSSS to independently calibrate its transmit and receive beams using signals from RAFT. This was accomplished with 2 picosatellites (RAFT1 and MARScom): 1 that actively transmitted and received signals, and 1 with a passively augmented radar cross section. Additionally, RAFT provided experimental communications transponders for the Amateur Satellite Service, the Navy Military Affiliate Radio System, and the Naval Academy's Yard Patrol Craft.

MEPSI (Keeney)

The MIcroelectromechanical System-based PICOSAT Inspector (MEPSI) experiment series was designed to demonstrate the concept of an onboard intelligent hardware agent, "InfoBot," that can be used to assist satellite operations. It is designed to enhance satellite command and control operations by providing active onboard imaging capability to assess spacecraft damage from human-made or environmental threats, monitor satellite early orbit testing operations, and augment servicing operations. MEPSI was developed through a series of 4 preflight missions, each of increasing complexity and each improving overall satellite performance over the previous version. In December 2002, MEPSI completed its third development mission with a successful launch from the Space Shuttle *Endeavour*, which was its first shuttle mission. Improvements from the 2002 version were included in this payload, which was deployed in December 2006 from STS-116.



The sequence of images shows the 2 RAFT satellite cubes being deployed from the space shuttle (STS-116). The bottom photo shows the onset of tumbling of the satellites. Department of Defense image.

Earth Benefits

Improvements in orbit calculations produced by data from ANDE may generate advancements in the fields of mathematics and physics. RAFT provides students the opportunity to design and build picosatellites and helps prepare the next generation for careers in the aerospace industry through the application of mathematic, engineering, and scientific concepts. The advancements in miniature imaging and relay technology resulting from MEPSI are applicable in a variety of settings from medicine to public safety.

Space Benefits

Density data gathered by ANDE will be used to better characterize the parameters that are used to calculate the drag coefficient of a satellite and improve orbit determination calculations of resident space objects. Results from RAFT support the development of an improved system to track an increasing population of picosatellites. MEPSI technology will lead to an image inspection capability for low-cost survey of spacecraft while on orbit.

Results

The ANDE satellite re-entered the atmosphere on December 25, 2007, over a year after deployment. Its orbital decay was tracked by the Maui Laser Ranging Tracking Station. Because the satellite carried packet radio communications systems operating in the Amateur Satellite Service, ham radio volunteer ground stations were critical for telemetry feeds that included temperature and battery life. RAFT was deployed on December 20, 2006, and deorbited on May 30, 2007, after 5 months in space. The deployment resulted in an applied torque to the satellites (see image). Several subsystems on the satellite, including solar panel and thermal, were monitored. Volunteer ground stations were used to track the satellites (Bruniga 2002).

Publication(s)

Bruninga RE, Smith B, Boden D. PCsat auccess! and follow-on payloads. *16th Annual AIAA/USU Conference on Small Satellites*, Logan, Utah; 2002.

This investigation is complete; however additional results are pending publication.

SPACE TEST PROGRAM-HOUSTON 3 (STP-H3), FOUR INVESTIGATIONS

Research Area: Small Satellites and Control Technologies
Expedition(s): 27-ongoing
Principal Investigator(s):

- Geoff McHarg, PhD, US Air Force Academy, Colorado Springs, Colorado
- Andrew Nichols, Naval Research Laboratory, Washington, DC
- Andrew Williams, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio
- Cecilia Penera, Northrop Grumman Aerospace Systems, Redondo Beach, California

RESEARCH OBJECTIVES

The complement of Space Test Program-H3 (STP-H3) investigations was delivered to the International Space Station (ISS) by STS-134/ULF6 on May 18, 2011.

STS-135 fly-around view of the zenith side of the P3 Truss, with STP-H3 on ELC-3 in view.

CANARY (MCHARG)

Canary investigates the interaction of ions with the background plasma environment around the ISS.

DISC (NICHOLS)

The Digital Imaging Star Camera (DISC) captures images of star fields for analysis by ground algorithms to determine the attitude of the ISS.

MHTEX (WILLIAMS AND PENERA)

The Massive Heat Transfer Experiment (MHTEX) investigates the in space performance of capillary pumped loop (CPL) heat transfer equipment, which uses continuous fluid flow to transfer heat from multiple spacecraft sources to an external radiator surface. This investigation intends to improve the understanding of heat transfer transport phenomena and two-phase flow (ie, liquid-vapor flow) performance in microgravity.

VADER (WILLIAMS)

The Variable emissivity radiator Aerogel insulation blanket Dual zone thermal control Experiment suite for Responsive space (VADER) investigation tests a variable emissivity radiator and a new form of multilayer insulation that uses Aerogel as the thermal isolator in order to protect the spacecraft from the harsh extremes of the space environment. The Aerogel material provides a more durable, lighter, and cheaper alternative to traditional spacecraft thermal blankets. The use of this material could reduce the costs related to spaceflight by reducing the required spacecraft mass and increasing design efficiency.

Earth Benefits
The improvements these technologies demonstrate will create more robust and capable satellites that are controlled by ground systems for Earth-bound communications.

Space Benefits
The full STP-H3 complement of investigations, including thermal control, attitude knowledge, and environmental sensing technologies, may be used in future spacecraft design and development, each technology offering an increase in efficiency and decrease in cost.

Results
Data is still being collected from this investigation, and analysis is ongoing.

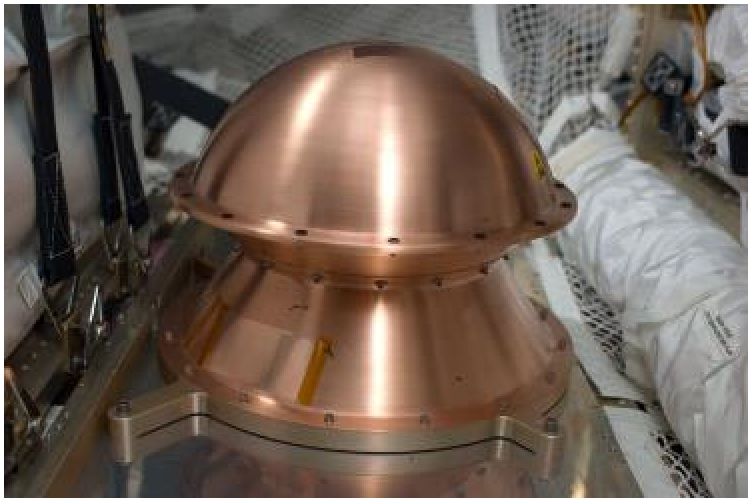
This investigation is ongoing and additional results are pending publication.

ReEntry Breakup Recorder (REBR)

Research Area: Space Structures
Expedition(s): 27-ongoing
Principal Investigator(s):
- William Ailor, PhD, The Aerospace Corporation, El Segundo, California

Research Objectives

The Re-Entry Breakup Recorder (REBR) tests a cost-effective system that rides a re-entering space vehicle, records data during the re-entry and breakup of the vehicle, and returns the data for analysis. Understanding how vehicles behave during atmospheric re-entry gives future spacecraft developers unique information that can enhance design efficiencies and safety.



View of the REBR installed in the ATV-2.

Earth Benefits

Data regarding how a spacecraft breaks up during deorbit can be applied to the design of future spacecraft to minimize hazards to people and property in the event the re-entering spacecraft becomes uncontrollable.

Space Benefits

REBR increases the understanding of vehicle breakup during re-entry, potentially resulting in removing the need for deorbit propulsion capability, thereby decreasing cost and complexity and increasing mission life and payload mass budget.

Results

REBR units were installed and activated in the H-II Transfer Vehicle 2 (HTV2) and Automated Transfer Vehicle-2 (ATV-2) 1 day prior to vehicle undock from ISS. The REBR in HTV2 was soft-mounted while the REBR in ATV-2 was hard-mounted. HTV2 undocked from the International Space Station (ISS) on March 28 and re-entered the atmosphere on March 29, 2011. ATV-2 undocked June 20 and re-entered on June 21, 2011 (Wada 2011).

According to REBR data, interaction with the atmosphere gradually slowed HTV2, put it into an unstable tumble, and heated its structure until breakup and release of REBR at an altitude of 66.5 km and speed of Mach 23. During re-entry, HTV2 experienced increasing rotation rates because of aerodynamic moments, which built to highly erratic behavior during HTV2 breakup and REBR release. Two hundred seconds after re-entry began, the rotation rates took on a damped oscillatory character, which was consistent with REBR stabilizing with its conical nose

Expedition 28 Flight Engineer Ron Garan applies copper tape to exposed wires on the ReEntry Breakup Recorder prior to installation in the ATV-2.

facing forward into the oncoming airstream. Initiation of HTV2's major breakup began as early as 120 seconds after re-entry was detected and extended over an altitude range of 75.6 to 66.5 km, while catastrophic disintegration probably began between 180 and 190 seconds after re-entry was detected. The acceleration magnitude trend measured by REBR was consistent with predictions (Ailor 2011). Once free of HTV2, REBR continued to record data while it initially tumbled, emerged from its housing, and aerodynamically stabilized. REBR impacted the South Pacific Ocean 727 seconds after start of data recording and 531 seconds after breakup of HTV2. Ballistic and drag coefficients were in agreement with preflight predictions. A second set of re-entry flight tests is in work for HTV3 and ATV-3 (Weaver 2012).

PUBLICATION(S)

Feistel AS, Weaver MA, Ailor W. Comparison of reentry breakup measurements for three atmospheric reentries. *6th IAASS Conference*, Montreal, Canada; May 21-23, 2013:8.

Ailor W, Weaver MA, Feistel AS, Sorge ME. Reentry breakup recorder: Summary of data for HTV3 and ATV-3 reentries and future directions. *6th European Conference on Space Debris*, Darmstadt, Germany; April 22-25, 2013:7.

Weaver MA, Ailor WH. Reentry breakup recorder: Concept, testing, moving forward. *AIAA SPACE 2012 Conference & Exposition*, Pasadena, CA; September 11-13, 2012.

Ailor WH, Weaver MA. Reentry breakup recorder: An innovative device for collecting data during breakup of reentering objects. *5th IAASS Conference*, Versailles, France; October 17-19, 2011.

Wada K, Yamanaka K, Uematsu H, Suzuki Y, Sasaki H. Evaluation results of the HTV atmospheric reentry trajectory. *62nd International Astronautical Congress*, Cape Town, South Africa; October 3-7, 2011.

This investigation is ongoing and additional results are pending publication.

ATMOSPHERIC NEUTRAL DENSITY EXPERIMENT – 2 (ANDE-2)

Research Area: Spacecraft and Orbital Environments
Expedition(s): 19-20
Principal Investigator(s):
- Robert E. Bruninga, United States Naval Academy, Annapolis, Maryland

RESEARCH OBJECTIVES

Atmospheric Neutral Density Experiment - 2 (ANDE-2) consists of 2 microsatellites launched from the shuttle payload bay that measure the density and composition of the low-Earth orbit atmosphere while being tracked from the ground. The data will be used to better predict the movement and decay of objects in orbit.

Deployment of Atmospheric Neutral Density Experiment-2 (ANDE-2). ANDE-2 is part of a Department of Defense project to provide high-quality satellites for calibrating techniques and models for precision orbit determination. It will also provide data on atmospheric composition for validating Air Force sensors.

EARTH BENEFITS

Improving calculations that are used when observing orbits may lead to advancements in the fields of mathematics and physics on Earth.

SPACE BENEFITS

Understanding the atmospheric effects on spacecraft in low-Earth orbit will lead to improved calculations for orbit determinations and collision avoidance.

This investigation is complete; however additional results are pending publication.

EUROPEAN TECHNOLOGY EXPOSURE FACILITY-DEBRIS IN ORBIT EVALUATOR-2 (EUTEF-DEBIE-2)

Research Area: Technology Demonstration - Space Debris and Micrometeoroids Measurement

Expedition(s): 16-20

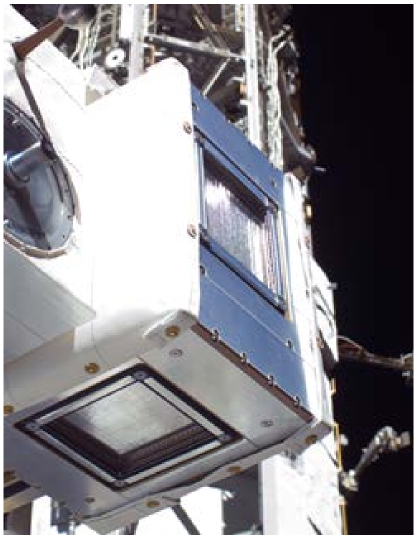
Principal Investigator(s):
- Gerhard Drolshagen, PhD, European Space Research and Technology Centre, Noordwijk, Netherlands

RESEARCH OBJECTIVES

The European Technology Exposure Facility-DEBris In Orbit Evaluator-2 (EuTEF-DEBIE-2) actively measures impact flux of sub-millimetre micro-meteoroids and space debris hitting its 3 sensor units oriented in different directions and thus provides an insight into this smaller type of orbital debris of which little is known. Knowledge of impacts, their seasonal variations, and long-term evolution are required for a reliable spacecraft risk assessment and the design of protective shielding.

RESULTS

DEBIE-2 data was highly dominated by noise events following a first analysis of potential impact events, with false events mainly being due to the International Space Station (ISS) plasma and thermal environment and ISS operations (eg, shuttle docking/undocking). After initial background noise filtering was undertaken, 931 events were identified as potential impact events in the period January-September 2009. From this data a significantly higher amount of impacts occurred on the upward (zenith)-facing sensor than on the forward-facing and starboard sensors.



DEBris In Orbit Evaluator-2 instrument on the external surface of the Columbus laboratory as part of the European Technology Exposure Facility. ESA image.

One of the surprising findings was that impact events came in clusters and were not randomly distributed. These peaks can be concentrated within the space of perhaps a minute to 80 seconds at a time, indicating the existence of dust clouds along the ISS orbit. These particles might be either natural or artificial in origin. Asteroids and comets leave trails of fine dust behind them while solid rocket boosters spray out fine droplets of aluminium oxide.

After retrieval of DEBIE-2, it was found that one wire of the upper grid on the sensor unit pointing to the zenith had been broken while in orbit. A postflight analysis was started including the use of optical microscopy. Hundreds of holes were observed in the area beneath the broken wire, indicating that the particle was vaporised during the impact. Since the impacted wire had a diameter of 75 µm, one can derive that the impactor should have had a minimum size of 25 µm and a maximum size of about 50 µm, otherwise it should have survived the impact.

The instrument could potentially be refurbished for a future space mission to the moon or around the L2 Lagrangian Point in space behind Earth where a number of science missions are planned.

PUBLICATION(S)

Menicucci A, Drolshagen G, Mooney C, Butenko Y, Kuitunen J. DEBIE (Debris-in-situ-evaluation) on-board of ISS: Results from impact data and post-flight analysis. *63rd International Astronautical Congress*, Naples, Italy; October 1-5, 2012: 6.

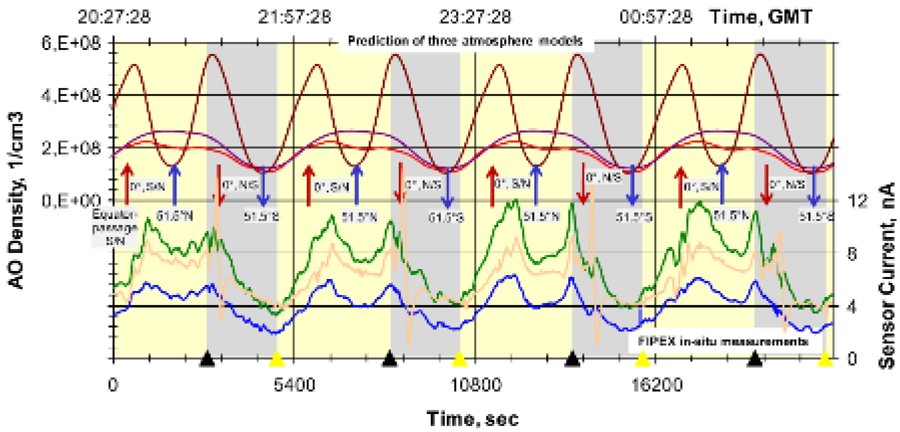
This investigation is complete and all results are published.

EUROPEAN TECHNOLOGY EXPOSURE FACILITY- FLUX (PHI) PROBE EXPERIMENT-TIME RESOLVED MEASURE OF ATOMIC OXYGEN (EUTEF-FIPEX)

Research Area: Spacecraft and Orbital Environments
Expedition(s): 16-20
Principal Investigator(s): ● Stefanos Fasoulas, PhD, University of Dresden, Germany

RESEARCH OBJECTIVES

The European Technology Exposure Facility- Flux (Phi) Probe Experiment-Time Resolved Measure of Atomic Oxygen (EuTEF-FIPEX) micro-sensor system is intended to measure the atomic oxygen flux as well as the oxygen molecules in the surrounding area of the International Space Station (ISS). The experiment includes 2 sensor units, each containing 6 sensors. One unit was facing the ISS flight direction measuring the dynamic pressure and the other unit was facing the zenith (away from Earth) direction measuring the static pressure of the atomic and molecular oxygen.



International Space Station ground track during the first 4 Flux (Phi) Probe Experiment-Time Resolved Measure of Atomic Oxygen (FIPEX) orbits and FIPEX sensor signals (3 sensors) versus predictions of atomic oxygen using the atmosphere models from April 16-17, 2008. ESA image.

RESULTS

First results of the sensor currents versus the prediction of atomic oxygen using the atmosphere models are illustrated in the associated graph. These first results show deviations of the transient behavior of atomic oxygen compared to the prediction of the higher atmosphere models U.S. Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Exosphere (NRLMSISE), which is an empirical model of temperatures/densities of atmospheric components, Marshall Engineering Thermosphere Model (MET) and Density Temperature Drag Model (DTM). The results showed an increase of atomic oxygen after local sunrise when ISS orbited from south to the equator followed by a decrease when continuing the orbit to higher latitudes. Some minutes before the ISS exited the local eclipse phase, the atomic oxygen level reached its minimum.

PUBLICATION(S)

Fasoulas S, GH, Lohle S. Overview experimental diagnostics for rarefied flows—Selected topics. *NATO Science and Technology Organization*; January 2011.

This investigation is complete and all results are published.

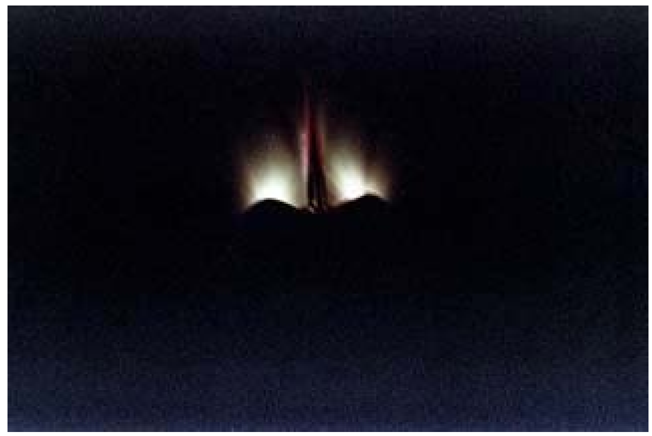
MAUI ANALYSIS OF UPPER ATMOSPHERIC INJECTIONS (MAUI)

Research Area: Spacecraft and Orbital Environments
Expedition(s): 13-16, 21-22, 25-28
Principal Investigator(s):

- Rainer A. Dressler, PhD, Hanscom Air Force Base, Lexington, Massachusetts

RESEARCH OBJECTIVES

Maui Analysis of Upper Atmospheric Injections (MAUI) observes the space shuttle engine exhaust plumes from the Maui Space Surveillance Site in Hawaii. A telescope and all-sky imagers take images and data during nighttime firings of the space shuttle engines. The images are analyzed to better understand the interaction between the spacecraft plume and the upper atmosphere of Earth.



View of Orbital Maneuvering System engine burn to boost the orbit of the space shuttle for rendezvous with the Mir space station.

EARTH BENEFITS

Results will help in the interpretation of spacecraft plumes when they are observed from Earth.

SPACE BENEFITS

Results can be used to develop a spacecraft interactions computer model for plume contamination assessment and to better understand the interaction between the spacecraft plume and the upper atmosphere.

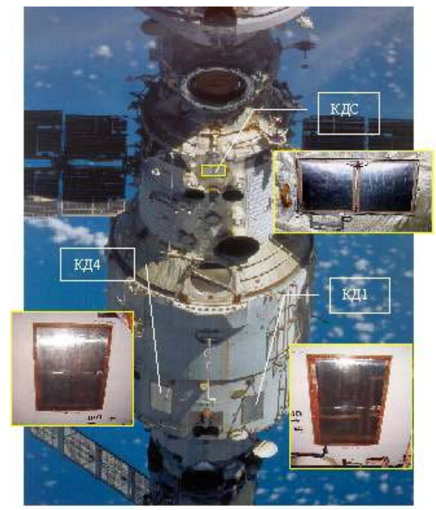
This investigation is complete; however additional results are pending publication.

Recording Micrometeoroid and Technogenic Particles on the External Surface of the ISS Russian Segment Service Module (Meteoroid)

Research Area: Spacecraft and Orbital Environments
Expedition(s): 2-13
Principal Investigator(s):
- Vyacheslav G. Sokolov, S.P. Korolev Rocket and Space Corporation Energia, Moscow, Russia

Research Objectives

Recording Micrometeoroid and Technogenic Particle on the External Surface of the ISS Russian Segment Service Module (Meteoroid) continuously monitors the meteoric and space debris environment in the proximity of the orbit of ISS operations. This is determined on one hand, by the continuous increase of the pollution level in the space environment, and on the other hand, by the ISS design life. The Meteoroid experiment is one component of a system being developed to monitor the meteoroid and technogenic elements of the space environment, covering the full range of the particle sizes.



General view of the Station and the placement of sensors on the planes of the Service Module. Roscosmos image.

Space Benefits

Meteoroid will aid in updating the Russian models of the technogenic environment in the range of small-sized particles (< 0.1 mm), which is characterized by significant dynamics in time, and specifically, for updating the developed model of the penetrating shower of meteoroid and technogenic particles with sizes 20 – 100 micron impacting thin barriers and to verify the predictions of the arrival time and intensity of meteor showers.

Results

The comparison of the data on MMOD showers obtained as a result of the Meteoroid experiment to results from orbital stations Salyut and Mir and other space objects, as well as to modeled values of the showers showed that in the range of particle sizes over 20 micron, there is an increase in the pollution levels of the near-Earth space environment over time for orbital altitude ranges 400-500 km (more than doubling over 10-15 years). For the range of particles with sizes below 20 micrometers, such effect is not observed as a result of a more intensive self-cleaning of the space environment at these altitudes from smaller-sized micro-particles due to aerodynamic deceleration and solar radiation pressure.

This investigation is complete; however additional results are pending publication.

HIGH-ACCURACY SPATIAL ORIENTATION OF SCIENTIFIC DEVICES TAKING IN ACCOUNT THE ISS HULL DEFORMATION (PRIVYAZKA)

Research Area: Spacecraft and Orbital Environments
Expedition(s): 1-9
Principal Investigator(s):
- Mikhail Y. Belyaev, PhD, S.P. Korolev Rocket and Space Corporation Energia, Korolev, Russia

RESEARCH OBJECTIVES

The High-Accuracy Spatial Orientation of Scientific Devices Taking in Account the ISS Hull Deformation (Privyazka) investigation assesses hull deformation and determines the error values of the reference coordinate system, to provide quality results for ISS investigations. For experiments to observe celestial objects, the Earth's surface, to study the atmosphere, and some others, it is important to have information on the accurate spatial orientation of the sensing axes of research devices.

Still camera mounted on a window in the ISS RS. Roscosmos image.

SPACE BENEFITS

The results will be used to increase the accuracy of determining the orientation of scientific equipment installed on the ISS, for planning, and high quality analysis of scientific experiments that require, for example, accurate tracking by scientific equipment of objects being studied, or knowledge of spatial position with high accuracy. In addition, results may be used to design and control other spacecraft and to conduct on them research and experiments, which require the highly accurate spatial positioning of scientific equipment.

RESULTS

The obtained results correspond to the data existing in this field calculated during Salyut and Mir station operations. Angular misalignments of the sensing axes of devices by approximately 1 - 2° due to ISS hull deformations occur just as they did on previous stations.

Nevertheless, the results obtained in the course of Privyazka enabled the development of corresponding mathematical models and the obtained measurements processing methods in order to determine ISS hull deformation, and device and system misalignments aiming to increase the accuracy of determining their orientation in the reference coordinate system for the high-quality analysis of scientific experiments conducted on the ISS.

This investigation is complete; however no publications are expected.

Ram Burn Observations (RAMBO), Two Investigations

Research Area: Spacecraft and Orbital Environments
Expedition(s): 13-16, 25-28
Principal Investigator(s):
- William L. Dimpfl, PhD, Aerospace Corporation, Los Angeles, California

Research Objectives

Ram Burn Observations (RAMBO) is an experiment in which the Department of Defense uses a satellite to observe space shuttle orbital maneuvering system engine burns. Its purpose is to improve plume models, which predict the direction the plume or rising column of exhaust will move as the shuttle maneuvers in orbit. Understanding the direction in which the spacecraft engine plume or exhaust flows could be significant to the safe arrival and departure of spacecraft on current and future exploration missions.

This image shows the Glow experiment documentation of Orbital Maneuvering System (OMS)/Reaction Control System (RCS) pods and vertical stabilizer from STS-007.

Earth Benefits

While interactions at hyperthermal energies are relatively rare on the surface of the Earth, there are potential applications relevant to the cutting-edge of technology, including the understanding of high-temperature plasmas and the production and derivation of energy from controlled fusion power sources.

Space Benefits

Applications in space include an understanding of plume flow fields that could be relevant to the safe approach and departure of supply ships to the International Space Station (ISS) or other spacecraft. They also include an understanding of background radiance produced by plumes, impacting sensors designed for other observations. More generally the applications include a contribution to understanding any phenomenon related to spacecraft that are impacted by the poorly understood interactions of atoms and molecules at hyperthermal energies that govern the environment around spacecraft in low-Earth orbit.

This investigation is complete; however additional results are pending publication.

SHUTTLE EXHAUST ION TURBULENCE EXPERIMENTS (SEITE)

Research Area: Spacecraft and Orbital Environments
Expedition(s): 18-28
Principal Investigator(s):
- Paul A. Bernhardt, PhD, Naval Research Laboratory, Washington, DC

RESEARCH OBJECTIVES

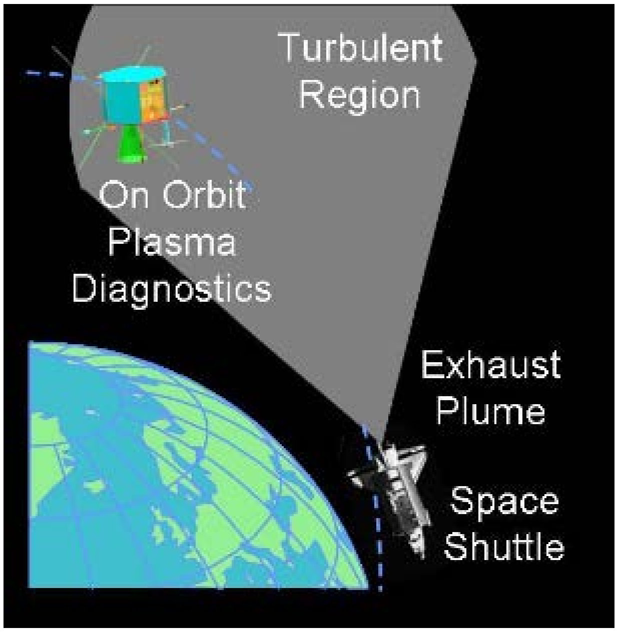
Shuttle Exhaust Ion Turbulence Experiments (SEITE) uses space-based sensors to observe the ionospheric turbulence from a Space Shuttle Orbital Maneuvering System (OMS) burn.

EARTH BENEFITS

Results will help in the interpretation of spacecraft plumes when they are observed from Earth.

SPACE BENEFITS

Artificially-created plasma turbulence can disrupt military navigation and communications using radio systems.



Shuttle Exhaust Ion Turbulence Experiment operational concept. US Department of Defense Space Test Program image, Houston, TX.

RESULTS

SEITE 1 and SEITE 2, conducted during STS-127/2JA and STS-129/ULF3 respectively, provided unique measurements of highly altered, neutral, and plasma environments that resulted from space shuttle Orbital Maneuvering System (OMS) burns in the ionosphere. During STS-127, an OMS burn was timed so the exhaust plume would cross the path of an Air Force satellite. The satellite, which flew through the near-center of the exhaust cloud, measured a 50% increase in ion temperature, 10% increase in electron density, increase in vertical neutral wind from 0 to 3.5 km/s in 6 seconds, and the conversion of 25% of ions to CO_2^+, which was the result of the exchange of charges between neutral CO_2 and ambient atomic ions. All of these results were consistent with predictions. Of particular interest was the detection of electromagnetic pulses (EMPs) in the form of a fast magnetohydrodynamic (ultra-low frequency) wave and multiple whistler (very low frequency) waves, as well as a broad band of high-amplitude noise that followed the initial EMPs. The source of the noise is still under investigation. The experiment was repeated during STS-129. This time, the satellite flew through only the edge of the exhaust cloud. Like SEITE 1, an EMP caused by the fast magnetohydrodynamic (MHD) wave was detected about 6 seconds after the OMS ignition. Unlike SEITE 1, no whistler modes were observed. These observations were in accordance with predictions: the fast MHD wave is the most likely mode to be detected by a remotely located satellite, since it propagates in all directions. The whistler modes, however, travel in a 19.5° cone around the magnetic field from the point of origin and therefore are only detected by a satellite if it is within this cone. While the satellite in SEITE 1 was within this cone and therefore detected the whistler waves, the satellite in SEITE 2 was well outside the whistler cone. Also like SEITE 1, a broad band of high amplitude noise was observed following the initial EMP during SEITE 2. The noise detected during the SEITE experiments demonstrated that a large number of electrostatic waves are produced after initially neutral rocket exhaust products are converted to high speed ions (Bernhardt 2012). Findings from SEITE will be used to develop quantitative models of plasma disturbance that can affect tracking and imaging radars.

PUBLICATION(S)

Bernhardt P, Ballenthin J, Baumgardner J, et al. Ground and space-based measurement of rocket engine burns in the Ionosphere, *IEEE Transactions on Plasma Science*. 2012;40, pp 1267–1286. doi: 10.1109/TPS.2012.2185814.

This investigation is complete; however additional results are pending publication.

Shuttle Ionospheric Modification with Pulsed Localized Exhaust Experiments (SIMPLEX)

Research Area: Spacecraft and Orbital Environments
Expedition(s): 18-28
Principal Investigator(s):
- Paul A. Bernhardt, PhD, Naval Research Laboratory, Washington, DC

Research Objectives

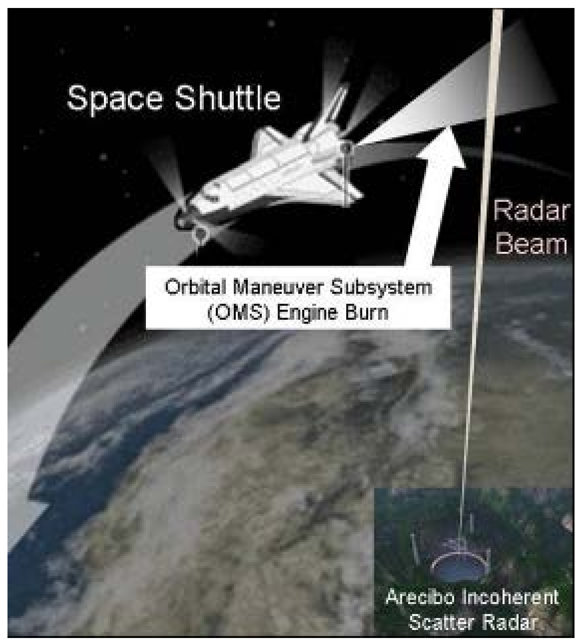
The Shuttle Ionospheric Modification with Pulsed Localized Exhaust Experiments (SIMPLEX) investigates plasma turbulence driven by rocket exhaust in the ionosphere using ground-based radars.

Earth Benefits

Results will help in the interpretation of spacecraft engine plumes when they are observed from Earth.

Space Benefits

Artificially created plasma turbulence can affect military navigation and communications using radio systems. The plasma turbulence can also be used to promote communications by opening radio channels at abnormally high frequencies. The processes by which chemical releases can produce plasma waves are fundamental to many applications. These processes are quantified with the SIMPLEX measurements.



Ground radar data collection during Orbital Maneuvering System (OMS) burn of the space shuttle. The radar scatter provides data on the ionospheric interactions of the high-speed OMS exhaust. (SIMPLEX concept image provided by Dr. Paul A. Bernhardt, Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375)

Results

The effect of shuttle OMS burns on the ionosphere at or near the equator was observed during shuttle flights STS-86, STS-93, and STS-122/1E. The first objective of SIMPLEX, to study the flow of plasma into an artificially created hole in the ionosphere, was accomplished during shuttle mission STS-86. The hole created by the burn recovered more quickly than was predicted by plasma diffusion models. The second objective, to trigger bubbles in the ionosphere, was accomplished during STS-93, when a 10-second burn produced a hole on the bottom side of the equatorial layer of the ionosphere, which researchers hoped would seed an ionospheric bubble. After the burn, an ionospheric disturbance was detected drifting eastward at 100 meters per second. While the appearance of the disturbance after the burn was consistent with hypothesis, it remains unclear whether the disturbance was naturally occurring or an effect of the OMS burn. The final objective, the use of artificial airglow to make natural ionospheric irregularities more easily observable, was accomplished when the STS-122/1E completed an OMS burn in a region of strong natural ionospheric irregularities. The burn exhaust created artificial airglow that enhanced the irregularities present in the ionosphere. The enhanced features were easily observed by ground-based imagers. Ground based radar was used to observe the effect of shuttle OMS burns on the ionosphere at midlatitudes during shuttle flights STS-110/8A, STS-128/17A, and STS-119/15A. The cases of STS-110 and STS-128 showed that the exchange of charges by exhaust molecules traveling at hypersonic speeds in the ionosphere yields high energy ion beams that create a backscatter signature detectable by radar that lasted from 30 to 90 seconds to over 20 minutes. The STS-119 case was the first reported detection of a rocket engine burn in the F-region, the topside and densest layer of the ionosphere, at a range of over 700 kilometers. The burn was detected by radar as a disturbed region of enhanced high frequency (HF) backscatter that lasted for 40 minutes. This disturbance was unique to the burn and was not seen near this location in the 2 weeks prior to or after the burn event. SIMPLEX demonstrated that rocket exhaust products can be used to better observe irregular features in the ionosphere (Bernhardt 2012).

PUBLICATION(S)

Bernhardt P, Ballenthin J, Baumgardner J, et al. Ground and space-based measurement of rocket engine burns in the Ionosphere, *IEEE Transactions on Plasma Science*. 2012;40:1267-1286. doi: 10.1109/TPS.2012.2185814.

This investigation is complete; however additional results are pending publication.

Analysis Experimentation Implementation Algorithms (ASIA)

Research Area: Spacecraft Materials
Expedition(s): 10 and 11
Principal Investigator(s):
- Andrea Orlandi, Information Technologies Services, Rome, Italy

Research Objectives

ESA astronaut Roberto Vittori with the Analysis Experimentation Implementation Algorithms hardware on the International Space Station in 2005. A, Orlandi image.

The Analysis, Experimentation, and Implementation Algorithms (ASIA) Flight experiment is a sophisticated instrument for the measurement of the effect of space radiation on high-level electronic components and microprocessors. The ASIA experiment was the core of the first super-computer for space application that can operate in a high radiation environment assuring high functionality and performance through the realization of innovative and self-configuring architecture without "radiation hardened" electronic components.

Results

The Commercial-off-the-shelf (COTS) hardware worked perfectly during its postflight tests. In 2005 it was one of the first attempts to demonstrate that COTS hardware could work in the space environment without protection, with respect to the radiation dose calculated analytically. The data/experience coming from the ASIA experiment is proving very important in the development of a microsatellite design based on the COTS hardware.

This investigation is complete; however, additional results are pending publication.

Elastic Memory Composite Hinge (EMCH)

Research Area: Spacecraft Materials
Expedition(s): 15
Principal Investigator(s):
- Corey Duncan, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico

Research Objectives

The elastic memory composite hinge (EMCH) experiment provides test data on new materials that will further space hardware technology. This technology may eliminate the need for highly complex deployment mechanisms by providing a simpler, lightweight alternative to mechanical hinges. EMCH builds on the previous space shuttle experiment, lightweight, flexible solar array hinge (LFSAH) that was flown on STS-93.

View of Expedition 15 Flight Engineer Sunita Williams during the EMCH experiment operations in the US Laboratory, Destiny. The EMCH assembly (gold box) is visible on right of photo.

Earth Benefits

Since composite materials are valued for being lightweight and strong, the hinges may have spin-off applications on Earth.

Space Benefits

EMC materials tested in this experiment are stronger and lighter than current material used in space hinges and could be used in the design of future spacecraft.

Results

EMCH was successfully completed aboard the International Space Station (ISS) during Expedition 15. The investigation was returned to Earth for a complete analysis by the investigator team in 2007. However, the preliminary assessment indicated that the experiment demonstrated the robustness and reliability of the TEMBO® EMC hinge in the zero-gravity environment. This test campaign consisted of both nominal and off-nominal conditions, with the final series of tests presenting the most challenging conditions for in-orbit TEMBO® hinges. The successful completion of these tests indicates that hinges meet the designed performance goals of a next-generation, spaceflight-qualified actuator. Additionally, the science gained from this experiment confirms engineering assumptions used to design the TEMBO® EMC hinges as well as other TEMBO® EMC-deployable structures that are being developed for space applications.

This investigation is complete; however additional results are pending publications.

European Technology Exposure Facility - Material Exposure and Degradation ExperimenT (EuTEF-MEDET)

Research Area: Spacecraft Materials Exposure
Expedition(s): 16-20
Principal Investigator(s):
- Sophie Duzellier, ONERA, Toulouse, France
- Adrian Tighe, European Space Research and Technology Centre, Noordwijk, Netherlands

Research Objectives

The objective of the European Technology Exposure Facility - Material Exposure and Degradation ExperimenT (EuTEF-MEDET) is to evaluate the effects of the complex low-orbit space environment on material properties and investigate material degradation due to contamination. The material samples consist of a selection of thermal control paints and foils, optical glasses, thin solar sail materials, and metallic anodisations.

ESA image.

Results

Preliminary analysis of the material degradation data showed the relative trends in the material behaviour and ageing/degradation mechanisms (yellowing, erosion from atomic oxygen, etc). However, more detailed modelling was required in order to acquire more accurate values for their thermo-optical properties.

The space debris experiment SODAD (composed of MOS capacitor sensors) recorded 11 impact events during the mission, and these flight results were being correlated with model predictions. The results from the environmental sensors on MEDET, and in particular the pressure gauge, have been used to show the influence that space station orbital maneuvers and the docking of the space shuttle have on the local International Space Station (ISS) environment. Further analysis is ongoing to analyse the in-orbit behaviour of the materials and to determine synergies between the different types of data.

The preliminary results from the QCM (quartz crystal microbalances) contamination monitors indicated that no significant molecular contamination deposition occurred during this period. This QCM data also covered the period when the space shuttle STS-123 docked to the ISS in March 2008. It is interesting to note that the erosion appeared to stop at the moment the shuttle docked and then continues after the shuttle had undocked. This corroborated evidence from the pressure gauge. Previously, this was attributed to a possible shielding effect caused by the space shuttle. However, it is now believed to be due to a "ram/wake" effect, caused by re-orientation of the station during the shuttle docking.

During 2010, the analysis of the in-orbit results were complemented with ground-based activities (environment simulation, calibration, chemical analysis, physica,l and optical properties).

The results showed the general trends in the material behavior. These were summarized as follows:

- There was no significant degradation of the white paints.
- There was no significant degradation of the Plasmocer.
- There was no significant degradation of the black bodies.
- Complete erosion of the Upilex S occurred.
- Darkening of the Y100 polyimide was followed by a decrease in absorptance.
- There was a small increase in absorptance of the RSR, MAP ATOX, and RSF coatings.

Preliminary results will need to be refined using a more detailed analysis, and a comparison will also be made with the postflight measurements after return of the samples.

PUBLICATION(S)

Rejsek-Riba V, Inguimbert V, Duzellier S, Pons C, Crepel M, Tighe AP. Spectrometers results of material exposure and degradation experiment onboard International Space Station. *Journal of Spacecraft and Rockets*. January 2011;48(1):38-44. doi: 10.2514/1.49443.

Tighe AP, Iwanovsky B, Van Eesbeck M, Duzellier S. In-orbit measurement of the Columbus Lab Vacuum Environment using the MEDET pressure gauge. *International Symposium on Materials in the Space Environment*, Provence, France; 2009.

Tighe AP, Iwanovsky B, Van Eesbeck M, et al. Overview of results from the Materials Exposure and Degradation Experiment (MEDET) after 18 months in orbit on the ISS. *11th International Symposium on Materials in a Space Environment*. Provence, France; September 15-18, 2009: 10.

Tighe AP, Van Eesbeck M, Duzellier S, et al. Preliminary flight data from the materials exposure and degradation experiment (MEDET). *Proceedings of the 9th International Conference: Protection of Materials and Structures From Space Environment,* Toronto, Canada; 2009: 195-206.

This investigation is complete; however additional results are pending publication.

EUROPEAN TECHNOLOGY EXPOSURE FACILITY - TRIBOLOGY LABORATORY (EUTEF-TRIBOLAB)

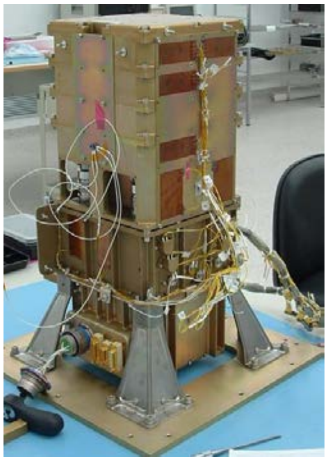
Research Area: Spacecraft Materials
Expedition(s): 16-20
Principal Investigator(s): • Marta Brizuela, INASMET, San Sebastian, Spain

RESEARCH OBJECTIVES

This series of European Technology Exposure Facility - Tribology Laboratory (EuTEF-TriboLab) experiments covers research in tribology (science of mechanisms of friction, lubrication, and wear of interacting surfaces that are in motion). This is of major importance for spacecraft systems. The Tribolab experiments cover both experiments in liquid and solid lubrication such as the evaluation of fluid losses from surfaces and the evaluation of wear of polymer and metallic cages weightlessness.

RESULTS

The first results from the "Pin on Disk" tests in the Tribolab experiment showed that the behavior of the lubricants under microgravity and vacuum conditions in orbit is similar to their behavior on Earth, with transferred material from the coated disk to the mating surface (ball). The main friction coefficient and the maximum endurance of the coating in orbit were similar to the ones obtained on Earth in a commercial tribometer.



TriboLab Flight model. Image courtesy of ESA.

PUBLICATION(S)

Garmendia I, Anglada E, Vallejo H, Ptaszliewicz M, Insausti N. Thermal Control of Tribolab, a materials experiment in the International Space Station. 50th Anniversary Conference. *Engineering: Science and Technology*, San Sebastian, Spain; 2012 May 31 to June 1.

Garmendia I, Landaberea A, Anglada E, Fernandez-Sanz R, Santiago R, Herrada F, Encinas JM. The vacuum tribology model (VTM) of TriboLAB. *10th European Space Mechanisms and Tribology Symposium*, San Sebastian, Spain; 2003 September 24-26 67-70.

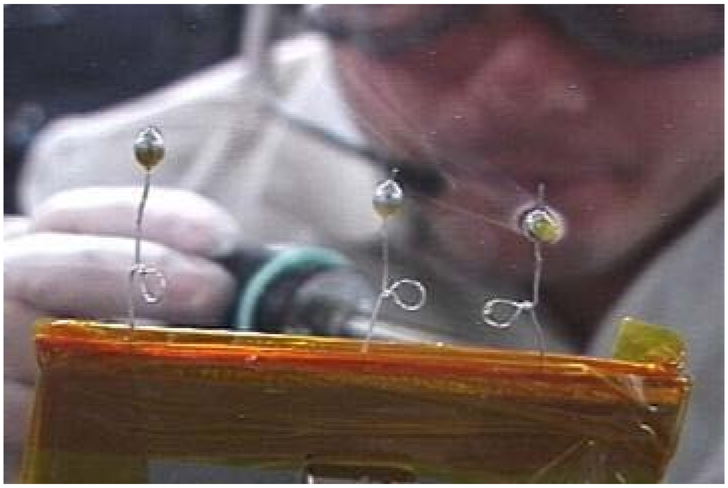
This investigation is complete, and all results are published.

In Space Soldering Investigation (ISSI)

Research Area: Spacecraft Materials
Expedition(s): 7-10
Principal Investigator(s):
- Richard N. Grugel, PhD, NASA's Marshall Space Flight Center, Huntsville, Alabama

Research Objectives

The In Space Soldering Investigation (ISSI) was rapidly developed after the *Columbia* accident as a low-mass experiment using hardware already aboard the International Space Station (ISS). While it was designed to promote understanding of joining techniques, shape equilibrium, wetting phenomena, and micro-structural development in space, its primary objective was to better understand the effects and consequences of soldering in microgravity. On Earth, soldering has a defined behavior and relies on gravity and convection to assist in solidification, joint shape, integrity, and microstructure. Unfortunately, detrimental gas bubbles (void spaces) can form in the solder joint and at contact surfaces. These voids reduce thermal and electrical conductivity and provide sites for crack initiation. In the microgravity environment, bubbles have less chance to escape, and therefore, are likely to be more of a problem. To better understand this potential problem, a systematic series of soldering samples was designed to investigate and understand porosity development, surface wetting, and equilibrium shape formation. The samples were heated in orbit and then returned to Earth for property testing and metallographic examination.



Video screen shot of science officer Mike Fincke using a soldering iron to perform In Space Soldering Investigation during Expedition 9.

Earth Benefits

The study of soldering in space leads to a better comprehension of materials processing techniques and fluid dynamic processes.

Space Benefits

The ISSI experiment provides unique insight into microgravity soldering methods, which could play a fundamental role in maintaining the ISS as well as providing repair capabilities during future exploration missions.

RESULTS

Five soldering sessions resulted in 86 samples. The experiment samples were returned to the investigator team in late 2005 and were evaluated both nondestructively and then destructively. A number of both expected and unexpected observations were made. Real-time downlink video of the experiment yielded direct observation of the solder melting, equilibrium shape attainment by the liquid, and flux movement. The flux movement was particularly noteworthy because it was entirely unexpected. When the flux was released from the solder during heating, it formed a droplet that spun around the larger solder drop. This surprising movement is driven by thermocapillary flow induced by the temperature gradient and cannot be duplicated on Earth. Researchers developed a model derived from both space-based observations and ground-based experiments to provide insight into the observed flux spinning (Grugel 2006, 2008).

Expedition 9 Science Officer Mike Fincke works on In Space Soldering Investigation in the US Laboratory, Destiny.

PUBLICATION(S)

Grugel RN, Luz P, Smith G, et al. Materials research conducted aboard the International Space Station: Facilities overview, operational procedures, and experimental outcomes. *Acta Astronautica*. 62 (2008):491–498. doi:10.1016/j.actaastro.2008.01.013.

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Grugel RN, Luz P, Smith GA, et al. Experiments conducted aboard the International Space Station: The Pore Formation and Mobility Investigation (PFMI) and the In-Space Soldering Investigation (ISSI): A current summary of results. *Proceedings of the 57th International Astronautical Congress (IAC)*, Valencia, Spain; October 2-6, 2006.

This investigation is complete; however additional results are pending publication.

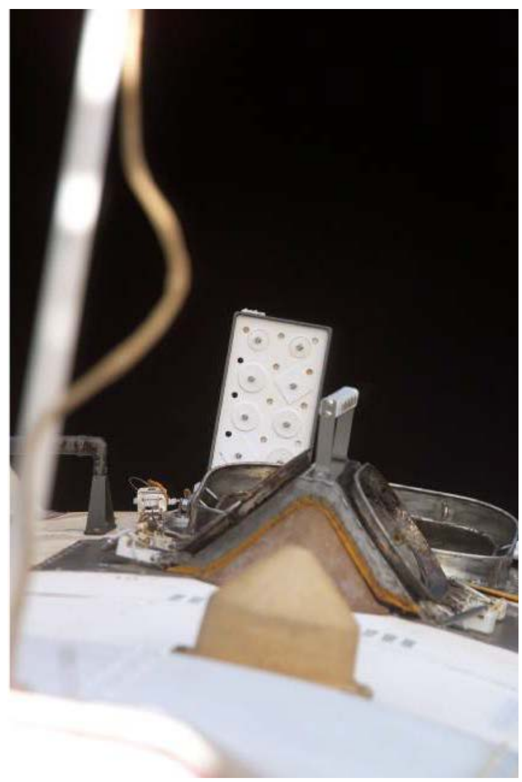
Study of the Dynamics of Contaminating Substances Emission from Control Liquid Propellant Low-Thrust Jet Engines during Their Pulse Firings and Verification of the Effectiveness of Deflectors for the Protection of ISS External Surfaces from from Contamination (Kromka)

Research Area: Spacecraft Materials
Expedition(s): 3, 4, 5, 9, 11, and 13
Principal Investigator(s):

- Yuriy I. Gerasimov, S.P. Korolev Rocket and Space Corporation Energia, Korolev, Russia, Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences, Moscow, Russia

Research Objectives
Study of the Dynamics of Contaminating Substances Emission from Control Liquid Propellant Low-Thrust Jet Engines during Their Pulse Firings and Verification of the Effectiveness of Deflectors for the Protection of ISS External Surfaces from Contamination (Kromka) studies the dynamics of contaminating substance emissions from control liquid propellant low-thrust jet engines during their pulse firings and studies the verification of the effectiveness of devices for the protection of ISS external surfaces from contamination.

Space Benefits
The introduction of deflectors on the control liquid propellant low-thrust jets will significantly decrease the deterioration of solar arrays, radiators, and other ISS components by extending their on-orbit service lives, and will decrease the risk of crewmembers' spacesuit contamination upon contact with surfaces during extravehicular activity.



ISS005E05422 - Shows the location of the Kromka tablet near the attitude and pitch thrusters unit (view from DC1 window).

Results
The studies included analysis of the chemical composition of fuel/oxidizer reaction products (FORP), visual and instrument-aided analysis of the composition of FORP deposits samples, analysis of the changes of sample optical characteristics, and densitometry of the images of control tablets. Using a specially developed procedure, the balance between the mass of deposited and vaporized FORP was determined. It was established that a deflector effectively limits the contamination area from roll thrusters with an angle of ~45°, thus preventing contamination of structural elements of the ISS Service module. Based on the study results, an angular distribution of FORP in the plume was obtained and used to calculate the predicted contaminating

effect of ISS Service module roll thrusters on structural elements and exterior surfaces. During the 4 stages of the Kromka space experiment, the assumptions on the mechanisms of FORP emissions from attitude thruster nozzles into the surrounding area were confirmed, which were determined based on the results of experiments in pressure chambers using actual thrusters and simulated nozzles.

Publication(s)

Gerasimov YI, Krylov AN. Results of studying the effect of contamination from the inherent external atmosphere on the characteristics of the structural materials and temperature control coatings of ISS vehicles and modules. *Physical/Chemical Kinetics in Gas Dynamics (Fiziko-Chimiceskaja Kinetika v Gazovoj Dinamike)*. 2011.

Gerasimov YI, Buryak AK. Conditions of formation of stable deposits of incomplete combustion products of liquid rocket fuels on the external elements of orbital stations. *Russian Journal of Physical Chemistry B*. October 2008;2(5):779-786. doi: 10.1134/S1990793108050205. [Original Russian Text © Gerasimov YI, Buryak AK. *Khimicheskaya Fizika*, 2008;27(10):26–34.]

Gerasimov YI, Yarygin IV. Methodology of studying the parameters of contaminant emissions from the orientation engines of orbital stations during and after the flight. *Russian Journal of Physical Chemistry B*. October 2008;2(5):787-794. doi: 10.1134/S1990793108050217. [Original Russian Text © Gerasimov YI, Yarygin IV. *Khimicheskaya Fizika.* 2008;27(10):35–43.]

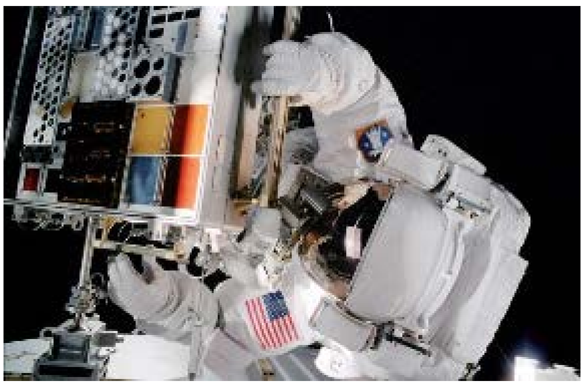
Gerasimov YI, Krylov AN, Sokolova SP, et al. Gas dynamics aspects of contamination of the International Space Station. 2. In-situ Experiments. *Thermophysics and Aeromechanics (Teplofizika i Aeromekhanika)*. 2003;10(4):555-565.

Materials International Space Station Experiment – 1 and 2 (MISSE-1 and 2)

Research Area: Spacecraft Materials
Expedition(s): 3-11
Principal Investigator(s):
- William H. Kinard, PhD, Langley Research Center, Hampton, Virgina

Research Objectives

Materials International Space Station Experiment – 1 and 2 (MISSE-1 and 2) are a test bed for materials and coatings reaction to space exposure. Attached to the outside of the International Space Station (ISS), MISSE accommodates several hundred samples that are being evaluated for the effects of atomic oxygen (AO), direct sunlight, and extremes of heat and cold. This experiment allows the development and testing of new materials to better withstand the rigors of space environments.



Astronaut Patrick G. Forrester prepares to work with the Materials International Space Station Experiment (MISSE). The experiment was installed on the outside of the Quest Airlock during the first extravehicular activity of the STS-105 mission. MISSE will collect information on how different materials weather in the environment of space. I NASA image.

Earth Benefits

The new advanced materials and components that make up MISSE represent research efforts to improve the performance, increase the useful life, and reduce the costs of future space operations of commercial weather, communication, and ground observation satellites that are crucial to everyday life on Earth.

Space Benefits

Results provide a better understanding of the durability of various materials when they are exposed to the space environment. Many of the materials may have applications in the design of future spacecraft.

Results

Researchers who took part in MISSE-1 and 2 had interests in polymers, nanocomposites, thermal control coatings, radiation shielding, environmental monitors, and marking processes designed to label parts exposed to the space environment. Primary data from MISSE were obtained by comparing the preflight laboratory characterization of the test specimens with postflight laboratory analyses after the specimens are retrieved.

Close up of Materials International Space Station Experiment with Earth backdrop. NASA image.

The following information is a sampling of the results obtained from MISSE-1 and 2 thus far. Some particulate contamination was observed. Optical property changes in thermal control materials were also seen. Several materials performed well in the harsh environment. Lack of widespread molecular contamination on MISSE gave confidence in using the ISS for future material studies. However, over 100 micrometeoroid and space debris strikes were found on MISSE surfaces. Atomic Oxygen completely eroded many polymer film samples, but some survived and were analyzed.

Many of the experiments provided space-validated results for ground-based experiments, such as the durability of materials to withstand Atomic Oxygen erosion (AO). Because AO erosion is the primary weathering force to spacecraft materials, and true space environmental conditions are difficult to replicate on Earth, MISSE provided a valuable test platform that enabled methods for validating ground results. Forty-one different polymers called Polymer Erosion and Contamination Experiment (PEACE) Polymers were tested with the objective to determine the atomic oxygen erosion yield for a variety of materials such as Kevlar®, polyethelene, Lucite, Kapton®, and Teflon® that are used in spacecraft and exposed to the space environment. The erosion yield data are immediately applicable to spacecraft designs. Even though the length of exposure was 4 times longer than planned, the sample preparation method of stacking many thin layers allowed for meaningful data with residual samples even after 4 years. In addition to testing various materials, experiments were also set up to measure the geometry of atomic oxygen scattering from oxidized aluminum surfaces.

MISSE-1 and -2 results expanded knowledge into atomic oxygen erosion and resulted in several patents and spin-offs ranging from cleaning artwork methods, parts etching to be used in human grafts, new methodologies for testing blood sugar, and more. Because MISSE assembled partners across industry and the Department of Defense, in addition to NASA scientists and academic partners, many of the results were proprietary.

Publication(s)

Banks BA, Simmons JC, de Groh KK, Miller SK. The effect of ash and inorganic pigment fill on the atomic oxygen erosion of polymers and paints. *12th International Symposium on Materials in the Space Environment*, Noordwijk, Netherlands; February 2013.

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This investigation is complete; however, additional results are pending publication.

Materials International Space Station Experiment – 3 and 4 (MISSE-3 and 4)

Research Area: Spacecraft Materials
Expedition(s): 13-15
Principal Investigator(s):
- William H. Kinard, PhD, Langley Research Center, Hampton, Virginia

Research Objectives

Materials on the International Space Station Experiment 3 and 4 (MISSE-3 and 4) are the third and fourth in a series of suitcase-sized test beds attached to the outside of the space station. Environmental sensors record the thermal cycling (the change in temperature), and the effects that atomic oxygen (single oxygen molecules) and ultraviolet light have on materials are also studied. New material that might be used in the next generation of extravehicular activity (EVA) suits is tested to examine how the material reacts to the harsh space environment. Research findings can be used to design stronger, more durable materials for space and Earth applications.

Earth Benefits

The new advanced materials and components tested in MISSE-3 and 4 could prove useful in improving the performance, increase the service life, and reduce costs of future space operations of commercial weather, communication and Earth observation satellites that we all now depend on. The participation of school children in experiments with plant seeds from the MISSE-3 and 4 stimulates their interest in science and helps to inspire and promote the development of future space scientists and research.

Space Benefits

Results provide a better understanding of the durability of various materials when they are exposed to the space environment. Many of the materials may have applications in the design of future spacecraft and equipment.

Materials on the International Space Station Experiment 3 and 4 following deployment on the outside of ISS on August 3, 2006. NASA image.

Results

MISSE-3 and 4 experiments were very similar to experiments flown on MISSE-1 and 2. The Electromagnetic Interference Shielding experiment was the only experiment flown on MISSE-3 and 4, which was not also flown on MISSE-1 and 2. MISSE-3 and 4 also exposed approximately a million basil seeds for school science experiments.

Preliminary assessments that included results from previous MISSE-flown materials, suggested that the contamination control for the station—the method for tracking whether scientific instruments, windows, radiators and other hardware is staying clean from contaminants such as dust, dirt, or hair—appeared to be working. Earlier experiments showed that samples of the glass used in station windows were better than 90% clear, and samples of the same white thermal coatings used on station radiators looked like new, even after 4 years in space.

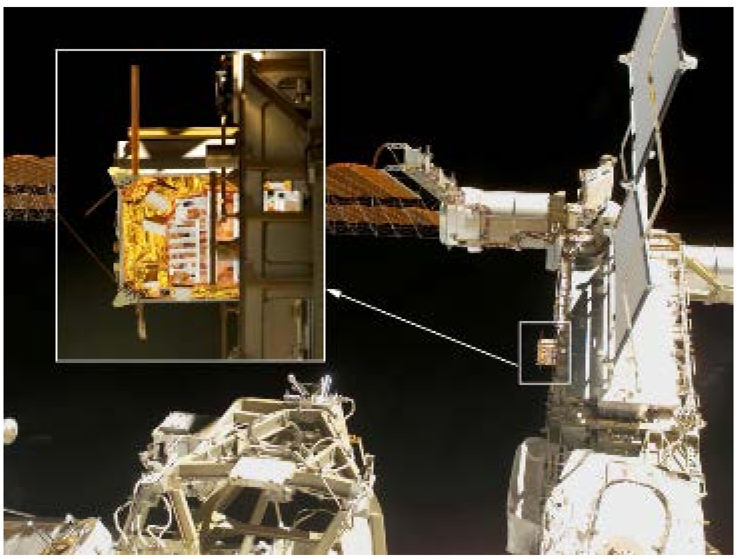
This investigation is complete; however additional results are pending publication.

MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT – 5 (MISSE-5)

Research Area: Spacecraft Materials
Expedition(s): 11-13
Principal Investigator(s):
- William H. Kinard, PhD, Langley Research Center, Hampton, Virginia
- Robert J. Walters, PhD, Naval Research Laboratory, Washington, DC

RESEARCH OBJECTIVES

The Materials on the International Space Station Experiment - 5 (MISSE-5) is a suitcase-sized experiment attached to the outside of the International Space Station (ISS). It exposes hundreds of potential space construction materials to the environment. The samples are returned to Earth for study after a set exposure period. Researchers can use the knowledge gained from the results to design stronger, more durable materials for a variety of applications.



Views of MISSE-5 mounted on the International Space Station P6 truss. PcSat-2 is protected by a golden thermal blanket with flexible material samples attached. NASA image.

EARTH BENEFITS

The new advanced materials and components tested in MISSE can help improve the performance, increase the useful life, and reduce the costs of future space operations of commercial weather, communication, and Earth observation satellites that we all now depend on.

SPACE BENEFITS

More reliable and robust materials help construction of spacecraft, instrument, and satellites that will last longer in the harsh conditions of space.

RESULTS

The following information is a sampling of the results obtained from MISSE-5 thus far.

MISSE-5 contained active and passive investigations: The Forward Technology Solar Cell Experiment (FTSCE), an active experiment that tested the performance of 36 current and advanced generation solar cells for use on future spacecraft; the active Second Prototype Communication Satellite System (PCSat-2) that provided a communication system and tested the Amateur Satellite Service off-the-shelf solution for telemetry command and control; and the passive MISSE-5 Thermal Blanket Materials Experiment, which consisted of several individual experiments to measure the degradation of more than 200 materials in the space environment.

MISSE-5 passive investigation tested a wide variety of materials. Some focused on new polymers with additives to slow the atomic oxygen erosion process. Others tested both new and old thermal control materials used in multilayer insulation blankets. MISSE 5 PFTC materials experiment consisted of 33 tensile specimens including many of the same types of polymer films exposed in the MISSE 1-4 Gossamer Materials and PFTC experiments. Results from this experiment are compared to ram and wake facing polymers in the MISSE 1-4 Gossamer Materials and PFTC experiments.

The data were compared with other flight experiments and analyzed for solar absorbance, contamination, and other effects. The majority of the samples flown on MISSE-5 experienced some loss in tensile strength and percent elongation as a result of exposure to the harsh environment. Comparing MISSE 1 and MISSE 5 test results indicated that the loss in tensile strength for the coated FEP Teflon samples was independent of the VUV and radiation levels or number of thermal cycles indicating that there may be a damage limit which MISSE 1 and 5 both exceeded for this property. The levels at which changes occurred, and which environment factor or combination of factors caused these changes was unclear and needs further investigation in experiments where these factors can be controlled or eliminated independently.

PUBLICATION(S)

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This investigation is complete; however additional results are pending publication.

Materials International Space Station Experiment - 6A and 6B (MISSE-6A and 6B)

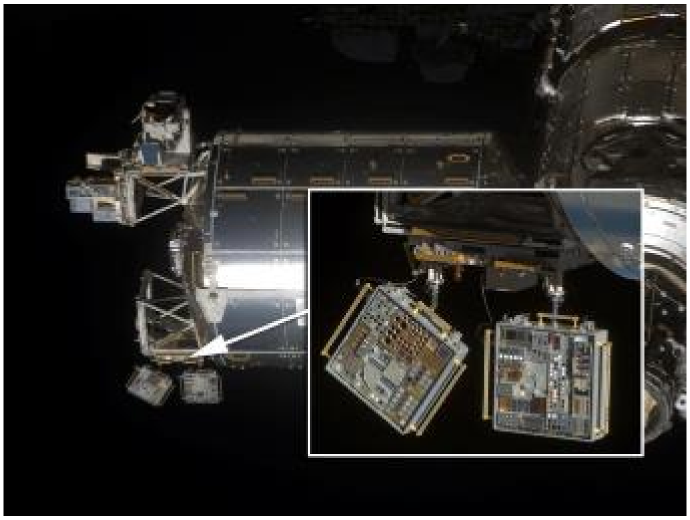
Research Area: Spacecraft Materials
Expedition(s): 16-20
Principal Investigator(s):
- William H. Kinard, PhD, Langley Research Center, Hampton, Virginia

Research Objectives

Materials International Space Station Experiment - 6A and 6B (MISSE-6A and 6B) is a sample box attached to the outside of the International Space Station (ISS); it is used for testing the effects of exposure to the space environment on small samples of new materials. These samples will be evaluated for their reaction to atomic oxygen erosion, direct sunlight, radiation, and extremes of heat and cold. Results provide a better understanding of the durability of various materials, with important applications in the design of future spacecraft.

Earth Benefits

These results provide an improved understanding of the durability of various silk and collagen materials in Earth orbit, with implications for the design of future materials for medical procedures and also physiology applications.



Close-up view of Materials International Space Station Experiment-6A and 6B Passive Experiment Container on European Laboratory/Columbus. NASA image.

Space Benefits

Results provide a better understanding of the durability of various materials when they are exposed to the space environment. Many of the materials may have applications for various needs during space travel. For example, protein-inorganic composites could be an important path forward in designing durable protein materials for space needs, as would protein materials pre-cross-linked on Earth to reduce the radiation impact.

Results

The following information is a sampling of the results obtained from MISSE-6A and 6B thus far.

Collagen and silk were flown to the ISS in the Materials International Space Station Experiment-6A and 6B (MISSE-6A and 6B) and exposed to space for nearly 18 months. All protein materials were changed but to different degrees depending on the material. Around 10-15% surface depth of silk and collagen films was etched away by heavy ionizing particles such as atomic oxygen, the major component of the low-Earth orbit space environment. Similar surface damage was created by oxygen plasma etching exposure control experiments on Earth. Unexpectedly, laboratory analysis revealed that more than 80% of the silk and collagen protein chains were chemically cross-linked by penetrating space radiation, which caused changes to the proteins. Silk-silica composites or triple-helix structures in native Type I collagens were more resistant to the impact of radiation in space than silk. It was also shown that resistance to high heat decreased after space travel for the protein samples. Results suggested that protein materials could be bioengineered to help protect them in the extreme space environments. Black Kapton® XC polyimide films on MISSE-6A and 6B exhibited a higher erosion rate when the films were stretched during the exposure period. Although a slight stress dependence was also observed in the ground-based samples, both in appearance and in the erosion yield, it was not to the extent seen in the space-exposed samples. Differences such as atomic oxygen, levels of UV radiation, temperature, and charged particles between the ground based and space environments could have caused this difference. Coatings of silicon dioxide and silicon showed evidence of cracking while under stress. This type of cracking can lead to failure of the underlying polymer material if cracks are exposed to high levels of atomic oxygen. This appeared to be the cause of failure for the silicon oxide (SiOx) coated Kapton flown on the ram side of MISSE-6A and 6B. Microscopic photos of the Kapton XC samples showed very little erosion on the unstressed samples but noticeable surface texturing under slight stress, and almost complete erosion under stresses greater than the tensile yield stress.

The failure of vapor deposited aluminum (VDA) polymer films appeared to be dependent on the level of environment exposure. VDA samples under stress exposed on the ram side of MISSE-6A and 6B failed while the sample exposed under stress on the wake side did not. MISSE-6A and 6B hosted samples with titanium and aluminum oxide cermet coating having the optical properties of high-solar absorptance and low infrared emittance. Spectral reflectance data obtained before and after flight revealed essentially no change in the optical properties of solar absorptance and infrared emittance upon low-Earth orbit exposure, consistent with ground laboratory evaluation of similar cermet coatings.

An atomic oxygen fluence monitor, flown as part of the MISSE-6B, was designed to measure the accumulation of atomic oxygen fluence with time as it impinged upon the ram (front) surface of MISSE-6B. This was an active experiment for which data was to be stored on a battery-powered data logger for post-flight retrieval and analysis. An atomic oxygen fluence of 1.37 ± 0.16×1021 atoms/cm^2 was measured. The fluence was approximately 30% lower than fluences measured using Kapton® H samples from an adjoining MISSE-6A passive experiment container.

Further testing is needed to isolate the factors that resulted in increased erosion under stress. These findings are critical for designing next-generation biocompatible materials and measurement systems for the space environments, where the effects of heavy ionizing particles and other cosmic radiation need to be considered. Further testing is needed to isolate the factors that result in increased erosion under stress.

Publication(s)

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Jaworske DA. Space durable solar selective coating cermet. *Journal of Thermophysics and Heat Transfer*. 2011;25(3):462-463. doi: 10.2514/1.T3663.

Banks BA, Miller SK, Waters DL. Materials International Space Station Experiment-6 (MISSE-6) Atomic Oxygen Fluence Monitor Experiment. *NASA Technical Memorandum*;May 2010.

This investigation is complete; however additional results are pending publication.

MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT – 7 (MISSE-7)

Research Area: Spacecraft Materials

Expedition(s): 21-28

Principal Investigator(s):

- Robert J. Walters, PhD, Naval Research Laboratory, Washington, DC

RESEARCH OBJECTIVES

The Materials International Space Station Experiment-7 (MISSE-7) is a test bed attached to the outside of the International Space Station for materials and coatings being evaluated for the effects of atomic oxygen, ultraviolet, direct sunlight, radiation, and extremes of heat and cold. This experiment allows the development and testing of new materials to better withstand the rigors of space environment. Results provide a better understanding of the durability of various materials when they are exposed to the space environment with applications in the construction of future spacecraft.

Materials International Space Station Experiment image taken from the STS-133 mission mounted outside the International Space Station. NASA image.

EARTH BENEFITS

The new advanced materials and components demonstrated in MISSE help to show how improvements can be made to the performance, useful life, and cost reduction of future space operations of commercial weather, communication, and Earth observation satellites that we all now depend on.

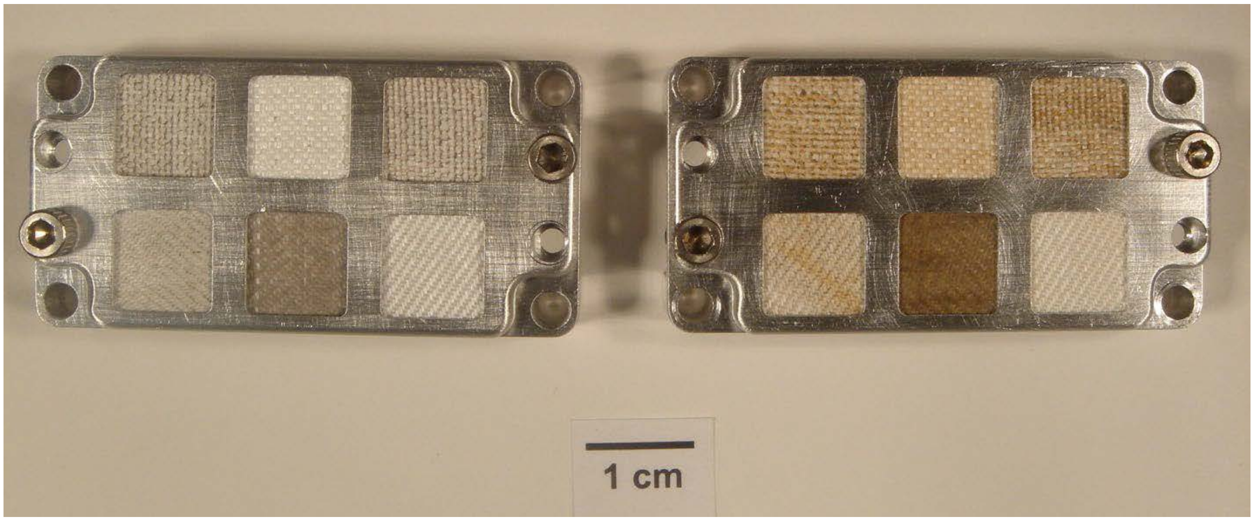
Space Benefits

Results provide a better understanding of the durability of various materials when they are exposed to the space environment. Many of the materials may have applications in the design of future spacecraft.

Results

The following information is a sampling of the results obtained from MISSE-7 thus far.

Six samples of pristine and dust-abraded, outer-layer spacesuit fabrics were exposed to the wake low-Earth orbit (LEO) environment on the International Space Station (ISS) for 18 months in order to determine whether abrasion by lunar dust increases fabric deterioration from radiation. Comparison of pre and postflight showed that space radiation darkened and reddened all 6 fabrics increasing their integrated solar absorptance by 7% to 38%. There was a decrease in the ultimate tensile strength and elongation to failure of lunar dust-abraded Apollo spacesuit fibers by a factor of 4 and an increase in the elastic modulus (tendency to be deformed) by a factor of 2. The lunar dust-laden Apollo 12 sample darkened, but did not appreciably redden, though it appeared redder to the eye. No evidence of contamination was found suggesting that the discoloration was due to radiation damage. Even though the samples were positioned on the wake (backward) side, because the ISS periodically reorients, the samples were exposed to the equivalent of about 38 days of ram (forward) atomic oxygen (AO) bombardment. Evidence for this was seen in the oxidation of silver-coated fasteners and the etching of fabric fibers. The erosion seen in the fibers was consistent with previously reported values for the erosion yields of the materials. The severity of the degradation of the fabric samples over the 18-month exposure period show that as materials wear out over time they absorb more energy and get hotter demonstrating the necessity to find ways to reduce radiation damage to spacesuits when planning extended exploration-class space missions.



Photograph of the control (left) and post-flight (right) MISSE-7 Spacesuit Fabric Exposure Experiment. Samples include abraded Ortho-fabric (a), pristine Ortho-fabric (b), double abraded Ortho-fabric (c), abraded Apollo era fabric (d), Alan Bean Apollo 12 fabric (e), and pristine Apollo era fabric (f). NASA image.

Modern multijunction (MJ) solar cells require stable optical coatings that provide wider spectral protection. The requirement to transmit shorter wavelengths to the top cell of the MJ device imposed new challenges for coatings. Ultraviolet reflection (UVR) and wide-band antireflection (AR) multilayer coatings were applied on working solar cell covers and test substrates and subsequently exposed in space on MISSE-7 along with space-simulated ground tests to determine their performance and stability. Observed effects of long space exposure on the coatings and assembled solar cells were small. UVR/AR coatings showed stable optical properties after exposure to proton, UV, atomic oxygen, and protected flexible polymer substrate materials. The technology for producing effective space-mission coatings that operate to UV wavelengths near 200 nm was successfully demonstrated. Further development is pending, including more exposure tests of UVR, AR, and transparent conductive oxide (TCO) coatings on flexible substrate alternatives and coatings integrated with MJ cells. Progress was made toward developing stable and protective coatings with improved resistance to radiation-induced darkening for extended space-mission applications. The additional requirements that the coatings on MJ flexible solar arrays tolerate deployment from being rolled up, and prevent static accumulation and discharge, were also satisfied.

PUBLICATION(S)

Prokop NF, Greer LC, Krasowski MJ, Flatico JM, Spina DC. A miniature microcontroller curve tracing circuit for space flight testing transistors. *Review of Scientific Instruments*. February 2015;86:024707. doi: 10.1063/1.4908163.

Pellicori SF, Martinex CL, Hausgen P, Wilt D. Development and testing of coatings for orbital space radiation environments. *Applied Optics*. February 1, 2014;53(4):A339-350. doi: 10.1364/AO.53.00A339.

Krasowski MJ, Prokop NF, Flatico JM, et al. CIB: An improved communication architecture for real-time monitoring of aerospace materials, instruments, and sensors on the ISS. *The Scientific World Journal*. 2013;2013(185769):12 pp. doi: 185769.

Gaier JR, Baldwin S, Folz A, et al. Degradation of spacesuit fabrics on low Earth orbit. *NASA Technical Memorandum*; August 2012.

Gaier JR, Waters DL, Jaworske DA, et al. Post-flight characterization of samples for the MISSE-7 spacesuit fabric exposure experiment. *NASA Technical Memorandum;* August 2012.

This investigation is complete; however, additional results are pending publication.

MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT - 8 (MISSE-8)

Research Area: Spacecraft Materials
Expedition(s): 27- ongoing
Principal Investigator(s):
- Robert J. Walters, PhD, Naval Research Laboratory, Washington, DC

RESEARCH OBJECTIVES

The Materials on International Space Station Experiment - 8 (MISSE-8) tests various materials and computing elements on the exterior of the space station. The payload container is mounted so one side faces the Earth and the other faces space. The harsh environment of low-Earth orbit exposes the materials to a vacuum, atomic oxygen, ultraviolet radiation, direct sunlight, and extreme heat and cold. The experiments provide a better understanding of material durability, from coatings to electronic sensors, which could be applied to future spacecraft designs.

View of STS-134 Mission Specialist Andrew Feustel working to install a new Materials International Space Station Experiment - 8 on the Expedite the Processing of Experiments to Space Station Logistics Carrier 2. NASA image.

EARTH BENEFITS

Ultraviolet radiation, oxidization, and other phenomena happen on Earth as well as in space. Research on atomic oxygen oxidation could improve designs of fire-retardant and rust-resistant material on Earth. Interactions between various materials and solar ultraviolet radiation could improve terrestrial structures, such as plastic siding for houses. In addition, the MISSE experiments could lead to better protective designs for communications and weather satellites.

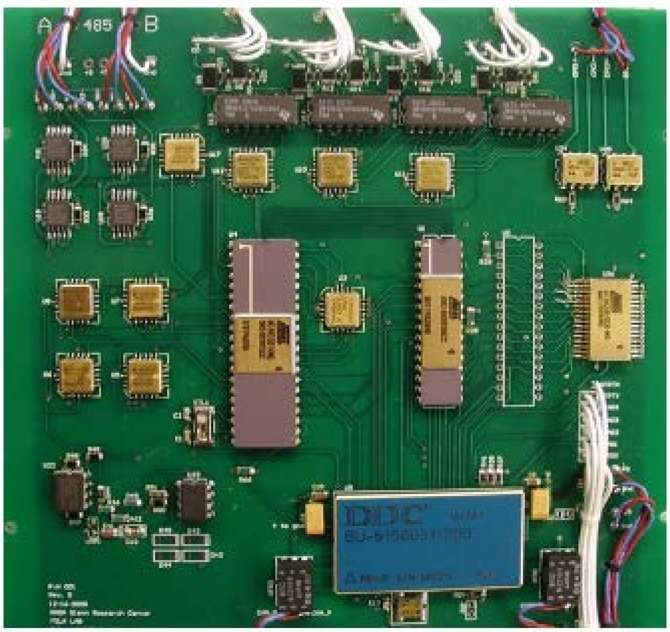
SPACE BENEFITS

Many of the materials and sensors tested in the MISSE experiments could be incorporated into new spacecraft designs. Advanced materials tested with MISSE could also improve the performance of satellites, solar cells, and other space-based technology. Missions on other planets have already benefitted from MISSE research: a static-dissipating paint tested in a previous MISSE experiment now coats components of NASA’s Curiosity Mars rover.

RESULTS

The following information is a sampling of the results obtained from MISSE-8 thus far.

The Communications Interface Board (CIB), developed with radiation tolerance and reliability as the primary design considerations, was an improved communications architecture demonstration on the ISS. MISSE-7 was the first spaceflight of this technology. The CIB simplified the communications interface to the ISS for real-time health monitoring, telemetry, and control of resident sensors or experiments. With over 40 months of spaceflight operation, the CIB successfully supported 2 sets of flight experiments: 1) the silicon carbide junction gate field-effect transistor (SiC JFET) is a high-temperature component that is used throughout a spacecraft including health monitoring in extremely hot environments. 2) the second Forward Technology Solar Cell Experiment (FTSCE II) demonstrated solar cell health monitoring on the ISS with real-time telemetry enabled by the CIB. The CIB accomplished this by acting as a bridge between the ISS low-rate telemetry (LRT) bus and the sensors that allowed for 2-way command and telemetry data transfer. The CIB, currently operating in flight on the ISS, also enabled future materials, software, and device development, which lead to further use in health monitoring systems.



Photograph of the flight Communications Interface Board circuit board. This image was taken prior to delivery, during functional testing of the circuit board, and prior to the insertion of the flight MIL-STD-1553 transceiver. NASA image.

PUBLICATION(S)

Krasowski MJ, Prokop NF, Flatico JM, et al. CIB: An improved communication architecture for real-time monitoring of aerospace materials, instruments, and sensors on the ISS. *The Scientific World Journal.* 2013;2013(185769):12 pp. doi: 185769.

This investigation is ongoing and additional results are pending publication.

Rigidizable Inflatable Get-Away-Special Experiment (RIGEX)

Research Area: Spacecraft Materials
Expedition(s): 16
Principal Investigator(s):
- Richard Cobb, PhD, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio

Research Objectives

Rigidizable Inflatable Get-Away-Special Experiment (RIGEX) operates in the Space Shuttle Cargo Bay and is designed to test and collect data on inflated tubes that are heated and cooled to form stiff structures in space.

Earth Benefits

This technology can lead to an increase in communication satellites that provide television, telephone, and communication services.

Space Benefits

Inflatable structures can be used for antennas, communication satellites, trusses for space stations, and support structures for solar sails and can also provide a light-weight, compact, and cost-reducing option for future spacecraft missions.

View of the RIGEX payload at the Space Station Processing Facility.

Results

There are no published results.

This investigation is complete and all results are published.

EUROPEAN TECHNOLOGY EXPOSURE FACILITY-THERMOMETER (EUTEF-EUTEMP)

Research Area: Thermal Management Systems
Expedition(s): 16-20
Principal Investigator(s):
- J. A. Romera, European Space Agency, Noordwijk, Netherlands

RESEARCH OBJECTIVES

European Technology Exposure Facility-Thermometer (EuTEMP) is an autonomous, battery-powered, multi-input thermometer that is used to measure temperatures on the European Technology Exposure Facility (EuTEF) during the unpowered transfer from the Shuttle Cargo Bay to the Columbus External Payload Facility to which EuTEF was attached for 18 months. Some of the EuTEF instruments could be sensitive to temperature variations, and ESA wants to determine what temperatures would be experienced during the transfer phase.

RESULTS

EuTEMP started recording temperature data 8 hours after activation of the 28V Stay Alive Feeders, which occurred on February 7, 2008. This was just under 80 minutes after launch of STS-122 Space Shuttle *Atlantis*. Once in orbit, the shuttle's cargo bay doors were opened to allow exposure of the shuttle's environmental control and life support system radiators for heat rejection of the orbiter's systems. Temperatures then decreased while in the usual cargo bay facing Earth, which is a standard attitude for the shuttle and also showed a decrease whenever Inertial Measurement Unit (IMU) alignment maneuvers were made that pointed the bay to space. The temperatures also decreased during rendezvous and docking with the International Space Station (ISS).

Following docking, the temperatures measured by EuTemp started rising after the Columbus laboratory was removed from the shuttle cargo bay (after 20.00 GMT) on February 10 for installation on the ISS. Two negative peaks followed on February 13 due to spacewalk activities to install a new Nitrogen Tank Assembly. The first peak was due to deactivation of the 28V Stay Alive Feeders between 15.26 and 16.36 GMT to remove the new Nitrogen Tank Assembly (NTA) from the cargo carrier in the shuttle's cargo bay (to which EuTEF and the Solar facility were also installed). The second peak was due to deactivation of the 28V feeders between 18.36 and 20.02 GMT to install an old Nitrogen Tank Assembly back onto the cargo carrier in the shuttle's cargo bay. A similar small peak was experienced on February 15 due to removal of the solar facility from the cargo carrier (feeders deactivated from 14:40-14:55 GMT).

The most significant drop was seen on February 15 after 16:56 GMT (when the feeders were again deactivated) due to the transfer of the EuTEF facility (with EuTemp) from the cargo bay to the Columbus External Facility. Following its installation, the temperatures started stabilization after 20:03 on February 16 after activation of the 120V feeders on the external Payload Facility.

This investigation is complete; however no publications are expected.

Heat Transfer Performances of a Grooved Heat Pipe (Heat)

Research Area: Thermal Management Systems
Expedition(s): 8 and 9
Principal Investigator(s):
- Jean-Claude Legros, University of Brussels, Belgium
- Laurent Barremaecker, Euro Heat Pipes, Nivelles, Belgium

Research Objectives

The goal of the Heat Transfer Performances of a Grooved Heat (Heat) experiment is the improvement of heat pipe design, not only for future application in spaceflight and space research but also for improved cooling systems here on Earth.

Internal view of Heat Transfer Performances of a Grooved Heat Pipe experiment container. EHP image.

Results

Typical burn-out conditions were analyzed in order to derive the maximum heat transport capabilities of the heat pipe. The heat transfer coefficients were also derived before the burn-out conditions.

- For the heat transport capability, it can be noticed that the performances of the AG110 (the specific aluminum grooved profile under testing) in weightlessness were equivalent or higher than the 1g horizontal conditions.
- For the heat transfer coefficient, a very significant improvement is observed in microgravity. For equivalent test configurations, the improvement factor was from 2 to 2.3 times better in weightlessness.
- The preliminary software correlation showed that the EHP weightlessness predictions were in line with the measurements (about 14%).

Very promising results were recorded and show good correlation with the heat pipe involved physical laws and predictions. Further tests in weightlessness are now needed to cover heat pipes with larger diameter and full operational temperature range.

Publication(s)

Goffaux C, Van Oost S, Barremaecker L. Numerical, experimental, and robust design investigations of a grooved heat pipe in microgravity-like conditions. *6th ASME International Conference* on Nanochannels, *Microchannels, and Minichannels*, Darnstadt, Germany; June 23-25, 2008: 827-834.

This investigation is complete and all results are published.

Transport Environment Monitor Packages (TEM)

Research Area: Thermal Management Systems
Expedition(s): 19-20, 25-26, ongoing
Principle Investigator(s):

- Mitsuyo Masukawa, Japan Aerospace Exploration Agency, Tsukuba, Japan
- Hiroe Kobayashi, Japan Aerospace Exploration Agency, Tsukuba, Japan
- Kohichi Shibasaki, Japan Aerospace Exploration Agency, Tsukuba, Japan

Research Objectives

The Transport Environment Monitor (TEM) investigation monitors temperatures inside cargo vehicles bound for the International Space Station. Environmental conditions during transportation are very important for biological specimens and reagents for life-science experiments. This investigation uses commercial small temperature data loggers to record the environmental conditions of cargo vehicles.

Transport Environment Monitor is composed of 3 commercial, small temperature loggers. JAXA image.

Earth Benefit

New knowledge is expected to be the major benefit of this investigation.

Space Benefit

It is now possible to offer temperature survey data in each vehicle to the users who are considering launching cargo aboard each vehicle to ISS. Thereby, it becomes easy to plan for launch or return of experimental samples.

Results

TEM packages were installed inside soft bags and launched by each assigned vehicle. Data loggers of TEM automatically measured and recorded temperatures during transportation to the ISS. After ISS docking, TEM packages were moved to an in-orbit storage area in the JEM. Data eventually retrieved is provided to the science team for analysis.

This investigation is ongoing and additional results are pending publication.

RESULTS FROM ISS OPERATIONS AND OTHER PROJECTS

Although not part of a formal investigation or payload on ISS, medical, environmental, and engineering data that are collected as part of the operation of ISS are an important source of information for scientific study. We include and summarize the results of operations that have generated valuable scientific data that enable scientists and engineers to better define problems and understand the space environment.

International Space Station Summary of Research Performed (ISS Summary of Research)

Research Objectives

The International Space Station (ISS) Program lends itself to periodically summarizing the status of the program as a whole or sometimes a particular area. The purpose of this entry is to capture those publications in one location for accessibility to the community as a whole.

Earth Benefits

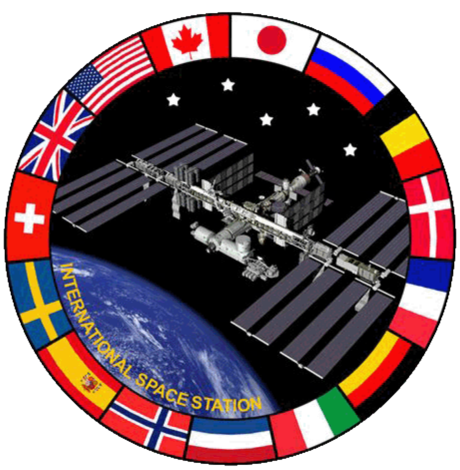
This project is applied to new knowledge and not specifically to advances in space exploration.

Space Benefits

New knowledge is expected to be the major benefit of this project.

Results

The ISS partnership has produced substantial research in a wide range of disciplines. Benefits come from the engineering development, the international partnership, and from the research results. To date, over 63 countries have directly participated in some aspect of ISS research or education (Thumm 2012).



The configurability and human-tended capabilities of the ISS provide a unique platform. The international utilization strategy is based on research ranging from physical sciences, biology, medicine, psychology, to Earth observation, human exploration preparation and technology demonstration. The ability to complete follow-on investigations in a period of months allows researchers to make rapid advances based on new knowledge gained from ISS activities. During the utilization phase, the ISS partners are working together to track the objectives, accomplishments and the applications of the new knowledge gained. Scientific knowledge and new technologies derived from research on the ISS will be realized through improving quality of life on Earth and future spaceflight endeavors (Thumm 2010).

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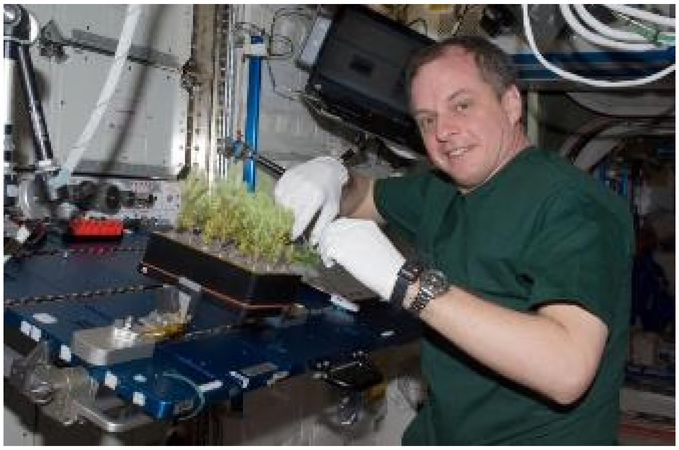

ISS023E036876 – NASA astronaut T.J. Creamer, services the Advanced Plant Experiments on Orbit-Cambium experiment in the Destiny laboratory of the International Space Station. NASA image.

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ISS038E16506 – The Salt Lake City metropolitan area is located along the western front of the Wasatch Range in northern Utah. NASA image.

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The ten SPHERES Zero-Robotics student teams watch 2 views of the International Space Station competition live from MIT. John Tylko from the Aurora Flight Science Corporation image.

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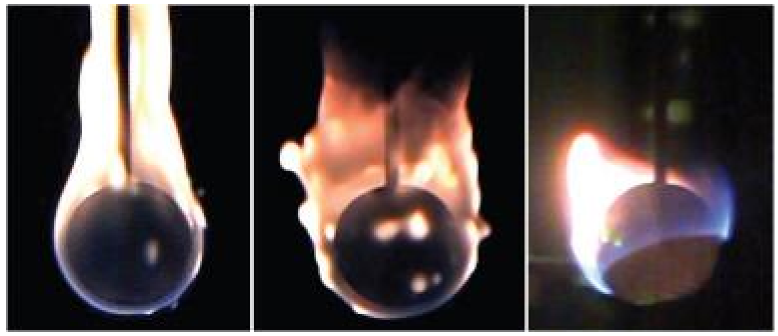

Zero-g facility test burning a 2 cm diameter PMMA sphere in 30 cm/s airflow. Left: 1 g; Middle: 0 g (1 s after drop); right: 0 g (4 s after application of nitrogen extinguishing agent). NASA image.

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ISS014E18822 – Astronaut Suni Williams, Expedition 14 flight engineer, works with the Lab-on-a-Chip Application Development-Portable Test System (LOCAD-PTS). Williams is placing the sample mixed with water from the swabbing unit into the LOCAD-PTS cartridge. NASA image.

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This investigation is ongoing and additional results are pending publication.

Buzz Lightyear

Research Area: Educational Activities and Outreach: Commercial Demonstrations
Expedition(s): 17-22
Principal Investigator(s):
- Mark T. Severance, NASA's Johnson Space Center, Houston, Texas

Video screen capture of Buzz Lightyear on the International Space Station with the fish that don't require a fish bowl. NASA image.

Research Objectives

Disney and NASA have come together to develop hands-on educational activities, demonstrations, and exhibits centered around the flight of Buzz Lightyear on STS-124, his year aboard the International Space Station (ISS), and his return on STS-128. These activities are designed to encourage children and young adults to pursue their dreams and develop an interest in exploration and discovery.

Earth Benefits

This partnership was created to give children a unique insight into life on the ISS, how to get there and back home again, and the unique challenges of microgravity through the perspective of one of Disney/Pixar's most enduring and favorite characters, Buzz Lightyear.

Space Benefits

This investigation is applied to new knowledge and not specifically to advances in space exploration.

Results

Disney, Pixar, and NASA chronicle Buzz Lightyear's more than 450 days in space through hands-on educational activities, demonstrations, and exhibits. Disney creates 6 web-based games based on Buzz Lightyear's experiences. Educational worksheets, games, and videos are also available. The following games were created and made available at: http://www.nasa.gov/externalflash/Buzz_Lightyear/web/.

Buzz Lightyear Returns From Space: To Infinity and Beyond!

- **Mission Game 1 - Load the Shuttle:** Buzz needs help loading the space shuttle as the equipment he takes with him cannot exceed a determined weight.
- **Mission Game 2 - Mission Matchup:** Help Buzz discover some of the accomplishments that lead humankind into space and ultimately to the construction of the International Space Station.
- **Mission Game 3 - I Spy:** The shuttle's liftoff really shook things up! Help Buzz find a list of items.
- **Mission Game 4 - Connect it:** Using commands, program a robotic arm to attach the Kibo module to the space station.

- **Mission Game 5 - Toys in Space:** Move Buzz to the platforms to learn how different toys behave in space. This game includes videos demonstrating the toys on Earth and the ISS.
- **Mission Game 6 - Putting It Together:** Help Buzz assemble the ISS and learn some fun facts about its construction.

Video screen capture of Buzz Lightyear in orbit with fellow crew members Greg Chamitoff and Mike Finke. NASA image.

Pixar created 3 Buzz Lightyear "Mission Logs" for the Toy Story 1, 2, and 3 Blue-ray DVDs. The Mission Logs are found in the bonus feature segments on each DVD.

- **Episode 1 (Toy Story 1) - Blast Off:** Buzz explains the time line from launch to rendezvous with the ISS. He also describes the 3 main parts of the shuttle. He explains how the ISS was built.
- **Episode 2 (Toy Story 2) - International Space Station:** Buzz discusses how hard crew members work every day to keep the ISS running. He explains why crew members must exercise to keep their muscles and bones healthy in microgravity. He also describes space suits and extra vehicular activities (spacewalks).
- **Episode 3 (Toy Story 3) - The Science of Adventure:** While on the ISS, Buzz observes hundreds of experiments in microgravity. He looks at studying Earth science from a space ship and the physics of a shuttle descent.

This investigation is complete and all results are published.

Get Fit for Space Challenge with Bob Thirsk Education (Get Fit for Space)

Research Area: Educational Activities and Outreach: Cultural Activities
Expedition(s): 19-22
Principal Investigator(s):
- Robert Thirsk, PhD, Canadian Space Agency, St. Hubert, Quebec, Canada

Research Objectives

The Get Fit for Space Challenge with Bob Thirsk (Get Fit for Space) invites Canadian citizens to celebrate the historic mission of Canada's first Expedition along with crew member Dr Bob Thirsk and to promote healthy living amongst Canadian citizens by tracking fitness data using a pedometer, allowing the citizens to interact with Canada's space program via innovative multimedia.

Earth Benefits

From an educational perspective, space exploration missions both inspire students, young and old, and motivate them to choose advanced studies and careers in the sciences and engineering. Participants were given the opportunity to directly contribute to Canada's space program, while enhancing their own studies and career prospects.

Dr Bob Thirsk together with his son Elliot is inviting Canadians to take the "Get Fit for Space" challenge. Canadian Space Agency image.

Space Benefits

Get Fit for Space allowed crew member, Bob Thirsk, to introduce the next generation of explorers to the space environment.

Results

To celebrate Canada's first Expedition mission, the Canadian Space Agency challenged their citizens to "Get Fit for Space with Bob Thirsk," the first Canadian to launch to the International Space Station (ISS) aboard a Soyuz spacecraft. Canadian citizens were provided the opportunity to engage in activities such as running, walking, cycling, and swimming, as they prepared to blast off and reach new fitness heights along with Canada's space program.

Participants signed up for the challenge on the Canadian Space Agency's website, and received a "Get Fit for Space" pedometer given away to the first 10,000 people to enroll in the program. Participants would enter their fitness data on CSA's website as they "virtually" traveled the 340 km to the ISS.

Dr Thirsk virtually met the participants at the airlock, invited them in, and provided a personal tour of his off-world home. Over the course of the long-duration mission, participants were allowed to interact with Dr Thirsk through photos, live weekly mission downlinks, media events, podcasts, inflight illustrations, and other innovative multimedia. In addition, Dr Thirsk delivered a “Get Fit for Space” challenge to the nation and broadcasted a personal message to the Canadian public from the ISS on special occasions.

This investigation is complete; however no publications are expected.

Amateur Radio on the International Space Station (ARISS)

Research Area: Educational Activities and Outreach: Educational Demonstrations
Expedition(s): 1-26
Principal Investigator(s):
- Frank Bauer, NASA's Goddard Space Flight Center, Greenbelt, Maryland

Research Objectives

With the help of Amateur Radio Clubs and ham radio operators around the globe, astronauts and cosmonauts aboard the International Space Station (ISS) have been speaking directly with large groups of the general public, showing teachers, students, parents, and communities how amateur radio energizes students about science, technology, and learning. The overall goal of Amateur Radio on the ISS (ARISS) is to get students interested in mathematics and science by allowing them to talk directly with the crews living and working aboard the ISS.

Students attending Space Camp at the Euro Space Center in Belgium gather in an auditorium to speak with astronaut Ed Lu, aboard the International Space Station during Expedition 7 in July 2003. ESA image.

Earth Benefits

Using a new approach in the classroom on spaceflight, science, and mathematics will capture the imagination of students. Allowing students to participate in activities that directly involve space will inspire them to pursue careers in science and engineering.

Space Benefits

ARISS introduces the next generation of explorers to the environment of space.

Results

ARISS has been instrumental in using amateur radio to connect teachers and students to the crew of the ISS sparking an interest in science and math for many students around the world. The ARISS activities continue to be met through the ISS Ham Radio investigation.

Publication(s)

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This investigation is complete and all results are published.

EDUCATION – HOW SOLAR CELLS WORK (EDUCATION-SOLAR CELLS)

Research Area: Educational Activities and Outreach: Educational Demonstrations
Expedition(s): 13
Principal Investigator(s):
- Christopher J. Ferguson, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

The astronaut discusses in detail how solar cells work and how they provide energy. The activity is videotaped for use in classroom lectures.

EARTH BENEFITS

Using a new approach in the classroom to spaceflight, science, and mathematics will capture the imagination of students. Allowing students to participate in activities that directly involve NASA will inspire them to pursue careers in science and engineering.

SPACE BENEFITS

Education-Solar Cells introduces the next generation of explorers to the environment of space.

Dan Hern, Oklahoma State University (OSU) masters student in aviation and space education, works on solar cell hardware that will fly aboard STS-115. OSU image.

RESULTS

The Teaching From Space Office at NASA's Johnson Space Center worked closely with Astronaut Christopher Ferguson, pilot of STS-115 (*Atlantis*); Lockheed Martin Corporation; Oklahoma State University and the Student Observation Network to provide classroom versions of solar cells and learning activities to NASA Explorer Schools. These activities have been designed to engage students through the STS-115 primary mission objective, deployment of a new solar array on the International Space Station (ISS).

Ferguson demonstrated how solar cells work in front of a video camera and discussed, in detail, how solar cells provide energy; open circuit voltage; and power measurement with resistors. With the aid of LED lights, a visual demonstration of solar flux was also performed.

Lockheed Martin Corporation donated solar cells to this project; engineering students at Oklahoma State University linked the solar cells together in packs for use in the space shuttle demonstration and for distribution to the schools. The NASA Student Observation Network created lessons and activities that were provided to the NASA Explorer Schools and the Aerospace Education Specialists when teaching this lesson.

This investigation is complete and all results are published.

International Space Station In-flight Education Downlinks (In-flight Education Downlinks)

Research Area: Educational Demonstrations
Expedition(s): 1-ongoing
Principal Investigator(s):
- Becky Kamas, NASA's Johnson Space Center, Houston, Texas

Research Objectives

International Space Station In-flight Education Downlinks (In-flight Education Downlinks) support the Agency's efforts to encourage K-12 students to study and pursue careers in science, technology, engineering, and math (STEM). Downlinks are facilitated by Teaching from Space, a NASA Education office, and use the unique experience of human spaceflight to promote and enhance STEM education.

Earth Benefits

In-flight Education Downlinks provide a new approach for capturing the imagination of students with respect to spaceflight and STEM subjects. Additionally, allowing students to participate in an activity that utilizes NASA-unique resources inspires them to pursue careers in science and engineering.

From 210 miles above Earth, Naval Postgraduate School alumni and Expedition 14 International Space Station Commander, Michael Lopez-Alegria, thrilled an audience of students, faculty, staff, and their kids on April 5, 2007. Pictured above is 8-year-old Mark and 9-year-old Julianne Lopez-Alegria asking Astronaut Michael Lopez-Alegria what it's like to float in microgracity and what does Earth look like from space. Photo by Javier Chagova.

Space Benefits

In-flight Education Downlinks introduce the next generation of explorers to the environment of space.

Results

As of July 2013, millions of students have participated in In-flight Education Downlinks, including 6 million students that were reached during a Channel One (network broadcast to schools) downlink during Expedition 18 and the STS-119 mission.

The following quotes are from students and educators that have participated in a downlink:

- “I didn’t know about all the good jobs we could get when we grow up. My parents say they didn’t have these opportunities when they were growing up, but we do.” - 7th grade student in Phelps, Kentucky
- “That's a moment I'll never forget. It's going to live with me for the rest of my life.” - 9th grade student in Lakeland, Florida
- “This is a once-in-a-lifetime opportunity for our students to meet an astronaut and to see that they can achieve anything they want in life.” - Elementary school educator in Springfield, Massachusetts
- “A lot of our students at the Central Florida Aerospace Academy, because of our focus, they want to be those people. So, for them to talk to those leaders, the people that are living the dream they have, was unbelievable.” - High school educator in Lakeland, Florida

PUBLICATION(S)

Ivey TA, Colston NM, Thomas JA. Bringing space science down to earth for preservice elementary teachers. *Electronic Journal of Science Education*. 2015;19:19.

This investigation is ongoing and additional results are pending publication.

Particle Flux Demonstrator (Particle Flux)

Research Area: Educational Activities and Outreach: Educational Demonstration
Expedition(s): 16, 18-20, 29-ongoing
Principal Investigator(s):
- Mark Pearce, Royal Institute of Technology, Stockholm, Sweden

Research Objectives

The Particle Flux Demonstrator (Particle Flux) is designed for use aboard the International Space Station (ISS). Particle Flux demonstrates the basic properties of the ionizing radiation environment aboard the ISS for educational purposes. Activities are filmed and included in a media package for high school and university students.

Particle Flux Demonstrator. ESA image.

Earth Benefits

Particle Flux provides a new approach for teaching students about ionizing radiation, allowing them to participate in an activity that utilizes the unique resources of ISS inspires them to pursue careers in science and engineering.

Space Benefits

This project introduces the next generation of space explorers to the environment of space.

Results

Hundreds of students have participated in capturing data for Particle Flux in Sweden, Norway, and Denmark.

This investigation is ongoing; however no publications are expected.

Science of Opportunity (Saturday Morning Science)

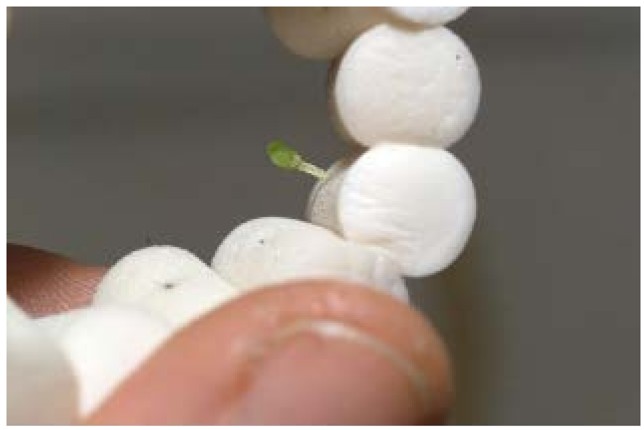
Research Area: Educational Activities and Outreach: Educational Demonstrations
Expedition(s): 6
Principal Investigator(s):
- Donald R. Pettit, PhD, NASA's Johnson Space Center, Houston, Texas

Research Objectives

Don Pettit, Expedition 6 NASA International Space Station science officer, used his free time, usually Saturday mornings, while living aboard the International Space Station to shed the light of science on a variety of subjects for students of all ages. These demonstrations were chronicled and dubbed "Saturday Morning Science."

Earth Benefits

The simple demonstrations using everyday material for Saturday Morning Science will play a major role in inspiring the next generation to take the journey into space.



ISS006E20853 – Close-up view of earplugs strung together by NASA International Space Station Science (ISS) Officer, Don Pettit, to create a sprouter for basil and tomato seeds used in the Growing Plants in Zero-G project of Saturday Morning Science during ISS Expedition 6. NASA image.

Space Benefits

The simple inspired demonstrations performed during Saturday Morning Science will provide insight into how fluids and other objects behave in microgravity compared to the gravity on Earth.

Results

Several articles have been published on Saturday Morning Science. Although simple, Saturday Morning Science often demonstrated phenomena that had not been seen in microgravity.

An article published in *Sky and Telescope* in October 2003 titled "Shooting the Heavens from Space" discussed the amazing views and images captured by astronauts as they live and work in space.

In April 2004, another article published in *Sky and Telescope* titled "Building Planets in Plastic Bags" based on water observations performed as a Saturday Science demonstration. The demonstration involved observing how salt grains clumped in water while in microgravity. During this demonstration, Pettit unknowingly demonstrated middle stage planetary accretion. A summary paper of the demonstration was published in *Lunar and Planetary Science* in 2004 concluded that although the demonstration lacked formal controls to identify the exact clumping mechanism, the mechanism is obviously electrostatic. Future investigations of this phenomenon will use realistic materials such as rock dust.

Video screen shot of a 13 cm free sphere of water stabilized by a wire loop aboard the International Space Station during Expedition 6. NASA image.

PUBLICATION(S)

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Love SG, Pettit DR. Fast, repeatable clumping of solid particles in microgravity. *35th Lunar and Planetary Science Conference*, Houston, TX; 2004.

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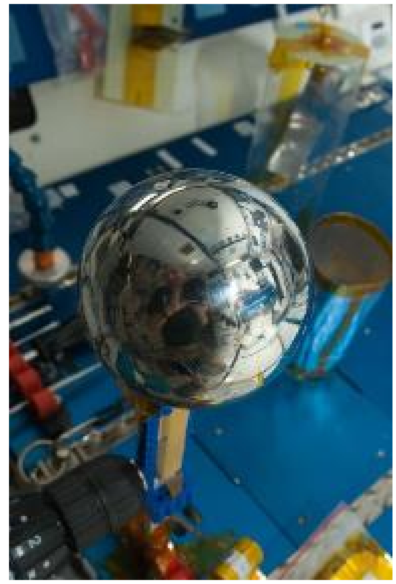
This investigation is complete and all results are published.

SCIENCE OFF THE SPHERE

Research Area: Educational Activities and Outreach: Educational Demonstrations
Expedition(s): 29-32
Principal Investigator(s):
- Donald R. Pettit, PhD, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

Science off the Sphere is a collaborative effort between Astronaut Dr Don Pettit and the American Physical Society demonstrating unique physical properties that occur on the International Space Station.



ISS031E035391 – Close-up view of a 4 inch polished metal sphere used to construct a Van de Graaff generator, along with Lego bricks, a rubber band, aluminum foil, and a drill. The image of Expedition 31 flight engineer Don Pettit is reflected in the sphere. Image was taken in the Harmony Node 2 during Expedition 31. NASA image.

EARTH BENEFITS

The simple demonstrations using everyday materials for Science off the Sphere play a major role in inspiring the next generation of scientists, engineers, and explorers.

SPACE BENEFITS

Science off the Sphere demonstrations provide insight into how fluids and materials behave differently in microgravity compared to gravity on Earth.

RESULTS

Astronaut and chemical engineer, Dr Don Pettit, demonstrates unique physical phenomena that occur in microgravity during his free time on the international Space Station. The videos are downlinked and posted to the Science off the Sphere website (http://www.physicscentral.com/explore/sots/). At the end of each video Dr Pettit poses a challenge question. A winner is chosen randomly from all correct answers submitted. The winner's name is read from space and they receive a snazzy T-shirt from Earth. The following videos are found at the Science off the Sphere website.

PUBLICATION(S)

Fontana P, Pettit DR, Cristoferetti S. Sodium chloride crystallization from thin liquid sheets, thick layers, and sessile drops in microgravity. *Journal of Crystal Growth*. October 15, 2015;428:80-85. doi: 10.1016/j.jcrysgro.2015.07.026.

Fontana P, Schefer J, Pettit DR. Characterization of sodium chloride crystals grown in microgravity. *Journal of Crystal Growth*. June 2011;324:207-211. doi: 10.1016/j.jcrysgro.2011.04.001.

This investigation is complete and all results are published.

Periodic Fitness Evaluation with Oxygen Uptake Measurement (PFE-OUM)

Research Area: Human Research: Cardiovascular and Respiratory Systems
Expedition(s): 13-16
Principal Investigator(s):
- Filippo Castucci, MD, European Astronaut Centre, Cologne, Germany

ISSE01356862 – NASA International Space Station (ISS) Science Officer Jeff Williams assisting Flight Engineer-2, Thomas Reiter performing his Periodic Fitness Evaluation with Oxygen Uptake Measurement on the CEVIS (Spell out CEVIS) during ISS Expedition 13. NASA image.

Research Objectives

The Periodic Fitness Evaluation with Oxygen Uptake Measurement (PFE-OUM) will demonstrate the capability of crew members to perform periodic fitness evaluations (PFE) with continuous oxygen consumption measurements within 14 days after arrival on the International Space Station, and once monthly during routine PFEs. Once the capability of the pulmonary function system (PFS) to perform PFEs is verified, crew members will be able to integrate their monthly PFE with oxygen consumption measurements to fulfill the requirement for cardiovascular fitness evaluations during long-duration spaceflight.

Earth Benefits

Little information is currently available on the effects of long-term exposure to a closed life control system microgravity environment on aerobic capacity of humans. This information is important to maintain crew health during long-duration exploration. The data will also provide valuable insight into the aerobic capacity of teams in closed environments on Earth, such as arctic bases and submarines.

Space Benefits

The PFE-OUM measurements will help flight surgeons to better understand the decline in cardiovascular function that occurs during long-duration stays in microgravity.

Results

Analysis of data from PFE-OUM is ongoing, conclusive results will be published upon completion of data analysis.

This investigation is complete; however additional results are pending publication.

International Space Station Medical Monitoring (ISS Medical Monitoring)

Research Area: Human Research: Crew Healthcare Systems
Expedition(s): 1-ongoing

Research Objectives

Medical Monitoring On Board the International Space Station (ISS) (Medical Monitoring) involves the collection of health data at regular intervals from long-duration International Space Station (ISS) crew members. Crew health before, during and following spaceflight is essential to overall ISS mission success. All of the partner agencies recognize the importance of crew health to mission success and are dedicated to maintaining the health of all crew members throughout all phases of ISS missions.

Earth Benefits

Maintaining crew member health and safety while in orbit better ensures that crew member functionality is not jeopardized as a result of time spent on a mission, therefore, allowing them to resume life on Earth unaffected by space travel.

ISS030E012609 – NASA astronaut Dan Burbank (foreground), Expedition 30 commander, and Russian cosmonaut Anton Shkaplerov, flight engineer, participate in a Crew Health Care System medical contingency drill in the Destiny laboratory of the International Space Station. This drill gives crew members the opportunity to work as a team in resolving a simulated medical emergency aboard the space station. Image courtesy of NASA.

Space Benefits

The optimization of crew health and safety increases the productivity of their performance while conducting in-orbit operations. With humans currently occupying the International Space Station (ISS) for 6 months and space exploration missions of 1 to 3 years on the horizon, preservation of crew member health status and monitoring is a major objective of the international space community.

Results

Medical Monitoring covers a wide array of distinct ISS investigational studies. Below are some of the results that encompass the Medical Monitoring on ISS.

A study has found that long-duration, but not short-, spaceflight prolongs cardiac electrical conduction and heart muscle recovery. Shifts in systemic cardiac regulation and primary cardiac changes may be responsible. Long-duration flight is associated with slower heart rate and may increase arrhythmia susceptibility. It is recommended that medication that decreases the heart rate should be administered with caution during and after long-duration spaceflight (D'Aunno 2003).

ISS020E040433 – Nicole Stott performs routine tasks aboard the International Space Station while ECG (using the HRF Holter Monitor 2) and continuous blood pressure data (using the ESA Cardiopres) are recorded for the Integrated Cardiovascular experiment. Image courtesy of NASA.

Highly sensitive and selective cardiovascular screening before flight is the most effective method of reducing the risk of a cardiac event in space. Current studies support adding electron-beam computed tomography (EBCT) and highly selective C-(capsular) reactive protein (hsCRP) for diagnosis of coronary artery disease (CAD) in current and future candidates for space missions. The recommended initial astronaut selection and long-duration mission assignment screening algorithms use EBCT-derived calcium scores and serum hsCRP levels to screen for CAD and predict individual cardiac risk. The proposed screening methods with the latest diagnostic capabilities attempt to improve on the current selection and retention standards, and also fulfill the operational space medicine goal of preventing the occurrence of cardiovascular illness or impaired performance during spaceflight (Hamilton 2006).

Research has shown that the immune system is less efficient during spaceflight. Miniature and semi-automated diagnostic systems to perform a set of biological and immunological tests aboard spacecrafts will allow the study of the causes of space-related immune deficiency and the development of countermeasures to maintain an optimal immune function and prevent infectious diseases during space missions. By monitoring the astronaut's immune responses on one side, and their environment on the other side, new set of diagnostic tools will fill our knowledge gap and decrease one of the risks of space missions. In addition, the development of a micro-flow cytometer (cell counter) with the characteristics needed for spaceflight (low power consumption, small footprint) will have great impact on point-of-care diagnostics and medical facilities in remote areas and resource-poor countries and in situ environmental monitoring and control. Similarly, the automation and miniaturization of DNA-based analytical tests will be greatly beneficial to medical care on Earth.

Three independent subject groups that included balance impaired patients, normal subjects before and after 30 minutes of 40% bodyweight unloaded treadmill walking, and astronauts before and after long-duration spaceflight were tested to determine body load-sensing and vestibular(inner ear canals) sensing influences on head movement control during treadmill walking after long-duration spaceflight. Data collected show that exposure to unloaded walking caused a significant increase in head pitch movements in normal subjects, whereas the head pitch movements of impaired patients were significantly decreased. This is the first evidence of adaptation of vestibular mediated head movement responses to unloaded treadmill walking. Astronaut subjects showed mixed response of both increases and decreases in the amplitude of head pitch movement. These results indicate that body load-sensing input centrally influences vestibular input and can adaptively modify vestibular control of head-movement during locomotion. Thus, spaceflight may cause central adaptation of the converging vestibular and body load-sensing systems leading to alterations in head movement control (Mulavara 2012).

PUBLICATION(S)

Mulavara AP, Ruttley TM, Cohen HS, et al. Vestibular-somatosensory convergence in head movement control during locomotion after long-duration spaceflight. J*ournal of Vestibular Research*. 2012;22(2-3):153-166. doi: 10.3233/VES-2011-0435.

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Cohen, Vernon, Bergeron. New molecular technologies against infectious diseases during spaceflight. *Acta Astronautica.* 2008;63:769-775. doi: 10.1016/j.actaastro.2007.12.024.

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This investigation is ongoing and additional results are pending publication.

Clinical Nutrition Assessment of ISS Astronauts (Clinical Nutrition Assessment)

Research Area: Human Research: Integrated Physiology and Nutrition
Expedition(s): 1-14
Principal Investigator(s):
- Scott M. Smith, PhD, NASA's Johnson Space Center, Houston, Texas

Research Objectives

Nutritional assessments of astronauts before, during, and after spaceflight ensure adequate intake of energy, protein, and vitamins during missions. Scientists use the information to understand the connections between nutrition and human health during spaceflight, and to develop effective dietary strategies to reduce adverse health impacts.

Earth Benefits

Increased understanding of the connections between nutrition and bone loss has potential value for patients suffering bone loss on Earth.

Space Benefits

Nutritional monitoring is vital to ensuring crew health during long-duration spaceflight. The results are being used to identify specific effects of microgravity on nutrient-dependent processes such as vitamin uptake, antioxidant production, and metabolism of iron. Alterations to nutrient assimilation in microgravity are also important for studies of bone loss while in microgravity.

Results

Results have been compiled and analyzed for International Space Station (ISS) crew members. Intake of energy (relative to World Health Organization standards) was observed to generally decrease over time during missions. However, when dietary counseling was provided to a single astronaut during flight, adequate energy intake was maintained throughout the mission. Body weight, total bone mineral content, and bone mineral density decreased during flight. Antioxidant capacity decreased during flight, leading to increased susceptibility to genetic damage from radiation. Vitamin D concentration in crew bone was decreased, and bone resorption increased, by long exposure to microgravity. The relative concentrations of other blood and urine analytes preflight and postflight were variable and subject to several confounding factors that limit conclusions as to particular effects of spaceflight (Smith, 2005, 2008). The results of this study formed the basis for the nutrition and repository experiments, currently being operated on the ISS.

ISS012E12635 – International Space Station Science Officer Bill McArthur during expedition 12, during check-out of the SLAMMD hardware of HRF-2. Measuring the mass of a crew member in space is difficult because mass does not equal weight in the absence of gravity. NASA image.

PUBLICATION(S)

Smith SM, Zwart SR, Heer MA, Hudson EK, Shackelford LC, Morgan JL. Men and women in space: Bone loss and kidney stone risk after long-duration spaceflight. *Journal of Bone and Mineral Research*. July 2014;29(7):1639-1645. doi: 10.1002/jbmr.2185.

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Smith SM, Zwart SR, Block G, Rice BL, Davis-Street JE. The nutritional status of astronauts is altered after long-term spaceflight aboard the International Space Station. *Journal of Nutrition*. 2005;135(3):437-443.

This investigation is complete; however additional results are pending publication.

PHARMACOKINETICS AND CONTRIBUTING PHYSIOLOGIC CHANGES DURING SPACEFLIGHT, DETAILED SUPPLEMENTARY OBJECTIVE 632B (PHARMACOKINETICS, DSO 632B)

Research Area: Human Research: Integrated Physiology and Nutrition
Expedition(s): 12-13
Principal Investigator(s):
- Lakshmi Putcha, PhD, NASA's Johnson Space Center, Houston, Texas

RESEARCH OBJECTIVES

The Pharmacokinetics and Contributing Physiologic Changes During Spaceflight, DSO 632B (Pharmacokinetics) is a detailed science objective (DSO) to determine changes in the gastrointestinal function and physiology by examining the pharmacokinetics (process by which a substance is absorbed, distributed, metabolized, and eliminated by the body) of acetaminophen (common pain reliever and fever reducer).

Image of acetaminophen tablets. Gary Gardiner/Bloomberg via Getty Images image.

EARTH BENEFITS

Understanding gastrointestinal disorders and diseases in adverse environmental conditions help to improve delivery methods of medications for treatment, establish innovative, non-invasive ways to measure drug availability in the body, and validate inexpensive ambient storage for biological samples.

SPACE BENEFITS

This project will help scientists improve the design of medications provided to crew members during space exploration to maximize the effect of the medication when taken in microgravity.

RESULTS

Analysis of data from Pharmacokinetics is ongoing, conclusive results will be published upon completion of data analysis.

This investigation is complete; however additional results are pending publication.

VISION IMPAIRMENT AND INTRACRANIAL PRESSURE (VIIP)

Research Area: Human Research: Integrated Physiology and Nutrition
Expedition(s): 1-ongoing

RESEARCH OBJECTIVES

Vision Impairment and Intracranial Pressure (VIIP) project examined the effect of long-term exposure to microgravity on the structure of the eye along with change in distance and near vision of crew members before and after they returned to Earth.

ISS030E235670 – Don Pettit performs Ultrasound Eye Imaging in the Columbus Module of International Space Station during Expedition 30. Image courtesy of NASA.

EARTH BENEFITS

New knowledge is expected to be the major benefit of this project.

SPACE BENEFITS

Possible countermeasures may be developed to mitigate space-induced ocular impairments.

RESULTS

Since 1989, as part of the postflight eye examination, astronauts were queried as to whether they perceived a subjective improvement or degradation in distant or near vision (none, mild, moderate, or severe) during their short- and long-duration missions. Prompted by persistent reports of vision changes, NASA began a stepwise operational process to determine the cause(s). Several ophthalmic procedures were initiated on astronauts, including dilated fundus (the rear portion of the eye) examinations with binocular ophthalmoscopy, cycloplegic refraction, optical coherence tomography (OCT), magnetic resonance imaging (MRI) of orbits, and fundus photography for before and after space missions.

In a follow-up study, twenty-seven astronauts underwent thin-section, three-dimensional, eye orbital, and conventional MRI brain scans. Eight astronauts underwent repeat imaging after an additional mission in space. All astronauts had previous exposure to microgravity. Image analysis of the optic nerve sheath, optic disc, posterior globe, and pituitary gland was performed and compared for association with intracranial evidence of excessive fluid buildup inside the skull, cells, tissues, or body cavities, venous blood clotting in the brain and/or mass lesion.

Visual acuity degradation in astronauts exposed to microgravity is a newly recognized phenomenon. Although the exact mechanism is yet to be fully determined, many MRI findings suggest that intracranial hypertension is an important component. However, a large proportion of astronauts do not show these ocular effects, suggesting there could be variable biologic response to the spaceflight environment and warrants a search for existing risk factors. Standardization of qualitative and quantitative imaging criteria will further help in the identification of asymptomatic changes and allow for the use of countermeasures to mitigate potential long-term vision damage. Future studies involving advance tissue imaging techniques would improve our understanding of the cause-versus-effect relationship of intracranial pressure after exposure to microgravity (Kramer 2012).

PUBLICATION(S)

Chylack Jr LT, Feiveson AH, Peterson LE, et al. NASCA Report 2: Longitudinal study of relationship of exposure to space radiation and risk of lens opacity. *Radiation Research.* 2012;178(1):25-32. doi: 10.1667/RR2876.1.

Kramer LA, Sargsyan AE, Hasan KM, Polk JD, Hamilton DR. Orbital and intracranial effects of microgravity: Findings at 3-T MR Imaging. *Radiology.* 2012;263:819-827. doi: 10.1148/radiol.12111986.

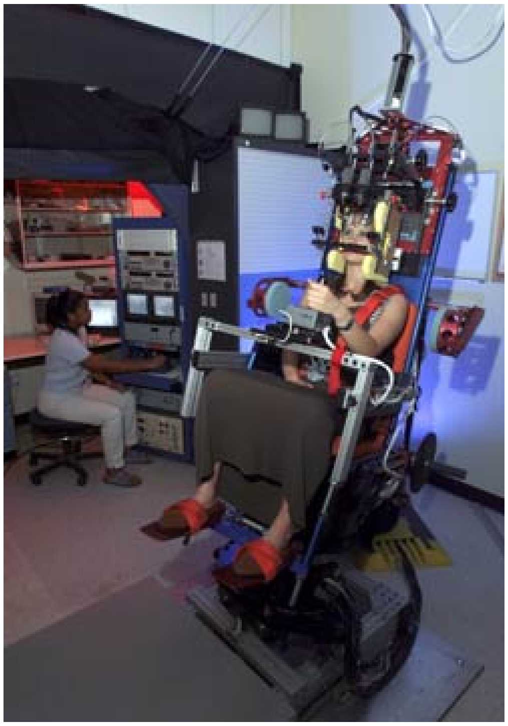
Zwart SR, Gibson CR, Mader TH, et al. Vision changes after spaceflight are related to alterations in folate- and vitamin B-12-dependent one-carbon metabolism. *Journal of Nutrition.* March 1, 2012;142(3):427-431. doi: 10.3945/jn.111.154245.

Mader TH, Gibson CR, Pass AF, et al. Optic disc edema, globe flattening, choroidal folds, and hyperopic shifts observed in astronauts after long-duration spaceflight. *Opthalmology.* 2011; 118(10):2058-2069. doi: 10.1016/j.ophtha.2011.06.021.

This investigation is ongoing and additional results are pending publication.

Off-Vertical Axis Rotation: Eye Movements and Motion Perception Induced By Off-Axis Rotation at Small Angles of Tilt After Spaceflight, Detailed Supplementary Objective 499 (OVAR)

Research Area: Human Research: Nervous and Vestibular Systems
Expedition(s): 10-11
Principal Investigator(s):
- Gilles Clement, PhD, International Space University, Strasbourg, France



Off Vertical Rotation - Measurement of Perception and Video Recording of Eye Movements. ESA image.

Research Objectives

The Eye Movements and Motion Perception Induced By Off-Axis Rotation at Small Angles of Tilt After Spaceflight (OVAR) study allows for better understanding of normal balance and suggests causes for abnormal balance after spaceflight.

Earth Benefits

This study will allow for better understanding of normal balance and suggest causes for abnormal balance in patients on Earth. If OVAR, associated with a 3-D eye movement measuring system, proves that reliable information about otolith organs can be obtained, then this test has obvious clinical value to assess vestibular disorders.

Space Benefits

This study will allow for better understanding of normal balance and suggest causes for abnormal balance related to microgravity exposure. In particular, spaceflight will provide knowledge and understanding of the vestibular system (sensory system that contributes to balance and sense of orientation), which is one of the systems most affected by gravity.

Results

OVAR has the advantage of generating cyclic testing control of OCR, allowing averaged measurements over several cycles, presumably improving measurement accuracy over static head tilt tests. Results show there was no significant difference in OCR during OVAR immediately after landing compared to preflight. However, the perceived degree of the roll tilt during OVAR was significantly larger immediately postflight, and then returned to control values in the following days. Since the OCR response is mainly due to the shearing force exerted on the otoliths by tilt relative to gravity, the absence of change in OCR postflight suggests that the peripheral otolith organs function normally after short-term spaceflight. However, the increased sense of roll tilt indicates an adaptation in the central neural processing of gravitational input, supposedly related to a re-weighting of the internal model of gravity, or lack thereof, as an adaptation to microgravity.

These results suggest a separation between otolith-driven eye movement and orientation perception during passive vestibular stimulation by inertial motion after spaceflight, and support the conclusion that otolith-driven compensatory eye movement and orientation perception are controlled by different neural mechanisms. OCR is primarily a direct response of otolith activation by low-frequency linear acceleration along the axis between the ears, whereas perception of tilt is primarily governed by the integration of otolith inputs, as well as bodily sensations such as position of limbs and pressure on the skin and internal organs. Apparently, the peripheral vestibular organ showed little or no changes after 10-13 days spaceflight, thus otolith-driven eye movements appear relatively unaffected by short-term exposure to microgravity. However, the central processing of orientation relative to gravity is likely to be affected and suggests why perceptual and oculomotor responses dependent on central vestibular processing can be greatly disrupted (Clement 2007, 2012).

PUBLICATION(S)

Clement G, Wood SJ. Eye movements and motion perception during off-vertical axis rotation after spaceflight. *Journal of Vestibular Research*. January 1, 2013;23(1):13-22. doi: 10.3233/VES-130471.

Clement G, Denise P, Reschke MF, Wood SJ. Human ocular counter-rolling and roll tilt perception during off-vertical axis rotation after spaceflight. *Journal of Vestibular Research*. 2007;17(5-6):209-215.

This investigation is complete and all results are published.

Spatial Reorientation Following Spaceflight, Detailed Supplementary Objective 635 (Spatial, DSO 635)

Research Area: Human Research: Nervous and Vestibular Systems

Expedition(s):

- William H. Paloski, PhD, NASA's Johnson Space Center, Houston, Texas

A view of the posturography (the study of posture and its effects on health) system located in the JSC Neuroscience Laboratories. As a part of the medical requirement test battery, posturography is currently being performed on returning short and long duration crewmembers to assist in determining their return-to-duty status. ESA image.

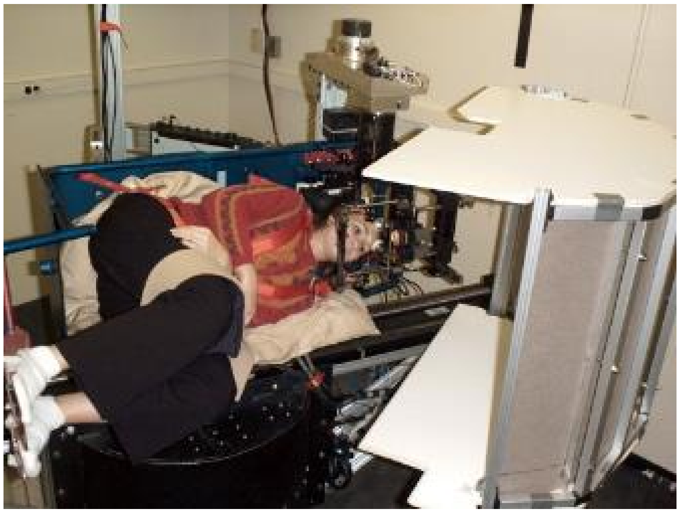
Research Objectives

The Spatial Reorientation Following Spaceflight (Spatial) study examines adaptive changes in spatial processing for balance control following short-duration spaceflight.

The first specific aim of this study was to examine adaptive changes in spatial processing for balance control following spaceflight by incorporating static and dynamic tilts that disassociate head and gravity reference frames. Impairments to sensorimotor (sensory and motor) coordination of body segments following spaceflight are more pronounced after landing when the head is actively tilted with respect to the trunk. This suggests that central vestibular processing shifts from a gravitational frame of reference (aligned with gravity vector) to a head frame of reference (aligned to head position) in microgravity. A major effect of such changes is a significant postural instability. Decreases in functional performance may still be underestimated when head and gravity reference frames remained aligned. A second aim of this study was to examine the feasibility of altering the re-adaptation process by providing discordant visual-vestibular somatosensory (sensory system perception) stimuli using short-radius pitch centrifugation. Previous observations suggested that conflicting sensory stimuli caused by an unusual motion environment disrupted spatial orientation and balance control in a returning crew member possibly by triggering a change in the central vestibular system (inner ear, eyes, and the central nervous system).

Earth Benefits

A better understanding of the characteristics of sensorimotor recovery from short-duration spaceflights will help in understanding the mechanisms related to the adaptation of balance control. The findings are also expected to demonstrate the feasibility of triggering state changes between sensorimotor control sets using a centrifuge device. The results will also be of use to clinical and military researchers interested in adaptive changes in spatial processing to altered gravitational environments, and the fragility of the sensorimotor adaptive processes. These findings will improve the understanding of the functional risks to crew members after transitions between altered gravito-inertial (having different strengths of gravity) environments.



The Short Arm Centrifuge (SAC) in the JSC Neuroscience Laboratories allowed pitch centrifugation which produced discordant canal-otolith-somatosensory stimuli to illicit changes in the readaptation process. NASA image.

Space Benefits

Conducting studies involving balance control before and after spaceflight will provide information and understanding of the effects introduced by space habitation in regards to sensorimotor function. Understanding such changes is essential in maintaining the health and functional performance of crew members during missions in micro- and partial- gravity environments.

Results

Analysis of data from Spatial is ongoing, conclusive results will be published upon completion of data analysis.

This investigation is complete; however additional results are pending publication.

International Space Station Acoustic Measurement Program (ISS Acoustics)

Research Area: Technology Development and Demonstration: Air, Water, and Surface Monitoring

Expedition(s): 1-ongoing

Principal Investigator(s):
- Christopher S. Allen, Johnson Space Center, Houston, Texas

Research Objectives

The International Space Station Acoustic Measurement Program (ISS Acoustics) is responsible for ensuring a safe, healthy, and habitable acoustic environment on the ISS in which crews can live, communicate, and work. This means ensuring that space vehicle environments are not too noisy, do not have irritating audible sounds, and do not have startling bursts of acoustic energy.

Earth Benefits

Data resulting from measuring acoustics on the ISS are useful in other extreme environments on Earth, such as submarines or underwater laboratories.

Space Benefits

Information from ISS Acoustics is used to ensure safe and habitable noise levels for crew members living and working aboard the ISS. ISS Acoustics data are used to compare with noise level predictions for upcoming spaceflight missions.

ISS005E12372 – Flight Engineer Sergei Treschev takes measurements with a sound level meter in the US laboratory during Expedition 5. NASA image.

Results

The ISS presents a significant acoustics challenge considering all of the modules and equipment that make it an in-orbit laboratory and home with long-duration crew occupation. The acoustic environment aboard the ISS has become one of the highest crew habitability concerns. The acoustics mission support function, including training, mission control support, and data analysis, is necessary to monitor crew exposure and ensure that the crew members' hearing is not at risk. Without accurate in-orbit data, all preventative ground efforts are rendered ineffective. Mission monitoring and support is critical to the control and mitigation of acoustic noise on the ISS. ISS Acoustics preserves crew members' hearing and provides for a safe, productive, and comfortable noise environment (Limardo 2011).

The Acoustics Office at Johnson Space Center (JSC) performs valuable management oversight over acoustic activities. The JSC acoustics team provides beneficial support of modules, payloads, and government furnished equipment requirements definition, design and development, consultation, and applies proactive efforts to help hardware providers achieve compliance (Allen 2011). The acoustic team also manages predictions for flight readiness, in-orbit measurements, and maintains a database of measurements, and distributes reports and assessments of the data. It is important that the ISS noise be in compliance with current specifications. This is important to ensure acceptable crew communications, health, and well-being. Data collected from the space shuttle and Mir programs indicate that levels at or close to 70 dBA should be considered ISS daily exposure limits. These limits are justified in view of crew experience, especially considering the variability in crew member physiological and psychological response to noise (Goodman 2003).

ISS Acoustics develops measures to safeguard the crew members' hearing, ensures there are work-arounds for excessively noisy areas or mission events, and provides for a secure, productive, and comfortable noise environment. This is aided by module noise monitoring, noise abatement, and restricting crew noise exposure during a mission (Pilkinton 2003).

PUBLICATION(S)

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This investigation is ongoing and additional results are pending publication.

ON-ORBIT DEMONSTRATION OF A NOVEL LEON-2 BASED COMPUTER SYSTEM AND ITS APPLICATION FOR ACQUISITION AND TRANSMISSION OF MILLI-G ENVIRONMENT AND ACOUSTIC NOISE DATA IN THE COLUMBUS ATTACHED PRESSURIZED MODULE, STATION DETAILED TEST OBJECTIVE 15010-E (LEON-2, SDTO 15010-E)

Research Area: Technology Development and Demonstration: Characterizing Experiment Hardware

Expedition(s): 17

Principal Investigator(s):
- Helmut Luttmann, Astrium, Bremen, Germany

RESEARCH OBJECTIVES

The On-Orbit Demonstration of a Novel LEON-2 Based Computer System and Its Application for Acquisition and Transmission of Milli-g Environment and Acoustic Noise Data in the Columbus Attached Pressurized Module (LEON-2) study will assess the performance of a new generation of on-board computer with respect to radiation behavior, vibrations, noise, and temperature.

EARTH BENEFITS

This study involves a demonstration of an on-orbit computer system assessing environmental data, for the purpose of securing valuable payload data and crew health, which makes it unrelated to Earth applications.

SPACE BENEFITS

Data acquired in this study will be used to assess radiation behavior and to correlate possible disturbances of experiments carried out in scientific payloads with milli-g accelerations; eg, by crew activities, re-boost, or docking of spacecraft to the ISS. Follow-up data analysis will provide valuable data for scientific payloads and for crew health support with respect to otology (the science of the ear and its diseases). Such technologies are necessary to continuously provide state-of-the art computers for replacement and extension of the ISS data management system and the ISS primary payload computers.

RESULTS

Analysis of data from LEON-2 is ongoing, and conclusive results will be published upon completion of data analysis.

This investigation is complete; however additional results are pending publication.

Sensor Test for Orion Relative Navigation Risk Mitigation, Detailed Test Objective 703 (STORRM, DTO 703)

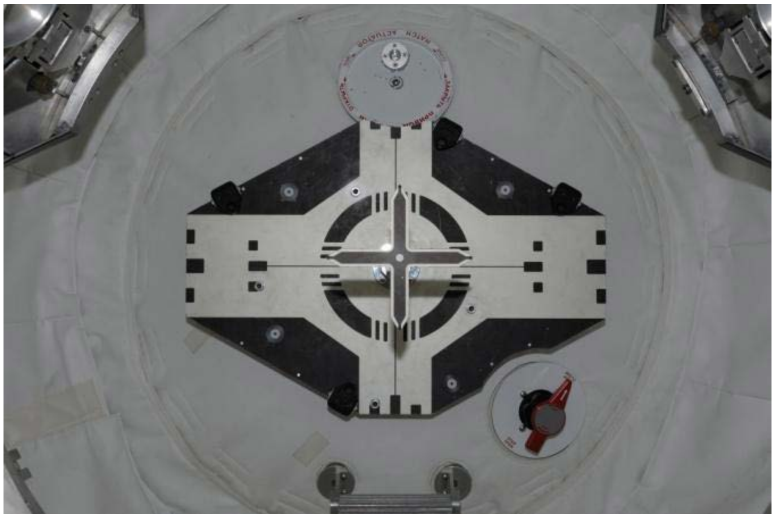
Research Area: Technology Development and Demonstration: Communication and Navigation

Expedition(s): 27/28

Principal Investigator(s):
- Heather Hinkel, NASA's Johnson Space Center, Houston, Texas

Research Objectives

Sensor Test for Orion Relative Navigation Risk Mitigation - DTO 703 (STORRM) tests the Vision Navigation Sensor, Star Tracker, and Docking Camera planned for Orion both during shuttle approach to and departure from the International Space Station (ISS). This test determines how well the navigation system performs during the mission.



STORRM Docking Target. NASA image.

Earth Benefits

Results allow for improved math models and design of future hardware.

Space Benefits

STORRM demonstrates and characterizes in-orbit performance of new navigation system technology prior to the first Orion mission to ISS.

Results

The Space Shuttle Orbiter Trajectory Control Sensor (TCS) interference testing is complete. The testing consisted of 4 reflective elements that are being considered for use on the STORRM DTO (DTO 703). The purpose of the testing was to ensure that the reflective elements, which are required for the DTO, did not interfere or cause any unwarranted operation of the Shuttle TCS. The laser and detector for the TCS are designed for the visible spectrum as compared to the STORRM Vision Navigation System designed for the near infra-red spectrum. Preliminary results eliminate the concern that the DTO reflective elements will interfere with TCS operations. DTO 703 collected data from the Vision Navigation Sensor and Docking Camera during Orbiter Operations.

This investigation is complete and all results are published.

SCIENCE FOR THE IMPROVEMENT OF FUTURE SPACE EXPLORATION (ISS EXPLORATION)

Research Area:	Technology Development and Demonstration: Life Support Systems and Habitation
Expedition(s):	1-ongoing

RESEARCH OBJECTIVES

Constructing and operating the International Space Station (ISS) serves as a testbed for new technologies and techniques in support of future crew exploration vehicle hardware design and development. Lessons learned from the operation of life support technologies on station are directly applicable to the selection and operation of systems for future exploration vehicles. ISS Exploration encompasses these publications.

EARTH BENEFITS

New knowledge is expected to be the major benefit of ISS Exploration.

SPACE BENEFITS

ISS Exploration investigates new knowledge to advance space exploration.

RESULTS

The mission of the ISS Program is to advance science and technology research, expand human knowledge, inspire and educate the next generation, foster the commercial development of space, and demonstrate capabilities to enable future exploration missions beyond low-Earth orbit (LEO).

ISS037E006296 – The first Cygnus commercial cargo spacecraft built by Orbital Sciences Corp., seen here attached to the International Space Station's Harmony node. NASA image.

To execute this mission, the ISS Program utilized the space station as a test bed to demonstrate operational techniques and capabilities, and demonstrate technologies and advanced systems that benefit space science capabilities and human and robotic exploration beyond LEO. Working with the international exploration community, capabilities are defined that will be needed for future exploration.

PUBLICATION(S)

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This investigation is ongoing and additional results are pending publication.

Solid State Lighting Module, Station Detailed Test Objective 15008U (SSLM, SDTO 15008U)

Research Area: Technology Development and Demonstration: Life Support Systems and Habitation

Expedition(s): 18

Principal Investigator(s):
- Daniel Shultz, NASA's Kennedy Space Center, Cape Canaveral, Florida

Research Objectives

The Solid-State Lighting Module (SSLM), SDTO 15008U is a Station Development Test Objective sponsored by the National Aeronautics and Space Administration (NASA) to demonstrate the advantages of Light-Emitting Diode (LED) lighting systems within the spacecraft environment.

ISS018E010657 – Michael Fincke holds a General Luminaire Assembly in Node 2. NASA image.

Earth Benefits

Analysis of the crew evaluations will be presented to several NASA boards after data return. A final report will be completed and archived for use in design of lighting systems in the next generation of exploration vehicles.

Space Benefits

SSLM on the International Space Station (ISS) will begin the evaluation of LED lighting systems for the next generation of crew exploration vehicles. SSLM will effectively evaluate potential savings of LED technology vs currently installed systems.

Results

The new solid-state lighting technology provides an important opportunity for re-lamping of the ISS with an energy-efficient lighting system that has a significantly longer lifespan and does not contain potentially toxic mercury vapor. A prototype Solid-State Lighting Assembly (SSLA) was developed at NASA's Kennedy Space Center and successfully installed on the ISS during Expedition 18. This new lighting system will provide multiple settings that can support astronaut vision and potentially serve as a lighting countermeasure for sleep and circadian disruption aboard the ISS.

Three ground-based studies were completed on visual performance, color discrimination, and melatonin (melatonin promotes sleepiness) suppression in healthy human subjects under different SSLA light exposure conditions inside a high-fidelity replica of the ISS crew quarters (CQ). Color discrimination tests showed no significant differences in color discrimination for indirect daylight, fluorescent room light, and SSLA light in the CQ. Also, there were no significant differences in score or time for subjects performing contrast tests. Presently, the data demonstrate that bright white Solid-State Lighting Module-Research light supports visual performance and color discrimination equivalently to typical indoor exposures to indirect daylight and overhead fluorescent light. In addition, increasing exposures to SSLA inside the CQ elicit increasingly stronger melatonin suppressions in healthy volunteers. The findings demonstrate the feasibility of doing controlled studies on visual, neuroendocrine and circadian responses in a high-fidelity replica of an ISS component.

Early studies represent a start towards quantifying the broader range of visual, biological, and behavioral responses to light once the current fluorescent lighting system is replaced by solid-state lighting. The data reported here begin to address long-duration space exploration, and the rapid development of solid-state lighting that will ultimately revolutionize how our public facilities, work places, and homes are illuminated in the coming decades. Similar to some of the astronauts, a significant portion of the global population suffers from chronic sleep loss or circadian-related disorders. By refining multipurpose lights for astronaut safety, health and well-being in spaceflight, the door is opened for new lighting strategies that can be evolved for use on Earth (Brainard 2012).

PUBLICATION(S)

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This investigation is complete and all results are published.

International Space Station External Radiation Monitoring (ISS External Radiation Monitoring)

Research Area: Technology Development and Demonstration: Radiation Measurements and Shielding

Expedition(s): 1-ongoing

Research Objectives

External Radiation Monitoring aboard the International Space Station (ISS) is responsible for gathering, analyzing, and interpreting the external environment radiation data for the ISS in order to help ensure vehicle protection. All the partner agencies recognize the importance of vehicle health to mission success and are dedicated to maintaining the health of ISS.

Earth Benefit

New knowledge is expected to be the major benefit of this project.

Space Benefit

ISS External Radiation Monitoring provides new knowledge to advance space exploration.

Results

The International Space Station provides the proving ground for future long-duration human activities in space. Ionizing radiation measurements in ISS form the ideal tool for the experimental validation of radiation environmental models, nuclear transport code algorithms, and nuclear reaction cross sections. Indeed, prior measurements on the space shuttle have provided vital information impacting both the environmental models and the nuclear transport code development by requiring dynamic models of the low-Earth orbit environment. Previous studies using Computer Aided Design models of the evolving ISS configurations with Thermo-Luminescent Detector area monitors, demonstrated that computational dosimetry requires environmental models with accurate non-isotropic as well as dynamic behavior, detailed information on rack loading, and an accurate 6 degree of freedom description of ISS trajectory and orientation. It is imperative that we understand ISS exposures dynamically for crew career planning, and insure that the regulatory requirements of keeping exposure as low as reasonably achievable (ALARA) are adequately implemented. This is especially true since the ISS was completed.

S128E009988 – Overall view of the International Space Station shortly after the undocking of Space Shuttle *Discovery* during STS-128. NASA image.

Publication(s)

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This investigation is ongoing and additional results are pending publication.

International Space Station Internal Radiation Monitoring (ISS Internal Radiation Monitoring)

Research Area: Technology Development and Demonstration: Radiation Measurements and Shielding

Expedition(s): 1-ongoing

ISS009E06471 – EXPRESS Rack 5 with the Intravehicular Charged Particle Directional Spectrometer (IV-CPDS) (gold box in left field of view) and the Tissue Equivalent Proportional Counter Radiation Detector (gold cylinder) and upper storage compartments visible. EXPRESS Rack 5 is in the Destiny module/U. laboratory. NASA image.

Research Objectives

International Space Station Internal Radiation Monitoring is responsible for gathering, analyzing, and interpreting the internal environment radiation data for the ISS in order to help ensure crew health protection. Crew health before, during, and following spaceflight is essential to overall ISS mission success. All of the partner agencies recognize the importance of crew health to mission success and are dedicated to maintaining the health of all crew members throughout all phases of ISS missions.

Earth Benefits

Maintaining crew member health and safety while in orbit better ensures that crew member functionality is not jeopardized as a result of time spent on a mission, therefore, allowing them to resume life on Earth unaffected by space travel.

Space Benefits

Human exploration and development of space without exceeding acceptable risk from exposure to ionizing radiation is one of NASA's main objectives. Moral, legal, safety, and practical considerations require that NASA limit postflight risks incurred by humans living and working in space to acceptable levels.

Results

The ISS is performing well within expectations with respect to total ionizing dose (TID) degradation and single event effects (SEE) impacts on electromechanical (EEE) parts and avionics performance. Until recently, ISS has been flying at altitudes between 350 and 400 km during solar maximum, well below the 500 km specified for the worst-case radiation design environment. TID accumulated to date is well below the performance degradation threshold for EEE parts. Ionizing radiation dose measurements, made within the habitable volume with thermoluminescent dosimeters and crew personal dosimeters, range from 5 to 12 microGy (0.5

to 1.2 milli rads) per hour, depending on location in the habitable volume, corresponding to an annual dose range of 44 to 105 milliGy (4.4 to 10.5 rads). The variation in TID with location in the habitable volume is largely a result of variations in effective shielding mass with location.

No destructive SEE events of any kind have been observed during the first two years of flight. Only one ISS vehicle equipment item fault that may be uniquely attributed to SEE with a reasonable level of confidence has been observed.

Detailed consideration of the effects of both the natural and induced ionizing radiation environment during ISS design, development, and flight operations has produced a safe, efficient manned space platform that is largely immune to deleterious effects of the low-Earth orbit ionizing radiation environment. However, model estimates show the need for more work directed to development of a practical understanding of secondary particle production in massive structural shielding for single event effect (SEE) design and verification. Utilizing computer-aided design it was determined that total dose estimates for shielding mass distribution were reasonable and accurate for the ISS pressurized elements (Koontz 2005).

ISS015E12111 (June 15, 2007) – View of the Tissue Equivalent Proportional Counter (TEPC) Radiation Detector (gold cylinder) and the TEPC Spectrometer (gold box) in the US Laboratory/Destiny during Expedition 15. The TEPC monitors radiation doses at the cellular level.

At present, the best active dosimeters used for radiation linear energy transfer (LET) are the tissue equivalent proportional counter (TEPC) and silicon detectors. The best passive dosimeters are the thermoluminescence dosimeters (TLDs), optically stimulated luminescence dosimeters (OSLDs) for low LET, and CR-39 plastic nuclear track detectors (PNTDs) for high LET. TEPC, CR-39 PNTDs, TLDs, and OSLDs dosimeters were all used to investigate the radiation environment for ISS Expedition 12, STS-112, and STS-114, and proven to be successful and consistent in measuring the LET spectra and all radiation quantities with excellent agreement among different detector types. The sensitivity fading of CR-39 detectors for long-time exposures was observed, and the method of “internal LET calibration using GCR iron peak” was developed to correct the sensitivity fading giving final CR-39 results that are consistent with those measured by TEPC and TLDs/OSLDs. This study indicates the LET spectrum method using CR-39 PNTDs, the LET calibration for CR-39 detectors, and the combination method for results measured by passive dosimeters are reliable and will be continually used in future space missions (Zhou 2007).

PUBLICATION(S)

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This investigation is complete and all results are published.

Component Repair Experiment – 1, Station Detailed Test Objective 17012U (CRE-1, SDTO 17012U)

Research Area: Technology Development and Demonstration: Spacecraft and Orbital Environments

Expedition(s): 18

Principal Investigator(s):
- John W. Easton, National Center for Space Exploration Research, Cleveland, Ohio

Research Objectives

The Component Repair Experiment -1, SDTO 17012U (CRE-1) is an incremental step toward providing an electronics repair capability during future long-duration space missions. Implementation of repair capabilities can help reduce the burden of replacement hardware. Specifically, CRE-1 demonstrates the physical steps of component-level electronics repair conducted by crew members aboard the International Space Station (ISS). These physical processes all have a direct gravitational dependence (such as the soldering process itself) or an indirect, operational dependence on the gravity environment (such as placing, aligning, and securing small replacement parts). Therefore, the repair processes must be demonstrated in a relevant environment as part of a repair cap ability development.

ISS018E035796 – Astronaut Sandra Magnus removing conformal coating during the CRE-1 experiment. NASA image.

Earth Benefits

Development of improved toolsets, procedures, and training methods can help enable in-the-field repairs by deployed US military forces, thereby assisting in reducing the logistical support requirements of US forces.

Space Benefits

The current strategy for electronics' repair aboard the ISS calls for replacement of failed hardware that relies on spares provided by resupply flights from Earth. For future exploration missions beyond low-Earth orbit, this logistical support will be much more constrained. Repairing electronics at the lowest component level could potentially ease the logistical burden by minimizing the upmass and volume of required spares. Implementation of such a strategy on the ISS could serve as a test bed for future operations as well as offer additional options for actual contingency maintenance. Before such a strategy can be adopted, data must be gathered about the practicality of performing such repairs in microgravity. CRE-1 serves to advance the state of knowledge and experience involved in manual component-level electronics repair by demonstrating such repairs in an operational environment.

Results

The results of the CRE-1 operations show a great deal of potential for future astronauts to perform low-level electronics repair during a mission. Each crew member was able to remove and replace components successfully, demonstrating that with limited training and tools these low-level repairs are a realistic option for future missions. However, each crew member experienced difficulties with some of the tasks. These problems range from forming solder joints that are functional but do not pass current standards, to failed solder joints, and damage to the component or circuit board. The difficulties encountered by the crew point to areas requiring improvement. Further, the crew members were not trained to identify and correct mistakes or flaws in their work, which contributed to the number of components that did not pass a visual inspection to NASA standards. The results of the CRE-1 work show 2 main areas for improving an electronics repair capability: improving crew training and improving the tools provided.

PUBLICATIONS(S)

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Easton JW, Pettegrew RD, Struk PM. Electronic repair concepts for long-duration spaceflight. 45th *Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2007.

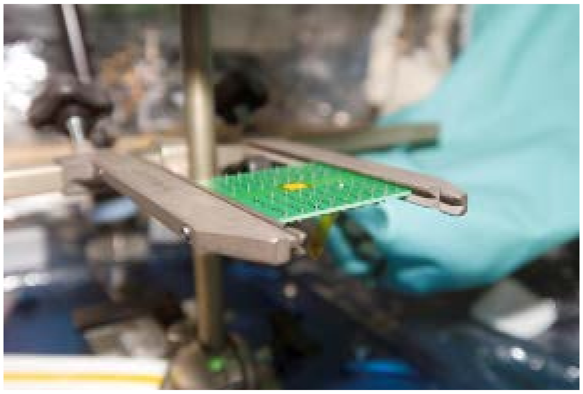
This investigation is complete; however additional results are pending publication.

Soldering in Reduced Gravity Experiment, Station Detailed Test Objective 17003-U (SoRGE, SDTO 17003-U)

Research Area: Technology Development and Demonstration: Repair and Fabrication Technologies

Expedition(s): 16, 18-20, 29, 30

Principal Investigator(s):
- Peter M. Struk, PhD, NASA's Glenn Research Center, Cleveland, Ohio



ISS015E06764 – This image shows the samples that were used during SoRGE. SoRGE will examine how the microgravity environment affects soldering joints. Image courtesy of NASA.

Research Objectives

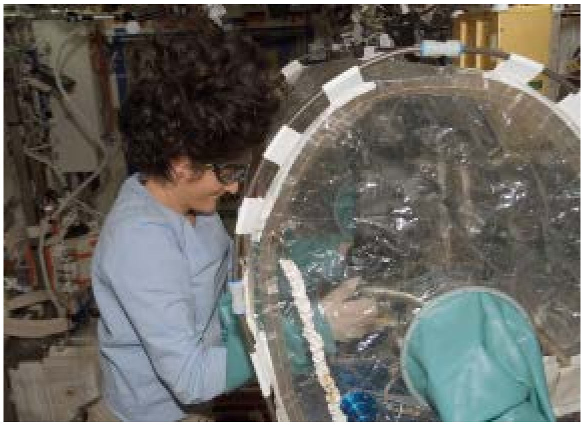
The Soldering in Reduced Gravity Experiment (SoRGE) will examine solder joints created in microgravity. Recent simulated microgravity (aboard the KC-135 and C-9B reduced gravity aircraft) testing has shown that, on average, solder joints produced in microgravity (space) exhibit approximately 3-times more voids (defects) compared with those produced in normal gravity (Earth). Without gravity, gas bubbles (from solder flux or water vapor) form pores or void defects in solder joints and can reduce their strength. For SoRGE operations, crew members will be soldering small electronic components using the International Space Station (ISS) soldering iron to validate the results observed in C-9B aircraft testing, including potential mitigation techniques for reducing solder joint voids.

Earth Benefits

Through better understanding of the inherent physics, the study of soldering in space could lead to better soldering techniques on Earth.

Space Benefits

The current strategy for electronics maintenance aboard the ISS calls for replacement of Orbital Replacement Units and relies on re-supply flights from Earth to provide the replacement units. This logistical support may not be easily available for future exploration missions beyond low-Earth orbit. Repairing electronics at the lowest component level could ease the logistical burden by minimizing the upmass and volume of required spares. Before such a strategy can be adopted, data must be gathered about the practicality of performing such repairs in microgravity. This includes understanding how



ISS015E06769 – Astronaut Suni Williams performs the Soldering in Reduced Gravity Experiment (SoRGE) in the Maintenance Work Area (MWA). SoRGE will examine how the microgravity environment affects soldering joints. NASA image.

the physical processes (such as soldering) are affected by the microgravity environment. SoRGE is the next step in understanding the role that reduced gravity plays in the repair of electronic components.

RESULTS

Analysis of data from SoRGE is ongoing, conclusive results will be published upon completion of data analysis.

This investigation is complete; however additional results are pending publication.

Boundary Layer Transition, Detailed Test Objective 854 (BLT, DTO 854)

Research Area: Technology Development and Demonstration: Spacecraft and Orbital Environments

Expedition(s): 18-20

Principal Investigator(s):
- Gerald Kinder, The Boeing Company, Huntington Beach, California
- Charles H. Campbell, NASA's Johnson Space Center, Houston, Texas

Research Objectives

The Boundary Layer Transition (BLT) involves the use of 10 modified tiles, equipped with thermocouples (indicate a temperature change based on voltage between a junction of 2 different metals), placed on the bottom of *Space Shuttle Discovery's* left wing. One tile is also equipped with a protuberance (specially modified speed bump) to study the characteristics of how the airflow is tripped from laminar (smooth) to turbulent (rough) during re-entry. BLT improves the understanding of the parameters associated with re-entering the atmosphere and including the significant heat increase caused by turbulent boundary layer flow.

Earth Benefits

BLT provides scientists and engineers with the incredible opportunity to demonstrate how NASA is working to understand spaceflight better and an opportunity to successfully apply what has been learned to improve space vehicles.

Space Benefits

The data gathered from BLT will be utilized to support analytical computer modeling and design efforts for the space shuttle and NASA's next generation spacecraft.

STS-119 Post-flight image of BLT.NASA image.

Results

The Boundary Layer Transition (BLT) was successful in obtaining BLT onset data near Mach 16 and turbulent heating data after Mach 16 with a 0.25 inch tile protuberance downstream of the port landing gear door. Flight hardware performance and thermocouple data was excellent, and no anomalies were identified.

This investigation is complete; however no publications are expected.

International Space Station External Environments (ISS External Environments)

Research Area: Technology Development and Demonstration: Spacecraft and Orbital Environments

Expedition(s): 1-ongoing

Research Objectives

The International Space Station (ISS) is subject to several sources of contamination, including component outgassing and breakdown, water dumps, thruster plumes from both the service module and visiting spacecraft, orbital debris, and micrometeorites. Several papers provide data that model these different contamination sources on the ISS. Certain surfaces of the ISS are particularly sensitive to contamination; knowledge of the station environment leads to mitigation strategies and feeds back into materials and mission designs for future missions.

Earth Benefit

New knowledge is expected to be the major benefit of this project.

Space Benefit

ISS External Environments provides new knowledge to advance space exploration.

S123E010030 – Backdropped by a blue and white part of Earth, a close-up view of the International Space Station is seen from Space Shuttle *Endeavour* as the two spacecraft begin their relative separation. NASA image.

Results

The data are used to help predict component life cycles; provide data that are relevant to performance; create operational rules for spacecraft and extravehicular activity (spacewalks); and feed into future mission design considerations. NASA's Image Science & Analysis Lab produces regular reports of their findings. ISS engineers use the data for the various studies that are reported here. Below is a sample of these results to date.

Liquid droplets of partly reacted propellants are produced by thruster exhaust plumes from visiting spacecraft. Both the chemical nature and the physical acceleration of the drops can produce pitting, mechanical erosion, and other damage on surfaces. For critical surfaces, such as solar arrays, the models influenced flight rules for array-positioning during thruster firings (Alred 2003; Pankop 2004).

An experiment was performed in 2001 to document a water dump and venting event with video for analysis. The venting was characterized from the imagery, including the extent of the cone of the vent, number of particles outside the cone, and velocities of ice particles. Because the particles can be large (2 mm) and have significant velocities (30–50 ft/sec), they have the potential for creating damage on station hardware. When the video was analyzed, some of the ice particles were observed bouncing off of the nearby ISS hardware. Results agreed well with models; during the nominal phase of the vent, larger particles stayed within a cone with a 20-degree half-angle (Schmidle 2001, 2002). These data were used to develop an operational constraint on the location of the solar arrays and photovoltaic radiators to mitigate potential damage.

PUBLICATION(S)

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Pankop, Alred J, Boeder. Mitigation of thruster plume-induced erosion of ISS sensitive hardware. *Protection of Materials and Structures from Space Environment;* 2006.

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Soares CE, Mikatarian RR, Scharf RA, Miles EA. International Space Station Flights 1A/R - 6A external cantamination observations and surface assessment. *47th Annual International Symposium on Optical Science and Technology,* Seattle, WA; July 7-11, 2002.

This project is ongoing, and additional results are pending publication.

International Space Station Internal Environments (ISS Internal Environments)

Research Area: Technology Development and Demonstration: Spacecraft and Orbital Environments

Expedition(s): 1-ongoing

Research Objectives

Evaluation of the International Space Station Internal Environment (ISS Internal Environment) from air, water, and surface samples of International Space Station (ISS) provides a baseline of the contaminant characterization aboard the ISS. All of the partner agencies recognize the importance of crew health to mission success and are dedicated to maintaining the health of all crew members throughout all phases of ISS missions. The data obtained from environmental monitoring provides insight into the environmental contamination during the stages of construction and habitation of ISS.

ISS010E11563 – An example of contamination that has developed on one of the interior panels aboard the International Space Station (ISS). This image shows how contamination can form on interior ISS surfaces. Crews have weekly sessions to clean ISS surfaces. The Surface, Water, and Air Biocharacterization (SWAB) investigation will help us understand the microbes involved in contamination and how to deal with them. NASA image.

Earth Benefits

Understanding the effects of a closed space environment on humans will increase the knowledge of living in extreme conditions. Due to widespread growth in the use of colloidal silver as a biocidal agent, the development of a simple and cost efficient method of silver testing is valuable.

Space Benefits

Environmental monitoring is vital to ensure crew and spacecraft health during spaceflight. The results are being used to identify specific effects of a closed space environment on astronauts. This knowledge will allow scientists to develop systems that enable the crew to remain healthy on future long-duration missions to the moon and Mars.

Results

Several studies on ISS Internal Environments have been conducted; below is a sampling of the results to date.

During one study of the ISS atmosphere, 12 bacterial strains were isolated and fingerprinted from the ISS water system. The bacteria consisted of common strains and were encountered at levels below 10,000 colony-forming units/10 cm^2, which is well below the minimum bacteria needed to cause illness. This data represents the beginning of ISS habitation and indicates that the lessons learned from the Mir and Skylab missions were implemented and have been effective in keeping the ISS a safe place to live and work (Castro 2004).

Solid waste in space must be safely processed and stored in a confined environment. Most of the solid waste is wet and poses a high risk of culturing the growth of undesirable microorganisms. Analysis was performed in order to assess potential crew risks resulting from microbial decay. Results show certain levels of volatile organic compounds, ethylene, methane, and carbon dioxide. These gases are being contained within the trash compartments, minimalizing potential risk for crew members (Peterson 2004).

ISS021E010366 – Expedition 21 Commander Frank De Winne fills a bag with water from the Potable Water Dispenser in the US Laboratory/Destiny for analysis. NASA image.

On station, silver is used as a biocidal agent based on its antimicrobial properties in the potable water system. Recent studies have shown that colloidal silver is possibly toxic to humans. Researchers are currently developing and testing a simple technique that will enable crew members to test silver levels in the water system in less than 2 minutes (Hill 2010).

Continual efforts to ensure crew safety will accompany the lifetime of the ISS. A new type of air testing was performed in 2010, evaluating threshold (T) values for 16 adverse health effect groups. All T levels were within the safe limit. The highest values were found in mucosal limits, headaches, central nervous system depression, and cardiac sensitization. This evaluation is an integral tool to NASA's Lifetime Surveillance of Astronaut Health (James 2012).

Publication(s)

Checinska A, Probst AJ, Vaishampayan PA, et al. Microbiomes of the dust particles collected from the International Space Station and Spacecraft Assembly Facilities. *Microbiome*. 2015;3:50. doi: 10.1186/s40168-015-0116-3.

Willsey GG, Wargo MJ. Extracellular lipase and protease production from a model drinking water bacterial community is functionally robust to absence of individual members. *PLOS ONE*. November 23, 2015;10:e0143617. doi: 10.1371/journal.pone.0143617.

Garcia HD, Tsuji JS, James JT. Establishment of exposure guidelines for lead in spacecraft drinking water. *Aviation, Space, and Environmental Medicine*. July 2014;85:715-720. doi: 10.3357/ASEM.3853.2014.

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This investigation is ongoing and additional results are pending publication.

Analysis of International Space Station Plasma Interaction (Plasma Interaction Model)

Research Area: Technology Development and Demonstration: Spacecraft and Orbital Environments

Expedition(s): 16, 18-20, 29, 30

Principal Investigator(s):
- Ronald R. Mikatarian, Boeing, Houston, Texas

Research Objectives

This analysis created a model to predict the voltage difference between the International Space Station (ISS) and the plasma background. The ionospheric plasma interacts with the ISS solar arrays and conducting surfaces, causing excess charge to be accumulated, thus creating the potential difference. This model will be used to predict the ISS floating potentials to assess vehicle and extravehicular mobility unit dielectric breakdown.

Earth Benefits

This model will be the standard for solar arrays in space. With an energy crisis upon us, solar power is a viable alternative. Ultimately, solar arrays in space create more power than solar arrays on the ground. This model will be invaluable for those seeking to pioneer solar arrays in space for the private sector.

Space Benefits

This Plasma Interaction Model models the interaction of the spacecraft, with high-voltage solar arrays, to the local plasma environment.

Results

The Plasma Interaction Model has been used to predict the charge build-up and associated dangers for future ISS solar array configurations. Ground data were collected from various locations around the world. Additionally, historical data—eg, the IRI 2001 model, FPP data, and the Dynamics Explorer-2 Satellite data, are available. Using these data, the PIM has been able to characterize the peak voltage levels for the various ISS stage builds. (Reddell 2006).

Publication(s)

Reddell B, Alred J, Kramer L, Mikatarian RR, Minow J, Koontz S. Analysis of ISS plasma interaction. *44th Aerospace Sciences Meeting and Exhibit.* Reno, NV; January 9-12, 2006.

This investigation is complete; however additional results are pending publication.

INTERNATIONAL SPACE STATION ZERO-PROPELLANT MANEUVER DEMONSTRATION (ZPM)

Research Area: Technology Development and Demonstration: Spacecraft and Orbital Environments

Expedition(s): 14 and 15

Principal Investigator(s):
- Nazareth Bedrossian, PhD, Charles Stark Draper Laboratory, Incorporated, Houston, Texas

RESEARCH OBJECTIVES
International Space Station Zero-Propellant Maneuver (ZPM) Demonstration introduces new technology that rotates the station by not expending in-orbit propellant.

EARTH BENEFITS
New knowledge is expected to be the major benefit of this project.

SPACE BENEFITS
The ZPM concept can substantially reduce the International Space Station (ISS) lifetime propellant use while avoiding thruster plume loads and contamination of solar arrays. A reduction in propellant use not only saves money, but increases payload capacity for resupplying vehicles. Even more importantly, ZPM provides the only means of control if ISS thrusters are unavailable. ZPM will also reduce propellant use for spacecraft maneuvers using only thrusters. This technology will be even more valuable for future human exploration of the solar system as the propellant savings will allow for increased payload or provisions.

Naval Postgraduate School Professor of Mechanical and Astronautical Engineering I. Michael Ross briefs NPS Space Systems Academic Group students on NASA's use of his optimal control software to maneuver the International Space Station cost-free, without the need to use thrusters and expend valuable fuel. Photo credit: US Navy, by Javier Chagoya.

RESULTS
The ZPM concept was successfully demonstrated on the ISS. On November 5, 2006, and March 3, 2007, the ISS was rotated 90 degrees and 180 degrees, respectively, without using any propellant.

The 90-degree maneuver of ISS Stage12A was completed in 2 hours and reached 70% of CMG momentum capacity (Bedrossian, 2007[a]). The 180-degree maneuver of ISS Stage 12A.1 was completed in 2 hours and 47 minutes and reached 76% of CMG momentum capacity (Bedrossian, 2007[b]). The same 180-degree maneuver was performed with thrusters on January 2, 2007, and consumed 50.8 kilograms or 112 pounds of propellant. At an estimated cost of $10,000 per pound, the 180-degree maneuver with ZPM saved $1,120,000 (Kang, 2007).

The flight results were documented and compared to predicted performance. The data included attitude, momentum, and gimbal rates during the maneuver. Flight reconstruction was performed to resolve discrepancies between predicted and flight results.

The impact of this new technology is to substantially reduce ISS lifetime propellant use, and avoid solar array contamination and loads. Future applications that can also be performed non-propulsively include maneuvering the ISS to unload accumulated CMG momentum, recovering attitude control when CMGs are saturated, and recovering attitude control in the event of a tumbling ISS. Since ZPM will also reduce propellant consumption for maneuvers using thrusters, it can also be used for future long-duration space exploration missions where propellant savings are even more valuable than for ISS and will allow for increased payload and provisions.

PUBLICATION(S)

Bedrossian N, Bhatt SA, Lammers M, Nguyen L, Zhang Y. First ever flight demonstration of zero propellant maneuver attitude control concept. *AIAA Guidance, Navigation and Control Conference,* Hilton Head, SC; 2007.

Bedrossian N, Bhatt SA, Lammers M, Nguyen L. Zero propellant maneuver flight results for 180deg ISS rotation. *20th International Symposium on Spaceflight Dynamics*, Annapolis, MD; 2007.

Kang W, Bedrossian N. Pseudospectral optimal control theory makes debut flight, saves NASA 1M dollars in under three hours. *Society for Industrial and Applied Mathematics News,* 2007; 40(7).

This investigation is complete and all results are published.

APPENDICES

APPENDIX A

PUBLICATIONS RESULTING FROM RESEARCH ABOARD THE INTERNATIONAL SPACE STATION

Investigation	Citation	Sponsoring Agency
Biology and Biotechnology: Animal Biology – Invertebrates		
Ageing	Herranz R, Hill RJ, Dijkstra CE, Eaves L, van Loon JJ, Medina F. The behavioral-driven response of the Drosophila imago transcriptome to different types of modified gravity. *Genomics Discovery*. 2013;1(1):1. doi: 10.7243/2052-7993-1-1.	ESA
Ageing	Hill RJ, Larkin O, Dijkstra CE, et al. Effect of magnetically simulated zero-gravity and enhanced gravity on the walk of the common fruitfly. *Journal of the Royal Society Interface*. 2012;9(72):1438-1449. doi: 10.1098/rsif.2011.0715.	ESA
Ageing	Herranz R, Benguria A, Laván DA, et al. Spaceflight-related suboptimal conditions can accentuate the altered gravity response of Drosophila transcriptome. *Molecular Ecology*. October 2010;19(19):4255-4264. doi: 10.1111/j.1365-294X.2010.04795.x.	ESA
Ageing	Serrano P, van Loon JJ, Manzano AI, Medina F, Herranz R. Selection of Drosophila altered behavior and aging strains for Microgravity Research. *Journal of Gravitational Physiology*. 2010.	ESA
Ageing	Herranz R, Laván DA, Dijkstra CE, et al. Drosophila behavior and gene expression in altered gravity conditions: Comparison between space and ground facilities. *2008 Life in Space for Life on Earth Symposium*, Angers, France; 2008.	ESA
Ageing	de Juan E, Benguria A, Villa A, et al. The ageing experiment in the Spanish Soyuz Mission to the International Space Station. *Microgravity Science and Technology*. 2007;19(5-6):170-174. doi: 10.1007/BF02919475.	ESA

Investigation	Citation	Sponsoring Agency
Ageing	Horn ER, Dournon C, Frippiat J, Marco R, Boser S, Kirschnick U. Development of neuronal and sensorimotor systems in the absence of gravity: Neurobiological research on four soyuz taxi flights to the International Space Station. *Microgravity Science and Technology*. 2007;19(5-6):164-169. doi: 10.1007/BF02919474.	ESA
Akvarium	Alekseev VR, Levinskikh MA, Sychev VN. Impact of spaceflight conditions on the dormant stage of lower crustaceans, Akvarium experiments, Space Biology, and Medicine. *Biomedical research on the ISS Russian segment, Moscow*; 2011.	ROS
Akvarium	Gusev OA, Okuda T, Sychev VN, Levinskikh MA, Sugimoto M. Perspectives of RNA/DNA studies using latent stages of invertebrates and plants exposed to space flight and outer space environments. *Space Utilization Research*. 2007;344-346.	ROS
Akvarium	Sychev VN, Levinskikh MA, Podolsky IG, et al. Main results of experiments investigating higher plants and dormant forms of organisms on the Russian segment of the International Space Station. *Kosmonavtika i Raketostroenie (Cosmonautics and Rocket Engineering)*. 2007;4(49):54-64.	ROS
Akvarium	Gusev OA, Alekseev VR, Saigusa M, Okuda T, Sychev VN. Molecular chaperons-related studies using latent stages of invertebrates exposed to space environment. *Zoological Science*. 2006;23(12):1227.	ROS
Akvarium	Levinskikh MA, Sychev VN. Using an experimental microcosm to study the effect of spaceflight factors at the ecosystem level of biological organization, state, and problems of production hydrobiology. *Aquatic Ecology at the Dawn of the XXI Century*. 2006;291-305.	ROS

Investigation	Citation	Sponsoring Agency
CERISE	Etheridge T, Nemoto K, Hashizume T, et al. The effectiveness of RNAi in *Caenorhabditis elegans* is maintained during spaceflight**.** *PLoS One*. 2011;6(6): e20459.	JAXA
CERISE	Etheridge T, Nemoto K, Hashizume T, et al. The next phase of life-sciences spaceflight research: harnessing the power of functional genomics. *Communicative & Integrative Biology.* 2011;4:6, 1-2.	JAXA
CGBA	Benoit MR, Li W, Stodieck LS, et al. Microbial antibiotic production aboard the International Space Station. *Applied Microbiology Biotechnology*. 2006;70(4):403–411.	NASA
CGBA	Klaus DM, Howard HN. Antibiotic efficacy and microbial virulence during spaceflight. *Trends in Biotechnology*. March 24, 2006. doi: 10.1016/j.tibtech.2006.01.008.	NASA
CGBA	Klaus D, Benoit M, Bonomo J, et al. Antibiotic production in space using an automated Fed-Bioreactor System. *AIAA International Space Station Utilization – 2001*, Cape Canaveral, Florida; October 15–18, 2001.	NASA
CRISP-2	Horn ER, Dournon C, Frippiat J, Marco R, Boser S, Kirschnick U. Development of neuronal and sensorimotor systems in the absence of gravity: Neurobiological research on four Soyuz taxi flights to the international space station. *Microgravity Science and Technology*. 2007;19(5-6):164-169. doi: 10.1007/BF02919474.	ESA
CRISP-2	Kirschnick U, Agricola H, Horn ER. Effects of altered gravity on identified peptidergic neurons of the cricket *Acheta Domesticus*. *Gravitational and Space Biology*. August 2006;19(2):135-136.	ESA
FIT	Taylor K, Kleinhesselink K, George MD, et al. Toll mediated infection response is altered by gravity and spaceflight in *Drosophila*. *PLOS ONE*. January 24, 2014;9:e86485. doi: 10.1371/journal.pone.0086485.	NASA

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FIT	Marcu O, Lera MP, Sanchez ME, et al. Innate immune responses of Drosophila melanogaster are altered by spaceflight. PLOS ONE. 2011;6(1):1-10. doi: 10.1371/journal.pone.0015361.	NASA
FIT	Fahlen TF, Sanchez ME, Lera MP, Blazevic E, Chang J, Bhattacharya S. A study of the effects of space flight on the immune response in Drosophila melanogaster. Gravitational and Space Biology. 2006;19(2):133-134.	NASA
ICE-First	Honda Y, Honda S, Narici M, Szewczyk NJ. Spaceflight and ageing: Reflecting on *Caenorhabditis elegans* in space. *Gerontology*. 2014;60(2):138-142. doi: 10.1159/000354772.	NASA, JAXA, CSA, ESA
ICE-First	Higashibata A, Higashitani N, Imamizo-Sato M, et al. Space flight induces reduction of paramyosin and troponin T: Proteomic analysis on two dimensional electrophoresis of space-flown *Caenorhabditis elegans*. *Current Biotechnology.* 2013;2(3):262-271. doi: 10.2174/22115501113029990015.	NASA, JAXA, CSA, ESA
ICE-First	Honda Y, Higashibata A, Matsunaga Y, et al. Genes down-regulated in spaceflight are involved in the control of longevity in *Caenorhabditis elegans*. *Scientific Reports.* 2012;2:487. doi: 10.1038/srep00487.	NASA, JAXA, CSA, ESA
ICE-First	Adenle AA, Johnsen R, Szewczyk NJ. Review of the results from the International *C. Elegans* first experiment (ICE-FIRST). *Advances in Space Research.* 2009;44(2):210-216. doi: 10.1016/j.asr.2009.04.008.	NASA, JAXA, CSA, ESA
ICE-First	Adachi R, Takaya T, Kuriyama K, Higashibata A, Ishioka N, Kagawa H. Spaceflight results in increase of thick filament but not thin filament proteins in the paramyosin mutant of *Caenorhabditis Elegans*. *Advances in Space Research.* 2008;41(5):816-823. doi: 10.1016/j.asr.2007.10.016.	NASA, JAXA, CSA, ESA

Investigation	Citation	Sponsoring Agency
ICE-First	Selch F, Higashibata A, Imamizo-Sato M, et al. Genomic response of the nematode *Caenorhabditis elegans* to spaceflight. *Advances in Space Research.* 2008;41(5):807-815. doi: 10.1016/j.asr.2007.11.015.	NASA, JAXA, CSA, ESA
ICE-First	Szewczyk NJ, Tillman J, Conley CA, et al. Description of International *Caenorhabditis Elegans* experiment first flight (ICE-FIRST). *Advances in Space Research.* 2008;42(6):1072-1079. doi: 10.1016/j.asr.2008.03.017.	NASA, JAXA, CSA, ESA
ICE-First	Higashibata A, Higashitani A, Adachi R, et al. Biochemical and molecular biological analyses of space-flown nematodes in Japan, the First International *Caenorhabditis elegans* experiment (ICE-First). *Microgravity Science and Technology.* 2007;19(5-6):159.	NASA, JAXA, CSA, ESA
ICE-First	Leandro LJ, Szewczyk NJ, Szewczyk NJ, et al. Comparative analysis of *Drosophila melanogaster* and *Caenorhabditis elegans* gene expression experiments in the European Soyuz flights to the International Space Station. *Advances in Space Research.* 2007;40:506-512. doi: 10.1016/j.asr.2007.05.070.	NASA, JAXA, CSA, ESA
ICE-First	Zhao Y, Jones M, Baillie D, Rose A. Developing an integrating biological dosimeter for spaceflight. *Microgravity Science and Technology.* 2007;19(5-6):201-204. doi: 10.1007/BF02919482.	NASA, JAXA, CSA, ESA
ICE-First	Higashibata A, Szewczyk NJ, Conley CA, Imamizo-Sato M, Higashitani A, Ishioka N. Decreased expression of myogenic transcription factors and myosin heavy chains in *Caenorhabditis elegans* muscles developed during spaceflight. *Journal of Experimental Biology.* 2006;209(pt 16):3209-3218. doi: 10.1242/jeb.02365.	NASA, JAXA, CSA, ESA

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ICE-First	Zhao Y, Lai K, Cheung I, et al. A mutational analysis of *Caenorhabditis elegans* in space. *Mutation Research - Fundamental and Molecular Mechanisms of Mutagenesis.* 2006;61(1-2):19-29. doi: 10.1016/j.mrfmmm.2006.05.001.	NASA, JAXA, CSA, ESA
ICE-First	Higashitani A, Sasagawa Y, Sugimoto T, et al. Checkpoint and physiological apoptosis in germ cells proceeds normally in spaceflown *Caenorhabditis elegans*. *Apoptosis.* 2005;10(5):949-954.	NASA, JAXA, CSA, ESA
Rad Silk	Furusawa T, Fukamoto K, Sakashita T, et al. Targeted heavy-ion microbeam irradiation of the embryo but not yolk in the diapause-terminated egg of the silkworm, *Bombyx mori*, induces the somatic mutation. *Journal of Radiation Research.* 2009;50(4):371-375. doi: 10.1269/jrr.09021.	JAXA
Rad Silk	Furusawa T, Nojima K, Ichida M, et al. Introduction to the proposed space experiments aboard the ISS using the silkworm, *Bombyx mori*. *Biological Sciences in Space*. 2009;23(2):61-69. doi: 10.2187/bss.23.61.	JAXA
Statokonia	Bukiya RD, Gorgiladze GI, Taktakishvili AD, Kalandarishvili EL. Light and electron microscopy of cellular components in statocysts of the land snail *Helix lucorum*. *Bulletin of the Russian Academy of Sciences: Biological series;* 2010.	ROS
Statokonia	Gorgiladze GI, Bukiya RD, Davitashvili MT, et al. Morphological Peculiarities Statoconia in Statocysts of Terrestrial Pulmonary Snail Helix Lucorum. *Bulletin of Experimental Biology and Medicine.* July 17, 2010;149(2):269-272. doi: 10.1007/s10517-010-0924-1.	ROS

Investigation	Citation	Sponsoring Agency
Statokonia	Gorgiladze GI. Morphological features of the inertial mass in statocysts of the terrestrial gastropods Helix lucorum and Pomatias rivulare exposed to microgravity. *Doklady Biological Sciences.* August 17, 2010;433(1):271-274. doi: 10.1134/S0012496610040101. [*Original Russian Text © G.I. Gorgiladze, 2010, published in Doklady Akademii Nauk, 2010, Vol. 433, No. 4, pp. 566–569.*]	ROS
Statokonia	Gorgiladze GI. Regenerative capacity of the planarian Girardia tigrina and the snail Helix lucorum exposed to microgravity during an orbital flight on board the international space station. *Doklady Biological Sciences.* August 20, 2008;421(1):244-247. doi: 10.1134/S0012496608040078. *[Original Russian Text © G.I. Gorgiladze, 2008, published in Doklady Akademii Nauk, 2008, Vol. 421, No. 1, pp. 131–134.]*	ROS
Statokonia	Gorgiladze GI, Bukiya RD, Davitashvili MT, et al. The destructive impact of increased gravitational force on the inertial mass in statocysts of *Helix lucorum*. *Proceedings of the Academy of Sciences.* 2006;406(3):416-418.	ROS
Statokonia	Gorgiladze GI, Bukiya RD, Kozyrev SA, Kalandarishvili EL. Structural/functional organization of the statocyst in *Helix lucorum* in normal conditions and conditions of a changing gravitational field*. XIII Conference Space Biology and Aerospace Medicine,* Moscow, Russia; June 13-16, 2006.	ROS
Statokonia	Bukiya RD, Taktakishvili AD, Kalandarishvili EL, Gorgiladze GI. Morphological features of the cellular components of the statocyst in the land snail *Helix lucorum*. *Bulletin of the Academy of Sciences of Georgia: Biological series A.* 2005;31(6):815-822.	ROS

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Xenopus	Horn ER, Gabriel M. Gender-related sensitivity of development and growth to real microgravity in Xenopus laevis. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*. September 30, 2013. doi: 10.1002/jez.1831.	ESA
Xenopus	Gabriel M, Frippiat J, Frey H, Horn ER. The sensitivity of an immature vestibular system to altered gravity. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*. 2012;317(6):333-346. doi: 10.1002/jez.1727.	ESA
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Xenopus	Horn ER, Gabriel M. Gravity-related critical periods in vestibular and tail development of Xenopus laevis. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*. November 1, 2011;315(9):505-511. doi: 10.1002/jez.698.	ESA
Xenopus	Horn ER, Dournon C. Experiences from a French-German project - on the integration of pupils in an actual space experiment. *Microgravity Science and Technology*. 2007;19(5-6):230-234. doi: 10.1007/BF02919488.	ESA
Xenopus	Horn ER, Boser S, Membre H, Dournon C, Husson D, Gualandris-Parisot L. Morphometric investigations of sensory vestibular structures in tadpoles (Xenopus laevis) after a spaceflight: Implications for microgravity-induced alterations of the vestibulocular reflex. *Protoplasma*. 2006;229(2-4):193-203. doi: 10.1007/s00709-006-0213-z.	ESA

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Xenopus	Horn ER. Microgravity-induced modifications of the vestibulocular reflex in Xenopus laevis tadpoles are related to development and the occurrence of tail lordosis. *Journal of Experimental Botany*. 2006;209(15):2847-2858. doi: 10.1242/jeb.02298.	ESA
Xenopus	Horn ER. “Critical Periods” in vestibular development or adaptation of gravity sensory systems to altered gravitational conditions. *Archives Italiennes De Biologie*. 2004;142:155-174.	ESA
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Aquarius	Boser S, Dournon C, Gualandris-Parisot L, Horn ER. Altered gravity affects ventral root activity during fictive swimming and the static vestibuloocular reflex in young tadpoles (Xenopus laevis). *Archives Italiennes De Biologie*. March 2008; 146(1):1-20.	ESA
Aquarius	Horn ER, Dournon C. Experiences from a French-German project - on the integration of pupils in an actual space experiment. *Microgravity Science and Technology*. 2007;19(5-6):230-234. doi: 10.1007/BF02919488.	ESA
Aquarius	Horn ER, Boser S, Membre H, Dournon C, Husson D, Gualandris-Parisot L. Morphometric investigations of sensory vestibular structures in tadpoles (Xenopus laevis) after a spaceflight: Implications for microgravity-induced alterations of the vestibuloocular reflex. *Protoplasma*. 2006;229(2-4):193-203. doi: 10.1007/s00709-006-0213-z.	ESA
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CBTM	Lloyd SA, Morony SE, Ferguson VL, et al. Osteoprotegerin is an effective countermeasure for spaceflight-induced bone loss in mice. *Bone*. December 2015;81:562-572. doi: 10.1016/j.bone.2015.08.021.	NASA
CBTM	Allen DL, Bandstra ER, Harrison BC, et al. Effects of spaceflight on murine skeletal muscle gene expression. *Journal of Applied Physiology.* 2008.	NASA
CBTM	Bateman TA, Bandstra ER. Chapter 20: How animal models inform the debate. *Bone Loss During Spaceflight: Etiology, Countermeasures, and Implications for Bone Health on Earth*, Cleveland, OH; 2007.	NASA
CBTM	Bateman TA. Molecular therapies for disuse osteoporosis. *Gravitational and Space Biology*. 2004;17(2):83-89.	NASA
CBTM	Milstead J, Simske SJ, Bateman TA. Spaceflight and hindlimb suspension disuse models in mice. *Biomedical Sciences Instrumentation*. 2004;40:105-110.	NASA
CBTM	Gridley DS, Nelson GA, Peters LL, et al. Genetic models in applied physiology: selected contribution: effects of spaceflight on immunity in the C57BL/6 mouse. II. Activation, cytokines, erythrocytes, and platelets. *Journal of Applied Physiology*. 2003;94(5):2095-2103.	NASA
CBTM	Harrison BC, Allen DL, Girten BE, et al. Skeletal muscle adaptations to microgravity exposure in the mouse. Journal of Applied Physiology. 2003;95(6):2462-2470. doi: 10.1152/japplphysiol.00603.2003.	NASA
CBTM	Pecaut MJ, Nelson GA, Peters LL, et al. Genetic models in applied physiology: selected contribution: effects of spaceflight on immunity in the C57BL/6 mouse. I. Immune population distributions. *Journal of Applied Physiology*. May 2003; 94(5):2085-2094. doi: 10.1152/japplphysiol.01052.2002.	NASA

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CBTM-2	Romer C, Forsman AD. The effects of the spaceflight environment on the vaginal mucin layer of the mouse. *Gravitational and Space Research*. July 2015;3:20-28.	NASA
CBTM-2	Latchney SE, Rivera PD, Mao XW, et al. The effect of spaceflight on mouse olfactory bulb volume, neurogenesis, and cell death indicates the protective effect of novel environment. *Journal of Applied Physiology*. June 15, 2014;116:1593-1604. doi: 10.1152/japplphysiol.01174.2013.	NASA
CBTM-2	Zawieja DC, Mao XW, Stodieck LS, et al. Changes in mouse thymus and spleen after return from the STS-135 mission in Space. *PLOS ONE*. September 19, 2013;8:e75097. doi: 10.1371/journal.pone.0075097.	NASA
CBTM-2	Sung M, Li J, Spieker AJ, et al. Spaceflight and hind limb unloading induce similar changes in electrical impedance characteristics of mouse gastrocnemius muscle. J*ournal of Musculoskeletal and Neuronal Interactions*. December 2013;13:405-411.	NASA
CBTM-2	Forsman AD, Nier HA. The effects of spaceflight on mucin production in the mouse uterus. *Gravitational and Space Research*. October 2013;1:20-28.	NASA
CBTM-2	Mao XW, Pecaut MJ, Stodieck LS, et al. Spaceflight environment induces mitochondrial oxidative damage in ocular tissue. *Radiation Research.* October 2013;180(4):340-350. doi: 10.1667/RR3309.1.	NASA
CBTM-2	Dabertrand F, Porte Y, Macrez N, Morel J. Spaceflight regulates ryanodine receptor subtype 1 in portal vein myocytes in the opposite way of hypertension. *Journal of Applied Physiology.* February 1, 2012;112(3):471-480. doi: 10.1152/japplphysiol.00733.2011.	NASA

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CBTM-2	Gridley DS, Pecaut MJ, Green LM, et al. Effects of space flight on the expression of liver proteins in the mouse. *Journal of Proteomics & Bioinformatics*. 2012;05:256–261. doi:10.4172/jpb.1000246.	NASA
CBTM-2	Smith IM, Forsman AD. Ovarian follicular and luteal development in the spaceflight mouse. *Gravitational and Space Biology*. 2012; 26: 30–37.	NASA
CBTM-2	Lebsack TW, Fa V, Woods CC, et al. Microarray analysis of spaceflown murine thymus tissue reveals changes in gene expression regulating stress and glucocorticoid receptors. *Journal of Cellular Biochemistry*. 2010;110(2):372-381. doi: 10.1002/jcb.22547.	NASA
CBTM-2	Tian J, Pecaut MJ, Slater JM, Gridley DS. Spaceflight modulates expression of extracellular matrix, adhesion, and profibrotic molecules in mouse lung. *Journal of Applied Physiology*. 2010;108:162-171. doi: 10.1152/japplphysiol.00730.2009.	NASA
CBTM-2	Gridley DS, Slater JM, Luo-Owen X, et al. Spaceflight effects on T-lymphocyte distribution, function, and gene expression. *Journal of Applied Physiology*. 2009;106:194-202.	NASA
CBTM-2	Ortega MT, Pecaut MJ, Gridley DS, Stodieck LS, Ferguson VL, Chapes S. Shifts in bone marrow cell phenotypes caused by space flight. Journal of Applied Physiology. February 2009;106(2):548-555. doi: 10.1152/japplphysiol.91138.2008.	NASA
CBTM-3 Sclerostin Antibody	Gridley DS, Mao XW, Tian J, et al. Genetic and apoptotic changes in lungs of mice flown on the STS-135 mission in space. *In Vivo*. July 8, 2015;29:423-433.	NASA

Investigation	Citation	Sponsoring Agency
CBTM-3 Sclerostin Antibody	Hwang S, Crucian BE, Sams CF, Actor JK. Post-spaceflight (STS-135) mouse splenocytes demonstrate altered activation properties and surface molecule expression. *PLOS ONE*. May 13, 2015; 10:e0124380. doi: 10.1371/journal.pone.0124380.	NASA
CBTM-3 Sclerostin Antibody	Philippou A, Minozzo FC, Spinazzola JM, et al. Masticatory muscles of mouse do not undergo atrophy in space. *FASEB: Federation of American Societies for Experimental Biology Journal*. 2015;28(7):2769-2779. doi: 10.1096/fj.14-267336.	NASA
CBTM-3 Sclerostin Antibody	Mao XW, Pecaut MJ, Stodieck LS, et al. Biological and metabolic response in STS-135 space-flown mouse skin. *Free Radical Research*. August 2014;48:890-897. doi: 10.3109/10715762.2014.920086.	NASA
CBTM-3 Sclerostin Antibody	Bailey JF, Hargens AR, Cheng K, Lotz JC. Post-spaceflight recovery of biomechanical properties of murine intervertebral discs. *Gravitational and Space Biology*. October 2012;26(2):38-47.	NASA
CBTM-3-Vascular Atrophy	Gridley DS, Mao XW, Tian J, et al. Genetic and apoptotic changes in lungs of mice flown on the STS-135 mission in space. *In Vivo*. July 8, 2015;29:423-433.	NASA
CBTM-3-Vascular Atrophy	Ishihara A, Nagatomo F, Terada M, Fujino H, Kondo H, Ishioka N. Effects of microgravity on the mouse triceps brachii muscle. *Muscle & Nerve*. July 2015;52:63-68. doi: 10.1002/mus.24491.	NASA
CBTM-3-Vascular Atrophy	Hwang S, Crucian BE, Sams CF, Actor JK. Post-spaceflight (STS-135) mouse splenocytes demonstrate altered activation properties and surface molecule expression. *PLOS ONE*. May 13, 2015;10:e0124380. doi: 10.1371/journal.pone.0124380.	NASA

Investigation	Citation	Sponsoring Agency
CBTM-3-Vascular Atrophy	Ritchie LE, Taddeo SA, Weeks BR, et al. Space environmental factor impacts upon murine colon microbiota and mucosal homeostasis. *PLOS ONE*. June 17, 2015;10:e0125792. doi: 10.1371/journal.pone.0125792.	NASA
CBTM-3-Vascular Atrophy	Taylor CR, Hanna M, Behnke BJ, et al. Spaceflight-induced alterations in cerebral artery vasoconstrictor, mechanical, and structural properties: Implications for elevated cerebral perfusion and intracranial pressure. *The FASEB Journal*. 2013;27(6):2282-2292. doi:10.1096/fj.12-222687.	NASA
CBTM-3-Vascular Atrophy	Stabley JN, Dominguez JM, Dominguez CE, et al. Spaceflight reduces vasoconstrictor responsiveness of skeletal muscle resistance arteries in mice. *Journal of Applied Physiology*. 2012;113(9):1439–1445. doi:10.1152/japplphysiol.00772.2012.	NASA
Elerad	Oczypok EA, Etheridge T, Freeman J, et al. Remote automated multi-generational growth and observation of an animal in low-Earth orbit. *Journal of the Royal Society Interface*. 2012;9(68):596-9.	CSA
Elerad	Adenle AA, Johnsen B, Szewczyk MJ. Review of the results from the International *C. Elegans* first experiment (ICE-FIRST). *Advances in Space Research*. 2009;44:210-216.	CSA
Elerad	Johnsen RA , Jones MA , Szewczyk NB, Baillie DA. *C. Elegans*: A model system for studying biological effects of the space environment. *Space Exploration Research*. 2009:55-73.	CSA
Elerad	Zhao Y, Jones M, Baillie D, Rose A. Developing an integrating biological dosimeter for spaceflight. *Microgravity Science and Technology*. 2007;XIX(5/6):201-204.	CSA
Elerad	Zhao Y, Lai K, Cheung I, et al. A mutational analysis of *Caenorhabditis elegans* in space. *Mutation Research*. 2006;601:19-29.	CSA

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MDS	Albi E, Curcio F, Lazzarini A, et al. How microgravity changes Galectin-3 in thyroid follicles. *BioMed Research International*. 2014;2014:5. doi: 10.1155/2014/652863.	NASA
MDS	Albi E, Ambesi-Impiombato FS, Lazzarini A, et al. Reinterpretation of mouse thyroid changes under space conditions: The contribution of confinement to damage. *Astrobiology*. July 2014;14:563-567. doi: 10.1089/ast.2014.1166.	NASA
MDS	Ohira T, Ohira T, Kawano T, et al. Effects of gravitational loading levels on protein expression related to metabolic and/or morphologic properties of mouse neck muscles. *Physiological Reports*. January 2014;2. doi: 10.1002/phy2.183.	NASA
MDS	Camerino GM, Pierno S, Liantonio A, et al. Effects of pleiotrophin overexpression on mouse skeletal muscles in normal loading and in actual and simulated microgravity. *PLOS ONE*. August 28, 2013;8:e72028. doi: 10.1371/journal.pone.0072028.	NASA
MDS	Albi E, Curcio F, Spelat R, et al. Loss of parafollicular cells during gravitational changes (Microgravity, Hypergravity) and the secret effect of Pleiotrophin. PLOS ONE. 2012;7(12):e48518. doi: 10.1371/journal.pone.0048518.	NASA
MDS	Albi E, Curcio F, Spelat R, et al. Observing the mouse thyroid sphingomyelin under space conditions: A case study from the MDS Mission in comparison with hypergravity conditions. Astrobiology. 2012;12(11). doi: 10.1089/ast.2012.0881.	NASA

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MDS	Cancedda R, Liu Y, Ruggiu A, et al. The mice drawer system (MDS) experiment and the space endurance record-breaking mice. *PLOS ONE.* 2012;7(5):e32243. doi: 10.1371/journal.pone.0032243.	NASA
MDS	Masini MA, Albi E, Barmo C, et al. The impact of long-term exposure to space environment on adult mammalian organisms: A study on mouse thyroid and testis. *PLOS ONE.* 2012;7(4):e35418. doi: 10.1371/journal.pone.0035418.	NASA
MDS	Rizzo A, Corsetto P, Montorfano G, et al. Effects of long-term space flight on erythrocytes and oxidative stress of rodents. *PLOS ONE*. 2012;7(3):e32361. doi: 10.1371/journal.pone.0032361.	NASA
MDS	Sandona D, Desaphy J, Camerino GM, et al. Adaptation of mouse skeletal muscle to long-term microgravity in the MDS mission. *PLOS ONE.* March 28, 2012;7(3):e33232. doi: 10.1371/journal.pone.0033232.	NASA
MDS	Santucci D, Kawano F, Ohira T, et al. Evaluation of gene, protein, and neurotrophin expression in the brain of mice exposed to space environment for 91 days. PLOS ONE. 2012;7(7):e40112. doi: 10.1371/journal.pone.0040112.	NASA
MDS	Tavella S, Ruggiu A, Guiliana A, et al. Bone turnover in wild type and pleiotrophin-transgenic mice housed for 3 months in the International Space Station (ISS). *PLOS ONE*. 2012;7(9):e33179. doi: 10.1371/journal.pone.0033179.	NASA
Mouse Immunology	Mednieks M, Khatri A, Hand AR. Salivary gland protein expression after Bion-M1 and Space Shuttle STS-135 missions. *Gravitational and Space Research*. July 2015;3:18.	NASA

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Mouse Immunology	Chang TT, Spurlock SM, Candelario TT, Grenon SM, Hughes-Fulford M. Spaceflight impairs antigen-specific tolerance induction in vivo and increases inflammatory cytokines. FASEB: Federation of American Societies for Experimental Biology Journal. 2015 June 17; 29: 4122-4132. DOI: 10.1096/fj.15-275073.	NASA
Mouse Immunology	Martinez EM, Yoshida MC, Candelario TT, Hughes-Fulford M. Spaceflight and simulated microgravity cause a significant reduction of key gene expression in early T-cell activation. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*. March 15, 2015;308(6):R480-R488. doi: 10.1152/ajpregu.00449.2014.	NASA
Mouse Immunology	Mednieks M, Khatri A, Rubenstein R, Burleson JA, Hand AR. Microgravity alters the expression of salivary proteins. *Oral Health and Dental Management*. June 2014;13:6.	NASA
Mouse Immunology	Blaber EA, Dvorochkin N, Lee C, et al. Microgravity induces pelvic bone loss through osteoclastic activity, osteocytic osteolysis, and osteoblastic cell cycle inhibition by CDKN1a/p21. *PLOS ONE*. April 18, 2013;8(4):e61372. doi: 10.1371/journal.pone.0061372.	NASA
Mouse Immunology	Stabley JN, Dominguez JM, Dominguez CE, et al. Spaceflight reduces vasoconstrictor responsiveness of skeletal muscle resistance arteries in mice. *Journal of Applied Physiology*. November 1, 2012;113(9):1439-1445. doi: 10.1152/japplphysiol.00772.2012.	NASA
Mouse Immunology	Zhao L, Tanjung N, Swarnkar G, Ledet E, Yokota H. Regulation of eIF2α phosphorylation in hindlimb-unloaded and STS-135 space-flown mice. *Advances in Space Research*. 2012;50(5):576-583. doi: 10.1016/j.asr.2012.05.024.	NASA

Biology and Biotechnology: Cellular Biology		
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ISS Summary of Research	Roe LB, Uri JJ. Research progress and accomplishments on the International Space Station. *Acta Astronautica.* 2003;53:665-680. doi: 10.1016/S0094-5765(03)00107-3.	NASA, ESA, JAXA, CSA, ROS
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ISS Summary of Research	Nall ME, Robinson RK. First commercial operations on the International Space Station. *40th Aerospace Sciences Meeting and Exhibit*, Reno, NV; January 14-17, 2002.	NASA, ESA, JAXA, CSA, ROS
ISS Summary of Research	Benton ER, Benton EV. Space radiation dosimetry in low-Earth orbit and beyond. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms.* September 2001;184(1-2):255-294. doi: 10.1016/S0168-583X(01)00748-0.	NASA, ESA, JAXA, CSA, ROS

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ISS Summary of Research	Utkin VF, Lukjaschenko VI, Borisov VV, Suvorov VV, Tsymbaljuk MM. Long-term research program for Russian segment of the International Space Station. *Journal of Low Temperature Physics.* 2000;119(3/4):185-193.	NASA, ESA, JAXA, CSA, ROS
ISS Summary of Research	Wilke D, Padeken D, Weber T, Gerzer R. Telemedicine for the International Space Station. *Acta Astronautica.* 1999;44(7-12):579-581.	NASA, ESA, JAXA, CSA, ROS
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ARISS	Wright RL. Remember, We're Pioneers! The First School Contact with the International Space Station. *AMSAT-NA Space Symposium*, Arlington, VA; 2004.	NASA

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Saturday Morning Science	Love SG, Pettit DR, Messenger SR. Particle aggregation in microgravity: Informal experiments on the International Space Station. *Meteoritics & Planetary Science*. May 2014;49(5):732-739. doi: 10.1111/maps.12286.	NASA
Saturday Morning Science	Love SG, Pettit DR. Fast, repeatable clumping of solid particles in microgravity. *35th Lunar and Planetary Science Conference*, Houston, TX; 2004.	NASA
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Saturday Morning Science	Grunsfeld JM. Shooting the Heavens from Space. *Sky and Telescope.* 2003:128-132.	NASA
Science of the Sphere	Fontana P, Pettit DR, Cristoferetti S. Sodium chloride crystallization from thin liquid sheets, thick layers, and sessile drops in microgravity. *Journal of Crystal Growth*. October 15, 2015;428:80-85. doi: 10.1016/j.jcrysgro.2015.07.026.	NASA
Science of the Sphere	Fontana P, Schefer J, Pettit DR. Characterization of sodium chloride crystals grown in microgravity. *Journal of Crystal Growth*. June 2011;324:207-211. doi: 10.1016/j.jcrysgro.2011.04.001.	NASA
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ISS Medical Monitoring	Mulavara AP, Ruttley TM, Cohen HS, et al. Vestibular-somatosensory convergence in head movement control during locomotion after long-duration spaceflight. J*ournal of Vestibular Research*. 2012;22(2-3):153-166. doi: 10.3233/VES-2011-0435.	NASA, ESA, JAXA, CSA, ROS
ISS Medical Monitoring	Gibson CR, Mader TH, Schallhorn. Visual stability of laser vision correction in an astronaut on a Soyuz Mission to the International Space Station. *Journal of Cataract and Refractive Surgery*. 2012;38(3):1486-1491. doi: 10.1016/j.jcrs.2012.06.012.	NASA, ESA, JAXA, CSA, ROS

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ISS Medical Monitoring	Snigiryova GP, Novitskaya NN, Fedorenko BS. Cytogenetic examination of cosmonauts for space radiation exposure estimation. *Advances in Space Research.* August 15, 2012;50(4):502-507. doi: 10.1016/j.asr.2012.05.010.	NASA, ESA, JAXA, CSA, ROS
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ISS Medical Monitoring	Hamilton DR, Murray JD, Ball. Cardiac health for astronauts: Coronary calcification scores and CRP as criteria for selection and retention. *Aviation, Space, and Environmental Medicine*. 2006;77(4):377-387.	NASA, ESA, JAXA, CSA, ROS
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ISS Medical Monitoring	Hamilton DR, Murray JD, Kapoor D, Kirkpatrick AW. Cardiac health for astronauts: Current selection standards and their limitations. *Aviation, Space, and Environmental Medicine*. July 2005;76(7):615-626.	NASA, ESA, JAXA, CSA, ROS
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ISS Medical Monitoring	D'Aunno DS, Dougherty AH, DeBlock HF, Meck JV. Effect of short- and long-duration spaceflight on QTc intervals in healthy astronauts. *American Journal of Cardiology*. February 15, 2003;91:494-497. doi: 10.1016/S0002-9149(02)03259-9.	NASA, ESA, JAXA, CSA, ROS
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Clinical Nutrition Assessment	Hall PS. Past and current practice in space nutrition. Cleveland, OH: *Bone Loss During Spaceflight: Etiology, Countermeasures, and Implications for Bone Health on Earth*. 2007.	NASA
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ISS Acoustics	Limardo JG, Allen CS. Analysis of noise exposure measurements acquired onboard the International Space Station. *41st International Conference on Environmental Systems,* Portland, Oregon; July 17-21, 2011:16.	NASA
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ISS Acoustics	Pilkinton GD. ISS acoustics mission support. *Noise Conference,* Cleveland, OH; 2003.	NASA
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ISS Exploration	Scimemi SJ. The International Space Station and the commercialization of low-Earth orbit. *AIAA Space 2015 Conference & Exposition*, Pasadena, CA; August 31-September 2, 2015; AIAA 2015-4581:11. doi: 10.2514/6.2015-4581.	NASA, ESA, JAXA, CSA, ROS

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ISS Exploration	Ansdell M, Ehrenfreund P, McKay C. Stepping stones toward global space exploration. *Acta Astronautica.* 2011;68:2098-2113. doi: 10.1016/j.actaastro.2010.10.025.	NASA, ESA, JAXA, CSA, ROS
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ISS Exploration	Djordjevic IB. Deep space and near-Earth optical communications by coded orbital angular momentum (OAM) modulation. *Optics Express.* July 18, 2011;19(15):14277-14289.	NASA, ESA, JAXA, CSA, ROS
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ISS Exploration	Miller FJ, Niederhaus C, Barlow K, Griffin DW. Intravenous solutions for exploration missions. *45th Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2007.	NASA, ESA, JAXA, CSA, ROS
ISS Exploration	Ruff GA, Urban DL. Technology development for fire safety in exploration spacecraft and habitats. *45th Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2007.	NASA, ESA, JAXA, CSA, ROS
ISS Exploration	Jordan NC, Saleh JH, Newman DJ. The extravehicular mobility unit: A review of environment, requirements, and design changes in the US spacesuit. *Acta Astronautica.* 2006;59(12):1135-1145.	NASA, ESA, JAXA, CSA, ROS
ISS Exploration	Kobrick RL, Dara S, Burley J, Gill S. A new countermeasure device for long duration spaceflights. *Acta Astronautica*. 2006;58:523-536. doi: 10.1016/j.actaastro.2005.12.013.	NASA, ESA, JAXA, CSA, ROS
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ISS Exploration	Carrasquillo RL. ISS ECLSS technology evolution for exploration. *43rd Aerospace Sciences Meeting and Exhibit*, Reno, NV; 2005.	NASA, ESA, JAXA, CSA, ROS
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ISS Exploration	Rochlis JL, Newman DJ. A tactile display for international space station (ISS) extravehicular activity (EVA). *Aviation, Space, and Environmental Medicine*. June 2000;71(6):571-578.	NASA, ESA, JAXA, CSA, ROS
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APPENDIX B

ACRONYMS AND ABBREVIATIONS

ABRS	Advanced Biological Research System
ACE	Advanced Colloid Experiment
ACK	Acoustic Countermeasure Kit
Actin	Role of Weightlessness on Metabolism
ADF	Avian Development Facility
ADF-Otolith	Development and Function of the Avian Otolith System in Normal and Altered Gravity Environments
ADF-Skeletal	Skeletal Development in Embryonic Quail on the ISS
ADUM	Advanced Diagnostic Ultrasound in Microgravity
AdvAsc	Advanced Astroculture
AEA	ancillary equipment area
AEA	N-arachidonoylethanolamine
AEM	animal enclosure module
AES	Agrospace Experiments Suite
AFRL	Air Force Research Laboratory
AGEING	Drosophila Motility, Behaviour and Ageing
AGN	Active Galactice Nucleus
AIS	Automatic Identification System
Akvarium	Study of the Resistance of a Modeled Closed Ecosystem and Chains of its Components in Microgravity
ALARA	as low as reasonably achievable
ALS	advanced life support
ALTCRISS	Alteino Long Term Cosmic Ray Measurements on board the International Space Station
ALTEA	Anomalous Long-term Effects in Astronauts' Central Nervous System
Alteino	Space Radiation Effects on the Central Nervous System
AMD	arithmetic mean diameter
Amphibody	Antibody V(D)J Recombination Machinery in Normal and Altered Gravity
AMS-02	Alpha Magnetic Spectrometer
ANDE	Atmospheric Neutral Density Experiment
ANDE - 2	Atmospheric Neutral Density Experiment - 2

ANGKASA	National Space Agency, Malaysia
ANITA	Analyzing Interferometer for Ambient Air
Antigen	Optimizing Heterologous Expression in Saccharomyces Yeast in Micro-gravity based on the Example of Hepatitis B Surface Antigen Synthesis
AO	atomic oxygen
Aorta	Physiological Parameters That Predict Orthostatic Intolerance After Spaceflight
APCF	Advanced Protein Crystallization Facility
APEX Cambium	Advanced Plant Experiments – Cambium
APEX-CSA2	Advanced Plant Experiment - Canadian Space Agency 2
APIS	Analysis of Inertial Solid Properties
APRSAF	Asia-Pacific Regional Space Agency Forum
APS	Antibiotic Production in Space
Aquarius	Embryonic Development of Amphibians in Weightlessness
Area PADLES	Area PAssive Dosimeter for Life Science Experiments in Space
ARED	Advanced Resistance Exercise Device
ARIS	Active Rack Isolation System
ARISS	Amateur Radio on the International Space Station
Aryl	Effect of Spaceflight Factors on the Expression of Producer Strains of Interleukin 1α, 1β, and Aryl
ASD	air supply diffuser
Aseptik	Development of Methods and Onboard Equipment to Assure Aseptic Conditions Performing Biotechnology Experiments During Manned Space Flight
ASI	Italian Space Agency
ASIA	Analysis, Experimentation and Implementation Algorithms
AST-ir	allatostatin-A immunoreactivity
Astrovaktsina	Cultivating Escheria coli Producer of CAF1 Protein in Weightlessness
AT-Space	Arabidopsis thaliana in Space: Perception of Gravity, Signal Transductions and Gravitresponse in Higher Plants
ATP	adenosine triphosphate
ATU	audio terminal unit
AuroraMAX	Coordinated Aurora Photography from Earth and Space
Avatar Explore	Autonomous Robotic Operations Performed from the International Space Station
Bakteriofag	Study of the Effects of Spaceflight Factors on Bacterophages
Bar	Selecting and Testing Procedures and Equipment for Detecting Locations of Module Depressurization on the International Space Station
BARS	brefeldin A-ADP ribosylated substrate
BASE-A	Bacterial Acclimation and Adaptation to the Space Environment Conditions-A

BASE-B/C	Bacterial Acclimation and Adaptation to the Space Environment Conditions-B/-C
BASS	Burning and Suppression of Solids
BBND	Bonner Ball Neutron Detector
BBT	Beacon-Beacon Test
BCAT-3-4-CP	Binary Colloidal Alloy Test -3 and 4: Critical Point
BCAT-3-SC	Binary Colloidal Alloy Test -3 Surface Crystallization
BCAT-4-Poly	Binodal Colloidal Aggregation Test-4: Polydispersion
BCAT-5	Binary Colloidal Allot Test-5
BCAT-6	Binary Colloidal Allot Test-6
bFGF	basic fibroblast growth factor
BFOs	blood-forming organs
Bif	Study of the Effects of Space Flight Factors on the Technological and Biomedical Characteristics of Bifidobacteria
BIMS	Study of Processes for Informational Support of In-Flight Medical Support using an Onboard Medical Information System Integrated into the Information Control System of the ISS Russian Segment
Biodosimetry	Biodosimetry in Astronauts
Bioekologiya-M /Bioekologiya-R	Obtaining Highly-Efficient Strains of Microorganisms for the Production of Biological Petroleum Degrading Compounds, Organophosphate Substances, Plant Protection Means, and Exopolysaccharides used in the Petroleum Industry
BIOKIS	BIOKon In Space
Biological Rhythms	The Effect of Long-term Microgravity Exposure on Cardiac Autonomic Function by Analyzing 24-hours Electrocardiogram
Biopsy	Effect Of Prolonged Spaceflight On Human Skeletal Muscle
Biotest	Biochemical Status of Humans in Long-term Spaceflight
BISE	Bodies in the Space Environment
Bisphosphonates	Bisphosphonates As a Countermeasure To Spaceflight-Induced Bone Loss
BLT	Boundary Layer Transition
BMD	bone mineral density
BMI	Blood Pressure Measurement Instrument
BMSC	bone marrow stromal cells
BOI	broth-only isolatese
BONEMAC	Differentiation Of Bone Marrow Macrophages In Space
BOP	bone proteomics
BOS	Blood and Oxidative Stress
BP/ECG	blood pressure/electrocardiograph
BPS	Biomass Production System
Bradoz	Bioradiation Dosimetry in Spaceflight

BRIC-SyNRGE Environment	Biological Research in Canisters Symbiotic Nodulation in a Reduced Gravity Environment
BTN-Neytron	Study of the Fluxes of Fast and Thermal Neutrons
BSTC	biotechnology specimen temperature controller
BugNRG	Bug Energy-Study of Output of Bacterial Fuel Cells in Weightlessness
C	Celsius
$CaCl_2$	calcium chloride
CAD	coronary artery disease
CAOX	calcium oxalate
Card	Long Term Microgravity: A Model for Investigating Mechanisms of Heart Disease with New Portable Equipment Card
Cardiocog-1, -2	Cognitive Cardiovascular Experiment -1, -2
Cardio-ODNT	Comprehensive Study of the Pattern of Main Indicators of Cardiac Activity and Blood Circulation
CardioRespir	Cardiorespiratory Adaptation to the Space Environment
CASPER	Cardiac Adapted Sleep Parameters Electrocardiogram Recorder
CBEF	Cell Biology Experimental Facility
CBOSS	Cellular Biotechnology Operations Support System
CBPD	continuous blood pressure device
CBTM	Commercial Biomedical Testing Module
CC	culture chambers
CCAP-ir	crustacean cardioactive peptide immunoreactivity
CCF	Capillary Channel Flow
CCM	Cell Culture Module
CCM-Immune Response	Cell Culture Module - Immune Response of Human Monocytes in Microgravity
CCM-Wound Repair	Cell Culture Module - Effect of Microgravity on Wound Repair: In Vitro Model of New Blood Vessel Development
CCISS	Cardiovascular and Cerebrovascular Control on Return from ISS
CCR	Cube Corner Reflector
cDNA	complementary deoxyribonucleic acid
CDRA	carbon dioxide removal assembly
CDP	computerized dynamic posturography
CEA	carcinoembryonic antigen
CELL WELL	Reverse Genetic Approach to Exploring Genes Responsible for Cell Wall Dynamics in Supporting Tissues of Arabidopsis Under Microgravity Conditions
CeMM	*C. elegans* maintenance medium
CEO	Crew Earth Observations
CEO-IPY	Crew Earth Observations – International Polar Year

CERISE	Caenorhabditis Elegans RNAi Space Experiment
CETSOL and CETSOL-2	Columnar-to-Equiaxed Transition in Solidification, and -2
CEV	crew exploration vehicle
CEVIS	Cycle Ergometer with Vibration Isolation System
CFE	Capillary Flow Experiment
CFE - 2	Capillary Flow Experiment - 2
CFS-A	Growth and Survival of Colored Fungi in Space-A
CFU	Colony Forming Units
CGBA	Commercial Generic Bioprocessing Apparatus
CGSM	Canadian GeoSpace Monitoring
CHab	*C. elegans* habitat
CHAMP	challenging minisatellite payload
CHIRO	Crew's Health: Investigation on Reduced Operability
Chondro	Study on the Development of Methods to Produce Artificial Cartilage
Chromosome-1, -2	Chromosomal Aberrations in Blood Lymphocytes of Astronauts-1, -2
CIB	Communications Interface Board
CIR	combustion integrated rack
Circa	24-hour Pattern of Blood Pressure and Heart Rate in Weightlessness
CL	Contact Line
CLCA2	chloride channel accessory 2
CLCN4	chloride Channel, Voltage-Sensitive 4
Clinical Nutrition Assessment	Clinical Nutrition Assessment of ISS Astronauts
ClO	chlorine monoxide
cm2	square centimeter
CMG	control moment gyroscope
CNRS	Centre National de la Recherche Scientifique
CNS	central nervous system
CO	carbon monoxide
CoCl2	cobalt chloride
COLBERT	Combined Operational Load Bearing External Resistance Treadmill
CORE	Central Operations of Resources for Educators
COSMIC	COmbustion Synthesis Under MIcrogravity Conditions
CO2	carbon dioxide
COTS	commercial off-the-shelf
COX-2	Cyclooxygenase-2
CPC	cardiopulmonary coupling
CPCG-H	Commercial Protein Crystal Growth-High-density
CPDS	charged-particle directional spectrometer
CPL	capillary pumped loop

CRAND	cosmic ray albedo neutron decay
CRE-1	Component Repair Experiment-1
CREB	cAMP response element-binding protein
CRISP-2	Crickets in Space-2
CSA	Canadian Space Agency
CSI-01	Commercial Generic Bioprocessing Apparatus Science Insert-01
CSI-02	Commercial Generic Bioprocessing Apparatus Science Insert-02
CSI-03	Commercial Generic Bioprocessing Apparatus Science Insert-03
CSI-05	Commercial Generic Bioprocessing Apparatus Science Insert-05
CSLM-2	Coarsening in Solid Liquid Mixtures-2
CT	computed tomography
CTP	citrate transporter protein
Cult	Cultural Determinations of Co-working, Performance and Error Management in Space Operations
CVB	Constrained Vapor Bubble
DAFT	Dust and Aerosol Measurement Feasibility Test
DCAM	Diffusion-Controlled Crystallization Apparatus for Microgravity
DCCO	Diffusion Coefficient in Crude Oils
DcoH	4a-hydroxy-tetrahydropterin dehydratase
DCPCG	Dynamically Controlled Protein Crystal Growth
DCS	decompression sickness
DECLIC-ALI	Device for the study of Critical Liquids and Crystallization – Alice Like Insert
DECLIC-DSI	Device for the Study of Critical Liquids and Crystallization –Directional Solidification Insert
DECLIC-HTI	Device for the study of Critical LIquids and Crystallization - High Temperature Insert
DEXA	dual-energy X-ray absorptiometry
DFA	diferulic acid
DGGE	denaturing gradient gel electrophoresis
DHEA	dihydroergocryptine
DHEAS	dehydroepiandrosterone
Diatomeya	Stability of Geographical Position and Configuration of Borders of Bioproductive Water Zones of the World's Oceans Observed by OrbitalStation Crews
DIDO	digital input digital output
DISC	Digital Imaging Star Camera
Diurez	Study of Fluid and Electrolyte Metabolism and Hormonal Regulation of Fluid Volume in Spaceflight Conditions
DLR	Deutsches Zentrum fur Luft und Raumfahrt

DNA	deoxyribonucleic acid
DOA	Department of Agriculture
DOBIES	Dosimetry for Biological Experiments in Space
DOD	Department of Defense
DOD SPHERES-CSAC	Department of Defense Synchronized Position, Hold, Engage, Reorient, Experimental Satellites - Chip Scale Atomic Clock
DomeGene	Control of Cell Differentiation and Morphogenesis of Amphibian Culture Cells
DOSIS	Dose Distribution Inside the International Space Station
DOSMAP	Dosimetric Mapping
DOSTEL	silicon dosimetry telescope
DRAGONSat	Dual RF Astrodynamic GPS Orbital Navigator Satellite
DSB	double strand break
DSO	detailed science objective
DTN	Disruption Tolerant Networking
DTO	Detailed Test Objective
D_20	deuterium oxide (heavy water)
DU	detector unit
DUST	Dust and Aerosol Measurement Feasibility Test
DXA	dual-energy X-ray absorptiometry
Dykhaniye	Study of the Regulation and Biomechanics of Respiration in Spaceflight
E. coli	Escherichia coli
EAP	Educator Astronaut Program
EarthKAM	Earth Knowledge Acquired by Middle School Students
EBCT	electron-beam computed tomography
EBV	Epstein-Barr Virus
ECG	echocardiograph
ECLSS	Environmental Control and Life Support System
EDA	education demonstration activity
EDOS	Early Detection of Osteoporosis in Space
ETD	Eye Tracking Device
EDTA	ethylenediamine-tetraacetic acid
Education-SEEDS	Space Exposed Experiment Developed for Students
Education-Solar Cells	Education- How Solar Cells Work
EEG	electroencephalograph
EGN	enhanced gaseous nitrogen
EGNOS	European Geostationary Navigation Overlay Service
EGR-1	early growth response-1
EKE	Assessment of Endurance Capacity by Gas Exchange and Heart Rate Kinetics During Physical Training

Elerad	Elegans to Assess Genomic Damage on Long-Duration Flights
ELITE-S2	ELaboratore Immagini TElevisive - Space 2
EMA	epithelial membrane antigen
EMC	elastic memory composite
EMCH	elastic memory composite hinge
EMCS	European Modular Cultivation System
EMG	electromyography
EMU	extravehicular mobility unit
ENEIDE	Esperimento di Navigazione per Evento Italiano Dimostrativo di EGNOS
Energy	Astronaut's Energy Requirements for Long-Term Space Flights
E-Nose	Electronic Nose Monitoring
ENT	ear, nose, and throat
EPO	Education Payload Operations
EPO - Demos	Education Payload Operations - Demonstrations
EPO - Cloud Observation-Demos	Education Payload Operations - Cloud Observation-Demonstrations
EPO - Educator	Education Payload Operations - Educator
EPO-International Toys in Space	Education Payload Operations - International Toys in Space
EPO - Kit C	Education Payload Operations - Kit C Plant Growth Chambers
EPO - Kit D	Education Payload Operation - Kit D
EPO-Lewis and Clark-Demos	Education Payload Operations - Lewis and Clark-Demonstrations
EPO-MAEA	Education Payload Operation s- Museum Aerospace Education Alliance
EPO-Robo	Education Payload Operations - Robotics
EPO-Sesame Street-Demos	Education Payload Operations-Sesame Street-Demonstrations
EPO-Tomatosphere II	Education Payload Operations-Tomatosphere II
Epstein-Barr	Spaceflight-Induced Reactivation of Latent Epstein-Barr Virus
Epstein-Barr	Erasmus Recording Binocular, and -2
ERB, and ERB-2	extracellular-signal-regulated kinase
ERK	event related potentials
ERP	European Space Agency
ESA	European Space Agency – Education Payload Operations – Foam-S
ESA-EPO-Foam-S	European Space Agency – Educational Payload Operations – Fuji 3D
ESA-EPO-Fuji 3D	European Space Agency – Education Payload Operations – Greenhouse
ESA-EPO-Greenhouse	European Space Agency – Education Payload Operations – Mission-X
ESA-EPO-Mission-X	European Space Agecny Hand Posture Analyzer
ESA-HPA	Electrostatic Self-assembly Demonstration

ESD	experiment support module
ESM	Engelhard titanosilicate structure
ETS	endotoxin unit
EU	European Technology Exposure Facility-DEBris In Orbit Evaluator-2
EuTEF-DEBIE-2	European Technology Exposure Facility-Thermometer
EuTEMP	European Technology Exposure Facility-Earth Viewing Camera
EuTEF-EVC	European Technology Exposure Facility - Exposure Experiment - Adapt
EuTEF-Expose-Adapt	European Technology Exposure Facility - Exposure Experiment - Life
EuTEF-Expose-Life	European Technology Exposure Facility- Plasma
EuTEF-Expose-Process	European Technology Exposure Facility - Exposure Experiment-Protect
EuTEF-Expose-Protect	European Technology Exposure Facility - Exposure Experiment – Seeds
EuTEF-Expose-Seeds	European Technology Exposure Facility- Flux (Phi) Probe Experiment-Time Resolved Measure of Atomic Oxygen
EuTEF-FIPEX	European Technology Exposure Facility- Flux (Phi) Probe Experiment-Time Resolved Measure of Atomic Oxygen
EuTEF-MEDET	European Technology Exposure Facility - Material Exposure and Degradation ExperimenT
EuTEF-PLEGPAY	European Technology Exposure Facility- Plasma Electron Gun Payload
eV	electron volt
EVA	extravehicular activity
EVARM	EVA radiation monitoring
Expert	Investigation of Early Symptoms of Microdestruction of Structures andInstrument Modules in the Russian Segment of ISS
Expose-R-Amino	Expose – R Photochemical Processing of Amino Acids in Earth Orbit
Expose-R-Endo	Expose – R Screening of Ultra-Violet Radiation in Endothilic and Microalgal Communities from Antartica
Expose-R-Organic	Expose – R Evolution of Organic Matter in Space
Expose-R-Osmo	Expose – R Exposure of Osmophilic Microbes to Space Environment
Expose-R-Photo	Expose – R Photo DNA Photodamage: Measurements of Vacuum Solar Radiation-induced DNA Damages Within Spores
Expose-R PUR	Expose – R Responses of Phage T7, Phage DNA and Polycrystalline Uracilto the Space Environment
Expose-R R3DR	Expose – R Radiation Risks Radiometer-Dosimeter
Expose-R Spores	Expose – R Spores in Artificial Meteorites
Expose-R Subtil	Expose – R Mutational Spectra of Bacillus subtilis Spores and Plasmid DNA Exposed to High Vacuum and Solar UV Radiation in the Space Environment
EXPPCS	ExPRESS Physics of Colloids in Space
ExPRESS	Expedite the Processing of Experiments to Space Station

FA	ferulic acid
Facet	Faceted Cellular Array Growth
Farma	Research on the Particulars of Pharmacological Effects During Long-term Spaceflight
FC	Flight Control
FCal	Fence Calibration
FDA	Food and Drug Administration
FDI	Fluid Dynamics Investigation
FE	Flight Experiment
FENO	Fractional Exhaled Nitric Oxide
Ferulate	Regulation by Gravity of Ferulate Formation in Cell Walls of Rice Seedlings
FFQ	Food Frequency Questionnaire
FIR	fluids integrated rack
Fish Scales	Investigation of the Osteoclastic and Osteoblastic Responses to Microgravity Using Goldfish Scales
FIT	Fungal Pathogenesis, Tumorigenesis, and Effects of Host Immunity in Space
5-LOX	5-lipoxygenase
Fizika-Obrazovaniye	Scientific and Educational Demonstration of Physical Laws and Phenomena in Microgravity
FLEX	Flame Extinguishment Experiment
FLEX-2	Flame Extinguishment Experiment - 2
FLOW	Bone Cell Mechanosensitivity in Weightlessness
FLT	flight
Flywheel	Flywheel Exercise Device
FMVM	Fluid Merging Viscosity Measurement
FOAM-Stability	Foam Optics and Mechanics - Stability
FOB	Forward Osmosis Bag
FOOT	Foot/Ground Reaction Forces During Spaceflight
FORP	fuel oxidizer reaction product
FPEF	Fluid Physics Experiment Facility
FPDS	Fire Prevention, Detection, and Suppression
FPMU	floating potential measurement unit
FPP	floating potential probe
FRTL5	Fischer Rat Thyroid Low Serum 5
FSB	Fundamental Space Biology
FTSCE	Forward Technology Solar Cell Experiment
Functional Task Test	Physiological Factors Contributing to Postflight Changes in Functional Performance

G	gravity
GAP-FPA	Group Activation Pack-Fluid Processing Apparatus
GASMAP	gas analyzer system for metabolic analysis physiology
GATOR	Grappling Adaptor to On-Orbit Railing
GC	Ground Control
GCF	Granada Crystallisation Facility
GCR	galactic cosmic ray
GDS	Gas Delivery System
Gematologiya	Study of Morphofunctional Properties of Blood Cells and Intensity of Erythropoiesis in Humans Subjected to Spaceflight Factors
Genara-A	Gravity Related Genes in Arabidopsis - A
Gene Expression	Expression of Microbial Genes in Space
Geoflow-I and II	Simulation of Geophysical Fluid Flow under Microgravity-I and -II
Get Fit for Space	Get Fit for Space Challenge with Bob Thirsk
GeV	giga-electron volt
GFP	Green Fluorescent Protein
GHab	garden habitat
Glikoproteid	Identifying and Investigation Surface Glycoproteins E1-E2 of Alpha-viruses on Earth and in Space
GMCSF	granulocyte-macrophage colony-stimulating factor
GO	gene ontology
GOES	geostationary operational environmental satellite
GraPhoBox	Study into the Interaction of Effects of Light and Gravity on the Growth Process of Plants
Gravi-1	Threshold Acceleration for Gravisensing-1
Great Start	Popularizing Achievements in Russian Manned Space Exploration
GSC	gas slit camera
GSC	grab sample container
GTS-1/-2	Global Transmission Services-1 and -2
Hair	Biomedical Analysis of Human Hair Exposed to Long-term Space Flight
HB	Hepatitis B
HCl	hydrogen chloride
HDBR	head-down bed rest
HDPCG	High-Density Protein Crystal Growth
HD-SDI	high-definition serial digital interface
HDTV	high-definition television
HDTV MPC	High Definition Television Multi-Protocol Converter System
HDTV in SM	High Definition Television Camera Utilizing The Service Module
HDV	high-definition video

Heart	Physiological Parameters That Predict Orthostatic Intolerance After Spaceflight
Heat	Heat Transfer Performances of a Grooved Heat Pipe
HEPA	high-efficiency particular accumulator
HET-Smartphone	Human Exploration Telerobotics - Smartphone
HGD/PFD	Handgrip and Pinch Force Dynamometers
HICO	Hyperspectral Imager for the Coastal Ocean
HIR	Humoral Immune Response
HiRAP	high-resolution accelerometer package
HIV	Human Immunodeficiency Virus
HOG	high osmolarity glycerol
H-PGDS	hematopoietic prostaglandin D synthase
HPA	Hand Posture Analyzer
H-Reflex	Effects of Altered Gravity on Spinal Cord Excitability
HREP	HICO and RAIDS Experiment Payload
HREP HICO	HICO and RAIDS Experiment Payload - Hyperspectral Imager for the Coastal Ocean
HRF	Human Research Facility
HRP	Human Research Program
HR	heart rate
HRV	heart rate variability
hsCRP	highly selective capsular reactive protein
HSP	heat shock proteins
HTI	Hydration Technology Innovations
H_2O_2	hydrogen peroxide
HUVEC	Human Umbilical Vein Endothelial Cells
Hydro Tropi	Hydrotropism and Auxin-Inducible Gene Expression in Roots Grown Under Microgravity Condition
Hypersole	Cutaneous Hypersensitivity and Balance Control in Humans
i-APE	Italian-Astronaut Personal Eye
IAA	International Academy of Astronautics
IBMP	Institute of Biomedical Problems
ICAM-1	Intercellular Adhesion Molecule-1
ICE	ISS Characterization Experiment
ICE Crystal	Pattern Formation during Ice Crystal Growth
ICE-First	International Caenorhabditis Elegans Experiment First Flight
ICES	International Conference on Environmental Systems
ICF	Interior Corner Flow
ICM	isothermal containment module
ICU	internal cargo unit

Identifikatsiya	Identification of Sources of Disturbances During Disruption of Microgravity on the International Space Station
IDZ	impurity depletion zone
I-ENOS	Italian-Electronic NOse for Space
INFy	interferon gamma
IFRECOR	l’Initiative Française pour les Récifs Corallines
IGF-1	insulin-like growth factor 1
IgM	Immunolglobin M
IGRF	International Geomagnetic Reference Field
Il-2	Interleukin-2
IMCs	intermetallic matrix composites
Imedias	Observation of Environmental Phenomena
Infrazvuk-M	Integrated Research on Low-Frequency Acoustic and Electromagnetic Fields in the ISS Habitation Compartments
Immuno	Neuroendocrine and Immune Responses in Humans During and After Long Term Stay at ISS
Impuls Stage 1	Altering the Ionosphere by Pulsed Plasma Sources
In-flight Education Downlinks	International Space Station In-flight Education Downlinks
INS	Inertial navigational systems
InSb	indium antimonide
InSPACE	Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsion
Interactions	Crew Member and Crew-Ground Interaction During International SpaceStation Missions
Intercellular Interaction	Research on Intercellular Interaction in Space Flight
IPY	International Polar Year
iRED	Interim Resistance Exercise Device
IRI	International Reference Ionosphere
IRIS	Image Reversal in Space
Iskazheniye	Determining and Analyzing the Magnetic Interference on the ISS
ISR	Incoherent Scatter Radar
ISS	International Space Station
ISS Acoustics	International Space Station Acoustic Measurement Program
ISS Exploration	Science for the Improvement of Future Space Exploration
ISS External Environments	International Space Station External Environments
ISS External Radiation Monitoring	International Space Station Internal Radiation Monitoring

ISS /internal Environments	International Space Station External Environments
ISS Internal Radiation Monitoring	International Space Station Internal Radiation Monitoring
ISS Medical Monitoring	Medical Monitoring On Board the International Space Station
ISS Summary of Research	International Space Station Summary of Research Performed
ISSAC	International Space Station Agricultural Camera
ISSI	In-space Soldering Experiment
ITB	Bandung Institute of Technology
IZECS	Improved Zeolite Electronic Control System
Izgib	A Study of the Effects of Onboard System Operating Modes on ISS Flight Conditions
JAXA Holter	Check out of the On-orbit Digital Holter ECG and HDTV Camera Monitoring for Telemedicine
JAXA	Japan Aerospace Exploration Agency
JAXA-Astro Report	Japan Aerospace Exploration Agency - Astronaut Report
JAXA-GCF	Japan Aerospace Exploration Agency – Granada Crystalization Facility High Quality Protein Crystallization Experiment
JAXA EPO	Japan Aerospace Exploration Agency Educational Payload Observation
JAXA Holter	Check out of the On-orbit Digital Holter ECG and HDTV Camera Monitoring for Telemedicine
JAXA PCG	Japan Aerospace Exploration Agency Protein Crystal Growth
JEM	Japanese Experiment Module
JES	joint excursion sensor
Journals	Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of Astronaut Journals
JSC	Johnson Space Center
K	Kelvin
Kappa	Influence of Weightlessness on th e Activation of NF-κβ Proteins
K-cit	potassium citrate
KCGE	Kidney Cell Gene Expression
KCNG2	potassium voltage-gated channel subfamily G member 2
KCNJ14	potassium inwardly-rectifying channel, subfamily J, member 14
KCNT1	potassium channel, sodium activated subfamily T, member 1
Kids In Micro-g	Kids In Micro-gravity
km	kilometers

Kromka	Study of the Dynamics of Contaminating Substances Emission from Control Liquid Propellant Low-Thrust Jet Engines during Their Pulse Firings and Verification of the Effectiveness of Deflectors for the Protection of ISS External Surfaces from Contamination
KSS	Karolinska Sleepiness Score
Kulonovskiy Kristall	Study of the Dynamics of a System of Charged Particles in a Magnetic Field in Microgravity Conditions
Lada-VPU-P3R	Validating Vegetable Production Unit Plants, Protocols, Procedures and Requirements Using Currently Existing Flight Resources
LAN	local area network
LAPAN	National Institute of Aeronautics and Space, Indonesia
LAZIO-SiRAD	Low Altitude Zone Ionizing Observatory
LBNP	lower body negative pressure
LBs	liquid bridges
LBP	Low Back Pain
LC	Laboratory Control
LCD	liquid crystal display
LC-MS-MS	Liquid Chromatography-tandem Mass spectrometry
LDL	low-density lipoprotein
LDM	long-duration missions
LED	light-emitting diode
LEMS	lower extremity monitoring suit
LEO	low Earth orbit
LES -2, -3	Lessons from Space -2,-3
LET	linear energy transfer
Leu2	leucine dipeptide
Leukin-2	Role of Interleukin-2 Receptor in Signal Transduction and Gravi-sensing Threshold of T-Lymphocytes
LFA-1	Lymphocyte function-associated antigen 1
LFSAF	lightweight flexible solar array hinge
LMM	Light Microscopy Module
L-PGDS	lipocalin-type prostaglandin D synthase
LPS	lipopolysaccharides
LOCAD-PTS	Lab-on-a-Chip Application Development-Portable Test System
LOH	Detection of Changes in LOH Profile of TK mutants of Human Cultured Cells
LRT	low-rate telemetry
LSO	Lightning and Sprite Observations
LSS	life support system

MAA	Mock ANDE Active
MABE	Microheater Array Boiling Experiment
MACE-II	Middeck Active Control Experiment-II
MAI-75	Spacecraft and Modern Technologies for Personal Communications
MAMS	Microgravity Acceleration Measurement System
Marangoni-Exp	Chaos, Turbulence and its Transition Process in Marangoni Convection
Marangoni-UVP	Spatio-temporal Flow Structure in Marangoni Convection
MARDI	Malaysian Agricultural Research and Development Institute
Massoperenos	Study of Mass-Exchange Properties of Capillary-Porous Bodies, Root Habitable Media, in Spaceflight Conditions
Matroshka-2A	Measuring Radiation Hazards in Space
Matroshka-2B	Study of the Depth Dose Distribution Inside a Human Phantom Using the Matroshka Facility Onboard the Russian Segment of the International Space Station
Matroshka-Kibo	Study of Depth Dose Distribution Inside a Human Phantom Using the Matroshka Facility
MATI-75	Demonstrating the Effect of Restoring the Form of Billets Made of Cellular Polymer Materials
MAUI	Maui analysis of upper atmospheric injections
MAXI	Monitor of All-sky X-Ray Image
MAX-SSC	MAXI Solid-state Slit Camera
Mb-YQR	triple mutant myoglobin
mBAND	Multicolor Banding Fluorescence In-Situ Hybridization
MBP	multi-body platform
MDA	Materials Diffusion Apparatus
MDRV	microbial drug resistance and virulence
MDS	Mice Drawer System
MDS	microbe detection sheet
MDU	mobile detector unit
MEIS	Marangoni Experiment in Space
MELFI	Minus Eighty Degrees Celsius Laboratory Freezer
MEMS	Microelectromechanical System
MEPS	Microencapsulation Electrostatic Processing System
MEPSI	Microelectromechanical System-based Picosat Inspector
MER	Mars exploration rover
MESA	miniature electro-static accelerometer
MESSAGE-1, -2	Microbiological Experiment on Space Station About Gene Expression-1,-2
Meteoroid	Recording Micrometeoroid and Technogenic Particle on the External Surface of the ISS Russian Segment Service Module
MeV	mega electron volt

mFISH	Multicolor Fluorescence In-Situ Hybridization
MFMG	Miscible Fluids in Microgravity
mGy	milligray
MHTEX	Massive Heat Transfer Experiment
MIA	Cell to Cell Interaction of Monocytes and T-Lymphocytes in Microgravity
MICAST, and MICAST -2	Microstructure Formation in Casting of Technical Alloys under Diffusive and Magnetically Controlled Convective Conditions, and -2
Microspace	Microbial life in Space: Response to environmental factors in a space vehicle
Micro-2	Gravitational Effects on Biofilm Formation During Space Flight
Micro-2A Micro-4	Microbial Biofilm Formation During Space Flight
Microbe	Effect of Spaceflight on Microbial Gene Expression and Virulence
Microbe-I/II	Microbial Dynamics in International Space Station
Midodrine-Long and SDBI	Midodrine as a Countermeasure Against Postflight Orthostatic Hypotension – Long- and Short-Duration Biological Investigation
Mikrosputnik	Study of Physical Processes Associated with Atmospheric Lightning Discharges Using the Chibis-M Microsatellite and Progress Cargo Vehicle
MISSE - 1 and - 2	Materials International Space Station Experiment – 1 and 2
MISSE - 3 and - 4	Materials International Space Station Experiment – 3 and 4
MISSE - 5	Materials International Space Station Experiment – 5
MISSE – 6A and – 6B	Materials International Space Station Experiment – 6A and 6B
MISSE - 7	Materials International Space Station Experiment –7
MISSE -8	Materials International Space Station Experiment –8
MJ	Modern multijunction
MKCIT	magnesium potassium citrate
ML-I	mistletoe lectin-I
MLI	multilayer insulation
MMOD	micrometeoroid and orbital debris
MMTP	mitochondrial metabolite transport proteins
MnCl2	magnesium chloride
MnSOD	manganese superoxide dismutase
MOBIAS	Multiple Orbital Bioreactor with Instrumentation and Automated Sampling
Mobility	Promoting Sensorimotor Response to Generalizability: A Countermeasure to Mitigate Locomotor Dysfunction After Long-duration Spaceflight
MOE	Ministry of Education
Molniya-Gamma	Investigating Atmospheric Burst of Gamma-Ray and Optical Emissions During Thunderstorm Activity

Molniya-SM	Study of the Electrodynamic Interaction Processes in the Earth's Atmosphere, ionosphere, and Magnetosphere Using the ВФС-3М Videophotometric System
MOP	Motion Perception: Vestibular Adaptation to G-Transitions
MOSFET	metal oxide semiconductor field effect transistor
Mouse Immunology	Effect of Space Flight on Innate Immunity to Respiratory Viral Infections
MPC	multi-protocol converter
MPD	hexylene glycol
MPV	Meerwein-Pohhdorf-Verley
MR	magnetorheological
MRI	magnetic resonance imaging
mRNA	messenger RNA
MRSA	methicillin-resistant staphylococcus aureus
MSG	microgravity sciences glove box
MSL	Materials Science Laboratory
mSv	milliSieverts
MSRR	materials science research rack
MSSS	Maui Space Surveillance Site
Multigen	Molecular and Plant Physiological Analyses of the Microgravity Effects on Multigeneration Studies of Arabidopsis Thaliana
Muscle	Study of Low Back Pain in Crewmembers During Space Flight
Myco	Mycological Evaluation of Crewmember Exposure to ISS Ambient Air
Myocyte	Microgravity on Expression of Calcium Channels in Myocytes
Myolab	Cbl-b-Mediated Protein Ubiquitination Downregulates the Response of Skeletal Muscle Cells to Growth Factors in Space

NaCl	sodium chloride
NanoRacks-FCA-Concrete Mixing	NanoRacks-Faith Christian Academy-Concrete Mixing
NanoRacks-FCHS-Robot	NanoRacks-Fremont Christian High School-Micro-Robot
NanoRacks-NCESSE-1 and -2	NanoRacks-National Center for Earth and Space Science Education, Two Investigations
NanoRacks-Terpene	NanoRacks-Terpene Extraction in Microgravity
NanoRacks-UF-Squids-1	NanoRacks-University of Florida-Squids-1
NanoRacks-VCHS	NanoRacks-Valley Christian High School
NanoRacks-WCHS E. Coli and Kanamycin	NanoRacks-Whittier Christian High School-E.Coli Bacteria and Kanamycin Antibiotic
Nanoskeleton	Production of High Performance Nanomaterials in Microgravity

Nanoslab-1, -2	Study of Aggregation Mechanism and Kinetics of ZSM-5 and Silicate-1 Nanoslabs into ZSM-5/Silicate-1 Hybird Phases Under Near-2 Weightless Conditions
Nanosputnik	Preparing Nanosatellite and Launching it from the Russian Segment of the International Space Station
NaOH	sodium hydroxide
NEEMO	NASA Extreme Environment Mission Operations
Neocytolysis	Effects of Microgravity on the Haemopoietic System
Neurocog	Directed Attention Brain Potentials in Virtual 3-D Space in Weightlessness
Neuro Rad	Biological Effects of Space Radiation and Microgravity on Mammalian Cells
Neurospat	Effect of Gravitational Context on EEG Dynamics: A Study of Spatial Cognition, Novelty Processing and Sensorimotor Integration
NF-κβ	nuclear factor kappa beta
NGM	nematode growth medium
NiSO4	nickel sulfate
NK	natural killer cells
NKA	Natural Killer Cell Activity in Microgravity
NLP	National Laboratory Pathfinder
nm	nanometer
NO	nitric oxide
NOA-1, -2	Exhaled Nitric Oxide-1, -2
NOAA	National Oceanic and Atmospheric Administration
NORAIS	The Norwegian Automatic Identification System
NPBX	Nucleate Pool Boiling Experiment
NRS	numeric rating scale
NSSS	Navy Space Surveillance System
NSTDA	National Science and Technology Development Agency, Thailand
NTDP	nuclear track detectors with and without converter
N-USOC	Norwegian User Support Operations Center
Nutrition	Nutritional Status Assessment
ODK	Onboard Diagnostic Kit
OEE	Oil Emulsions Experiment
OH	hydroxide
OH	orthostatic hypotension
OLP(s)	Ordered Liquid Phase(s)
OMS	Orbital Maneuvering System
OOR	otolith-ocular reflex
OPE	on-board proficiency enhancer

OPG	osteoprotegerin
ORZS	Optimization of Root Zone Substrates
OSLDs	optically stimulated luminescence dosimeters
Otolith	Otolith Assessment During Postflight Re-adaptation
OUM	oxygen uptake measurement
PACE	Preliminary Advanced Colloids Experiment
PADIAC	Pathway Different Activators
PADLES	Passive Dosimeter for Life Science Experiments in Space
PAM	Photoacoustic Analyzer Module
PAMELA	Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics
Parodont	Study of the Condition of Periodontal Tissues in Space Flight
Particle Flux	Particle Flux Demonstrator
PAS	particle accumulation structure
Passages	Scaling Body-related Actions in the Absence of Gravity
Pb	lead
PBMCs	Peripheral Blood Mononuclear Cells
PBU	plunger box unit
PCAM	Protein Crystallization Apparatus for Microgravity
PCDF	Protein Crystallization Diagnostics Facility
PCG-EGN	Protein Crystal Growth-Enhanced Gaseous Nitrogen
PCG-STES	Protein Crystal Growth-Single Locker Thermal Enclosure System
PCR	polymerase chain reaction
PCG	Protein Crystal Growth
PCS	Physics of Colloids in Space
PCSat	Prototype Communications Satellite
PCU	plasma conductor unit
PDB	phorbol 12,13-dibutyrate
PDC	protein depletion zone
PDGF	Platelet-Derived Growth Factor
PEACE	Polymer Erosion and Contamination Experiment PEC
PEG	polyethylene glycol
PESTO	Photosynthesis Experiment and System Testing and Operation
PEU	plant experimental unit
PFE	periodic fitness evaluation
PFM	Pulmonary Function Module
PFMI	Pore Formation in Microgravity
PFP	perfluoro propane
PFS	Pulmonary Function System
PGBA	Plant Generic Bioprocessing Apparatus

PGC	plant growth chamber
PHA	phytohemagglutinin
Pharmacokinetics,DSO6a32B	Pharmacokinetics and Contributing Physiologic Changes During Spaceflight DSO 632B
Photosynth	PhotosynthTM Three-Dimensional Modeling of ISS Interior and Exterior
Pilot	Study of the Individual Features of the Psychological and Physiological Regulator of State and Reliability of Work Performance in Crew-members in Long-term Spaceflight
PIM	plasma integration model
PKE-Nefedov	Plasma Crystal Experiment – Nefedov
PKinase	Mechanisms and Functional Consequences of Protein Kinase C Isoform Translocation in Monocytes Exposed to Microgravity
PK-3 Plus	Plasma Crystal Research on the ISS
Plasma Interaction Model	Analysis of International Space Station Plasma Interaction
PLATAN	Searching for Low-Energy Heavy Nuclei of Solar and Galactic Origin Using the PLAstic Track ANalyzer
Plazma-Progress	Observation of the Reflective Characteristics of the Spacecraft Plasma Environment during Engine Firing in Space Using Ground-Based Instruments
Plazmenniy Kristall	Studying Plasma Dust Crystals and Liquids in Microgravity on the ISS RS
PM2	pressurized module 2
PMC	polar mesopheric cloud
PMDIS	Perceptual-Motor Deficits in Space
PMZ	Promethazine
Pnevmocard/Pnevmocard Perfection	Study of the Impact of Spaceflight Factors on the Vegetative Regulation of Blood Circulation, Respiration, and Contractile Function of the Heart in Long-Term Spaceflight
PNTDs	plastic nuclear track detectors
POEMS	Passive Observatories for Experimental Microbial Systems
Polca	Effect of weightlessness on the distribution of calcium in the statocytes of Rapeseed roots, Brassica napus
PPAR	Activator Peroxisome Proliferator Associated Receptor
PCC	premature chromosome condensation
PPG10	pro-pro-gly
PRDX5	peroxiredoxin 5
Privyazka	High-Accuracy Spatial Orientation of Scientific Devices Taking in Account the ISS Hull Deformation
Profilaktika	Mechanism of Activity and Effectiveness of Various Countermeasures Intended to Prevent Disruptions to the Motor Apparatus in Microgravity
PROMISS-1,-2,-3,-4	Protein Crystal Growth Monitoring by Digital Holographic Microscope for the International Space Station -1,- 2, -3, -4

PSF	point spread function
PSI	physiological strain index
PSK-ir	perisulfakinin immunoreactive
PSSC	Pico-Satellite Solar Cell Experiment
P3R	plants, protocols, procedures and requirements
PuFF	Pulmonary Function in Flight
Puls	Study of Vegetative Regulation of the Cardiorespiratory System in Weightlessness
PVA	polyvinyl alcohol
PVT	Psychomotor Vigilance Test
Pro K	Dietary Intake Can Predict and Protect Against Changes in Bone Metabolism during Spaceflight and Recovery
QCT	quantitative computed tomography
qRT-PCR	quantitative real time-polymerase chain reaction
QTCMA	Quad Tissue Culture Module Assembly
QUS	quantiative ultrasound
Rad Gene	Gene Expression of p53-regulated Genes in Mammalian Cultured Cells After Exposure to a Space Environment
RaDI-N	Radi-N Neutron Field Study
Rad Silk	Integrated Assessment of Long-term Cosmic Radiation Through Biological Responses of the Silkworm, *Bombyx mori*, in Space
RAFT	radar fence transponder
RAIDS	Remote Atmospheric and Ionospheric Detection System
RAMBO	Ram Burn Observations
RANKL	receptor activator of NF-B ligand
RASV	Recombinant Attenuated Salmonella Vaccine
rbx-1	ring-box 1
RCS	Reaction Control System
Reaction Self Test	Psychomotor Vigilance Self Test on the International Space Station
REBR	Re-Entry Breakup Recorder
Relaksatsiya	Processes of Relaxation in the Ultraviolet Band Spectrum by High-Velocity Interaction of Exhaust Products on ISS
Renal Stone	Renal Stone Risk During Spaceflight: Assessment and Countermeasure Validation
Repository	National Aeronautics and Space Administration Biological Specimen Repository
Resist Wall	Role of Microtubule-Membrane-Cell Wall Continuum in Gravity Resistance in Plants
RFII	Radio Frequency Impedance Interrogation
Rho Signalling	Signalling through Rho GTPases in microgravity

Rhythm	Cardiovascular Adaptation to Weightlessness
RIGEX	Rigidizable Inflatable Get-Away-Special Experiment
RM	root module
RNA	ribonucleic acid
RNAi	ribonucleic acid
rRNA	ribosomal ribonucleic acid
ROALD	Role of Apoptosis in Lymphocyte Depression
Root	Effects of the Space Environment on the Nuclear Structure and Functionof Plant Root meristematic Cells Grown in Microgravity
ROS	reactive oxygen species
Roscosmos	State Space Corporation of Russia
RPA	Replication Protein A
RPI	Rensselaer Polytechnic Institute
RPM	Random Positioning Machine
RPM	revolutions per minute
RR	inter-beat
RRM	Robotic Refueling Mission
RSA	respiratory sinus arrhythmia
RSD	respiratory sinus dysrhythmia
RTS	remote triaxial sensor
rVOR	roll-induced vestibulocular reflex
RWV	rotating wall vessel
SAA	South Atlantic Anomaly
Sally Ride EarthKAM	Sally Ride Earth Knowledge Acquired by Middle School Students
SAME	Smoke and Aerosol Measurement Experiment
SAMS-II	Space Acceleration Measurement Systems-II
Sarcolab	Myotendinous and Neuromuscular Adaptation to Long-term Spaceflight
SARJ	solar array rotary joint
SAS	space adaptation syndrome
SAT S- Interact	Supervision of Autonomous and Teleoperated Satellites - Interact
Saturday Morning Science	Science of Opportunity
SCE	Spinal Cord Excitability
SCN	succinonitrile
SDB	Surface tension dominated boiling
SDBI	Short-duration Biological Investigation
SDL	Space Dynamics Laboratory
SDS	sodium dodecyl sulfate
SDTO	Station Development Test Objective
SeaWiFS	sea-viewing wide field-of-view sensor

SEE	single event effect
SEED	Space Environment Exposure Device
SEEDS	Space Exposed Experiment Development for Students
Seeds	Seeds in Space
SEDA-AP	Space Environment Data Acquisition Equipment - Attached Payload
SEITE	Shuttle Exhaust Ion Turbulence Experiments
SEM	scanning electron microscope
SEM	Space Experiment Module
SETA-2	Solidification along a Eutectic path in Ternary Alloys - 2
SEU	Single Event Upset
SF6	sulphur hexafluoride
SGSM	slow growth sample module
SHERE	Shear History Extensional Rheology Experiment
SHERE-II	Shear History Extensional Rheology Experiment - II
SHS	self-propagating high-temperature combustion synthesis
SIC	sickness induced by centrifugation
SiC JFET	silicon carbide junction gate field-effect transistor
SIMPLEX	Shuttle Ionospheric Modification with Pulsed Localized Exhaust Experiments
SiO2	silicon dioxide
SiOX	silicon oxide
Skin	Skin Care
S/L	solid/liquid
SLAMMD	space linear acceleration mass measurement device
Sleep	Sleep-Wake Actigraphy and Light Exposure During Spaceflight
SLICE	Structure and Liftoff in Combustion Experiment
SLM	sound level meter
SLR	Satellite Laser Ranging
SLR	single lens reflex
SM	Synaptogenesis in Microgravity
SM	Service Module
SM/MPAC	Service Module/Micro-Particles Capturer and Space Environment Exposure Device
SMILES	Superconducting Submillimeter-Wave Limb-Emission Sounder
Sn	tin
SNFM	serial network flow monitor
SODI-Colloid	Selectable Optical Diagnostics Instrument - Aggregation of Colloidal Suspensions
SODI-IVIDIL	Selectable Optical Diagnostics Instrument - Influence of VIbrations on DIffusion of Liquids
SolACES	Solar Auto-Calibrating EUV/UV Spectrophotometers

Solar-SOLSPEC	SOLar SPECtral Irradiance Measurements
Solar- SOVIM	SOlar Variable and Irradiance Monitor
SOLO	SOdium LOading in Microgravity
Sonocard	Studying the Body's Physiological Functions Using a Non-contact Method During Sleep During Long-term Space Flight
SoRGE	Soldering in Reduced Gravity Experiment
Space Headaches	Space Headaches: Incidenence and Characteristics
Space Poem Chain	Ucyu Renshi: Connecting Global People with Words
Space Seed	Life Cycle of Higher Plants Under Microgravity Conditions
Spatial DSO635	Spatial Reorientation Following Space Flight, Detailed Supplementary Objective 635
SPE	solar particle event
SPEGIS	*Streptococcus pneumoniae* Expression of Genes in Space
SPENVIS	Space Environment Information System
SPHERES	Synchronized Position Hold, Engage, Reorient, Experimental Satellites
SPHERES-Zero-Robotics	Synchronized Position Hold, Engage, Reorient, Experimental Satellites - Zero - Robotics
SPHINX	SPaceflight of Huvec: an Integrated eXperiment
SPICE	Smoke Point In Co-flow Experiment
Spin	Validation of Centrifugation as a Countermeasure for Otolith Deconditioning During Spaceflight
Spinal Elongation	Spinal Elongation and its Effects on Seated Height in a Microgravity Environment
Sprint	Integrated Resistance and Aerobic Training Study
SPQR	Specular Point-like Quick Reference
Sprut-MBI	Study of the State of Fluids in the Human Body During Long-term Spaceflight
Sprut-2	Study of Changes in Body Composition and Distribution of Fluids Within the Human Body During Long-term Spaceflight
SSAF	Space Seeds for Asian Future
SSEP	Student Spaceflight Experiments Program
SS-HDTV	Super Sensitive High Devinition TeleVision Camera System
SSLM DTO 15008U	Solid-State Lighting Module, Station - Detailed Test Objective 15008U
SSN	U.S. Space Surveillance Network
Stability-Nutrition	Stability of Nutritional Compounds
Stability-Pharmacothera-peutic	Stability of Pharmacotherapeutic
Statokonia	Study of the Growth Potential of Statoconia in the Organ of Balance of Gastropods in Weightlessness
STELLA	Software Toolkit for Ethernet Lab-Like Architecture
STEM	science, technology, engineering, and mathematics

STES	Single-locker Thermal Enclosure System
STI/VAST	Space Technology Institute of the Vietnam Academy of Science and Technology
STL	space tissue loss
STORRM DTO 703	Sensor Test for Orion Relative Navigation Risk Mitigation Detailed Test Objective 703
STP-H2	Space Test Program-H2
STP-H3	Space Test Program-H3
STRE	Stress Response Element
Stroma-2	Bone Marrow Stroma Cell Differentiation and Mesenchymal Tissue Reconstruction in Microgravity
Subregional Bone	Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Spaceflight
SUBSA	Solidification Using Baffle in Sealed Ampoules
SUCCESS	Space Station Utilization Contest Calls for European Student
SUIT	Tactile Display-aided Orientation Awareness
Sv	Sievert
SVR	Systemic vascular resistance
SVS	Self-Propagating High Temperature Synthesis in Space
SVV	subjective visual vertical
SWAB	Surface, Water and Air Biocharacterization - A Comprehensive Characterization of Microorganisms and Allergens in Spacecraft
Sympatho, and -2	Sympathoadrenal Activity in Humans During Spaceflight, and -2
T	threshold
TAGES	Transgenic Arabidopsis Gene Expression System
TAS	total analysis system
TCM	tissue culture module
TCO	transparent conductive oxide
TCS	Thermal Control System
TCS	Trajectory Control Sensor
TD	theoretical density
TEB	triethylbenzene
TEM	Transport Environment Monitor
Ten-Mayak	Developing a Procedure for Radiosounding of the Satellite Coverage Area using a Network of Ground Receivers
Tenzor	Telemetry Data-Based Determination of the Dynamic ISS Characteristics
TEPC	tissue-equivalent proportional counter
TeSS	temporary sleep station
Test	Experimental Studies of the Possible Development of Microscopic Deterioration of ISS RS Module Structural Elements when Impacted by

	the Components of the Station's External Atmosphere and Conditions Promoting the Life of Microflora on Pressure Hull Surfaces under MLI
TF-FGI	total force-foot ground interface
TFS	Teaching From Space (Office)
3-D	three-dimensional
3-DPC	three-dimensional photonic crystals
3DpQCT	three-dimensional peripheral quantitative computed tomography
3-D-PTV	three-Dimensional Particle Tracking Velocimetry
3D-Space	Mental Representation of Spatial Cues During Space Flight
Thebas	Test of the Basic Principles of Mechanics in Space
THEMIS	Time History of Events and Macroscale Interactions during Substorms
Thermolab	Thermoregulation in Humans During Long-term Spaceflight
Ti-Al-B	aluminum-titanium-boron
TID	total ionizing dose
TiO2	titanium dioxide
Tipologia	Study of the Typological Characteristics of ISS Crew Operator Activity During Long-term Space Flight
TLD	thermo-luminescence dosimeter
TMD	trimethylbenzene
TNF	tumor necrosis factor
TNIoB/VAST	Tay Nguyen Institute of Biology of the Vietnam Academy of Science Total and Technology
Toksichnost	Creation of an Express Water-Toxicity Monitoring System for Spaceflight Conditions
TOR	Target Of Rapamycin
Torso	Organ Dose Measurement Using the Phantom Torso
TPSC-1	two pore segment channel 1
TRAC	Test of Reaction and Adaptation Capabilities
TROPI	Analysis of a Novel Sensory Mechanism in Root Phototropism
TRPM1	transient receptor potential cation channel subfamily M member 1
TRY Zero-G	Try Zero-Gravity
Tubul/Tubul-2	Influence of Gravity on the Cytoskeleton and the Determination of the Division Plane in Plants
TVIS	Treadmill Vibration Isolation System
TVT	Technology Validation Test
2-D	two-dimensional
2D-Nanotemplate	Two-Dimensional Nanotemplate in Microgravity
25(OH)	25 hydroxy
unc-15	uncoordinated protein 15 (paramyosin)
URC-Microbial-1	URC-Microbial-1

USB	universal serial bus
UTBI	Under the Background Influence
UV	ultraviolet
UVP	Ultrasonic Velocity Profiler
VADER	Variable emissivity radiator Aerogel insulation blanket dual zone thermal control Experiment suite for Responsive
Vaktsina-K	Structural Research on Protein Candidates for an AIDS Vaccine in Earth and Space Condition
Vascular	Cardiovascular Health Consequences of Long-Duration Space Flight
VCAM	Vehicle Cabin Atmosphere Monitor
Veterok	Developing New Technologies for the Optimization of Gaseous Environment in Living Compartments of the International Space Station Russian Segment
Vektor-T	Study of a High-Precision System for Predicting ISS Motion
VEE	Venezuelan equine encephalitis
VEMPs	vestibular evoked myogenic potentials
Vessel Imaging	Vascular Echography
VG	Vane Gap
Viable ISS	E**V**aluat**I**on **A**nd Monitoring of Micro**B**iofi**L**ms Insid**E** **I**nternational **S**pace **S**tation
VIIP	Vision Impairment and Intracranial Pressure
VINO	Vine in Near Orbit
Visual Subjective Vertical	On the Contribution of Visceral Receptors to the Sense of Subjective Vertical
Vitamin D	Effects of Microgravity on the Action of Vitamin D in Osteoblasts
Vitok-2	Study of Cosmonauts' Capabilities when Performing Visual/Instrument Observations and Test Tasks during the First Orbits and Days of Flight
VLE-I	Video Lesson European Space Agency - I
VOA	volatile organic analyzer
Volny	Observation, in the Near-IR Range of the Spectrum, of Wave Disturbances in the Middle Atmosphere
VO2max	Evaluation of Maximal Oxygen Uptake and Submaximal Estimates of VO2max Before, During, and After Long Duration International Space Station Missions
VPU	vegetable production unit
Vsplesk	Monitoring Seismic Effects—Bursts of High-Energy Particles in Near-Earth Space
VTR	video tape recorder
VZV	Varicella zoster virus
Vzaimodeystviye	Monitoring Group Activity by Crewmembers During Spaceflight

WAICO	Waving and Coiling of Arabidopsis Roots at Different g-levels
WBCs	white blood cells
WORF	Window Observation Research Facility
Xenon1	Effect of Microgravity on the Peripheral Subcutaneous Veno Arteriolar Reflex in Humans
Xenopus	Cellular Modifications within the Vestibulo-ocular System during Adaptation to Microgravity in a Developing Amphibian, Xenopus laevis
Yeast-B: Part 2	Yeast In No Gravity - The Influence of Microgravity on Cellular Adhesions, Biofilm Formation and In Invasive Growth in the Model Eukaryote Saccharomyces cerevisiae
Yeast-GAP	yeast-group activation packs
YING-A: Part 1	Yeast In No Gravity - The Influence of Microgravity on Cellular Adhesions, Biofilm Formation and In Invasive Growth in the Model Eukaryote Saccharomyces cerevisiae
YPD	Yeast extract Peptone Dextrose
Zag	Ambiguous Tilt and Translation Motion Cues After Space Flight
ZCG	Zeolite Crystal Growth
ZPM	zero-propellant maneuver
ZSM-5	Zeolite Socony Mobil-5

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Canadian Space Agency
http://www.asc-csa.gc.ca/eng/iss/default.asp

Japan Aerospace Exploration Agency
http://iss.jaxa.jp/en/

National Aeronautics and Space Administration
http://www.nasa.gov/iss-science/

European Space Agency
http://www.esa.int/esaHS/iss.html

Roscosmos – Russian State Space Corporation
http://knts.tsniimash.ru/ru/site/CenterInfRes.aspx
http://www.energia.ru/english/index.html

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