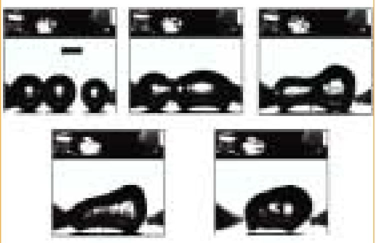
NASA PHYSICAL SCIENCES RESEARCH DIVISION

ANNUAL REPORT 2001-2002

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812



In microgravity, a large bubble grows as smaller ones come in contact and surface tension breaks to let the gas pockets join.

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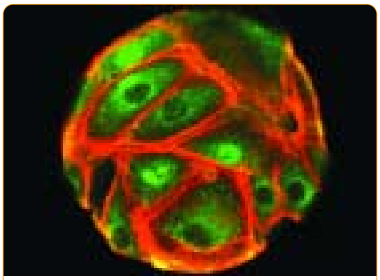

Researchers have found that the genetic expression of human renal cells can be manipulated in microgravity to produce hormones that are valuable in the treatment of disease.

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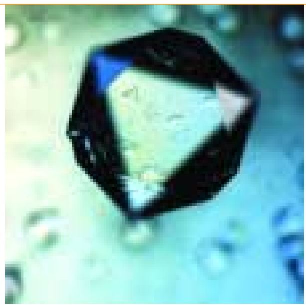

This crystal of satellite tobacco mosaic virus grown under microgravity conditions is more than 30 times the size of similar crystals grown on Earth.

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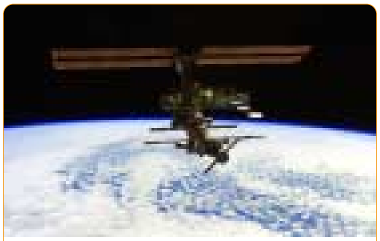

The International Space Station provides a unique environment in which scientists from various disciplines can conduct research free from some of the effects of gravity.

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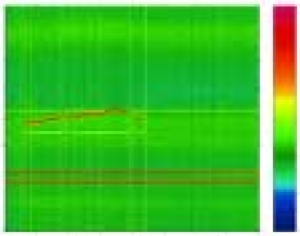

Researchers can review acceleration measurement data to find out when and at what frequency vibrations occur on the International Space Station.

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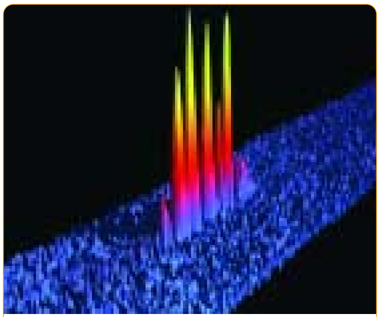

Each peak in a matter-wave soliton train is a collection of atoms cooled to a temperature of nearly absolute zero.

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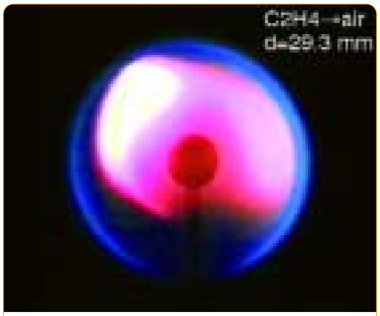

Better understanding of combustion mechanisms will help scientists control levels of soot and nitrous oxides, combustion by-products and contributors to air pollution.

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The newly installed Microgravity Science Glovebox has been used for several Materials Science experiments, including the Pore Formation and Mobility Investigation.

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Editor's Note:
This report covers activity of the Physical Sciences Research Division October 1, 2000–September 30, 2002. Many research descriptions reference mission STS-107, which would be flown on Space Shuttle *Columbia*. The crew perished, and most of the experiments onboard the science-dedicated flight were lost, on February 1, 2003, when the space shuttle broke apart during its reentry into Earth's atmosphere.

NASA's goal is to improve the quality of life on Earth by using ground- and space-based research to promote new scientific and technological discoveries. The Physical Sciences Research Division plays a vital role in our nation's economic and general health by carefully selecting, funding, and supporting scientists across the country. It also serves as an important link in the international endeavors that are the hallmark of America's space program.

By disseminating knowledge and transferring technology among private industries, universities, and other government agencies, the Physical Sciences Research Division continues to build on a foundation of professional success, which is evidenced by the number of publications and conferences attended, while reaching out to encompass the populace at large. Educational outreach and technology transfer are among the program's top goals, making the benefits of NASA's research available to the American public. Space shuttle research missions, as well as experiments performed in short-duration microgravity facilities, are yielding new understandings about our world and the universe around us, while long-duration microgravity science on the International Space Station is making possible advances in research that were not possible before.

Under the direction of the Biological and Physical Research Enterprise, the Physical Sciences Research Division will continue to advance cutting-edge research led by the best scientists from across the nation. For more information about the enterprise and ongoing microgravity research, use the following contact information:

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http://microgravity.nasa.gov

When the International Space Station (ISS) Expedition 1 crew was launched to the station aboard a Russian Soyuz spacecraft from Baikonur, Kazakhstan, on October 31, 2000, they ushered in a new era of human presence in low–Earth orbit. By the close of fiscal year (FY) 2002, the three members of the Expedition 5 crew were busy carrying out a wide range of hands-on scientific and technological investigations on the orbiting outpost. Fiscal years 2001 and 2002 have coincided almost exactly with the first two years of continuous human occupation of the ISS. During these two years, the Physical Sciences Research (PSR) Division has been actively participating in pioneering space-based scientific endeavors while carrying out significant programmatic reassessment and redirection.

In December 2001, the first integrated annual NASA Research Announcement (NRA) for Physical Sciences Research in the Office of Biological and Physical Research (OBPR) was released. The NRA solicited time-staggered submissions of research proposals in the five traditional microgravity disciplines of biotechnology, combustion science, fluid physics, fundamental physics, and materials science. In addition, a special topic for original research in the area of advanced materials supporting space exploration technology was included in the announcement. Together with a previous special-topic solicitation of proposals targeting advanced materials characterization for high-energy radiation protection, this focused request reflects a heightened attention to applied research supporting advanced space technology development. The programmatic shift from single-discipline NRAs appearing every two years on a varying schedule to a fixed-date, annual NRA integrating multiple disciplines and special topics was designed to establish a more regular schedule for the solicitations and to enhance the opportunities for proposal submissions.

The scientific accomplishments funded through NRAs in these past two years are nothing short of impressive, reflecting the quality and productivity of the multidisciplinary research community assembled under the PSR Division. For example, exciting new accomplishments obtained through both Earth- and space-based investigations have allowed the growth of three-dimensional ovarian tissues from cells and the preservation of immune system cells in the NASA-developed specialized bioreactor that mimics microgravity. Combustion scientists have made advances in the understanding and prediction of smoldering combustion under normal and microgravity conditions. Fluid physicists have carried out revealing new flight experiments on the ISS and the space shuttle on colloidal crystallization, probing the mysteries of phase transition and solidification, and on particle collision in dust, simulating planetary processes.

One of our brilliant young investigators, Wolfgang Ketterle, shared the 2001 Nobel Prize in physics for his inspired work in Bose-Einstein condensation and for his leading role in the demonstration of the feasibility of the atom laser. Some of his colleagues in the program have attracted worldwide attention with their artistry in controlling Bose-Einstein condensates to slow down and completely stop the transfer of information contained in light and to simulate processes in distant stars by using supercold condensates of fermions. In materials science, the first ISS investigations on solidification processes using baffles in sealed ampoules were successfully carried out in the Microgravity Science Glovebox facility, provided by the European Space Agency. Using the availability of extended-duration exposure to microgravity on the ISS, researchers have been able to grow crystals of superoxide dismutases — the body's own fighter of free radicals — that are large enough and of high enough quality to obtain the never-before-seen three-dimensional structure of the hydrogens on each amino acid of the protein.

After reviewing research investigations such as these, the National Research Council Committee on Microgravity Research released at the end of FY 2002 a glowing assessment of the progress and quality of the research carried out under the auspices of the previous Microgravity Research Division and the current Physical Sciences Research Division, praising significant past accomplishments and noting promising future developments. In fact, the National Research Council Board on Physics and Astronomy's assessment of the "Grand Challenges in Physics" for the first decade of the 21st century indirectly endorses a large portion of the OBPR Physical Sciences Research Division. Armed with these findings, the division has embarked upon a strategic redirection of the research objectives that places a renewed emphasis on applied research aimed toward enabling new space technologies while preserving the valuable and productive fundamental research component unique to NASA and to the country.

— Eugene Trinh
Director, Physical Sciences Research Division

Table 1 — Physical Sciences Research Overview	2000	2001	2002
Research tasks	584	553	533
Principal investigators	455	451	449
Co-Investigators	667	719	514
FY budget ($ in millions)	108.7	130.4	120.0

Table 2 — Program Bibliographic Listings	2000	2001	2002
Journal articles	904	688	758
Presentations	1,062	719	817
Proceedings papers	422	325	250
NASA technical briefs	13	0	12
Books/chapters	50	43	58
Total	2,451	1,775	1,895

Table 3 — Grant Statistics	2000	2001	2002
Students funded	1,146	1,407	1,690
Degrees granted	457	N/A	N/A
Patents applied for	22	15	16

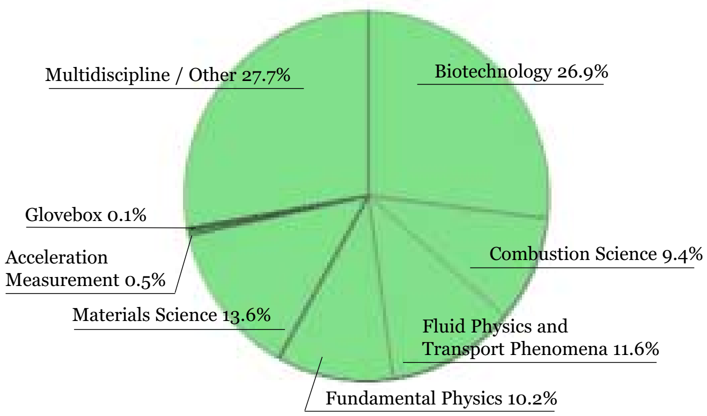
Table 4 — Glenn Research Center Task Summary	2000	2001	2002
Ground-based	189	158	176
Flight program	55	54	46
Total	244	212	222

Table 5 — Jet Propulsion Laboratory Task Summary	2000	2001	2002
Ground-based	40	64	55
Flight program	9	12	11
Total	49	76	66

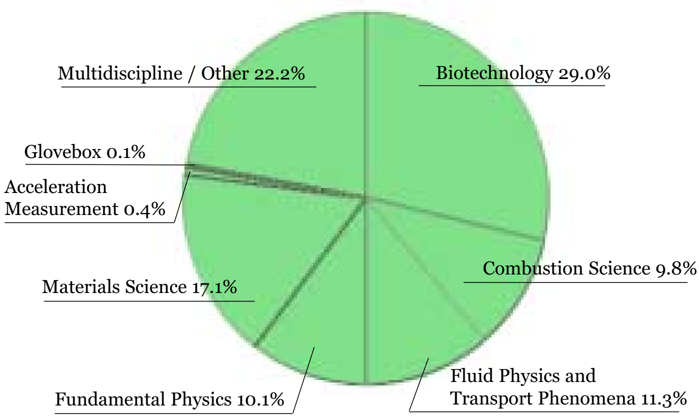
Table 6 — Johnson Space Center Task Summary	2000	2001	2002
Ground-based	56	49	48
Flight program	2	0	0
Total	58	49	48

Table 7 — Marshall Space Flight Center Task Summary	2000	2001	2002
Ground-based	180	173	144
Flight program	46	38	34
Total	226	211	178

FY 2001 Microgravity Funding Distribution by Science Discipline
(Total Budget in Millions:$130.359)

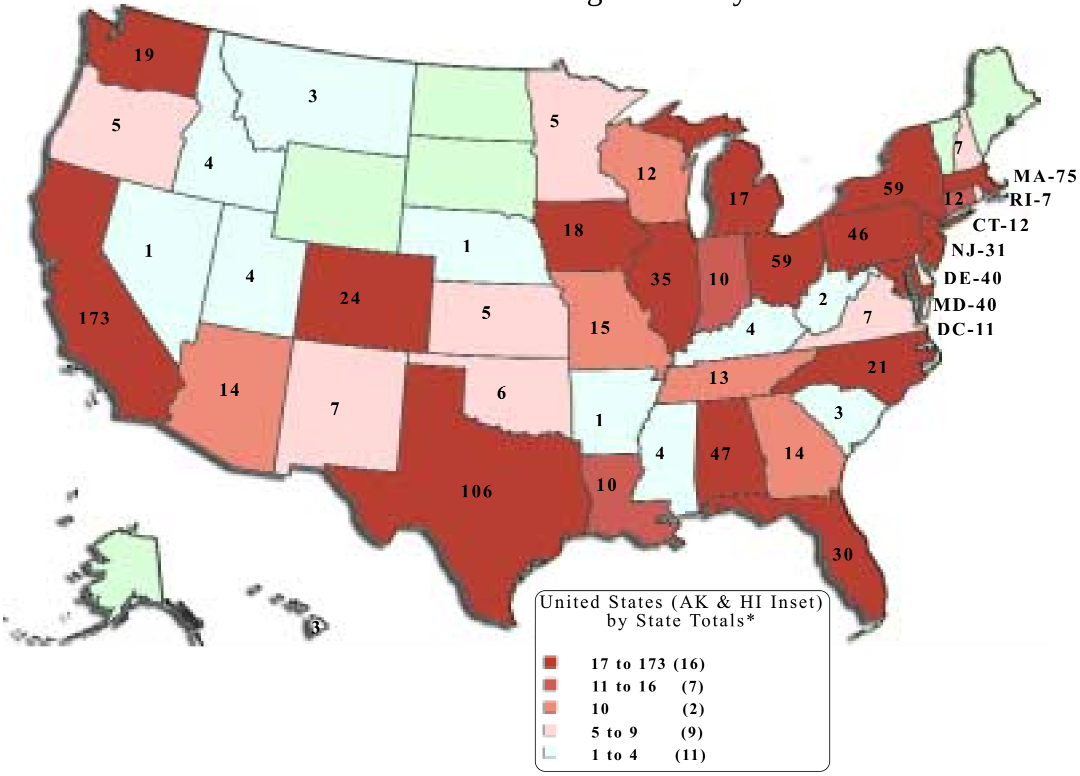


FY 2002 Microgravity Funding Distribution by Science Discipline
(Total Budget in Millions:$120.018)



Office of Biological and Physical Research

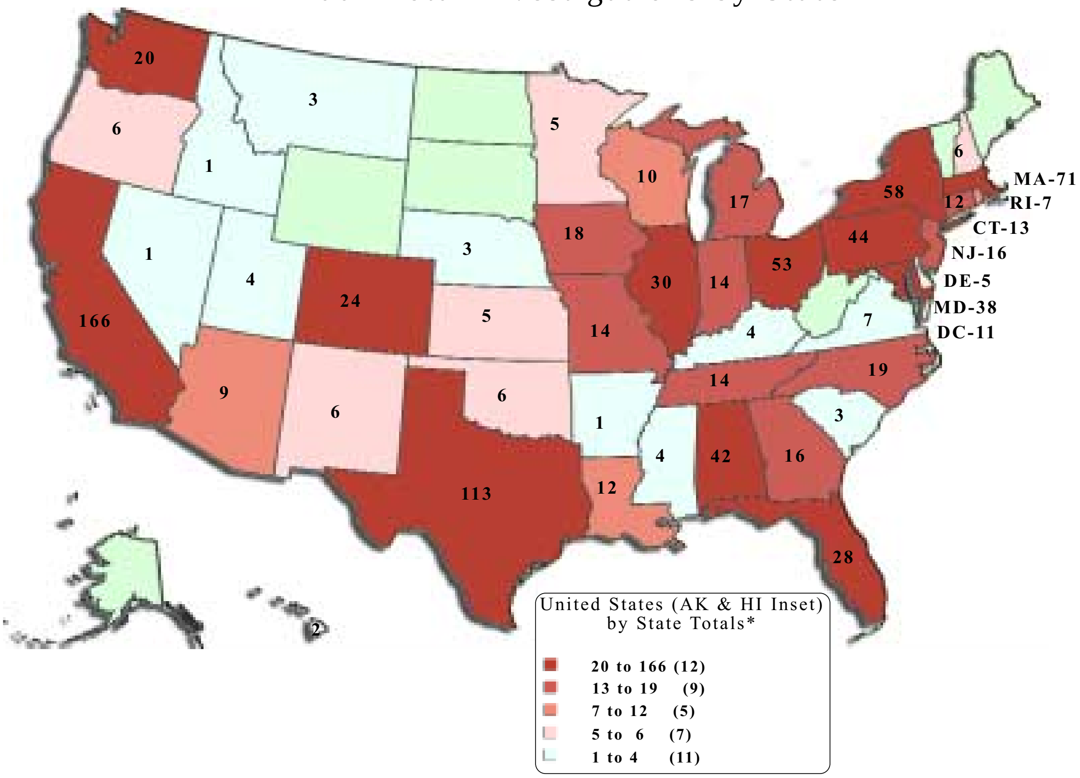
FY 2001 Total Investigations by State



992 Flight and Ground Research Programs in 44 States and the District of Columbia
*Excludes Graduate Student Research Projects

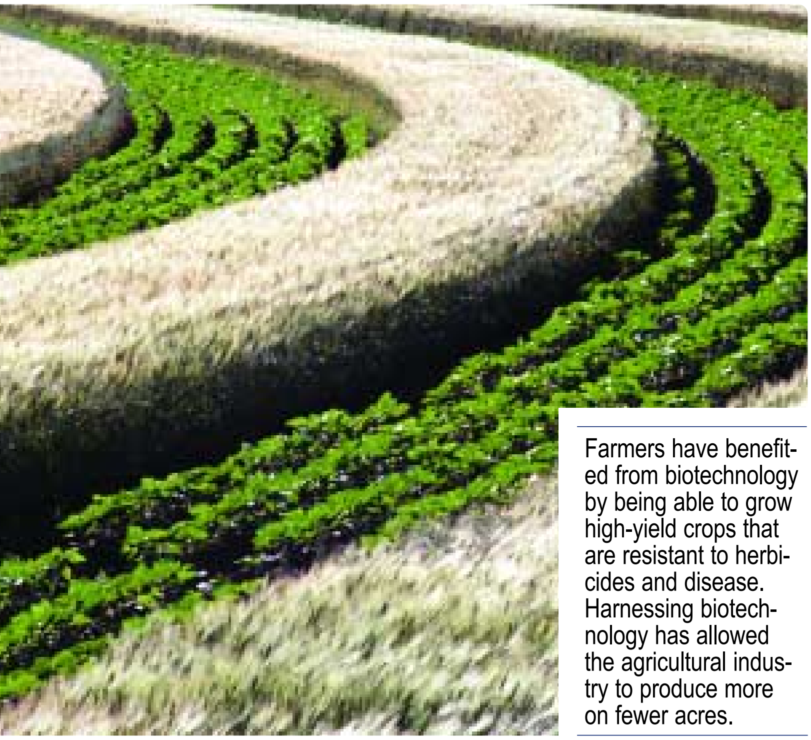
Office of Biological and Physical Research

FY 2002 Total Investigations by State



947 Flight and Ground Research Programs in 44 States and the District of Columbia
*Excludes Graduate Student Research Projects

OVERVIEW



Farmers have benefited from biotechnology by being able to grow high-yield crops that are resistant to herbicides and disease. Harnessing biotechnology has allowed the agricultural industry to produce more on fewer acres.

Did you ever stop to consider that some of the foods in your refrigerator are products of biotechnology? Biotechnology is the application of knowledge concerning biological systems to the production of consumer goods and services. Foods like cheese, yogurt, and beer are all products of biotechnology in its most basic form — harnessing existing biological processes, such as bacterial fermentation, to produce goods for human consumption.

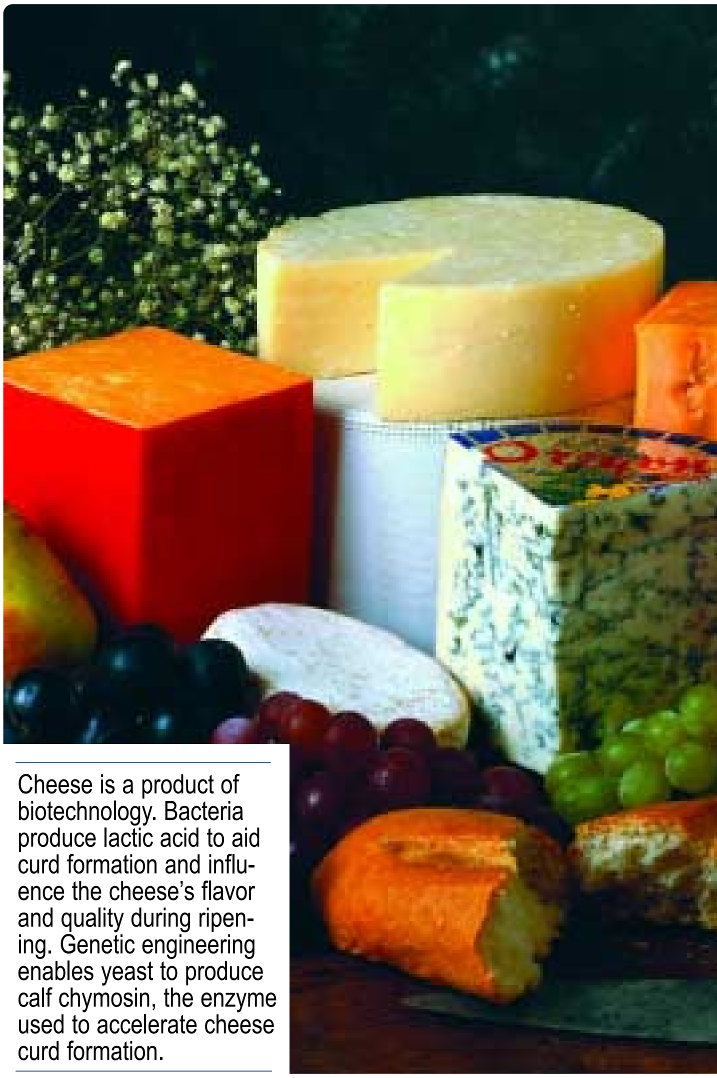
The term biotechnology probably also brings to mind genetically engineered bacteria, plants, and animals. It is this facet of biotechnology that allows farmers to plant crops that can withstand certain herbicides or diseases and helps researchers to develop bacteria that can produce human insulin, which is essential for the treatment of diabetes, and drugs to dissolve blood clots, reducing the risk of heart attack and stroke.

Although most biotechnology research benefits the medical and agricultural fields, this kind of work also supports a broad range of manufacturing industries. Processes that use biological components or that mimic biological systems can be used for a variety of purposes, including creating new materials, removing contaminants, and improving the efficiency of chemical reactions. For example, microbes are used to process sewage at city wastewater treatment plants and to produce alcohol-based fuels for motorized vehicles. Bacteria that can break down oil

Biotechnology has enabled scientists to turn to natural sources for pollution control. Bacteria have been genetically altered to perform a variety of environmental clean-up tasks, including ingesting oil slicks.

and petroleum have been discovered, and researchers have genetically altered these bacteria to create microbes that can feed on oil slicks.

Biotechnology research focuses on how organisms and their components function. Large organisms are composed of systems of organs. If you look in the mirror, you can see the largest organ in the human body — the skin. The skin and other organs consist of tissues specialized to perform specific functions in the body. These tissues in turn are made up of a smaller structure — the cell. How the cell functions in a particular tissue is determined by its molecular components. Cells contain billions of biological macromolecules, which are much larger and more complex than nonbiological molecules. The unique chemical traits of these molecules determine how a cell differentiates to become part of a particular type of tissue and, ultimately, how an organism grows, lives, and dies.



Cheese is a product of biotechnology. Bacteria produce lactic acid to aid curd formation and influence the cheese's flavor and quality during ripening. Genetic engineering enables yeast to produce calf chymosin, the enzyme used to accelerate cheese curd formation.

The microgravity environment of space provides special advantages to biotechnology researchers studying cell growth and biological molecules. NASA's microgravity biotechnology program, therefore, supports research in two main areas: macromolecular biotechnology, overseen by Marshall Space Flight Center (MSFC) in Huntsville, Alabama, and cell science, overseen by Johnson Space Center in Houston, Texas. The program's contributions to understanding the foundations of life at the molecular and cellular levels may enable the development of new drugs and other therapies for disease and dysfunction, as well as measures to safely send humans into space for extended time periods.

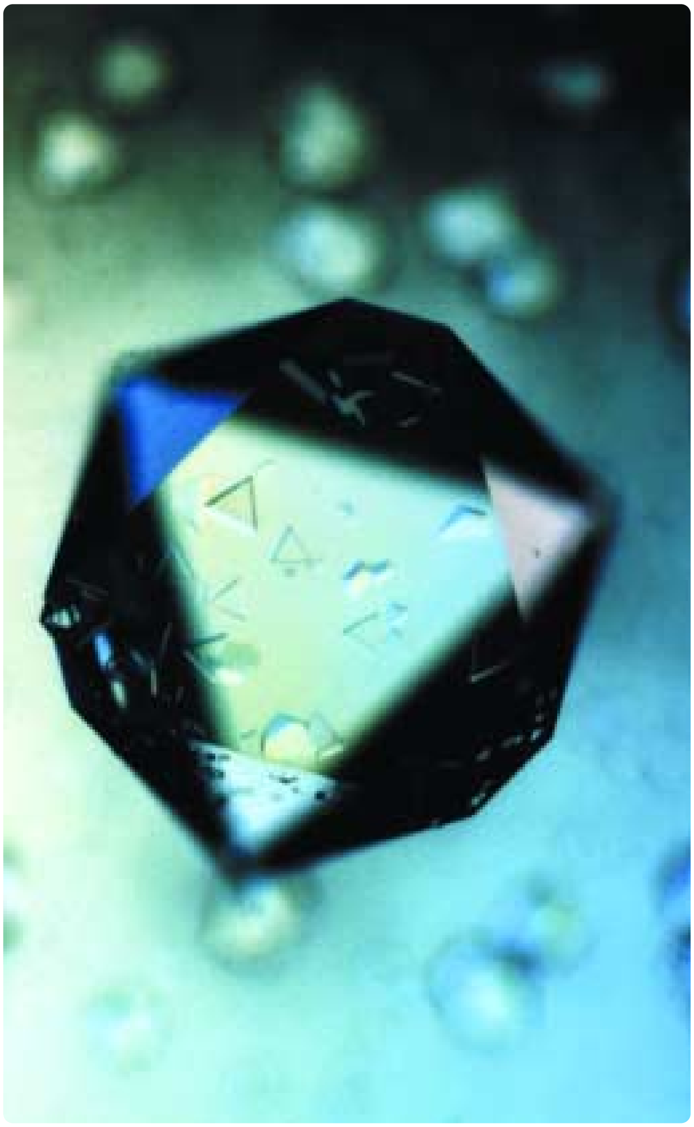
There are tens of thousands of biological macromolecules at work in the human body. These molecules, mostly proteins and nucleic acids, perform or regulate all functions that maintain life. Proteins, for example, transport oxygen and chemicals in the blood, form major components of muscle and skin, and, in the form of antibodies, aid in fighting infection. Enzymes, which are a class of proteins, catalyze specific chemical reactions in cells and control metabolic pathways, which are a series of chemical reactions that together perform one or more important functions, like the conversion of sugar to energy.


credit: NASA

Proteins are the building blocks of our bodies and the living world around us. If the structure of a protein is known, then companies can develop new or improved drugs to fight the disease of which the protein is a part. On Earth, convection currents, sedimentation, and other gravity-induced phenomena hamper crystal growth efforts, and the result is crystals with flaws, as shown on the left. In microgravity, researchers can grow high-quality crystals in an environment free of these effects to obtain better quality crystals that yield more structural data, as shown on the right. Research on crystals of human insulin, like these, could lead to improved treatments for diabetes.

Nucleic acids are another type of biological macromolecule. The best-known examples of nucleic acids are ribonucleic acid (RNA) and deoxyribonucleic acid (DNA). Nucleotides, which are subunits of nucleic acids, exist in a particular order along the DNA molecule. Each unit of three nucleotides along a strand of DNA forms a “letter” of the genetic code, with the letters specifying particular amino acids, the building blocks of proteins. So each section of the genetic code actually specifies the production of a specific protein, which in turn supports the maintenance of life at both the cellular and whole-organism levels. Small differences in genetic codes can result in major differences within and between organisms.

To unlock some of the mysteries about how a biological molecule carries out its role, scientists need knowledge of the molecule’s structure. A biological molecule’s shape and chemical components determine the types of other molecules with which it can interact. Proteins have active sites that allow them to fit with other molecules to perform a specific function. Active sites on proteins, when inappropriately triggered, can cause disease or unwanted functions. Drug designers seek knowledge of these sites so they can develop drugs to block the sites or otherwise render them inactive.



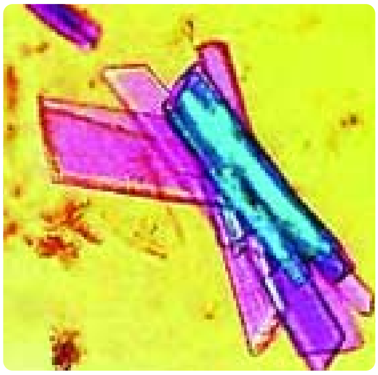
credit: NASA

This unusually large cubic crystal of satellite tobacco mosaic virus grown under microgravity conditions is more than 30 times the size of similar crystals grown on Earth.

Information about molecular structure is important to scientists in other fields as well. Genetic engineers use this information to chemically alter genetic codes to make bacteria, plants, or fungi with desirable properties, such as yeast that has been altered to produce insulin. Knowledge of molecular structure is also the key to understanding how some species survive and even thrive in extreme conditions like the arctic or in volcanic vents. And because some biological molecules, such as enzymes, catalyze processes, understanding their structure may enable their use as miniature manufacturing plants to process materials — the ultimate in nanotechnology.

X-ray crystallography is the most common method by which scientists study the structure of biological molecules. Crystals of the molecule of interest are formed, and X-rays are passed through a single crystal at various angles. The resulting diffraction patterns are analyzed using computers to estimate the size, shape, and structure of the molecule. A flawed crystal will yield a blurry and/or weak diffraction pattern, whereas a well-ordered crystal will yield a sharp and/or strong diffraction pattern and thus useful information about the structure of the crystal.

A microgravity environment reduces the effects of fluid flows and sedimentation within the crystallization solution that can interfere with the crystal growth process and the quality of the crystal.



credit: NASA

Enzymes catalyze specific chemical reactions in cells and control metabolic pathways. Studying the structure of enzymes will help researchers to better understand how the enzymes function. Creatine kinase, pictured here, converts the major storage form of high energy phosphate into a usable energy form. Creatine kinase is a major muscle enzyme and is implicated in some muscle diseases. Understanding how the enzyme works could lead to therapies for those diseases.

When a crystal begins to form in a solution, molecules diffuse from the solution around the crystal to join the growing crystal lattice. As a result, the solution in the immediate vicinity of the crystal has a lower concentration of the crystal-forming material than the remainder of the solution, and therefore has a lower density. Under the influence of Earth's gravity, this difference in density creates currents next to the growing crystal. Such fluid flows can alter the orientation and position of the biological molecules added to the crystal lattice, thereby creating disorder in the crystal. Molecules are added to the crystal lattice in the same way on Earth and in microgravity, but in microgravity the lower concentration at the crystal surface can slow crystal growth enough to enable misplaced crystals to disassociate and then reattach in a better orientation.

Likewise, sedimentation, another effect of gravity, can result in poor-quality crystals. When crystals grow to a size that cannot be supported by suspension in the drop of solution in which the crystals are forming, then the crystals will drift to the bottom of the drop. There they may settle on top of other crystals and grow into those adjacent crystals. X-ray crystallography requires single crystals for analysis, and thus sedimentation can render potentially high-quality crystals unusable. In the microgravity environment of low Earth orbit, the effects of sedimentation and fluid flow are nearly eliminated, and the conditions for growing diffraction-quality crystals are improved.

Ground-based research in molecular science includes crystallization of biological macromolecules (including analysis of crystals and methods to control crystal quality); the development of biomaterials, which are substances that are synthetic or natural in origin that can be used to treat, augment, or replace a tissue, organ, or function of the body; research on separation technology; and biologically oriented nanotechnology.

Program Summary

Following the release in 2000 of the National Research Council's* (NRC) report, titled *Future Biotechnology Research on the International Space Station*, the biotechnology program implemented the Structural Biology Initiative to enact the recommendations of the NRC panel. The goals of the initiative are to accelerate the process by which investigators get their research projects to flight, to decrease the time interval between developing a research idea and obtaining data, and to match the speed of the ground-based research process.

To achieve these goals, the biotechnology program will integrate new hardware for use on the International Space Station (ISS) that will allow increased sample throughput and provide video microscopy of crystallization experiments. Also in response to the NRC panel, the biotechnology program began developing and testing an external review process that will accommodate both large-scale research projects funded by NASA's peer-reviewed grant process and small-scale ad-hoc investigations. An external, nonadvocate panel will be used to peer-review and prioritize experiments and to make decisions in a timely manner to better match the pace of ground-based biotechnology research. This program will provide the scientific community with one, well-advertised point of contact for access to spaceflight experiments. To obtain information on the associate investigator program, visit *http://crystal.nasa.gov/technical/assoc_invest_prg.html* or *http://www.nisb.org*.

The NASA Research Announcement (NRA) for macromolecular and cellular biotechnology that was released in August 2000 directly addressed the recommendations of the NRC report. Research proposals in a number of areas, detailed in the following paragraphs, were solicited from scientists.

Proposals were sought for structural biology research to produce crystals of macromolecular assemblies with important implications for cutting-edge biology problems, as recommended by the NRC. Systems that meet the criteria set forth in the NRA include membrane proteins, molecular motors, and biopolymer synthetic machinery. The NRC report described all of these systems as elaborate and fragile, which makes them difficult to crystallize except under optimal conditions. In these cases, microgravity conditions might improve the quality of the crystals enough to allow determination of key structures. Also included were macromolecular systems for which research efforts have already been undertaken but which have presented challenges for crystallization. In the area of crystallization studies and technologies, proposals were invited to support the aforementioned research with emphasis on providing a framework for understanding microgravity crystallization results, optimizing crystal growth conditions, characterizing crystal defect formation and the relationship between defect formation and crystal growth, and providing a more rational approach to the growth of macromolecular crystals.

NASA also invited proposals for developing technologies that seek to improve macromolecular crystallization throughput for structural biology and proteomics research on the ISS. Proteomics is the identification and study of proteins in the body, genes that code for particular proteins, protein-protein interactions, and the role of proteins in such activities as transmitting disease. Research for improving throughput includes automated crystal growth technologies, screening methods, and cryopreservation techniques.

In the area of biological nanotechnology, NASA sought research proposals for the development of molecular-sized sensors, signalers, and receptors; nanometer-scale biomaterials; and technologies to manipulate biomolecules to form useful devices or nanometer-scale structures. Nanotechnology research is important because it can be used to reduce experiments' weight, volume, and need for electrical power, all limiting factors during space missions.

Research solicited in the area of biomolecular self-assembling materials includes polymer biosynthesis, self-assembled monolayers and multilayers, decorated membranes, mesoscopic organized structures, and biomineralization. The area of biomolecular self-assembling materials combines molecular biology, physical sciences, and materials engineering. Biomolecular materials have ability to assemble themselves without external intervention, and understanding the mechanisms involved in such self-assembly could lead to the development of new processes and materials with significant technological impact, including applications in life support to enable humans to live and work permanently in space, as well as other Office of Biological and Physical Research (OBPR) goals.

Finally, in the area of structural protein-based materials, NASA solicited proposals for the production

* The NRC was organized by the National Academy of Sciences to associate the science and technology communities and to be the principal operating agency that provides services to the government, the public, and the scientific and engineering communities. These services include investigating, examining, experimenting, and reporting on any subject of science or art.

of protein-based materials or the isolation, in useable form, of such materials from cells. Collagen, keratin, and silk are examples of structural proteins. Researchers may be able to incorporate novel properties in such materials by genetically engineering the sequences or incorporating modular components from other proteins. Because these materials could be produced using recombinant DNA technology, it is possible to create a uniform and controllable architecture of the resulting material. Such biomaterials could also support OBPR goals.

Notices of intent for this NRA were due on September 6, 2000, and 225 proposals were received by the October 27, 2000, due date. Selections were made in June 2001; 20 of the selected proposals were to conduct research in macromolecular biotechnology, including projects on challenging problems in structural biology, artificial biomembranes, and membrane proteins. For additional information on the NRA and selections, visit *http://research.hq.nasa.gov/code_u/nra/current/NRA-00-HEDS-03/winners.html* on the WWW.

NASA macromolecular biotechnology principal investigators (PIs), co-investigators, guest investigators, and associate investigators published 69 peer-reviewed articles in scientific journals in fiscal year (FY) 2001 and 62 in FY 2002.

In early FY 2001, the Spallation Neutron Source (SNS) project and NASA cosponsored a workshop in Knoxville, Tennessee. Representatives from the biological neutron diffraction and microgravity crystal growth communities met to discuss the future use of the SNS for macromolecular single-crystal neutron diffraction. Academic, industry, and government advisers representing the countries of England, France, Japan, and the United States participated in the workshop and developed a set of recommendations regarding biological neutron diffraction crystallography.

Using neutrons to produce a diffraction pattern of protein crystals has advantages over X-ray diffraction. About one-half of the atoms that make up a protein are hydrogen atoms. When protein crystals are bombarded with X-rays, the X-rays are diffracted from the electron clouds of the individual atoms within the protein crystal to form a pattern from which the structure of the protein can be determined. But it is an incomplete picture of the structure, because hydrogen atoms have very little electron density and so go undetected by X-ray diffraction. In contrast, when a protein crystal is bombarded with neutrons, the neutrons interact with the nuclei of the protein crystal atoms. The diffraction pattern of the neutrons then allows the position of hydrogen atoms to be identified, and thus a more complete structure of the protein can be determined.

However, neutron diffraction techniques pose a particular challenge. Although neutron diffraction can provide a complete structural analysis using a single crystal, that crystal must be much larger than crystals that are suitable for X-ray analysis. The colloquium formally recognized that because of research supported by both NASA and the European Space Agency (ESA), the production of crystals sufficiently large for neutron diffraction studies is now an attainable goal. Growth of crystals 2 mm x 1.5 mm x 1 mm or larger is now common for an increasing number of proteins. Based on previous microgravity crystal growth experiments and the availability of a controlled environment for extended-duration missions afforded by the ISS, it was estimated that approximately 90 percent of proteins crystallized in orbit will have the potential to reach 1 mm x 1 mm x 1 mm — the size range needed for analysis by current and future neutron sources.

NASA was well-represented at the American Crystallographic Association's 2002 Annual Meeting, held in San Antonio, Texas, May 25–30, 2002. One-third of the microgravity macromolecular biotechnology program's principal investigators were key presenters at the meeting, which is the nation's largest gathering of structural biologists, drawing 800 attendees in 2002. At a well-attended session, "Biomacromolecular Crystal Growth and Perfection," which was sponsored by the macromolecular biotechnology program, NASA investigators made six presentations that covered hardware development, crystal quality analysis method development, and a new technique for judging the quality of the crystal cryocooling process.

Among the program presentations was a talk given by NASA Project Scientist Mark van der Woerd titled "About Small Streams and Shiny Rocks: Macromolecular Crystal Growth in Microfluidics." Van der Woerd provided an overview of work being conducted at MSFC using microfluidic technology for protein crystallization and reported on preliminary results from hardware incorporating that technology for crystal growth.

Aniruddha Achari, of MSFC, and his research team presented a poster titled "Equilibrium Kinetics Studies and Crystallization Aboard the International Space Station Using the Protein Crystallization Apparatus for Microgravity (PCAM)." The PCAM has been used to grow macromolecular crystals in a microgravity environment using a "sitting drop" method of vapor diffusion. The experiments were set up to gather data for a series of days of activation with different droplet volumes and precipitants. The results of these experiments will help future PCAM users to choose precipitants that will optimize crystallization conditions for their target macromolecules for a particular mission with a known duration.

In April 2002, a patent was awarded to macromolecular biotechnology PIs and project scientists William Witherow, of MSFC, R. L. Kurtz, of Pace and Waite Inc., Huntsville, Alabama; and R. R. Holmes, of MSFC, for their Laser Image Contrast Enhancement System (LICES). LICES allows objects that are hot enough to emit blackbody radiation to be illuminated and imaged. (A blackbody is a theoretically ideal radiator and absorber of energy at all electromagnetic wavelengths.) For example, in a furnace, an object is heated until it emits blackbody radiation. It is then illuminated from outside with laser light and viewed with a camera with a special optical system.

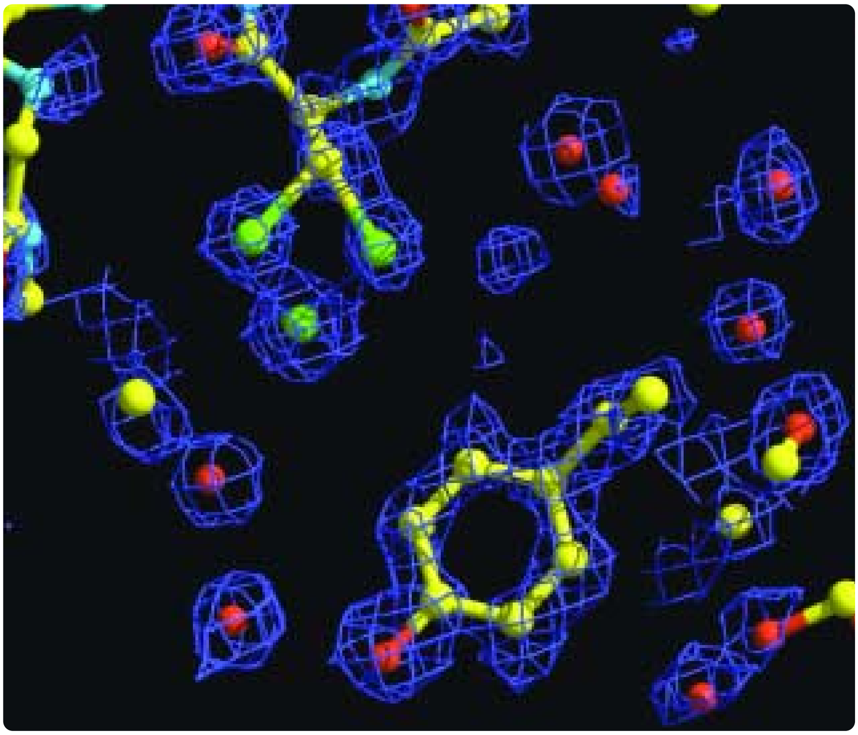
In FYs 2001 and 2002 the macromolecular biotechnology program made progress toward optimizing the analysis of microgravity-grown crystals by advancing techniques for cryocooling. Rapid cooling, or cryopreservation, is a technique routinely used to preserve crystals of biological molecules for structural analysis by X-ray diffraction. It is important that crystals are carefully preserved and stored not only to remain intact for later analysis but also to withstand radiation damage from the intense X-rays used. Flash cooling of crystals to near 100 kelvins (cryocooling) extends a crystal's lifetime and makes it less susceptible to the secondary radiation damage that occurs during X-ray analysis. Cryocooling also reduces thermal motions of the molecules and allows for data collection from very thin or small crystals.

Edward Snell, Russell Judge, and Mark van der Woerd, of MSFC, have provided a method by which scientists, for the first time, can actually see images of the temperature gradients as crystals of certain molecules are rapidly cooled. Using a camera sensitive to infrared radiation, the MSFC scientists determined the length of time it took to complete the cryocooling process. The experiment also demonstrated that it is possible to observe defects created by improper cooling or handling of the crystals. Being able to actually assess temperature distribution across a crystal and to observe defects caused by improper handling will help scientists to improve crystal preservation methods and ultimately obtain more complete and accurate data.

The researchers presented their work on cryocooling at several venues in FY 2002, including the American Crystallographic Association meeting in San Antonio. While investigating cryocooling of crystals, Snell and van der Woerd also studied water in the macromolecular structure to understand how cryoprotectants interact with the crystal at the molecular level. Cryoprotectants replace water in the structure and slow the formation of ice so that flash cooling the crystal vitrifies it — turns it into a glassy substance — rather than freezes it. The cryoprotectants do not react with the crystal and are simply present to protect the crystal from the effects of freezing. This work resulted in an invited talk in 2001, which was published in 2002 ("Neutrons and Microgravity," by E. H. Snell, in *Proceedings of the 3rd International Symposium on Development of New Structural Biology Including Hydrogen and Hydration in Organized Research Combination System*, 33–41). Complete neutron data sets have been collected to complement X-ray studies; these results will be published in 2003.

Flight Experiments

Three different pieces of macromolecular experiment hardware flew on the ISS in FYs 2001 and 2002, accommodating hundreds of macromolecular samples that successfully crystallized in the microgravity



credit: NASA

The structural model of thaumatin shown here was developed from information gleaned from thaumatin crystals grown in microgravity. The crystals grown in the Enhanced Gaseous Nitrogen Dewar on the International Space Station were of higher quality than any of those grown on Earth. Synchrotron studies of these crystals produced 50 percent more data than had been obtained from the best ground-grown crystal. Thaumatin is a protein from the African Serendipity berry and is highly prized for its sweet taste.

environment. Several technologies were also deployed to advance crystal studies and analysis, including real-time imaging of crystals during in-flight growth.

The first biological crystal growth experiments conducted aboard the ISS took place in the Enhanced Gaseous Nitrogen (EGN) Dewar in FY 2000 and were returned to Earth in early FY 2001. The dewar, which was developed by PI Alexander McPherson of the University of California, Irvine, flew on three ISS missions in 2001 (each lasting approximately 40 days) and carried a total of 881 samples of macromolecules to orbit for crystallization.

In the dewar, crystals were grown using the liquid-liquid diffusion method. In liquid-liquid diffusion samples, the material to be crystallized and the precipitant solutions are frozen separately, and then are thawed once in orbit, diffusing with each other and resulting in crystal formation. Under microgravity conditions, crystals of the biomolecular materials form without interference from the container, other crystals, or turbulent flows, which often results in a crystal with a more near perfect structure than those grown on Earth.

This was the case for the dewar-grown crystals of thaumatin, which were of higher quality than any of this molecule grown on the ground. Thaumatin is a protein from the African Serendipity berry (*Thaumatococcus danielli*) and is valued for its intensely sweet taste. NASA PI Craig Kundrot, of MSFC, grew crystals of thaumatin using the liquid-liquid diffusion method in the EGN. Synchrotron diffraction data collected from the best crystal extended to 1.28 angstroms and produced 50 percent more data than the best ground-grown crystal and 100 percent more data than earlier reports on thaumatin crystals in scientific literature. Results of the thaumatin crystal growth investigation were published in 2002 in a paper titled "Thaumatin Crystallization Aboard the International Space Station Using Liquid-Liquid Diffusion in the Enhanced Gaseous Nitrogen Dewar," by C. L. Barnes, E. H. Snell, and C. E. Kundrot, *in Acta Crystallographica Section D: Biological Crystallography(58),* 751–60.

FY 2001 also saw the transport of the Protein Crystallization Apparatus for Microgravity aboard STS-100, on April 19, 2001. PCAM had flown on 11 previous shuttle flights. PCAM, developed by Daniel Carter, of New Century Pharmaceuticals, and his colleagues at MSFC, is a self-contained crystal growth apparatus that uses multiple seven-chamber trays as a disposable interface. The sample chambers, which each hold a drop of protein solution, are surrounded by a "moat" of absorbent material that controls the crystal growth process after activation. The wells are filled prior to launch and sealed with rubber to prevent evaporation and subsequent crystal formation before launch. Nine plastic trays can be loaded in one PCAM cylinder, and six cylinders can be carried in a temperature-controlled locker.

For its first ISS mission, in April 2001, PCAM trays containing 756 samples of 11 different proteins were housed in two Single-Locker Thermal Enclosure Systems. The scientific objectives of these experiments ranged from producing crystals of superior size and quality for X-ray structure determination to experiments aimed at improving understanding of the underlying physical processes involved in biological macromolecular crystal growth in microgravity. PCAM equilibration studies conducted during the ISS increment produced data that will help future users of the PCAM equipment to optimize growth conditions for the macromolecules in which they are interested.

One of the PCAM experiments, led by Co-Investigator Jean-Paul Declercq of the University of Louvain, in Belgium, resulted in crystals of peroxiredoxin 5. Peroxiredoxin 5 is a protein thought to play an important antioxidant protective role in various tissues under both healthy and disease states. Peroxiredoxin may also be important to signal transduction, or communication, between cells. Crystals of the oxidized form of this protein grown on the ISS showed an improvement in resolution from 7 angstroms to 3.8 angstroms.

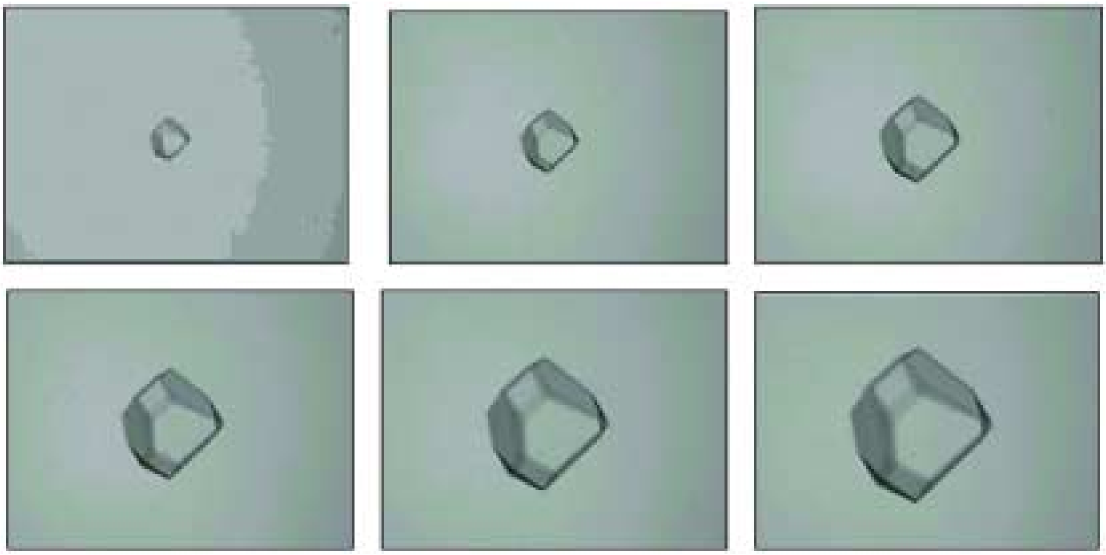
In FY 2002, PCAM flew on two space shuttle missions headed to the ISS, STS-108 in December 2001 and STS-111 in June 2002. On the STS-108 mission, several proteins produced significantly larger crystals and, in some cases, crystals that diffracted to the highest resolution to date for Earth- or space-grown crystals. On this flight, Carter and New Century Pharmaceuticals crystallized human serum albumin, the major protein of the human circulatory system. It contributes 80 percent to osmotic blood pressure and is chiefly responsible for maintaining blood pH. Additionally, albumin is involved with the binding and transportation of a variety of small molecules throughout the circulatory system, including the majority of currently known pharmaceuticals. Structural details of albumin and albumin-drug complexes can be used to explore the potential for improving the safety and efficacy of a broad base of therapeutics and for developing novel engineered albumins for a variety of applications. The highest resolution and quality native data to date on human serum albumin crystals were collected from one of the crystals grown on the ISS. Data were collected at a resolution of 1.9 angstroms, and these data indicated that even higher resolution data should be obtainable.

Co-Investigator Mark Wardell, of New Century Pharmaceuticals, crystallized human antithrombin III, which controls blood coagulation in human plasma and is an important target for understanding strokes and thrombolytic diseases, which include deep vein thrombosis, pulmonary embolism, and cerebral infarction. The first few ISS crystals analyzed have shown diffraction to at least 1.8 angstroms, with an overall completeness of more than 95 percent. As with the human serum albumin crystals, even higher resolution data may be obtainable from the antithrombin crystals. A detailed analysis of the improved structure is currently under way and will be published in the future. Another goal that was achieved during PCAM experiments flown to the ISS on STS-108 was the exploratory growth of crystals with a defined internal symmetry, called a space group, and morphology suitable for neutron diffraction. Carter's PCAM experiment was geared toward proof of concept for this protein/space group combination as a prelude for the more costly-to-prepare samples that are currently aboard the ISS. Neutron diffraction experiments are performed using specialized nuclear reactors and require unusually large crystals, which can be difficult to grow. The researcher's efforts, if successful, can be rewarded with an exceptional view into the hydrogen arrangement within the protein molecule — a key to understanding many of the chemical processes that underlie a protein's function.

The Dynamically Controlled Protein Crystal Growth (DCPCG) experiment flew on the ISS in FY 2001. The DCPCG hardware was developed by the Center for Biophysical Sciences and Engineering at the University of Alabama, Birmingham. The hardware is the first of its kind to allow the study of the physics of the biological crystal growth process. The DCPCG design includes a laser light scattering system that will be used to attempt to automatically detect the onset of nucleation, when the crystal begins to form. Microscopic high-resolution video cameras provide constant monitoring of crystal growth.

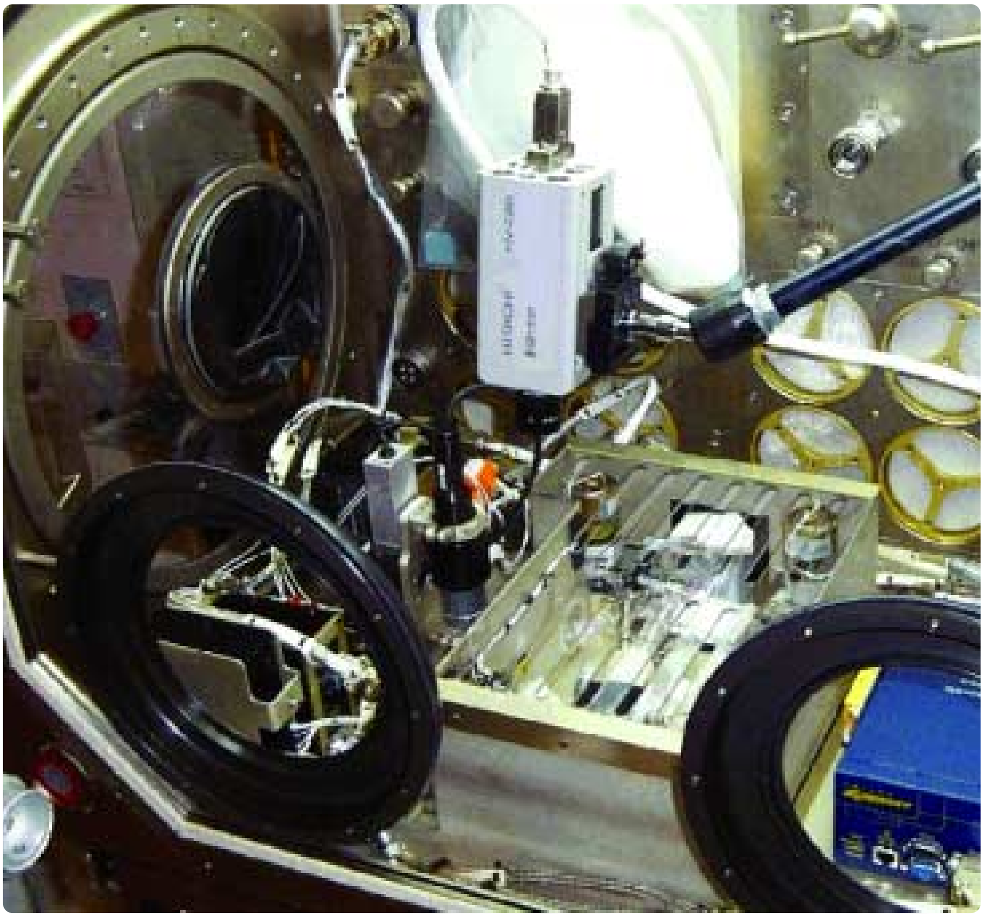
Carried to the station on STS-104 in July 2001, the DCPCG allowed, for the first time, dynamic control over crystal growth. This was accomplished through the ability to vary the rate of evaporation of the crystallization experiments using computers from the ground. This was also the first microgravity payload that allowed automated imaging of the crystal experiments in progress. Video images were collected every four hours and transmitted to Earth at a minimum of once each day. During operation of the DCPCG, half the chambers were activated and the experiments were monitored. Experiment conditions for the second half of the experiments were changed from the ground on the basis of the information obtained from the first set of chambers. The remote control and imaging capability of the DCPCG permitted scientists to observe two important phenomena regarding crystallization in microgravity: the effect of evaporation rates on crystal formation and the occurrence of significant movement of the crystals in solution.

Although differences in diffraction results between ground- and microgravity-grown crystals of the two model proteins flown in DCPCG were not statistically significant, the microgravity samples, having a slower evaporation rate, grew fewer and larger protein crystals. The ability to see the samples every four hours



credit: NASA

This series of images taken by Delta-L of one of 10 glucose isomerase crystals imaged automatically at 1.5-hour intervals can help give researchers insight into how growth rate dispersion can affect crystal growth and quality.



credit: NASA

Delta-L flight hardware, shown being tested in the ISS Microgravity Science Glovebox ground test unit, is expected to provide information to help researchers improve the quality of microgravity-grown crystals.

gave some very intriguing results regarding crystal movement, which was much more pronounced in the microgravity environment of the ISS than had been anticipated. It is not yet clear to what extent this movement was due to Marangoni effects, caused by convection that occurs as the result of surface tension differences, and what may have been the result of accelerations from various ISS activities. It is also not known whether the movement is a disadvantage to crystal growth — although it may be detrimental to ultimate crystal quality, it may also help to grow larger crystal volumes by moving the growing crystals into areas of fresh nutrient.

Engineers and scientists at MSFC have teamed to produce award-winning flight hardware named Delta-L. This equipment, which will fly on the ISS in late 2003, is expected to provide data that will test the hypothesis that growth rate dispersion plays a role in crystal quality improvement in microgravity. Growth rate dispersion is an occurrence in which individual crystals grow at slightly different growth rates under the same solution conditions. MSFC scientists participating in the study believe that microgravity may act to improve crystal quality by reducing growth rate dispersion. A reduction in dispersion has been shown to be an indicator of quality crystals on the ground.

The Delta-L experiment comprises a fluid assembly that allows crystallization fluid in the growth cell to be exchanged, thereby providing fresh growth solution to enable continued crystal growth; a data acquisition and control system; and an imaging system that allows images of crystals to be collected by using a video microscope camera.

MSFC scientists and engineers involved in the development of Delta-L are Dyana Beabout, Robert

Cooper, Eric Corder, Willie Dawson, Tim Dowling, Russell Judge, Paul Julino, Sharon Manley, Jim Meehan, Teresa Miller, Edward Snell, Mark van der Woerd, and Jason Waggoner.

Highlights

Understanding How Antioxidants Protect the Body

Few people look forward to aging, and history is full of stories of searches for a "fountain of youth." Theories abound as to why and how aging happens. One of the more popular of these theories states that aging is due to DNA and other cellular structures being damaged by a class of molecules known as free radicals. The body has its own defenders against free radicals, and NASA Principal Investigator Gloria Borgstahl, of the University of Toledo, is using space-grown crystals to discover how one of these "antioxidants" works.

Free radicals are produced in the body during oxidation, the reaction of oxygen with other molecules, which is a necessary chemical reaction that provides the energy to maintain life. A free radical has an unpaired electron in its outer orbital shell that is highly reactive and wants to pair with another electron to gain a more stable state. This electron makes free radicals very unstable. By reacting rapidly with nearby molecules, the unpaired electron is able to pair off with another electron, but the result is yet another unpaired electron, which leads to a kind of chain reaction of free radicals. The role of antioxidants is to react with free radicals, thereby stopping their chain reaction and preventing damage to molecules that are important to biochemical processes in the body.

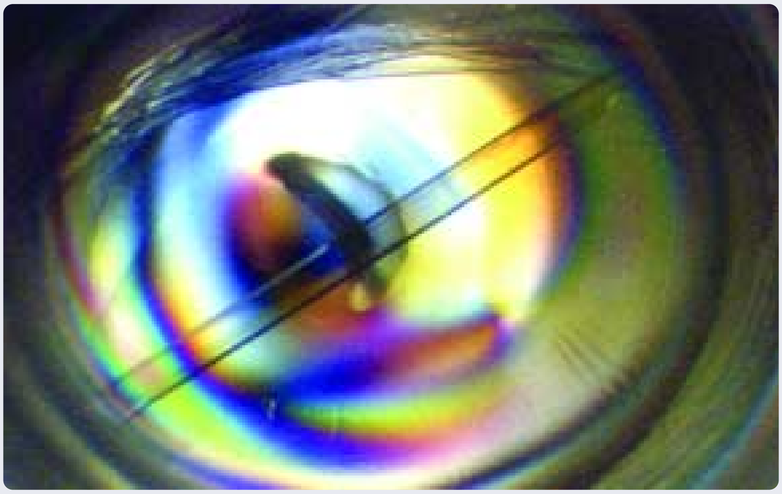
The aging body somehow loses its ability to provide the necessary antioxidants to protect vital biochemical processes from oxidation and the production of free radicals and becomes subject to various aging-related problems such as heart disease, diabetes, cancer, and Parkinson's disease. Free radicals can also react with fatty acids in the body to make them more saturated and can cause cross-linking of protein molecules. One of the best-known results of this type of cross-linking is the appearance of wrinkles and the loss of elasticity in skin as we age.

Borgstahl is studying the antioxidant called superoxide dismutases (SOD), which protects the body from the oxidative damage that is associated with aging. SODs are important enzymes that protect all living cells by reacting with the toxic superoxide radical, an oxygen molecule with a negative charge because of an extra electron, which is a normal by-product of respiration, the oxidation or burning of fuel within cells.

credit: Gloria Borgstahl

This microgravity-grown MnSOD crystal is pink due to the manganese metal ion in the active site. Earth-grown crystals typically grow as thin plates and are never thick enough to allow the viewer to see this vibrant pink color.

The ultimate goal of Borgstahl's research is to study the chemistry of SOD at the atomic level as it performs its job of detoxifying superoxides. She and her team hope that high-quality crystals of this enzyme grown in microgravity will help advance the understanding of how SOD works and will enable several types of technically challenging structure determinations. Although a naturally occurring manganese-containing form of superoxide dismutase (MnSOD) — the specific enzyme Borgstahl is working with — has been extensively studied biochemically, the crystal structure of this



credit: Gloria Borgstahl

According to one popular theory, aging is due to DNA and other cellular structures' being damaged by a class of molecules known as free radicals. The body has it own defenders against free radicals, including superoxide dismutases (SODs). PI Gloria Borgstahl hopes that high-quality crystals of MnSOD grown in microgravity, pictured here, will help advance the understanding of how SODs work and will enable several types of technically challenging structure determinations.

enzyme has not been solved. MnSOD and other metal SODs are part of the cell's defense against free radical–mediated damage. MnSOD also protects against the production of free radicals during inflammatory processes in the body.

Borgstahl's first microgravity crystallization experiments on the manganese-containing SODs were transported to the ISS by STS-108 in December 2001 and were returned to Earth in April 2002. At Advanced Photon Source in Chicago, Illinois, Borgstahl and her colleagues were able to collect the best X-ray diffraction data available to date from the crystals grown on the ISS. Crystals grown in Earth laboratories are typically long rectangular rods that are thin in cross section (120 microns x 50 microns x 1,000 microns). To the research team's great satisfaction, all 35 crystallization experiments on the ISS produced crystals, and more than half of them were of a dramatically larger volume in cross section (400 microns x 400 microns x 3,000 microns) than similar crystals grown on Earth. Several of the MnSOD crystals grown on the ISS were 80 times greater in crystal volume than Earth-grown crystals, and diffraction spots to 1.26-angstrom resolution were observed, providing significantly improved data compared with that obtained from crystals grown in Earth laboratories. Borgstahl has said that the difference in crystal size was "like comparing toothpicks to 4-inch x 4-inch planks of wood."

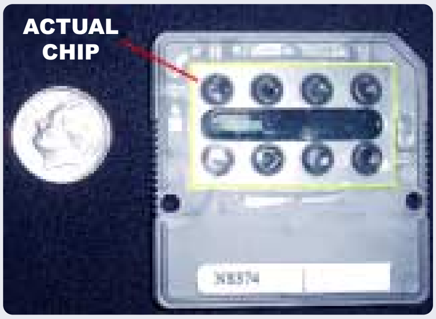
To answer fundamental biochemical questions concerning this enzyme, Borgstahl and her team needed to obtain these large, high-quality crystals of SOD for neutron studies and for time-resolved Laue studies. Both neutron and Laue methods require large (greater than 1 cubic millimeter), perfect crystals. With the neutron experiment, the researchers hope to be able to obtain the never-before-seen, three-dimensional structure of the hydrogens on each amino acid of the protein and thereby answer the unsolved questions concerning the source of these hydrogens in the enzyme reaction mechanism. With the time-resolved Laue experiments, the team will be able to generate the superoxide substrate within the crystals with a laser pulse and then make a "movie" of the enzyme converting it to peroxide and water.

The role of manganese-containing SODs in the body is important, and in-depth study of their structure is not only vital to understanding their function, but also may lead to new therapeutic treatments for various degenerative processes.

Stamp-Sized Laboratories for Space

Just as the world of electronics was reshaped by the philosophy that "smaller is better," biotechnology systems are being transformed by the drive to miniaturize. The result is the production of tiny biological laboratories on the scale of microns and millimeters. The function of several pieces of standard laboratory equipment and a lab technician can now be replaced with a postage stamp–sized "lab-on-a-chip." The science of microfluidics is making this new technology possible as it requires the ability to manipulate processes that involve fluid volumes measured in nanoliters (10^{-9} L) and picoliters (10^{-12} L). In the life sciences, microfluidic systems may be used for biochemical assays, genetic analysis, drug screening, electrochromatography (separating the components of a substance by applying a voltage), and blood-cell separation/analysis (to determine blood cell counts and the presence of disease), reducing the time and cost of performing complex biochemical processes.

NASA has also recognized the potential of these chips to process samples of macromolecules for crystal growth experiments in space. The tiny chips could greatly minimize the volume of valuable biological samples required to obtain results. With this objective, in late 2001, a collaboration began between NASA's Iterative Biological Crystallization (IBC) project and Caliper Technologies Corporation of Mountain View, California, the renowned mass producer of LabChip® devices. The result is chip NS374.



credit: NASA

In future space travel, miniaturized systems will be essential for reducing spacecraft system mass and volume. The functions of several laboratory instruments can now be placed on a chip that is not much larger than a dime. The size of the chips greatly minimizes the volume of valuable biological samples that must be used to obtain results, and the automated equipment that manages the chips allows scientists on Earth to use the Internet to set up and track crystallization experiments on the ISS.

In any experiment, for crystal growth to occur, a sample is prepared that contains the macromolecule in a solution and a precipitant that initiates evaporation and thus crystal formation. The new chip is capable of mixing prescribed recipes from up to five solution components and of selectively delivering each of the recipe mixtures to separate growth wells that reside on the same chip. Testing of this chip, which has been ongoing for several months in the IBC laboratories, has proven the efficacy of the approach. The IBC lab-on-a-chip system will provide a statistically significant sample, much higher throughput, and greater repeatability of macromolecular experiments. Automated equipment that manages the chips allows scientists on the ground to use the Internet to iteratively set up and visually evaluate hundreds of crystallization experiments throughout the duration of an ISS flight increment.

The lab-on-a-chip technology developed by IBC, with its capacity to meter and mix biological fluids with picoliter accuracy, is well suited for commercial or academic structural biology research on Earth as well as in space. The unit will also be adaptable for other areas of research that employ microfluidics.

In future space travel, miniaturized systems will be essential in reducing the mass and volume of spacecraft systems. Microfluidics has the potential to facilitate and automate scientific research across multiple disciplines. As NASA seeks to develop tools that will diminish the negative effects of long-term space travel on humans, lab-on-a-chip technology is a potential springboard for medical diagnostic and therapeutic devices that will ultimately make spaceflight safer for humans.

credit: Hauptman-Woodward Medical Research Institute

In June 2002 New York State Senator Hillary Rodham Clinton (second from left) announced the award of a $2.6 million grant over three years from NASA to the Hauptman-Woodward Medical Research Institute (HWMI) to establish the NASA Institute for Structural Biology at HWMI's Buffalo Niagara Medical Campus. From left to right: George DeTitta, HWMI executive director and CEO; Senator Hillary Rodham Clinton; Ron Porter, manager, Science Planning and Program Management Group, MSFC; Herbert Hauptman, HWMI president; and Christopher Greene, HWMI chairman of the board.

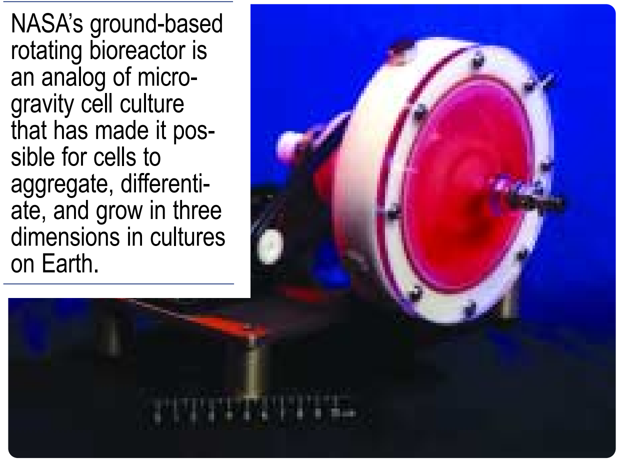
A New NASA Institute

In November 2001, NASA awarded the Hauptman-Woodward Medical Research Institute (HWMI) in Buffalo, New York, a grant to establish the NASA Institute for Structural Biology (NISB). Hauptman-Woodward is an independent, nonprofit facility specializing in basic research using structural biology and is known worldwide for its expertise in crystal growth. The new NASA institute will be devoted to fostering research in the field of macromolecular biology and in facilitating the use of low-gravity research opportunities. Principal Investigator George DeTitta and his co-investigator, HWMI Research Scientist Joseph Luft, and HWMI Executive Vice President and Principle Research Scientist Walter Pangborn were named to head the institute.

NISB was formed in part to help structural biologists access flight hardware through NASA's unified Associate Investigator Program, which is focused on opening up spaceflight opportunities to a larger community of scientific researchers. Shortly after its inception, NISB began to promote awareness of the new program. The NISB contacted groups and individual members of the structural biology community, providing information about how the institute can assist investigators who wish to fly macromolecular crystallization samples in ISS experiment hardware sponsored by NASA's Physical Sciences Research Division. Also provided was a list of upcoming flights available with instructions on how to make an application. An independent peer-review panel was set up to evaluate flight proposals, and the group began reviewing applications for early 2003.

Another important task for the NISB is to help selected researchers through the process of flying experiments on the ISS. To that end, the NISB will provide the support necessary to do adequate ground crystallization experiments and diffraction analyses to assess the effects of microgravity, including making synchrotron radiation available. Timely access to synchrotron beam time following retrieval of flight experiments is a high priority for researchers, as using electromagnetic radiation has become an indispensable tool in the field of X-ray crystallography for molecular structure determination. NISB will help investigators secure access to the Stanford Synchrotron Research Laboratory at Stanford University.

OVERVIEW



NASA's ground-based rotating bioreactor is an analog of microgravity cell culture that has made it possible for cells to aggregate, differentiate, and grow in three dimensions in cultures on Earth.

credit:: NASA

More than 70 years ago, cellular biologist E. B. Wilson wrote in his book *The Cell in Development and Heredity* that "the key to every biological problem must finally be sought in the cell." All living creatures are made of cells — small, membrane-bound compartments filled with a concentrated water-based solution of chemicals. The simplest forms of life are solitary cells that propagate by dividing in two. More complex organisms such as humans are like cellular cities in which groups of cells perform specialized functions and are linked by intricate communication systems. Cells occupy a halfway point on the scale of biological complexity. Scientists study cells to try to understand their molecular makeup and to learn about how they cooperate to enable a complex organism to function.

More than 200 types of cells make up the human body. They are assembled into a variety of tissues, such as skin, bone, and muscle. Most tissues contain a mixture of cell types. Cells are small and complex — a typical animal cell is about five times smaller than the smallest visible particle, and it contains all the molecules necessary to enable an organism to survive and reproduce itself. A cell's small size makes it difficult for scientists to see its structure, to discover its molecular composition, and especially to find out how its various components function. Differentiated cells perform specialized functions. For example, a heart muscle cell looks different from and performs different functions than a nerve cell. Specialized cells interact and communicate with one another, setting up signals to govern the character of each cell according to its place in the structure as a whole.

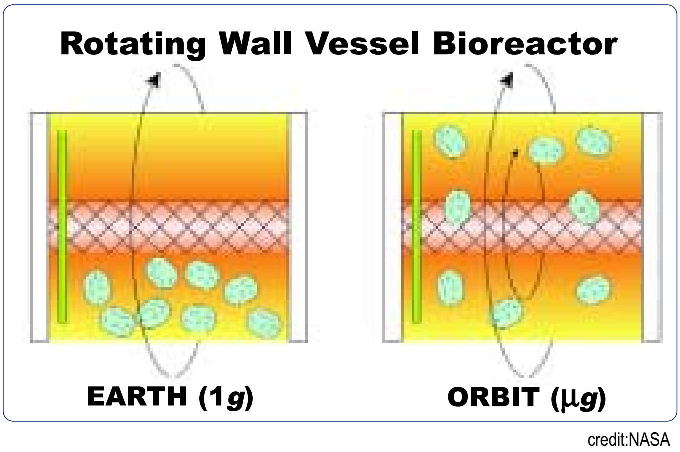
What can be learned about cells depends on the available tools. Culturing (growing) cells is one of the most basic techniques used by medical researchers. The growth of human cells outside the body enables the investigation of the basic biological and physiological phenomena that govern the normal life cycle and many of the mechanisms of disease. In traditional research methods, mammalian cells are cultured using vessels in which cells settle to the bottom surface of the vessel under the influence of gravity. This gravitational influence results in a thin sheet of cells, with the depth of a single cell, called a monolayer. Cells in human tissues, however, are arranged in complex, three-dimensional structures.

When cells are grown in a monolayer, they do not perform all the functions that the original tissue does.

Although much valuable information can be gained from monolayer cell cultures, further understanding of the processes that govern gene expression and cellular differentiation is limited because the cells are not arranged as they are in the human body. When the influence of gravity is decreased, the cells are able to grow in more tissue-like, three-dimensional aggregates, or clusters. Until the cellular biotechnology program developed a unique technology called the NASA Bioreactor, experiments to form three-dimensional cell formations were confined to the microgravity environment of space.

The NASA-designed bioreactor allows cells to be cultured in a continuous freefall state, simulating microgravity and providing a unique cell culture environment on the ground. The growth medium–filled cylindrical vessel rotates about a horizontal axis, suspending the cells in a low-shear* culturing environment. This allows for cell aggregation, differentiation, and growth. The bioreactor affords researchers exciting opportunities to create three-dimensional cell cultures that are similar to the tissues found in the human body.

Using both space- and ground-based bioreactors, scientists are investigating the prospect of developing tissues that can be used in medical transplantation to replace failed organs and tissues. Additionally, investigators are striving to produce models of human disease to be used in the development of novel drugs and vaccines for the treatment and prevention of disease, to devise strategies to reengineer defective tissues, and to develop new hypotheses for the progression of diseases such as cancer. Finally, cells exposed to simulated and true microgravity respond by making adaptations that give new insights into cellular processes, establish a cellular basis for the human response to microgravity and the space environment, and pave the way for cell biology research in space regarding the transition of terrestrial life to low-gravity environments.



The NASA rotating wall vessel bioreactor provides a low-turbulence culture environment that promotes the formation of large, three-dimensional cell clusters. Cell constructs grown in the bioreactor more closely resemble tumors or tissues found in the body. Cell constructs grown in a rotating bioreactor on Earth (left) eventually become too large to stay suspended in the nutrient medium. In the microgravity of orbit, the cells stay suspended (right). Rotation provides gentle stirring to replenish the medium around the cells.

* Shear is the force caused by the cells sliding against one another.

Program Summary

A recommendation was made by the National Research Council in 2000 for the Cellular Biotechnology Program to work with the Fundamental Biology Program of NASA's Life Sciences Division to take advantage of overlapping interests. Therefore NASA Cell Science conferences, which had for many years been sponsored by the Cellular Biotechnology Program (CBP) at Johnson Space Center in Houston, Texas, were jointly sponsored by the CBP and the Fundamental Biology Program at Ames Research Center in Moffett Field, California, in 2001 and in 2002. This successful collaboration between the two centers will continue.

The 2001 NASA Cell Science Conference and Annual Investigators Working Group Meeting was held March 6–8, 2001, in Houston, Texas; this was the first agencywide cell science conference. Approximately 190 scientists from universities, NASA centers, the National Institutes of Health, the National Space Biomedical Research Institute, and commercial cell culture enterprises attended the three-day conference. Sixty-three invited speakers gave talks in the following areas: cell movement/cytoskeleton, tissue modeling, biological responses to physical forces, models in lower organisms, immunology, cell culture technology, proliferation and differentiation, and gene expression. Eight industry exhibitors also attended to showcase their products.

The 2002 conference was held February 26–28, 2002, in Palo Alto, California, and was attended by approximately 160 scientists and 10 exhibitors. Currently, planning is under way for the 2003 NASA Cell Science Conference, scheduled for February 20–22, 2003. In addition to the research areas covered in past conferences, the 2003 conference will be expanded to include presentations on neoplastic disease (cancer), sensors and analytical equipment, and gravity and mechanical sensing. The area of sensors and analytical equipment encompasses work in advancing the state of the art in automated cell culture technology. In space, the culturing of cells must be highly automated because it may be performed by crewmembers who are not proficient in this very time-consuming and skill-intensive procedure. Thus, sensing systems that can detect cell culture conditions and control them autonomously to ensure they remain viable are necessary to ensure successful science. Gravity and mechanical sensing covers investigations into the molecular and cellular mechanisms behind the many varied responses seen in microgravity. Understanding these is critical to understanding why we see many decreases in quality of physiological functions such as muscle atrophy and bone loss associated with spaceflight.

Under the Cellular Biotechnology Program in fiscal years (FYs) 2001 and 2002, 47 principal investigators conducted scientific investigations in both ground- and flight-based environments, resulting in more than 50 publications in peer-reviewed scientific journals and proceedings. Additionally, a NASA Research Announcement for cellular biotechnology (NRA 01-OBPR-08-B) was issued in June 2002.

Research solicited under this announcement sought to establish the scientific foundations for future experiments on the International Space Station (ISS) and to support the development of biotechnology applications for long-duration spaceflight. The solicitation also sought coordinated research efforts involving both space- and ground-based research that would lead to potential flight experiments or development of new technologies for future NASA missions. NASA not only invited research in the areas that it has previously supported, such as tissue engineering, bioreactor design, and changes in gene expression, but also expanded the scope to include other research areas that have been identified as having potential to contribute to human exploration of space. These new areas of supported research include separation, purification, and remediation methods; microbiosensor monitoring devices; and selective pressures on cell populations, among others.

Separation, purification, and remediation methods are needed to clean and recycle water on spacecraft during future long-duration missions. Purification methods must be specific for toxic molecules, reliable, and inexpensive and must make minimal demands on spacecraft resources. The cellular biotechnology program can contribute in this area by researching the use of cellular organisms to convert or catalyze fluid waste to usable products such as drinking water, oxygen, or methane.

Likewise, the cellular biotechnology program can assist in the development of microbiosensor monitoring devices. The sensors will be microtechnology- and nanotechnology-based, will be extremely stable and small, and will be used for monitoring biological systems and experiments to aid in the advancement of biotechnological processes and their use in support of long-duration space missions.

Assessment of selective pressures on mammalian and microbial cell populations is critical to long-term occupation of space. Changes in cells that are both genotypic (changes in the makeup of the genes themselves) and phenotypic (changes in how the genes express themselves externally) occurring over numerous generations of cells exposed only to a space environment must be studied in order to determine risks to our biological integrity and to our life-based support systems wrought by extended (and even permanent) stays in space.

Proposals in response to the NRA were due September 6, 2002, and selections are expected to be made in May 2003. For additional information, visit *http://research.hq.nasa.gov/code_u/nra/current/NRA-01-OBPR-08-B/index.html* on the World Wide Web.

Most of NASA's previous work in cell science has taken place on shuttle flights and on the Russian space station, *Mir*. These experiments have demonstrated that microgravity and the space environment affect cell shape, signal transduction (the transfer of signals from outside the cell to inside the cell), replication and proliferation, gene expression, apoptosis (cell disintegration), and synthesis and orientation of intracellular and extracellular macromolecules. With the increased availability of research opportunities on the ISS and the new hardware developed specifically for this platform, more frequent and longer term investigations will undoubtedly accelerate the advancement of our understanding of how the microgravity environment affects cell structure, processes, and functions.

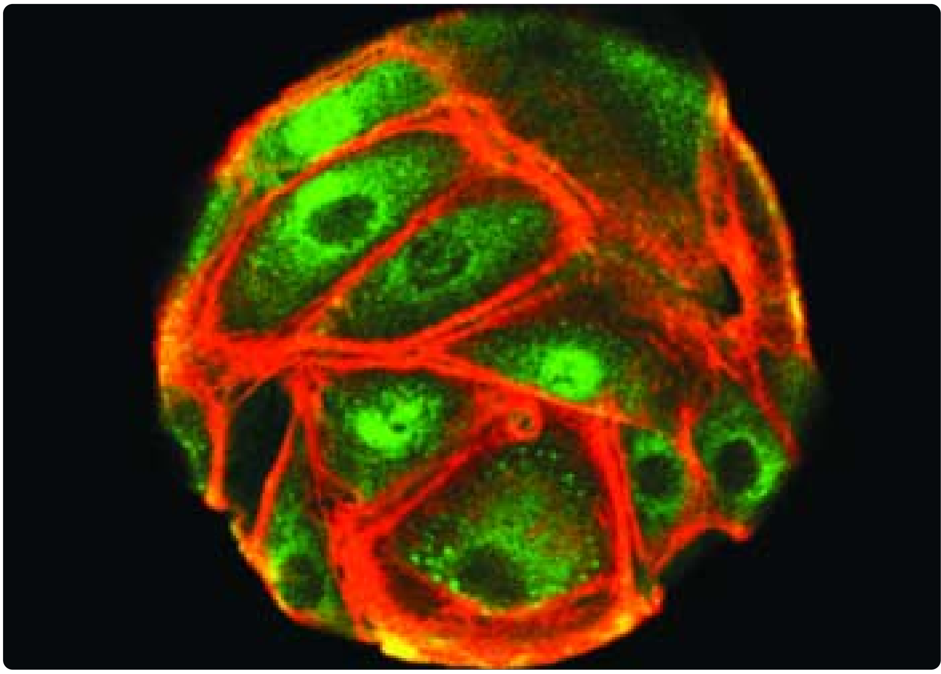
Flight Experiments

FY 2001 and FY 2002 were again years of advances for the cellular biotechnology flight program. Several researchers flew experiments on space shuttle flights and on the ISS. Flight experiments included studies of colon cancer metastasis, kidney cell gene expression, and erythroleukemia. Additionally, in FY 2002 the Cellular Biotechnology Program extended its efforts to expand biotechnology commercial ventures by enlarging its agreement with StelSys Inc. of Baltimore, Maryland, to include flight experiments aboard the ISS. Progress was also made on the development of the Biotechnology Facility for the ISS.

Principal Investigator (PI) J. Milburn Jessup's study of colon carcinoma metastasis using the NASA bioreactor flew to the ISS aboard STS-105 in August 2001. Jessup, of the Georgetown University Medical Center, is a veteran of two spaceflight experiments on shuttle missions STS-70 (July 1995) and STS-85 (August 1997). STS-70 provided the proof that NASA's rotating wall vessel bioreactor (RWV) could be used to grow three-dimensional cellular aggregates. The carcinoma cells provided by Jessup for the experiment formed masses 10 millimeters in diameter — 30 times the volume of those grown in the control experiment on the ground. The experiment was repeated on STS-85, again resulting in mature differentiated tissue samples and confirming that microgravity is an environment beneficial to cell culture and tissue growth.

Experimental results from these two space shuttle flights indicated that programmed cell death, or apoptosis, occurred in the RWV on the ground but was reduced in the actual microgravity cultures. The rate of apoptosis in the MIP-101 (human colorectal carcinoma) cells approached that of the same cells growing as nonrotated masses in three dimensions on a surface to which the cells did not attach. This finding was important because it suggested that rotation at the speeds necessary to suspend cells on Earth in the RWV may actually hurt the cells. Other researchers have reported that RWVs operated on Earth may also change the cytoskeleton, or backbone, of cells in such a way that rotation may lead to cell death. In microgravity, the RWV does not need to spin as fast to keep the cells suspended, so the cells more nearly approach the nonrotated three-dimensional cultures on the ground. Jessup has recently found that rotation on the ground also increases nitric oxide and reactive oxygen species production by as much as six to eight times. These substances can be quite toxic to cells and cause the apoptosis seen in the RWV.

Jessup's work from these flights resulted in two peer-reviewed publications in national journals regarding metastatic characteristics of colon carcinoma.

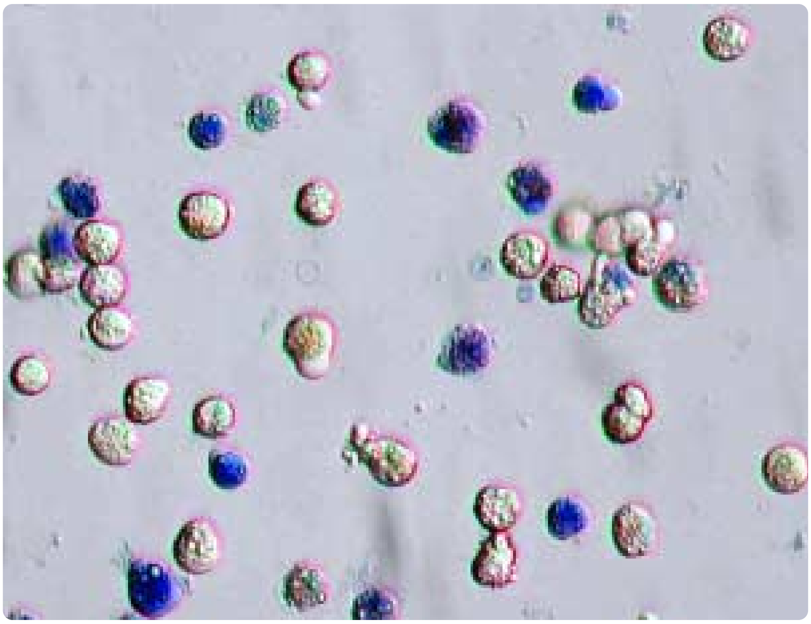


credit: NASA

Timothy Hammond is examining how microgravity alters the gene expression in renal cells that ultimately enables kidneys to develop and function normally. He has found that the genetic expression of human renal cells can be manipulated in microgravity to produce hormones that are valuable in the treatment of disease.

Preliminary ground research indicated that the metabolism of the MIP-101 line of colon cancer cells is significantly increased in microgravity; the cells essentially outgrew the capacity of the rotating wall vessel bioreactor under simulated microgravity conditions.

Additional flight experiments were conducted during the STS-108 mission in December 2001; analysis of those experimental samples is in progress. Jessup used the MIP-101 cells for the additional experiments because they differentiate, producing certain proteins, in the RWV. He conducted the experiment to assess how aggressively such cells will consume nutrients in microgravity when a three-dimensional culture is attempted, as well as to test the metabolic requirements of space-based bioreactors. Ultimately, Jessup hopes his research will aid in gaining additional needed information regarding the mechanisms involved in colon cancer metastasis.



credit: StelSys Inc.

Microgravity is valuable for peeling away the interfering effects of gravity and laying bare functions of an organism that might not be apparent on Earth. These human liver cells were flown on the International Space Station and then cultured for 24 hours on the ground. Scientists studying how space changes life-forms hope that a comparison between cells grown in microgravity and those grown on Earth will provide insight into the effects of microgravity on liver cell functions and result in a better understanding of liver functions both in space and on Earth.

Jessup is looking forward to testing the hypothesis that the apoptosis seen in the RWV on the ground and in some spaceflights is due to oxidative stress. In addition to the results gathered from his studies of cell death in MIP-101 cells, much evidence exists that reactive oxygen and nitrogen species are generated both in cells in culture and in muscles and organs in crewmembers and animals in space. This work may ultimately lead to a better understanding of the effects of reduced gravity on subcellular organelle distribution and oxidative stress. This may also help provide a means to assess new and better countermeasures for the deleterious aspects of weightlessness.

PI Timothy Hammond, of Tulane University Medical Center and the Veterans Affairs Medical Center in New Orleans, Louisiana, has conducted a series of spaceflight cell culture experiments using renal (kidney) cells. He is examining how microgravity alters the gene expression in renal cells that ultimately enables kidneys to develop and function normally. During shuttle mission STS-106 (September 2000), Hammond cultured three-dimensional constructs of normal human renal cells, and in early FY 2001, he analyzed the results regarding the genetic expression of human cells in microgravity and their ability to be manipulated to produce renal hormones that are valuable in the treatment of disease.

Continued studies of renal cells in microgravity aboard STS-105 in August 2001 revealed additional information about the mechanisms involved in these genetic manipulations and responses. Hammond was able to assess the cultured tissue's production of erythropoietin, a hormone produced mainly by the kidneys that stimulates the production of red blood cells by stem cells in bone marrow, and vitamin D_3, a substance converted by the kidneys that plays an important role in the absorption of calcium from the intestine, helping to maintain strong bones. As expected, the production of both of these substances increased dramatically in space. Hammond hopes to adapt the three-dimensional tissue model for commercial production of these hormones.

In FY 2002, Hammond flew renal cells on the ISS during Expedition 4 (December 2001–June 2002). In this study, Hammond examined the responses of normal human renal cells to a peptide sequence known to inhibit the vitamin D receptor under microgravity. In patients with kidney disease characterized by heavy protein excretion, it is believed that the elevated levels of protein in the kidney cause tissue damage and scarring. This toxicity is thought to be due to the binding of low–molecular weight proteins to scavenger receptors on the surface of the renal proximal tubules. Molecules that can disrupt the scavenger pathway by binding to the scavenger receptors include certain classes of antibiotics as well as artificial blood and hormone precursors like vitamin D. Hammond evaluated cellular structure and assessed the distribution of the vitamin D receptor and other biological molecules that control gene expression to understand the molecular mechanisms mediating gene expression changes in space. Long-term goals of Hammond's research include identification of genes that respond to microgravity, modeling of renal injury mechanisms, and production of renal hormones of pharmacological importance. Changes in gene expression in cells grown in space have demonstrated the metabolic pathways important in the response to microgravity, which is allowing the researchers to mimic the biologically and pharmacologically useful elements of this response on the ground.

PI Arthur Sytkowski, of Harvard Medical School, Cambridge, Massachusetts, conducted a flight experiment during ISS Expedition 4 to study erythroleukemia (EMS-3) cells. Erythroleukemia is a cancer of the blood-forming tissues in which large numbers of immature, abnormal red blood cells are found in the blood and bone marrow. The EMS-3 cells respond to erythropoietin, the natural inducer of the formation of red blood cells, and to other chemical inducers such as dimethyl sulfoxide (DMSO). Sytkowski and his team cultured EMS-3 cells in orbit to test their responsiveness when exposed to these inducers in microgravity and compare results to data from previous ground-based rotating wall vessel bioreactor experiments.

Because it has been known for some time that red blood cells do not evolve well in microgravity, this research has a direct bearing on the future of long-term human spaceflight as well as on human diseases experienced on Earth. Data from these experiments will improve our knowledge of the effects of microgravity on the hematopoietic (blood-forming) system and will suggest possible in-flight countermeasures and treatments for negative effects of microgravity on astronauts and provide insight into developing therapies for patients on Earth with diseases affecting blood cell formation.

To carry on NASA's commitment to developing real-world applications of NASA's bioreactor technology and to substantiate NASA's interest in the commercialization of microgravity research in areas related to biological systems, NASA signed an agreement with StelSys Inc. in 2002. This follows on the heels of the groundbreaking agreement NASA signed with StelSys in September 2000, which began a new biotechnology commercial venture. The first agreement fostered the exploration of a new frontier in biotechnology, infectious disease research and the development of a liver-assist device for patients in need of transplant surgery. The agreement signed in 2002 augmented the initial venture by providing for the flight of experiments on the ISS.

The main objective of the StelSys series of experiments is to test the hypothesis that a microgravity environment will facilitate three-dimensional propagation of cultured liver cells into differentiated, functional tissue equivalents. As with other tissues grown in microgravity, obtaining three-dimensional constructs that function like the liver *in vivo* would help researchers to better understand liver functions and develop drug therapies and test their efficacy before administering the drugs to patients. One of the specialized functions of the liver is to break down drugs or toxins into less harmful and more water-soluble substances that can be excreted from the body. ISS-based research will examine how human liver cells process drugs in space, using the microgravity environment to isolate individual cell functions.

Onboard the ISS, the StelSys experiments will test the function of human liver cells in microgravity versus the function of duplicate cells on Earth. Sponsors of this experiment hope that this work will elucidate the effects of microgravity on the proper functioning of liver cells and lead to earlier and more reliable screening of new drugs for patients in need of liver and kidney treatments prior to transplant. It could also accelerate development of new lifesaving drugs by pharmaceutical companies because drug developers would be able to test their drug candidates in tissue constructs that maintain their liver-specific functions for up to a week. Researchers could then choose only the best therapeutic candidates for further testing, which may take place in humans.

Albert Li, of StelSys, grew liver cells in the Cellular Biotechnology Operations Support System, managed by Neal Pellis at Johnson Space Center. Cells were transported on STS-111 in June 2002 to the ISS, where they were nurtured and grown. When cell growth was complete, the samples were frozen and then transported back to Earth for study by STS-112 in October 2002. Li and his colleagues will assess the liver constructs for true functionality to assess their usefulness for drug screening and to determine their utility for producing compounds that could improve human health.

Great progress was made during FY 2002 on design and development of the ISS Biotechnology Facility (BTF). The BTF is a complement of hardware and science experiments designed to use the unique microgravity environment of low Earth orbit as a tool in basic and applied cell biology. Researchers will be able to use BTF hardware that is based on an extensive heritage of spaceflight-proven designs, including incubators, refrigerators, analytical instruments, and gas- and water-supply devices. This hardware will be contained inside two refrigerator-sized enclosures known as research racks. For more about the BTF and milestones achieved in FYs 2001 and 2002, see the ISS chapter of this annual report.

The cellular biotechnology program has also made significant progress in the development of advanced sensors to support tissue culture. Growth of long-duration mammalian cell and tissue cultures in spaceflight bioreactor systems requires automated monitoring of culture parameters such as pH, glucose, and oxygen concentration. Four invention disclosures were made to NASA during 2002 for a pH control process, a glucose control process, a glucose sensor, and an oxygen sensor. The glucose sensor can continuously measure glucose present in cell culture medium in a perfused bioreactor system, in which cells are grown in an excess of medium that continuously flows through the bioreactor. The oxygen sensor is an optical sensor based on dynamic fluorescent quenching of a pulsed blue light that is emitted by a light-emitting diode. The sensor is designed for long-term continuous measurement of dissolved oxygen concentration in the cell culture medium in perfused bioreactors. In 2002, two papers describing the pH control process and the glucose sensor were published: "Continuous pH Monitoring in a Perfused Bioreactor System Using an Optical pH Sensor," by A. S. Jeevarajan, V. Sundeep, T. D. Taylor, and M. M. Anderson (in *Biotechnology and Bioengineering,78*(4), 467–72), and "On-Line Measurement of Glucose in a Rotating Wall Perfused Vessel Bioreactor Using an Amperometric Glucose Sensor," by X. Yuanhang, A. S. Jeevarajan, J. M. Fay, T. D. Taylor, and M. M. Anderson (in *Journal of the Electrochemical Society, 149*(4), H103–106).

Highlights

<u>Bringing Cancer Cells to Their Knees</u>

While much progress has been made in identifying the processes that give rise to cancer, new therapies for its treatment have not kept pace. Chemotherapy, which involves using drugs, including chemicals that damage DNA, remains the primary cancer treatment option for physicians. Unfortunately, cancer cells can exhibit resistance to chemotherapeutic agents. In some cases, this resistance develops during or very shortly after chemotherapy treatment, and often the resistance can happen with several therapy agents, even when only one was administered. This is called acquired resistance. In other cases, tumor cells appear to be completely unresponsive to treatment with therapeutic agents, even if they are agents to which the cancer cells have never been exposed. This is known as intrinsic resistance. In both scenarios, the result is the same: the chemotherapy does not destroy the cancer cells. The mechanisms underlying this rapid onset of drug resistance in human cancer are not clear. One problem in studying and combating this resistance is the lack of cancer models that reproduce conditions occurring *in vivo*, or in the body. This is also a problem in studying the effects of various therapies on cancer cells.

credit: NASA

In August 2001, PI Jeanne Becker sent human ovarian tumor cells to the ISS aboard STS-105. The tumor cells were cultured in microgravity for a 14-day growth period and were analyzed for changes in the rate of cell growth and for synthesis of associated proteins, as well as evaluated for the expression of several proteins that are the products of oncogenes, which cause the transformation of normal cells into cancer cells. This photo, which was taken by astronaut Frank Culbertson while he was performing the experiment for Becker, shows two cell culture bags containing LN1 ovarian carcinoma cell cultures.

NASA investigator Jeanne Becker and her team of researchers at the University of South Florida, in Tampa, have successfully used the NASA-developed High Aspect Ratio Rotating-Wall Vessel (HARV) to culture three-dimensional constructs of human ovarian tumor cells, which, as are breast tumor cells, are notoriously difficult to grow outside the body. Becker began working with the rotating wall vessel bioreactor in 1992 and continued with the HARV in her attempt to grow three-dimensional cancer cell aggregates that would function more like human tumors than the two-dimensional tissues obtained by traditional culture methods. The earlier rotating wall vessel bioreactor and the HARV both provide a growing environment for cell cultures that is similar to the one available in the microgravity conditions of low Earth orbit. The continuous rotation of the bioreactor keeps the growing cells in a state similar to the freefall experienced by the space shuttle and the ISS as they orbit Earth, thereby mitigating the effects of gravity that normally prevent the cells from growing in more than a single layer. The constructs grown in the rotating wall vessel bioreactor provide a model that is more biologically representative of conditions that occur *in vivo* than models afforded by traditional culture systems, and Becker plans to use them to study chemotherapeutic drug resistance.

Becker also prepared a spaceflight experiment to compare ovarian tumor growth in a true microgravity environment to cells cultured in concurrent experiments on the ground and in the HARV. In August 2001, her experiment was transported aboard STS-105 to the ISS, where it remained until December 2001. Human ovarian tumor cells were cultured in microgravity for a 14-day growth period. The cells were preserved at three time points during culture so that they could be analyzed for changes in the rate of cell growth and for synthesis of associated proteins, as well as evaluated for the expression of several proteins that are the products of oncogenes, which cause the transformation of normal cells into cancer cells.

The experiment results will be used to define potential points of tumor cellular development that may be targeted by chemotherapeutic drugs. Finding new targets for chemotherapeutic drugs is especially important in the case of ovarian cancer, which is usually not detected until it is already in an advanced, incurable stage.

Ultimately, Becker hopes that her research will provide oncologists with a better chance of predicting which drug treatments will work against ovarian cancer. With a three-dimensional model that behaves the way cancerous ovarian tissue in the body does, researchers will have a more reliable means of predicting drug and hormone treatment efficacy before administering those treatments to patients. Becker's study of three-dimensional cell development offers great potential for improving therapies for ovarian and other cancers.

In another example of using the rotating wall vessel bioreactor to culture three-dimensional constructs of cancer cells, Peter Lelkes, of Drexel University, in Philadelphia, Pennsylvania, is attempting to grow vascularized tissue, which contains blood vessels, *in vitro*. Cancerous tumors are able to grow only because the formation of new blood vessels within the tumor provides the oxygen and nutrients that are necessary to sustain growth. One of the strategies in combating such tumorous cancers, therefore, has been to look for ways to interfere with this blood vessel growth. If Lelkes can grow a vascularized tissue *in vitro*, he will have created a tool with which to investigate the efficacy of drug therapies that can interfere with or prevent the blood vessel growth that sustains tumors as they grow in the body, thereby slowing or stopping tumor growth. Lelkes is currently attempting to co-culture microvascular endothelial cells with prostate cancer cells in rotating wall bioreactors.

Becker and Lelkes are just two researchers out of many who are using rotating wall vessel bioreactors and the microgravity environment of low Earth orbit to try to develop a better understanding of the mechanisms of cancer development and better means of fighting cancer in humans.

Neutralizing Virulent Microbes

Spacefarers can remain in a closed system for weeks, sometimes months — and for proposed long-duration flights, maybe even years — breathing recycled air and drinking recycled water. Given that some virulent microbes appear to thrive in microgravity, that's not a promising scenario for health, according to Cheryl Nickerson, assistant professor of microbiology and immunology at Tulane University Health Sciences Center's program in molecular pathogenesis and immunity. Nickerson says that spacegoers already appear to have a higher risk of falling ill.

credit: Tulane Univers

Cheryl Nickerson's research focuses on the well-known pathogen, *Salmonella typhimurium*, whose genetic response to gravity's near absence could provide clues to infection protection. Here, Nickerson (fa right) works with her laboratory staff: from left to right, Carly LeBlanc, Rajee Ramamurthy, Kerstin Honer zu Bentrup, and Jim Wilson.

In ground-based studies simulating microgravity, Nickerson and her research team have found that a common strain of bacteria known as *Salmonella typhimurium* can alter its genetic profile, upping the production of certain self-protecting proteins that may enhance virulence. That could be unwelcome news for future astronauts. Microgravity may also reduce antibiotic effectiveness, and absent any new pharmacological approach, the difficult task of in-space treatment is made even more challenging.

In the course of their investigation, Nickerson and her colleagues found that more than 100 *Salmonella* genes, or about 3 percent of the salmonella genome, altered genetic expression. The changes made the bacteria far more lethal: mice injected with the strains grown in modeled microgravity died, on average, three days earlier than expected from shock and from large-organ failure.

Nickerson's original studies in simulated microgravity involved the use of the rotating wall vessel bioreactor, which mimics reduced gravity. Cells of *S. typhimurium* were placed in a culture within the bioreactor chamber. When the bioreactor spun, it maintained the cells in close approximation of freefall, which astronauts experience as up to one-millionth of Earth's normal gravity.

The researchers also cultured *S. typhimurium* under normal-gravity conditions.

In addition, to study how *S. typhimurium* causes infection in people, Nickerson and her colleagues used the bioreactor to culture three-dimensional human intestinal epithelial cells, which more accurately model the physiology of human intestinal tissue than does conventional tissue culture. In response to the microbial invasion, the cells produced higher levels of substances called anti-inflammatory cytokines, which may help limit damage to the intestinal tissue following salmonella infection. The three-dimensional intestinal cells also showed less damage and cell death following salmonella infection when compared with other types of cells known as monolayers. These observations are consistent with the self-limiting nature of salmonella infection, according to Nickerson, which can damage or kill epithelial cells in otherwise healthy individuals before being destroyed by immune reaction.

According to the Centers for Disease Control, salmonella-related maladies are among the most common intestinal infections in the United States, with 40,000 cases reported yearly. However, scientists estimate that because only 3 to 5 percent of salmonella cases are actually reported nationwide, and many milder cases are never diagnosed, the true incidence is much higher, likely in the millions. As many as 1,000 Americans die annually from salmonella infections.

Bacteria are not premeditated killers. Their goals, like all organisms, are to survive, thrive, and reproduce. To do so, they release certain proteins. In natural environments, these proteins neutralize substances harmful to the bacteria. When ingested into a human digestive tract, the same mechanisms are engaged. Although the strong acids found in the stomach kill up to 99 percent of the would-be bacterial colonizers, the 1 percent that do survive are able to “express,” or release, the protective proteins that cause so much upset to their human hosts. The immunologic battle between host and pathogen can be fierce. Most of the time, the immune system wins, containing the infection, but sometimes the bacteria can overcome all defenses, and death can result.

Although most *S. typhimurium*–caused infections in the United States don’t require hospitalization or serious medical intervention, at least in healthy people, they are potentially fatal if untreated in people with weakened immune systems. Deciphering the bacteria’s molecular responses could lead — with new drugs and vaccines — to a means to treat or even neutralize salmonella infections, quickly lessening or eliminating the characteristic nausea, vomiting, intestinal inflammation, and diarrhea that they cause.

As humans work for longer periods in space, they may bring with them preexisting infections. Moreover, despite precautions, foods brought on board could conceivably harbor salmonella bacteria. Depending on severity, a salmonella-induced illness could pose serious dangers. And those dangers could be even worse on a space mission, where astronaut immune systems may already be stressed. Nickerson explains, “Something like food poisoning could put a mission at risk, or in the worst case, threaten crew survival.”

Nickerson plans to send *S. typhimurium* into orbit to see if the results she obtains there are similar to those she obtained on the ground. Her hope is to build a detailed roadmap of how salmonella bacteria sense and respond to microgravity. Once that roadmap is complete, she hopes it will be a guide for developing effective remediation strategies.

How the Body Fights Back

One concern with space travel is the fact that exposure to the microgravity environment apparently causes impairment of the immune system. NASA’s highest priority is to ensure the health and safety of astronauts in space, and consequently, NASA supports many research investigations related to the immune system. NASA investigator Joshua Zimmerberg, with a team of researchers at the NASA/National Institutes of Health Center for Three-Dimensional Tissue Culture, Bethesda, Maryland, is contributing to unraveling the mystery of how the immune system changes in microgravity. The team is looking specifically at the effects on lymph tissue and lymphocytes.

The immune system is complex and composed of many elements, all of which work in concert to protect the body from foreign invaders like bacteria and viruses. Among the components of the immune system are the lymph system, a passive system of lymph fluid, or blood plasma, which provides nutrients obtained from the blood to cells and carries waste away; the thymus; the spleen; bone marrow; white blood cells; antibodies, also known as immunoglobulins; and hormones. Each component has a specific role in the body’s immune response.

The best-known defenders within the body are the white blood cells, which differ from other cells in the body in that they behave more like independent, single-celled organisms that are incapable of reproducing. Lymphocytes are a type of white blood cell. Some lymphocytes, known as B cells, produce specific antibodies for specific germs. When a B cell recognizes a marker on a germ called an antigen, it will clone itself and produce millions of antibodies against that germ. In contrast, T cells, the other type of lymphocyte, must actually

credit: National Institutes of Health

PI Joshua Zimmerberg is studying how microgravity affects the human immune system. In ground-based studies, Zimmerberg exposed human tonsil tissue to antigen markers and then grew that tissue under simulated microgravity in a rotating wall vessel. He then re-exposed the tissue to antigen markers to see if the cells would respond by producing antibodies.

come into contact with cells that contain viruses or bacteria in order to be able to kill them. Both B cells and T cells can be found in the bloodstream, but they tend to concentrate in the lymph tissue.

Zimmerberg and his team conducted experiments that involved growing human lymphoid tissue cells in the NASA-developed rotating wall vessel bioreactor (RWV), which simulates some aspects of microgravity by gently rotating growing cells to maintain them in an environment similar to freefall. The sample cells were isolated from the tonsils of five human donors for use during this experiment. Tonsils are granular tissue similar to lymph nodes that are found at the back of the throat. They work as part of the immune system by sampling and filtering germs that enter the body through the mouth. The results demonstrated that some immune functions became impaired with exposure to the simulated microgravity conditions provided by the RWV.

When the tissues cultured in the RWV were challenged with recall antigens, markers to which the lymphoid tissues had previously been exposed, they did not respond by producing specific antibodies, as they should have. The previous exposure should have caused the lymphoid tissue to recognize those markers and mount an immune response. The tissues grown in the RWV were also challenged with polyclonal antigens, which were descended from more than one group of cells, to try to obtain a general immune response, but unlike cultures grown by traditional, nonrotating methods, the tissues did not respond with increased immunoglobulin production. These results indicate that lymphocytes lose their ability to be activated when cultured in the RWV. However, when the lymphocytes were activated by exposure to antigens prior to being cultured in the RWV, they remained activated during the culture. This shows that the timing of the activation period is critical to the cells' immunogenic capability.

Subsequent studies were conducted on the ISS in order to determine if results obtained from the RWV cultures could be replicated in a true microgravity environment. The RWV creates an environment that mimics some, though not all, aspects of microgravity, and cells cultured in ground studies do not experience other factors associated with spaceflight that may affect immune function. Zimmerberg's flight experiment flew to the ISS on shuttle mission STS-108 in December 2001. The ISS samples were returned to investigators for analysis in April 2002.

On the ISS, the tonsil cell cultures were grown in Teflon bags and challenged with antigens. Preliminary results indicate that differences exist between the flight and ground samples and demonstrate an impaired immune response in the microgravity samples. Further analysis will determine whether these differences are similar to those seen between RWV and ground samples. Future experiments will examine patterns of membrane reorganization and changes in the cytoskeletons of cells cultured in the RWV; these changes could impair the cells' ability to recognize and respond to viruses and bacteria.

Preliminary results suggest that responses in true microgravity are similar to those seen in simulated microgravity. A second experiment to continue gathering information regarding T cell and B cell interactions leading to lymphocyte activation has been scheduled. If the results are indeed similar in both simulated and true microgravity, then it could be much easier to begin identifying the cause of immune impairments, because researchers could rely on the RWV for their experiments instead of having to wait for infrequent spaceflight opportunities. Conducting experiments in the RWV would also allow researchers to replicate their experiments, which is currently difficult due to limitations on payload capacity and time for conducting research aboard the ISS. The study of these immune impairments could have important impact on the future of space travel and on human health on Earth. The human immune response in space is blunted, and thus the potential for pathological diseases associated with reduced immunological capability on long-duration spaceflights, such as a mission to Mars, becomes a significant risk. Understanding why the immune response is adversely affected is a necessary first step in developing countermeasures that can mitigate this risk. On Earth, understanding the mechanisms of impaired immune response has potential applications in the study and treatment of autoimmune diseases and immunodeficiencies, such as AIDS.

OVERVIEW

Combustion and the results of combustion processes affect each of us every day. The majority of the world's electric power production, home heating, and ground and air transportation are made possible by combustion. Despite these benefits, combustion by-products are major contributors to air pollution and global warming. Additionally, unintentional fires claim thousands of lives and cost billions of dollars in property damage each year. Improved control of combustion would be of great benefit to society, yet it is impeded by a lack of fundamental understanding of combustion processes.

The effects of gravitational forces on Earth hamper combustion research. Gravity causes hot, lightweight gases produced during combustion to rise. The movement of the gases generates airflows that produce flames that are often unsteady and nonsymmetrical, such as flames produced by a campfire. This gravity-induced flow makes the flames very difficult to model mathematically. Combustion theories, therefore, are often based on nonbuoyant steady, symmetrical flames, and are difficult to test on real-world combustion processes. Research in microgravity offers unprecedented opportunities for critical measurement of large, steady, slow-moving, symmetric flames, since the forces of gravity and the resulting airflow movements are effectively eliminated.

The data from experiments conducted in microgravity are used to verify combustion theories, validate numerical models, and develop fresh insights into fundamental combustion phenomena, all of which can be applied to Earth-based combustion processes. Research in microgravity has revealed information about thermal and chemical processes that play a role in flame propagation and extinction, for example. These processes, while present on Earth, are difficult to observe because they are often hidden by more dominant reactions attributable to gravity.

Combustion processes provide us with power, enable transportation, and sometimes devastate the environment through fires and pollution. As the world becomes increasingly developed and industrialized, the need for better control and understanding of combustion has become clear.

Program Summary

In fiscal years (FYs) 2001 and 2002, the research program in microgravity combustion science maintained its primary focus of working toward an understanding of fundamental combustion processes and flame structures. At the same time, the program strengthened its applications-based focus to aid NASA in developing solutions for crew health and safety issues. During FY 2001, the microgravity combustion science program funded new and ongoing research projects for 75 principal investigators (PIs) working on 23 flight investigations and 58 ground-based projects. During FY 2002, there were 72 PIs working on 22 flight investigations and 58 ground-based projects. A list of all ongoing combustion science research projects, along with the names of the investigators conducting the research, is provided in Appendix A.

In FY 2001, research projects selected under the 1999 NASA Research Announcement (NRA) in combustion science were awarded funding and research began. In total, 20 investigations, all of them ground-based studies, were initiated. Six more research proposals submitted in response to the 1999 NRA were awarded funding in January 2001 from the Spacecraft Fire Safety (SFS) program. All of the SFS-selected proposals address critical needs in the area of spacecraft fire safety; two of the six were selected for flight-definition work. This suite of research, integrated within NASA's Bioastronautics initiative, focused on generating specific, attainable, applications-based solutions to NASA's fire safety issues for crew members living and working aboard spacecraft.

A workshop to further focus the SFS program was conducted in June 2001. Objectives included the identification of research needed to assess and improve fire protection strategies for the space shuttle, the International Space Station (ISS), and their payloads; the identification of fire safety concerns for prolonged crewed missions in Earth's orbit and beyond; and finally, the anticipation of research needs for future lunar

Researchers working on fire safety issues in space need to be able to predict the behavior of fires in order to better design protective measures for astronauts and equipment.

and Martian habitats. By the end of the workshop, the spacecraft fire safety research roadmap had been updated, dialogue was opened between microgravity combustion researchers and ISS designers and operations personnel, and many research needs were identified. (See *http://www.ncmr.org/events/firesafety* on the World Wide Web [WWW] for more information.)

The SFS program also published the first annual report of its research results in February 2002, titled *Bioastronautics Initiative Spacecraft Fire Safety Research FY01 Annual Report and Research Plan*. Included in the report were interim results from experiments started in FY 2001 on material flammability, fire and smoke detection, and fire suppression. For copies of the report, write to Gary Ruff, NASA Glenn Research Center, M/S 77-5, Cleveland, Ohio 44135.

Overall, the ground-based microgravity combustion science program continues on its path to contribute significantly to the body of knowledge in the combustion science community at large. Activities during FYs 2001 and 2002 have yielded significant findings both in fundamental scientific studies of phenomena and in areas having terrestrial and space-based applications. The combustion program has also addressed NASA's need to solve problems in spacecraft and nonterrestrial habitat fire safety that are key to pursuing long-term space exploration goals. These safety issues are linked to exploring regimes in material flammability phenomena, fire detection, and suppression. The results obtained are crucially important to the scientifically challenging missions that NASA plans to pursue. Current areas of ground-based studies include the development of an apparatus to assess material flammability in microgravity and research to understand the chemical and physical aspects of fire suppression in nonterrestrial environments. By the end of FY 2002, a majority of the 40 ground-based investigations initiated through the 1997 NRA in microgravity combustion science were completed. The 81 investigations supported in FY 2001 (from the 1997 and 1999 NRA grant pools) generated 34 journal articles and 16 papers published in conference proceedings. More than 20 presentations based on this research were delivered at national and international forums, and investigators made contributions to 4 books as a result of their work. In FY 2002, 80 funded investigations generated 37 journal articles, 20 papers published in conference proceedings, 30 presentations, and contributions to 9 books.

FY 2002 saw a new practice initiated within the Physical Sciences Research (PSR) Division. Instead of releasing biennial NRAs for each individual discipline, PSR will release every year a suite of NRAs covering all the disciplines. Within a suite, individual NRAs for each discipline will be on a staggered schedule. FY 2002's NRA suite was announced on December 21, 2001.

credit: NASA

Paul Ronney is studying Radiative Enhancement Effects on Flame Spread to better understand how flames spread over thick materials in low gravity. These data will enable scientists to improve spacecraft fire safety, as both flames and extinguishing agents function differently in low gravity than they do in normal gravity. Shown are the differences in flame spread over thick solid fuel in an oxygen–carbon dioxide atmosphere in microgravity (top) and in Earth's gravity (bottom).

Ninety combustion science proposals were received by March 22, 2002, and 22 proposals were selected for funding in September 2002. The awards will be funded in FY 2004. Topics solicited by the combustion science NRA included gaseous flames; droplets, sprays, particles, and dust clouds; surface combustion and fire safety; chemical vapor deposition and vapor infiltration processing; supercritical water oxidation; *in-situ* resource utilization and chemical processing; and thermal plasmas. A complete list of funded projects may be found on the WWW at *http://research.hq.nasa.gov/code_u/code_u.cfm*.

Flight Experiments

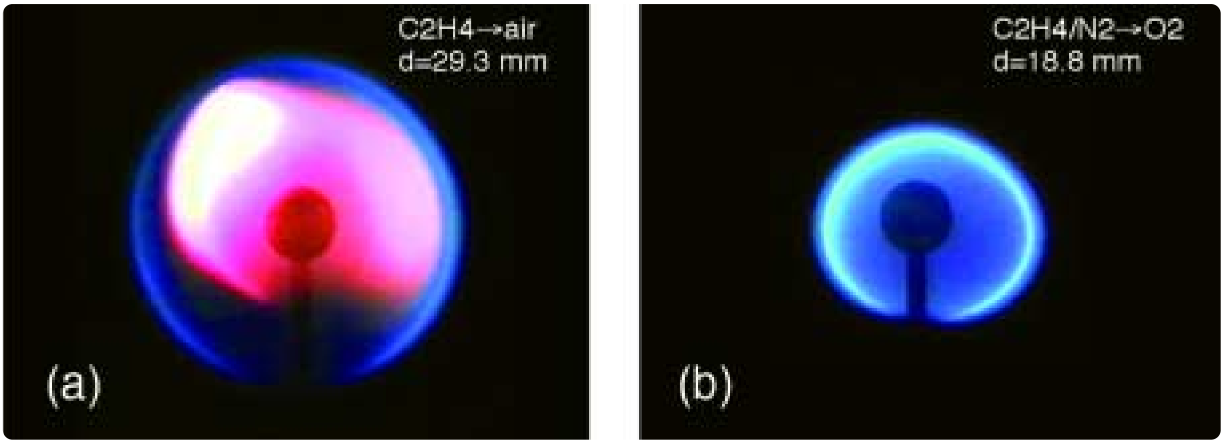
Experiments in space further refine and validate combustion theories and extend the understanding of combustion phenomena that are obscured by gravity. The longer periods — weeks or months — in microgravity and the generally higher-quality microgravity conditions that can be obtained in orbit on the space shuttles and the ISS are invaluable to combustion researchers, since some phenomena, such as slow-burning smoldering reactions, are difficult to observe over the seconds-long episodes of microgravity conditions obtainable in ground-based facilities.

In FYs 2001 and 2002, investigators continued preparations for 20 flight research projects that require the microgravity conditions available in orbit. Two investigations, the Spread Across Liquid (SAL) experiment and the Microgravity Smoldering Combustion Reflight Experiment (MSCRE), completed their final flights, one on a sounding rocket, and the other on a space shuttle flight. They are now in the data analysis phase, and final reports of results will be published within a year. Two more investigations have near-term flight opportunities aboard the space shuttle. The remaining 18 investigations continued along the research formulation and hardware implementation paths toward flight opportunities aboard the ISS.

The SAL experiment made its sixth and final flight aboard a Black-Brandt sounding rocket at the White Sands Test Range in 2001. The investigation provided unique data to PI Howard Ross, of Glenn Research Center, about the phenomenon of flame spread across liquid pools under varying conditions. The near absence of gravity during this experiment allowed detailed characterization of the liquid and gaseous flow phenomena that control the flame spread, and the factors that control the flame spread instability were determined and used to validate a numerical flame spread model.

MSCRE, led by PI Carlos Fernandez-Pello, of the University of California, Berkeley, completed its flight data collection aboard two space shuttle missions, STS-105 (launched August 10) and STS-108 (launched December 5), in 2001. Each flight provided an opportunity to conduct two independent smoldering combustion tests. MSCRE is a study of smoldering combustion in porous materials. Smoldering is a flameless form of combustion that can often lead to house fires. By conducting the experiment in microgravity, researchers were able to identify the limiting conditions for smoldering combustion to spread and ignite. These results suggest that smoldering fires can exist under microgravity conditions and are therefore a credible fire risk aboard spacecraft.

Throughout FYs 2001 and 2002, plans and mission hardware preparations for several flight missions were under way. The original Combustion Module system (CM-1), which flew aboard the first Microgravity Science Laboratory (MSL–1) mission on STS-83 (launched April 4, 1997) and STS-94 (launched July 1, 1997), has been refurbished as CM-2 and was integrated with the SPACEHAB carrier for a flight aboard STS-107 in the winter of 2003. The CM-2 system will support three investigations: Laminar Soot Processes (LSP), Structure of Flame Balls at Low Lewis-Number (SOFBALL), and Water Mist (MIST). PIs Gerald Faeth, of the University of Michigan, Ann Arbor, and Paul Ronney, of the University of Southern California, Los Angeles, will conclude their data collection for LSP and SOFBALL, respectively, with this flight. LSP studies the mechanisms



credit: NASA

Soot and nitrous oxides are primary combustion by-products that contribute significantly to air pollution, a growing environmental concern. Richard Axelbaum is studying flames in microgravity to better understand their mechanisms. He has found that removing the nitrogen from the oxidizer (air) and adding it to the fuel produces less soot and nitrous oxides than the usual flames with fuel reacting with air. This effect is shown in image (a) which shows a fuel air flame (white and pink indicate soot) and image (b) which shows a flame of nitrogen and fuel reacting with oxygen. The flames are otherwise identical with the soot being dramatically reduced by the movement of the nitrogen from the air to the fuel.

of soot production to determine ways of controlling it, as soot is a major contributor to pollution and an important factor in fire suppression. SOFBALL explores "flame balls": tiny, stable, spherically symmetric flames that occur only in microgravity. These flame balls may hold answers to some fundamental questions about fires. PI Thomas McKinnon, of the Colorado School of Mines, Golden, will be conducting MIST for the first time on STS-107. MIST reexamines the old practice of using water to fight fires, updating the technique by using a fine mist delivery system. Microgravity conditions will help researchers to determine optimal water concentration and droplet size for this new method of fire suppression. MIST is also proposed for flight aboard the ISS, where it will be accommodated in the Combustion Integrated Rack (CIR).

The transition from conducting combustion experiments aboard sounding rockets and the space shuttle toward full utilization of the research capability of the ISS continued in FYs 2001 and 2002. Two research facilities, the CIR and the Microgravity Science Glovebox (MSG), are still being prepared for upcoming flights. More details about these facilities can be found in the International Space Station section of this report.

In conjunction with the development of the CIR portion of the Fluids and Combustion Facility, the combustion science program is working to prepare a number of experiments and associated hardware for upcoming research flights to the space station. Detailed engineering of a Multi-User Droplet Combustion Apparatus (MDCA) and an apparatus known as FEANICS (Flow Enclosure Accommodating Novel Investigations in Combustion of Solids) is under way. Each apparatus will enable multiple experiments to be conducted within the CIR.

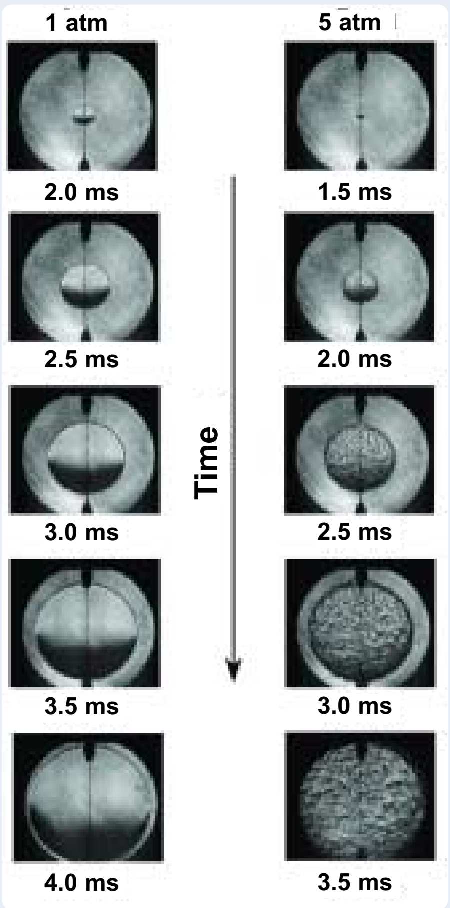
The MDCA, which enables droplet combustion research, will be the first research payload in the CIR. Research on the combustion of fuel droplets is important because there are many kinds of practical devices that deliver fuel to combustors in droplet form, including diesel engines and industrial turbine engines, and optimizing combustion in these devices could improve fuel efficiency and reduce pollution, among other things. Studies in microgravity allow researchers to investigate spherical fuel droplets, which are much easier to model mathematically than gravitationally influenced, tear-shaped droplets. Four investigations have been identified for an initial set of research projects utilizing the combined capabilities of the CIR and MDCA systems: the Droplet Combustion Experiment-2; the Bi-Component Droplet Combustion Experiment; the Sooting Effects in Droplet Combustion Investigation; and the Dynamic Droplet Combustion Experiment. The MDCA will also remain available for use with new droplet investigations that may be proposed in the future. Multiuser hardware such as the MDCA allows more effective resource utilization of the ISS and the CIR.

Subsequent to the completion of MDCA and its investigations, the research pace for the CIR will pick up, and six investigations in solid fuels research will be conducted in the FEANICS apparatus. This research has direct, tangible application to the Spacecraft Fire Safety initiative in that it contributes to understanding fire ignition, the persistence of combustion flames in real materials, and fire extinction in microgravity. The first group of FEANICS investigations are Forced Ignition and Spread Test; Radiative Enhancement Effects on Flame Spread (REEFS); Smolder, Transition, and Flaming in Microgravity; Analysis of Thermal and Hydrodynamic Instabilities in Near-Limit Atmosphere; Transition From Ignition to Flame Growth Under External Radiation in Three Dimensions; and Solid Inflammability Boundary at Low Speed. Results from these experiments will define characteristic events such as ignition susceptibility, transition from smolder to full flames, radiative effects of flames to self-feed an existing fire, three-dimensional combustion effects of ignition, and propagation of flames in a spacecraft environment.

Following the completion of the FEANICS investigations, the combustion program will expand its research portfolio into gaseous combustions, addressing flame design, clean flames, and spherical flames. Presently, 14 combustion investigations have been selected to be conducted within the CIR by 2011, with the possibility of four or more additional experiments sponsored and developed by commercial and international partners.

Three flight investigations, REEFS, Flame Design, and Clean Flames, passed their science concept reviews during FY 2002, thus completing the flight-definition phase and coming one step closer to being conducted aboard the ISS. Led by PI Paul Ronney, REEFS studies flame spread over flat, solid fuel beds as a means of understanding more complex flames, such as those found in fires inside enclosures like spacecraft or buildings. This experiment is a continuation of previous investigations geared toward studying the atmospheres and flow environments likely to be present in fires that might occur in microgravity.

Flame Design, led by PI Richard Axelbaum, of Washington University, St. Louis, Missouri, studies simple flames in microgravity to learn how to reduce soot and nitrous oxides, the main products of combustion that also contribute to air pollution. A normal combustion reaction consists of fuel mixed with air (nitrogen and oxygen). Researchers have found that soot and nitrous oxides can be reduced if the air is first separated into nitrogen and oxygen, then nitrogen is mixed with fuel, and oxygen is added separately. Reducing the production



credit: NASA

Combustion theory got an update when flames in a high-pressure combustion reaction revealed their "wrinkles." At 1 atm, the flame surface remained smooth as it propagated outward, but at even slightly increased pressures (5 atm), the flame developed a bumpy appearance. Modeling of flames in internal combustion engines will benefit from this new revelation.

of soot and nitrous oxides during combustion will be cheaper for industry than scrubbing out these pollutants afterwards. Combustion in microgravity produces one-dimensional, strain free flames, allowing direct study of flames using mixtures of air and fuel or fuel and nitrogen with oxygen added separately. These studies wouldn't be possible in normal gravity due to the loss of symmetry and to buoyancy-induced strain in the flames. The results will provide valuable fundamental insight into the mechanisms of combustion.

Clean Flames, led by PI Robert Cheng, of Lawrence Berkeley National Laboratory, Berkeley, California, aims to contribute to clean energy technology by studying lean premixed combustion, the least polluting way to burn gaseous hydrocarbon fuels like natural gas. The experiment seeks to take advantage of nonbuoyant flames produced in microgravity to study the interaction of flame turbulence with the combustor chamber. The results obtained will enable the design of more compact burners for small-scale heating needs (e.g., water heaters and furnaces).

Four combustion science investigations are slated to be conducted within the MSG on the ISS by 2006. Fiber-Supported Droplet Combustion will investigate fundamental combustion science issues in liquid fuels combustion, and Candle Flames will address solid and liquid fuel transitions. The other two experiments are applications-based. The Smoke Point in Coflow Experiment studies soot generation in gaseous flames; Smoke investigates spacecraft smoke detector performance in low-gravity conditions. The Smoke experiment directly supports knowledge regarding smoke detector performance on the ISS and space shuttles. Its results will provide insight into performance differences between Earth-based and on-orbit fire detection. Smoke is funded within the new SFS initiative.

Highlights

Combustion Under Pressure: A New Understanding Revealed

Automobiles, jet aircraft, and even rockets all have one thing in common: they are powered by internal combustion engines operated under high pressures, in the range of 5–100 atmospheres (atm). (By comparison, normal atmospheric pressure at sea level is only 1 atm.) Combustion under high pressures is thermodynamically more efficient, as well as more fuel efficient, leading to reduced emissions of pollutants and less production of carbon dioxide, a major contributor to global warming. However, combustion processes typically found within internal combustion engines are usually studied at 1 atm, where flames are relatively easy to control and observe. When pressure increases, as Principal Investigator Chung Law, of Princeton University, Princeton, New Jersey, explains, so does the difficulty in conducting well-controlled and useful experiments.

According to Law, extrapolations from experiments at 1 atm are highly unlikely to yield quality data for higher-pressure systems. The basis for extrapolation is just too limited for any reliable prediction of what could be happening with a flame at 50 or even 100 times the normal pressure. There is no substitute for conducting experiments under high-pressure conditions. But it is not easy to observe such experiments. High-pressure experiments have been frequently done in what are called "bombs"— totally enclosed, windowless systems. Within these systems, researchers can measure the pressure increase caused by combustion. From that, they can speculate about what happened inside the bomb based on some assumed combustion processes. While some useful data are obtained from these experiments, the lack of visual observation severely limits the value of the results.

To overcome this limitation, scientists would have to be able to observe the experiments in progress. But combustion chambers that allow the flame to be visually observable without distortion through special optical windows cannot tolerate the buildup of pressure and temperature caused by the combustion products. Challenged by the need to visually study the effects of pressure on flame propagation, Law and his research associates, Stephen Tse and Delin Zhu, devised an apparatus that would allow them to obtain images of the flame as it propagates, while maintaining the chamber pressure constant at its initial value, which can be as high as 60 atm.

The apparatus comprises two chambers, one inside the other, with aligned optical windows. A sleeve connecting the two chambers can be opened and closed. After evacuating both chambers, the sleeve is closed, and researchers pump the combustible gas under study into the inside chamber and an inert gas into the outer chamber. After the pressures inside the two chambers are equalized, the sleeve is opened. The inert gas and the combustible gas come into contact, but with very little mixing. A centrally located spark then immediately ignites the combustible gas. The resulting spherical flame propagates outward until it meets the boundary of the inert gas, where it is extinguished. Since the volume of the inner chamber is much smaller than that of the outer chamber, there is negligible pressure buildup within both chambers during combustion. The entire process, from flame ignition to propagation and extinction, can be recorded on high-speed video.

While observing the resulting images, Law was surprised to see that the flame surface looked different than expected at high pressures. At 1 atm, the flame surface remains smooth. However, at even a moderately high pressure of 5 atm, wrinkles develop over the flame surface. What surprised Law about his experimental observations was the strong propensity and prevalence of wrinkled flames at higher pressures. In hindsight, Law explains, this is reasonable, because chemical reactions progress faster at higher pressures, yielding faster-burning flames that are more unstable.

The recognition that flames wrinkle at high pressures fundamentally alters the understanding of the burning processes within internal combustion engines. The rate of fuel consumption increases with the flame's increasing area. Since wrinkles dramatically increase the flame's surface area, the flame actually burns much faster than previously realized. Without seeing the flame, an investigator could easily be misled about the meaning of the fast rate of fuel consumption.

Law has conducted a large portion of his research at Earth's gravity, where buoyancy can have a significant influence on the propagation of weak flames, such as those associated with fuel-lean burning. Moreover, the effects of gravity are aggravated under high pressures; gas is even more buoyant because density is proportional to pressure: the higher the pressure, the greater the density differences between the hot gases and the cooler gases surrounding the flame.

In NASA's 2.2-Second Drop Tower at Glenn Research Center in Cleveland, Ohio, Law is able to conduct his experiments on high-pressure burning without the disturbing influence of gravity. However, experiments with really slow-burning, weakly combustible mixtures, which are of relevance to the study of flame extinction phenomena, require much longer microgravity times in order to observe the burning process in its entirety. Eventually, these experiments may need to be conducted on the International Space Station, which provides longer-term access to microgravity conditions.

Fire Safety Gets New Emphasis From Space Research

As crews from the United States and its partners assemble the ISS, the casual observer might miss an underlying emphasis on safety that sometimes makes the work appear effortless. Safety has always been NASA's primary concern. Space travel, as with all forms of exploration, is vulnerable to a variety of hazards. NASA's determination to maintain a safe environment takes precedence over anything else.

Supporting research for in-orbit fire prevention is one way NASA meets its commitments to reducing hazards for ground and flight crews. Fire is a violent chemical reaction, combining oxygen with other materials to produce smoke, heat, and deadly chemicals. Fire safety research is furthering the understanding of the basic science behind combustion processes, enabling scientists to better understand and define the fire problems faced by the space program. Scientists are using this knowledge to develop advanced, fire-safe materials and to tackle new designs to mitigate or eliminate these problems.

The first step in fire safety is to select materials that don't burn easily in low gravity. The Materials Combustion Research Facility at Marshall Space Flight Center in Huntsville, Alabama, tests materials against a range of industry and NASA standards. But because it is

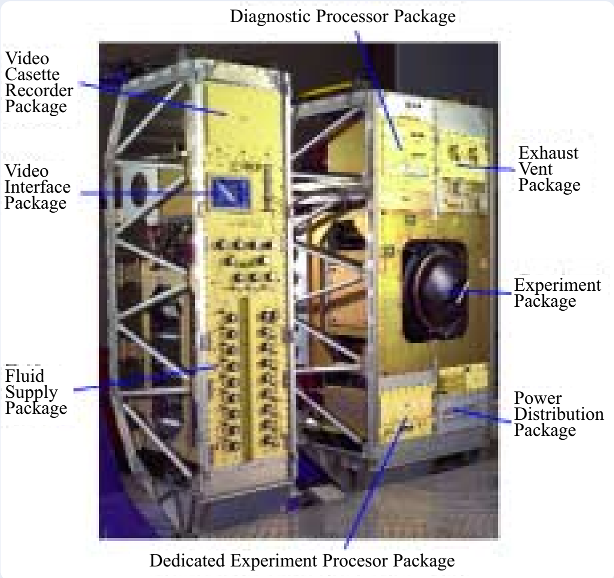
credit: U. S. Navy

A U.S. Navy firefighting instructor leads firefighters in battling an oil-fed fire during a military training session. Both NASA and the military put great emphasis on being prepared for such fire hazards, either on Earth or in space.

impossible to eliminate all combustible materials from inside a spacecraft, steps also must be taken to ensure that a fire can be detected and extinguished while protecting the crew and equipment. ISS fire detectors look for smoke particles sparkling in a laser beam. To fight fires, the crew is supplied with portable fire extinguishers that dispense carbon dioxide and portable breathing apparatus. To add to these prophylactic measures, NASA is looking for a nontoxic suppressant that does not foul the life support system or require extensive cleanup. Research is also needed in computational flow dynamics to understand where a fire goes inside a compartment in microgravity, how fire-fighting agents are transported, and how the agents interact with air and fuel.

Attention is now focused on understanding the physics and chemistry of putting out fires for applications on Earth as well as in orbit. The space shuttle's Research-1 mission (STS-107, scheduled for launch in early 2003) will take the first step in this new direction with the Water Mist (MIST) experiment. Frank Schowengerdt, director of the Center for Commercial Applications of Combustion in Space (CCACS), a NASA commercial space center located at the Colorado School of Mines, Golden, explains that his group is trying to understand the fundamentals. They want to understand how fire extinction depends on water particle size, water concentration, droplet distribution, and radiation from the fire. The CCACS is part of the Office of Biological and Physical Research's Space Product Development Division.

When the center was first set up, Thomas McKinnon, a CCACS chemical engineer, said he had always puzzled over just exactly how water puts out a fire. Five years ago, he wasn't taken seriously. However, McKinnon — now the principal investigator for MIST — persisted and developed more analytical experiments and models, believing that one cannot make significant advances without studying fundamental science. A scientist might get lucky in a trial-and-error approach, but it could be very expensive. Schowengerdt and his colleagues want to know the absolute minimum amount of water required to put a fire out so that cleanup is easier,



credit: NASA

The Combustion Module-2 (CM-2) is scheduled to fly on STS-107 in January 2003. Originally flown on STS-83 and STS-94 in 1997 as CM-1, it was later refurbished and renamed CM-2. Integrated into SPACEHAB for STS-107's upcoming flight, CM-2 will support three combustion investigations: Laminar Soot Processes, Structure of Flame Balls at Low Lewis-Number, and Water Mist.

postfire damage is reduced, and flight crews are exposed to fewer toxic by-products.

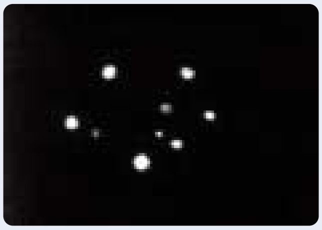
Exact details of the physics of extinguishing fires with water mist are difficult to determine, largely because the reactions happen so quickly in Earth's gravity. Droplets settle, so a controlled, uniform cloud of them can't be maintained to see what happens as the flame interacts with them. In microgravity, the droplets remain suspended, so researchers can better see what is taking place. The CCACS has conducted extensive tests on the ground, including some at a drop tower facility at the School of Mines, but experiments in orbit have more time to progress and experience less turbulence, so now it is time to move upward. Schowengerdt and his group are looking at a lot of different things that can be done far better aboard spacecraft.

The CCACS's work is getting attention from potential terrestrial users, including the Federal Aviation Administration, the U.S. Navy, computer system operators, and even restaurants. NASA also is interested in MIST as part of a larger investigation into fire safety aboard spacecraft.

Floating Flame Balls

Paul Ronney didn't set out to look for flame balls: they came as a complete surprise. It happened in 1984 when Ronney, a combustion researcher, was using the 2.2 Second Drop Tower at Glenn Research Center (GRC) in Cleveland, Ohio. He pressed a button and sent a can of burning hydrogen falling down a 24.1-meter (79-foot) shaft. For 2.2 seconds it plummeted in a freefall, with a 16 mm movie camera recording the action. Ronney knew that flames did strange things in low gravity, which is why he was doing the experiment, but he wasn't prepared for what he saw in the film room later. The flames had broken apart into tiny balls that moved around like UFOs. No one had ever seen anything like it, but the flame balls were real, as proved in later experiments.

Flame balls are the weakest known flames. Compared to a birthday candle's 50 to 100 watts, a flame ball produces only 1 to 2 watts of thermal power. They burn using very little fuel. It's almost as if a hydrogen-burning flame's last line of defense as it approaches extinction is to draw itself into a simple ball. Ronney, who is now a mechanical engineering professor at the University of Southern California, Los Angeles, believes that flame balls will help him and others crack the unsolved mysteries of burning. Despite the fact that combustion powers our automobiles, generates our electricity, and heats our homes, there's much about it we don't understand.



credit: NASA

The Structure of Flame Balls at Low Lewis-Number experiment investigates small flame balls that can ignite in the lean fuel-air mixture inside spacecraft. While weak (1 watt versus the 50 watts put out by a birthday candle), they can last for several minutes and are very difficult to detect. The flame balls in the above picture are visible only because they were captured in the dark by cameras with image intensifiers. In the normal light inside a spacecraft, they would be invisible to both astronauts and fire detectors.

Flames are extremely complicated. In an ordinary candle flame, for example, thousands of chemical reactions take place. Hydrocarbon molecules from the wick are vaporized and cracked apart by heat. They combine with oxygen to produce light, heat, carbon dioxide, and water. Some of the hydrocarbon fragments eventually form soot. Soot particles can themselves burn or simply drift away as smoke. The familiar teardrop shape of the flame is an effect caused by gravity. Buoyancy causes hot air to rise, and fresh cool air is drawn in behind it. These processes are what make the flame shoot up and flicker.

Flame balls, on the other hand, are simple. The balls form in low gravity, where buoyancy has little effect. Oxygen and fuel combine in a narrow zone at the surface of the ball. Once ignited and stabilized, the flame balls maintain a constant size. Unlike ordinary flames, which expand greedily when they need more fuel, flame balls let the oxygen and fuel come to them. Finally, the fact that flame balls are spherical reduces their dimension to one: the radius of the flame itself. Flame balls are to combustion scientists what fruit flies are to geneticists; they provide a simple model for testing hypotheses and checking computer models.

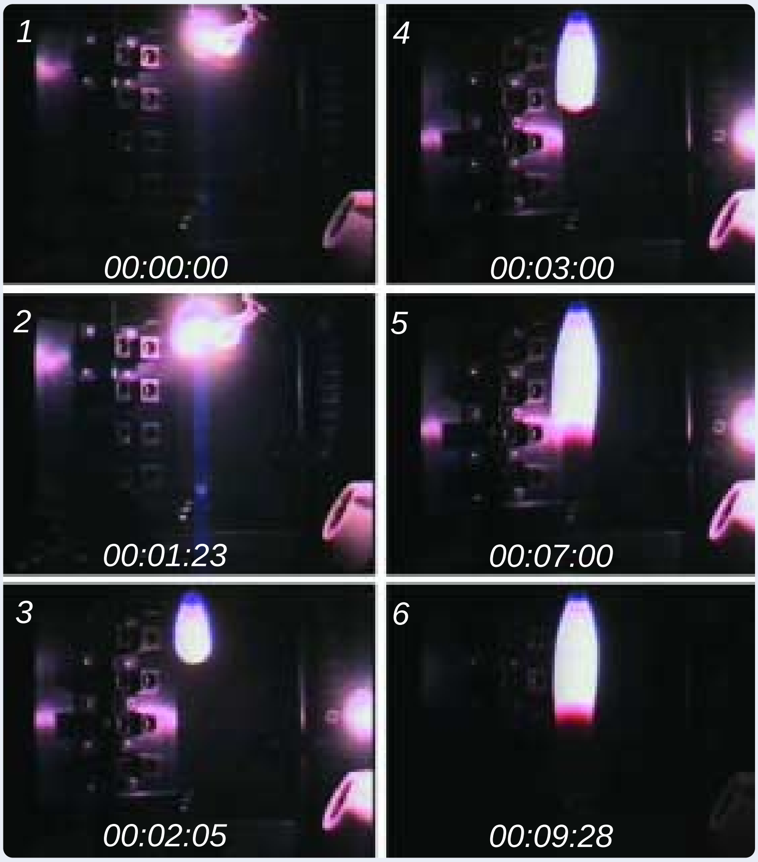
One of many mysteries about fire is why weak flames go out before their fuel is totally exhausted. It puzzles physicists and vexes automakers who want to build clean, efficient "lean-burning" engines that run on fuel-air mixtures with low fuel concentrations — much like a flame ball. Ronney believes that studying one system (flame balls) will help us with the other (cars).

Here on Earth, researchers can't study flame balls for long periods. A typical plunge down a drop tower lasts only seconds. So Ronney is working with NASA scientist Karen Weiland and others at GRC to design the Structure of Flame Balls at Low Lewis-Number (SOFBALL) experiment for flight aboard the space shuttle. The apparatus for the experiment consists of a sealed chamber where flame balls can burn for a long time during a space shuttle mission.

When SOFBALL orbited Earth for the first time in April 1997 aboard STS-83, it produced some surprises. Computer models had predicted the flame balls would be small and either extinguish or drift into the chamber walls in a few minutes. Instead, they were two to three times larger than predicted and burned for over eight minutes until the experimental system automatically extinguished them. Furthermore, although the flames were large, they were the weakest ever seen, emitting little more than 1 watt of thermal power.

To further explore these unexpected results the experiment was upgraded, renamed SOFBALL-2, and scheduled for launch onboard STS-107 in early 2003. During the mission, flame balls will be allowed to burn for 2 to 81 minutes. Instruments will monitor their temperature, brightness, heat loss, and the composition of their gaseous by-products. Because flame balls are so sensitive to motion, the space shuttle will be allowed to drift during the experiments instead of maintaining position using its reaction control thrusters.

Because this research is so fundamental, it touches on many areas related to combustion, including lean-burning engines for cars and airplanes, explosion hazards in mine shafts and chemical plants, emissions from cars and coal-burning plants, and arson investigations. The applications of the knowledge that may result from SOFBALL are many.



credit: NASA

Originally flown on STS-83 and STS-94 in April and July 1997, respectively, Laminar Soot Processes (LSP) studies the fundamental mechanisms of soot production, one of the main by-products of combustion. A better understanding of soot processes in flames will help scientists develop better fire safety methods for spacecraft. This image shows a laminar jet diffusion flame, created by flowing fuel-like propane through a nozzle and igniting it. LSP-2 is scheduled to fly aboard STS-107 in January 2003.

OVERVIEW

Evidence of gravity's sway over the movement of fluids here on Earth is everywhere. Outside, gravity guides the flow of rainwater into streams and rivers and the cascades of water into fountains. It also shakes seemingly solid ground into rippling waves of soil during an earthquake. At home, it causes bubbles of carbon dioxide to float to the top of a glass of root beer and a pot of water to go into a rolling boil when the bottom surface gets hot enough. In industry, gravity affects the mixing of molten materials, as denser liquids naturally drift to the bottom of the mixture. In fact, gravity has such a strong influence over fluids that it can mask evidence of other forces affecting fluid behavior.

Scientists in the microgravity fluid physics program conduct studies under conditions that minimize the effects of gravity so they can observe the effects of other phenomena, such as surface tension and capillary flow. Through their work, these scientists are striving to improve the ability to predict and control the behavior of fluids, including gases, liquids, plasmas (gases that are capable of conducting electric currents because they contain free ions and electrons), and in some circumstances, solids.

Fluid physics research in the Physical Sciences Research Division comprises five main areas: complex fluids, interfacial phenomena, dynamics and instabilities, biological fluid physics, and multiphase flows and phase changes.

Gravity guides the cascades of water into fountains.

Experiments in complex fluids involve gases or liquids that contain particles of other substances dispersed within them. One type of complex fluid is a colloid, which is a system of fine particles suspended in a fluid. Orange juice and paint are examples of colloids. Another complex

Orange juice is a household example of a colloid, a system of fine particles suspended in a fluid. Fluid physicists can study other colloids to observe the formation of crystals from colloidal particles.

fluid is a magnetorheological fluid, a colloid in which the viscosity, or resistance to flow, of the fluid can be varied by applying an external magnetic field. Foam, another complex fluid, exhibits features of solids, liquids, and vapors, although it is not classified as any of these.

Research on interfacial phenomena focuses on how an interface, like the boundary between a gas and a liquid, acquires and maintains its shape. Interface dynamics relate to the interaction of surfaces in response to heating, cooling, and chemical influences. Better understanding of these phenomena will help humans learn more about how duck feathers and waterproof tents repel water, how water spontaneously displaces air in the gaps of a sponge, and other interfacial phenomena.

The area of dynamics and instability includes research in drop dynamics, capillarity, and magneto/electrohydrodynamics. Drop dynamics deal with the behavior of liquid drops and gas bubbles under the influence of external forces and chemical effects. Capillarity refers to effects that depend on surface tension, such as the shape a liquid takes within a container or what causes a drop to take a spherical shape in microgravity. Research in magneto/electrohydrodynamics involves the study of the effects of magnetic and electric fields on fluid flows.

The biological fluid physics subdiscipline includes the flow of fluids and the transport of chemicals in biological systems and processes. The flow of blood in the cardiovascular system, the flow of air in the liquid-lined capillaries of the lungs, and the stretching of DNA in an evaporating droplet of liquid are a few examples.

Research on multiphase flows and phase changes, such as the transition from a liquid to a gas, focuses on complex problems of fluid flow in varying conditions. Scientists are seeking to add to their currently limited knowledge of how gravity-dependent processes, such as boiling and steam condensation, occur in microgravity. They are also studying the diffusion of energy and matter through liquids and gases. A more thorough understanding of these phenomena may lead to improvements in many applications, such as air conditioning and refrigeration.

Program Summary

The research that the microgravity fluid physics program sponsors supports NASA's overarching goals. In addition to contributing to fundamental knowledge of fluid phenomena, the results of fluid physics investigations conducted in orbit should yield beneficial applications for long-duration missions, exploration of other planets, and the enhancement of life on Earth. In fiscal year (FY) 2001, the program funded a total of 114 principal investigators. Of these, 97 were working on ground-based research projects and 17 were working on flight projects. In FY 2002, the program funded 122 principal investigators, including 26 who are working on new ground-based research projects. The new investigations were chosen in November 2001 from among 209 proposals submitted in response to a NASA Research Announcement (NRA) in microgravity fluid physics released February 2001. For a list of selectees, visit the World Wide Web at *http://spaceresearch.nasa.gov/general_info/OBPR-01-229_lite.html*. In addition, a list of all ongoing fluid physics research projects, along with the names of the investigators conducting the research, is provided in Appendix A.

Researchers learned about new funding opportunities through NASA and new directions and advances in microgravity fluid physics research when they gathered for the Sixth Microgravity Fluid Physics and Transport Phenomena Conference, held August 14–16, 2002, in Cleveland, Ohio. At the conference, which is held every two years, Eugene Trinh, the director of the Physical Sciences Research Division, discussed how the microgravity environment of orbit presents opportunities for unique and exciting research. He specified that such opportunities allow investigators to directly participate in developing the enabling technologies for space exploration and to exploit the unique experimental environment of space to unravel outstanding fundamental scientific mysteries. He explained that because convection and hydrostatic pressure are minimized in this environment, it is especially conducive for research involving classical fluids and transport processes, fluid-phase thermophysical properties, surface and interfacial phenomena, morphological stability and pattern formation, bio-fluids statics and dynamics, and multiphase systems and engineering. Because sedimentation is also greatly reduced in microgravity, it is conducive to research involving multiphase fluid physics, colloid dynamics, self-assembly and mesoscale structures, container-free experimentation, and spray and dust cloud dynamics. Current and potential researchers also learned about the schedule for the latest NRA in microgravity fluid physics. It was released in September 2002, with proposals due in December 2002 and selections to be made in 2003. Attendees also heard about the latest advances in research in their discipline, which were shared by current principal investigators (PIs).

Credit: City College of New York / CUNY

Acrivos Awarded President's National Medal of Science

Principal Investigator Andreas Acrivos, of City College of the City University of New York, New York City, was recently awarded the President's National Medal of Science for his lifelong study of fluid dynamics. The medal, awarded by U.S. presidents to nominees reviewed by the National Science Board, is the nation's highest honor given for lifetime achievement in scientific research.

Acrivos was recognized for his work in helping to establish the field of suspension mechanics (the mechanics of substances suspended in but not dissolved in a fluid) and for his contributions to modern theories of fluid mechanics and convective heat and mass transfer. He is widely recognized as being a pioneer in his field.

Nearly 70 fluid physicists from North America, Europe, and Asia (including several NASA PIs) participated in the Microgravity Transport Processes in Fluid, Thermal, Biological, and Materials Sciences II Conference held in Banff, Alberta, Canada, in October 2001. The main objective of the conference, which was sponsored by NASA and the National Science Foundation, was to exchange technical information and ideas among scientists and engineers working in microgravity fluid, thermal, biological, and materials sciences. The conference addressed the growing interdisciplinary aspects of microgravity research and technology development and provided a forum for exploring opportunities for collaborative research activities. Attendees heard keynote addresses from fluid physics PIs Gary Leal and Andrea Prosperetti and presentations from several PIs and other scientists in the areas of interfacial phenomena; two-phase flows of drops, bubbles, and particles; boiling phenomena; bio-transport processes; and space systems fluid and thermal management. They also heard presentations on materials processing, crystal growth, protein crystal growth, and electrostatic and electromagnetic phenomena. Fluid physics PI Satwindar Sadhal, of the University of Southern California, Los Angeles, chaired the conference. The next Microgravity Transport Processes Conference will be held September 14–19, 2003, in Davos, Switzerland.

Several notable papers describing the work of fluid physics PIs were published in prestigious journals in FYs 2001 and 2002, including *Science* and *Physical Review Letters*. Of particular note were “Real-Space Imaging of Nucleation and Growth in Colloidal Crystallization,” by U. Gasser, Eric R. Weeks, Andrew Schofield, P. N. Pusey, and D. A. Weitz, in *Science* 292 (April 13, 2001), 258–62; “Droplet Growth by Coalescence in Binary Fluid Mixtures,” by Brian E. Burkhart, Prasad V. Gopalkrishnan, Steven D. Hudson, Alex M. Jamieson, Michael A. Rother, and Robert H. Davis, in *Physical Review Letters 87* (August 27, 2001) 927; and “Nonlinear Compressional Pulses in a 2D Crystallized Dusty Plasma,” by V. Nosenko, S. Nunomura, and J. Goree, in *Physical Review Letters 88* (May 27, 2002).

Flight Experiments

Several notable milestones were achieved with flight experiments in the microgravity fluid physics program in FYs 2001 and 2002. During this time, the first fluids experiment on the International Space Station (ISS) was flown, an experiment was conducted on a space shuttle mission, and several other experiments made significant advances toward being ready for flight aboard one of the two platforms. Making these flights and advances possible were new hardware units designed for better physical or remote access with the capability for later reuse by related experiments.

The first microgravity fluid physics experiment to fly on the ISS was Physics of Colloids in Space (PCS). The experiment was carried to the station on STS-100 in April 2001, installed in the EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Rack 2 (see page 73 for more information on EXPRESS) once onboard the station, and run for 2,400 hours between early June 2001 and February 2002. Conceived by PI David Weitz, of Harvard University, and Co-Investigator (Co-I) Peter Pusey, of the University of Edinburgh, PCS involves observing the formation of crystals and other structures from colloidal particles (particles suspended in a fluid). In microgravity, these delicate structures can form without interference from convective flow or sedimentation.

For PCS, eight samples were selected from three types of colloids: binary colloids, which contain particles of two different sizes and may help explain the behavior of alloys; colloid and polymer mixtures in which the polymer makes the colloid particles slightly attractive as they form gels and crystals; and fractal colloids, which form gels with highly disordered networks, like the network that holds Jell-O™ together. These samples were used to study fundamental questions regarding the physics of colloids, colloid engineering (using colloids as precursors for building new materials), and the properties of new materials and their precursors. The PCS apparatus, a versatile and sophisticated digital imaging and light scattering instrument, allows for the change-out of samples once back on Earth with no need for realignment of its precision diagnostics.

With the help of this hardware, more than 80 percent of the scientific goals for the experiment were achieved. Potential payoffs include improvements in the properties of paints, ceramics, and food and drug delivery products, and possibly the development of photonic band-gap materials, an entirely new class of materials that can passively affect the properties of light passing through them. Due to its success and to the versatility of the instrument itself, the PCS hardware is being refurbished for use by a second investigator and will refly as PCS+ in 2003. In addition, the procurement and assembly of a whole new test section has been initiated, enabling PCS-3 to be conducted in 2004 on the heels of PCS+, with a reduction in launch mass. Further in the future, such swap-outs of hardware with completely new colloid experiments could be continued beyond PCS-3.

PCS-2, a related future flight experiment also conducted by Weitz and Pusey, will be inserted and run in the new Light Microscopy Module (LMM), a microscope adapted for conducting in-orbit colloid and fluid physics experiments. The LMM was designed by a team in the microgravity fluid physics program for use with the Fluids Integrated Rack (FIR), which will be the fluid physics facility in the Destiny laboratory of the ISS. (For more information about the LMM and the FIR, see page 74.) Also slated to use the LMM are the Constrained Vapor Bubble (CVB) experiment, led by Peter Wayner, of Rensselaer Polytechnic Institute; the Physics of Hard Spheres Experiment-2, led by Paul Chaikin, of Princeton University; and the Low Volume Fraction Colloidal Assembly experiment, led by Arjun Yodh, of the University of Pennsylvania. CVB investigates heat conductance in microgravity as a function of liquid volume and heat flow rate to determine the transport process characteristics in a curved liquid film. The other two experiments investigate various aspects of the nucleation, growth, structure, and properties of colloidal crystals in microgravity and the effects of micromanipulation upon their properties.

The Collisions Into Dust Experiment-2 (COLLIDE-2), led by Joshua Colwell, of the University of Colorado, Boulder, was conducted on shuttle mission STS-108 in December 2001. The experiment studied the effects of low-velocity particle collisions, which are believed to be responsible for the formation of planetary rings and protoplanetary disks. The experiment was designed to collect data on the outcome of low-velocity collisions of selected projectiles into a fine powder that simulates regolith, the dust and small particles that coat the surfaces of most bodies in the solar system.

The first flight of the experiment, on STS-90 in April 1998, revealed the unanticipated result that below a certain threshold energy, no material is ejected as a result of the impact. For COLLIDE-2, researchers expanded the space in which the data were collected to find the threshold energy. They also characterized the velocity of the ejected material as a function of impact velocity and energy.

The COLLIDE team has analyzed the results and learned that when the projectiles impact the powder at speeds below about 20 cm/second, the projectiles adhere to the target. This seems to support the hypothesis of planetesimal growth, which states that planets grew from small, solid, celestial bodies that may have existed at an early stage of the development of the solar system. The team also found that at speeds above 20 cm/second, projectiles are dispersed, making growth of planetesimals difficult. The results from impacts at these faster speeds suggest that planetesimal growth is assisted by aerodynamic or electrostatic forces acting on the slow-moving particles knocked off in the impact.

The third Mechanics of Granular Materials (MGM-III) experiment is scheduled to fly on space shuttle mission STS-107 in January 2003. MGM-III, led by PI Stein Sture and Co-I Nicholas Costes, both of the University of Colorado, Boulder, will use the microgravity environment to test the response of columns of sand to compression and relaxation, forces that occur during earthquakes and landslides when compacted soil loosens and flows much like a liquid.

In MGM's two previous flights, the researchers measured the effect of gravity on friction between grains of dry sand and discovered strength and stiffness properties of the sand columns to be many times greater than conventional theory predicted. For MGM's third flight, they will study the behavior of water-saturated sand in drained and undrained conditions using three sand samples in nine different experiments. The experiments are expected to provide the first-ever measurements of sand strength and stiffness properties and induced pore water pressures when pressure is cyclically applied and released, similar to the strong ground motions observed during earthquakes.

The science team will use a new specimen-reforming technique, which will prove beneficial to future space station research as it enables the reuse and retesting of the same sample many times under controlled initial conditions. The team will also be able to uplink instructions for the hardware and downlink results from the experiments live, a capability developed in FY 2001. Among the many applications of this research, discoveries from MGM investigations may help engineers design more earthquake-tolerant buildings, increase safety in mining operations, aid coastal and offshore engineering projects, and help researchers understand the geology of various planetary bodies for space exploration initiatives.

The experiment Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions (InSPACE) will be conducted in the Microgravity Science Glovebox (MSG) on the ISS and will be carried to the station on STS-114 in 2003. (For more information about the MSG, see page 76.) InSPACE, led by Alice Gast, of the Massachusetts Institute of Technology, will help researchers find out how a pulsed magnetic field will affect the fluid suspension in a magnetorheological (MR) fluid.

The study of these colloidal systems is beneficial to the development of "smart fluids" for use in feedback-controlled devices, such as shock absorbers and suspension systems, and as colloidal modifiers in protein crystallization or colloidal suspensions. Techniques that Gast's team is using can potentially be used to induce two-dimensional crystallization of proteins in these suspensions. In FYs 2001 and 2002, the InSPACE team measured the properties of membranous, fluid-filled pouches called vesicles that were coated with two-dimensional crystals of the protein streptavidin, which crystallized from a solution. They worked to study how changing the solution's pH changed the crystal structure and growth pattern. This procedure allowed the team to obtain regularly ordered protein arrays on a large spherical support. Such ordered surfaces may be used as templates for crystallizing other molecules or as a framework for biosensor arrays, arrangements of probes that integrate a biological component with an electronic component to yield a measurable signal.

When InSPACE is flown, three different particle concentrations will be tested. The MSG will provide cameras and video recorders to view and store the science

The study of magnetorheological fluids in the InSPACE experiment could benefit such feedback-controlled devices as shock absorbers in automobiles.

data. Observation of the microscopic structures will yield a better understanding of the interplay between magnetic, interfacial, and gravitational forces in MR suspension structures. This research will add to scientists' understanding of the complex properties of MR fluids, enabling methods of improving their characteristics and their implementation in devices such as vibration damping systems.

The Shear History Extensional Rheology Experiment (SHERE), led by Gareth McKinley, of the Massachusetts Institute of Technology, is scheduled to be conducted in the MSG on the ISS in 2004. The experiment will allow for the study of the extensional, or stretching, viscosity of fluids in microgravity. Most measurements of the flow of non-Newtonian fluids, which have a high viscosity, or resistance to flow, have been performed using highly elastic or "stiff" materials such as polymer melts, which can easily be elongated in normal gravity without sagging. By performing similar experiments on different materials in a long-term microgravity environment, it will be possible for the first time to get accurate measurements of the extensional viscosity of more "mobile" fluids such as polymer solutions, suspensions, and liquid crystalline materials.

This characterization of flow, or rheological data, will allow designers of both space- and ground-based material processes to create improved models of complex two- and three-dimensional fluid flows. Non-Newtonian fluids are significant in many industrial processes such as fiber-spinning, spraying, and film-coating operations. Gaining insight into the extensional viscosity of these fluids is also important to understanding the complex fluid phenomena involved in the stability and breakup of fluid jets; enhanced oil recovery; and turbulent drag reduction for advanced aircraft, boats, and submarines. In FY 2001, scientists flew SHERE twice on the NASA KC-135 airplane using hardware that is compatible with the space shuttle's Middeck Glovebox. In FY 2002, the SHERE team worked to ensure that the experiment would be physically and electronically compatible with the larger glovebox aboard the ISS.

The Boiling Experiment Facility (BXF) will accommodate experiments on the ISS beginning in 2004. Boiling is an important field of study since it can effectively move energy away from a surface through the phase change of liquid to gas, thus cooling the surface. Because boiling is a preferred mode of heat transfer in space, what investigators learn about boiling in microgravity can be applied to thermal management of many spacecraft systems, such as supply systems for life-support fluids and electronic packages powering various instrumentation and control systems.

Two experiments are planned for the BXF in 2004. The first will be the Nucleate Pool Boiling Experiment (NPBX), led by Vijay Dhir, of the University of California, Los Angeles. Dhir will study bubble nucleation, growth, and departure during the boiling process and the resultant cooling that is achieved under microgravity conditions. NPBX will increase in complexity from experiments using a single bubble to ones using three inline bubbles to ones with five bubbles placed on a two-dimensional grid. In FY 2001, Dhir's team developed two-dimensional bubble growth models; in FY 2002, they developed models in three dimensions. The second experiment slated for the BXF is the Microheater Array Boiling Experiment (MABE), led by Jungho Kim, of the University of Maryland, College Park. The study, which will help scientists know how much cooling can be achieved in a fluid in microgravity, will use two 96-element microheater arrays, 2.7 mm and 7.0 mm in size. This arrangement will allow local heat fluxes to be measured as a function of time and space. During FYs 2001 and 2002, the MABE team gathered data on the boiling process in microgravity, Earth's gravity, and hypergravity using a heater array on a KC-135 airplane flying in a parabolic pattern. Results to date indicate that boiling in microgravity is dominated by the formation of a large primary bubble whose size is on the order of the heater.

The Granular Flow Module (GFM) will be operated in the FIR beginning in 2007. The GFM is a multi-user mini-facility that will accommodate investigations studying the flow of granular materials, which are substances made up of solid particles distributed in a gas or liquid. (For more information on the GFM, see page 74.) The first three investigations to be conducted on the GFM are Microgravity Particle Segregation in Collisional Shearing Flows (µgSEG); Studies of Gas-Particle Interactions in Microgravity Flow Cell, also known as Solids Interacting with a Gas in a Microgravity Apparatus (SIGMA); and Gravity and Granular Materials (GGM). The objective of the µgSEG experiment, conducted by PI James Jenkins and his team at Cornell University, is to test mechanisms of granular segregation that are not controlled by gravity. The µgSEG hardware features rotating cylindrical walls with bumps that have specific shapes and collision properties and a digital video that records particle trajectories between the rotating walls. The experiment is scheduled to run in 2007. It will isolate and investigate differences in the inertia of spheres with different masses but equal diameters as they tumble in the cylinders. It will also study the geometric segregation of spheres with different diameters but equal masses. In FY 2001, the µgSEG team constructed a prototype shear cell for parabolic flight on the KC-135 aircraft. In FY 2002, the shear cell flew on the KC-135 to test its operation and imaging features, and team members undertook theoretical studies and developed numerical programs to predict results of future experiments.

SIGMA, conducted by PI Michel Louge and his team at Cornell University, studies collisions among particles, which can transfer a significant amount of momentum within and at the boundaries of the particle flow. The experiment, scheduled to run in 2008, will use the same hardware as µgSEG. In FY 2001, the SIGMA team designed a prototype cell to be tested on the KC-135 aircraft flying in a parabolic pattern. In FY 2002, the team flew the prototype on the KC-135 and demonstrated that the cell can produce the desired granular flows.

GGM, conducted by PI Robert Behringer, of Duke University, in Durham, North Carolina, will explore the fluctuation of forces in low-density and high-density granular samples. The effects of the fluctuation range from clustering in low-density samples to chains of particles jamming at high density. In the flight hardware, the sample volume is the space between two concentric cylinders of different diameters with one stationary end plate and one end plate that rotates to drive a shearing motion. The granular particles are 0.8-mm glass beads. The volume of the beads will vary from gaslike (with relatively long distances between each bead) to liquidlike (with the average gap between each bead less than the diameter of the bead). Findings from the experiment, which will be run in 2008, may lead to better understanding of the mechanical behavior of granular materials and how to avoid such industrial problems as clogged chutes, silo failures, and poorly mixed medicinal components. In FY 2001, the GGM team completed studies of granular friction by using a novel shaking device, studies of texture and force propagation, and studies of gaslike granular systems. In FY 2002, the team developed a science requirements document and presented it at a science concept review.

Highlights

Learning the Basics of "Moon Face"

Studying the fluid physics of cells may bring answers to why astronauts get all stuffy in the head and puffed up in space. John Tarbell, of Pennsylvania State University, is using a cell culture model to find the cause of and countermeasures for "Moon face," the shift of fluids to the upper body of astronauts in orbit that gives them a rounder, fuller face.

Tarbell is studying the endothelial cell layer, which lines blood vessels from the aorta to the capillaries. These cells provide the principal barrier to transvascular transport, the passing of water and solutes between blood and underlying tissue. On Earth, these cells are continuously exposed to the mechanical shearing force and the pressure imposed by blood flowing over their surfaces, and they are adapted to this environment. When the cardiovascular system is placed in microgravity, which affects fluid flow, pressure in the blood vessels changes, and the shearing force is eventually reduced. These adaptations increase the endothelial cell layer's hydraulic conductivity, or its ability to transport water and solute, inhibiting the layer's barrier properties and, Tarbell proposes, allowing the transvascular transport that causes fluid to shift in humans in microgravity.

In ground-based research using a tissue culture model of the endothelial transport barrier, Tarbell has shown that a sudden increase in vascular pressure, which occurs in the human face in microgravity, induces an early adaptive response. The endothelial layer's resistance to the flow of water from blood into tissue space increases for about an hour after the pressure increases. This natural control mechanism tends to limit facial swelling. The ground-based experiments further demonstrate that after an hour of altered pressure, the resistance begins to drop substantially, leading to a condition in which there is excessive leakage of fluid from the blood to the tissue. This loss of control of transvascular transport exacerbates facial swelling.

credit: NASA

Astronauts experience a coldlike sinus and nasal stuffiness and a rounder, fuller face called “Moon face” (shown at right) when the barrier that normally prevents fluid from passing from blood vessels into surrounding tissues on Earth becomes ineffective in microgravity.

Tarbell is studying the biomolecular mechanisms that mediate the response of the endothelial transport barrier to changes in pressure. His group has found that the loss of resistance to fluid transport from blood to tissue can be blocked completely by inhibiting the formation of nitric oxide (NO) using pharmacologic agents. Findings in Tarbell’s research related to NO tie in to studies by other NASA scientists in biomedicine and fundamental space biology who are studying how NO affects fluid-related conditions experienced by astronauts such as bone blood flow, orthostatic intolerance (lightheadedness upon standing or sitting up), cardiac atrophy, and disruption of circadian rhythms (natural sleep patterns).

Tarbell also has found that the loss of resistance can be reversed by elevating intracellular levels of cyclic adenosine monophosphate, a signaling molecule that affects the hydraulic conductivity of endothelial cells. Tarbell says, “The results suggest a variety of possible approaches for pharmacologic intervention to regulate hydraulic activity of endothelial cells in microgravity,” thereby reducing the degree of “Moon face” and other fluid-related conditions experienced by astronauts.

On Earth, Tarbell’s research findings could provide insight into the importance of maintaining normal tissue homeostasis and knowledge about how its breakdown becomes critical in various diseases that include atherosclerosis, a degenerative disease of arteries that underlies heart attacks and strokes; diabetic retinopathy, leakage of albumin into the retina; and when tissue is inflamed, the transvascular transport that leads to swelling in tissue.

Sorting Out the Effects of Turbulence on Particle Dynamics

From dust storms to volcanic eruptions to industrial spray applications, the movement of particles by a turbulent fluid, such as air, can have far-reaching consequences. Turbulent pockets of air form eddies, swirling around any particles that cross their paths. However, gravity, rather than the force of the eddies, controls most of the dynamic behavior of the particles on Earth, pulling them through the turbulent air pockets at a relatively fast rate. What happens to those particles if the effects of gravity are temporarily removed? Principal Investigator Chris Rogers and his team at Tufts University are studying how glass and ceramic particles disperse in air, and they are trying to understand the role gravity plays in their motion.

A number of studies of particle dynamics in turbulent media had already been conducted using computer-based numeric simulations, but in 1996, Rogers and his team set out to conduct experiments using real particles and real turbulence in order to improve upon computer models and to better understand the dynamic phenomena of particles in motion. They started with a quasinumeric technique, which combines mathematical calculations and experiment data on a real fluid, a channel of water flowing in one direction.

A unique system developed at the Tufts University Fluid Turbulence Lab uses a laser velocimeter probe comprising four laser beams to provide instantaneous measurement of the speed of the water and calculate what would happen to a particle of a given mass experiencing gravity acting in a given direction with a given amount of force. The particle’s acceleration and position in the fluid are then mimicked by the movement of the laser beam, which bounces through the fluid as if the beam were the particle. Rogers’s team was able to vary the force of gravity on the model to begin to define gravity’s role in the path the particles took through the fluid. But they realized that to validate and further refine results of both the computer-based and quasinumeric simulations, they would have to conduct their experiments in microgravity.

credit: NASA

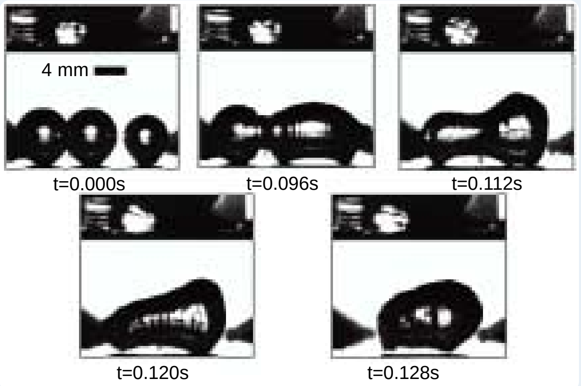
Just past the peak of the KC-135's parabolic flight path, the experiment rig floats in midair, free from the effects of gravity. Temporarily removing some of gravity's influences allows researchers to study the effects of turbulence on airborne particles.

A first parabolic flight of the experiment on NASA's KC-135 aircraft involved mounting a large box with the rig inside to the floor. This setup didn't account for the effects of outside turbulence encountered by the plane, so the team redesigned the experiment rig. On subsequent flights, a smaller apparatus was used, allowing researchers to release the rig, which included the experiment chamber and the video recording equipment, during freefall, when it would float in midair.

The method for creating turbulence for the glass and ceramic particles inside also became more sophisticated. Little fans with model airplane propellers on them blew the air into the corners of the rig, where it spread along the walls, keeping the particles from sticking to the walls. This rig provided the team with the turbulence and freefall conditions they were looking for. What they found when analyzing the video bore out theories based on computer simulation.

Small particles, when subjected to turbulence in microgravity, showed what is called preferential concentration, which computer models had predicted. As the particles entered the turbulent air, they were thrown about by eddies in the flow field. The eddies, spinning the particles about, tended to throw the particles into the spaces between the eddies. Here the particles clustered into strings; they preferentially concentrated between the eddies where they could move more easily through the air.

But what about larger particles? Simulations of turbulence had shown that heavy particles would agglomerate just as smaller ones would. However, a simulation has its limitations, and Rogers and his team had their doubts about whether tests on real particles in turbulent flow fields would show the same agglomeration behavior.



credit: NASA

A large bubble grows as smaller ones come in contact and surface tension breaks to let the gas pockets join. The entire sequence took about one-eighth of a second on a KC-135 flight.

Video from the KC-135 flights confirmed what the simulation had predicted: in microgravity, big particles would also agglomerate due to the influence of the turbulent flow field. In order to test out this theory on even larger particles, however, longer tests in microgravity will be necessary.

For a better understanding of the fluid properties in the experiment, Rogers returns to the quasinumeric technique using the laser system and the model water channel. He hopes to be able to draw some conclusions about the fluid properties in his experiment based on what he has observed in the KC-135 experiments on particle dynamic properties. The next set of investigations in the KC-135 may help Rogers answer questions regarding how the total amount of turbulence is affected by adding particles to the experiment apparatus and how the turbulence generated in microgravity compares to turbulence measured on the ground.

Tiny Bubbles Create Better Cooling

Put a clear glass pot of water on the stove and turn the burner to high. Soon the heat turns liquid water at the bottom of the pot into bubbles of steam that almost instantly detach and zip to the surface. Cooler water flowing in behind is heated in turn to become more steam, and the entire pot boils as the transition of liquid to gas carries heat away from the bottom of the pot.

Now imagine that gravity's effects are turned off. Without buoyancy to make lighter materials float to the top, the bubbles don't detach; rather, they stay in place and grow. The heat is not carried away from the bottom of the pot, and the heating element melts and fails altogether. The stove, a power plant, a computer, or any other active system — even a human — must shed heat or break down.

Principal Investigator Vijay Dhir, of the University of California, Los Angeles, wants to understand boiling so it can be used safely in systems operating in a microgravity environment. One of the most efficient means of cooling, boiling has been a fundamental part of modern industry since the dawn of the Steam Age, yet it is poorly understood in many respects, especially where gravitational effects are involved.

Dhir has designed the experiment Investigations Associated With Nucleate Boiling Under Microgravity Conditions to allow precise control of the locations where bubbles form and the timing of their release — something that the design of earlier microgravity experiments did not permit. Silicon wafers, 10 centimeters (4 inches) in diameter, make this control possible. The wafers have "designed surfaces" with tiny wells only 4, 7, or 10 microns wide and 100 microns deep, backed by tiny heating elements. The wells serve as nucleation sites, where water heats to boiling and then turns to vapor. Each well or combination of wells can be heated to produce a single bubble or an array of bubbles. The patterned surfaces will allow Dhir and his colleagues to study boiling across a range of controlled variations, to quantify how heat moves from a solid surface into liquid and then to vapor, and to understand how heat transfer in one tiny area can affect transfer in another.

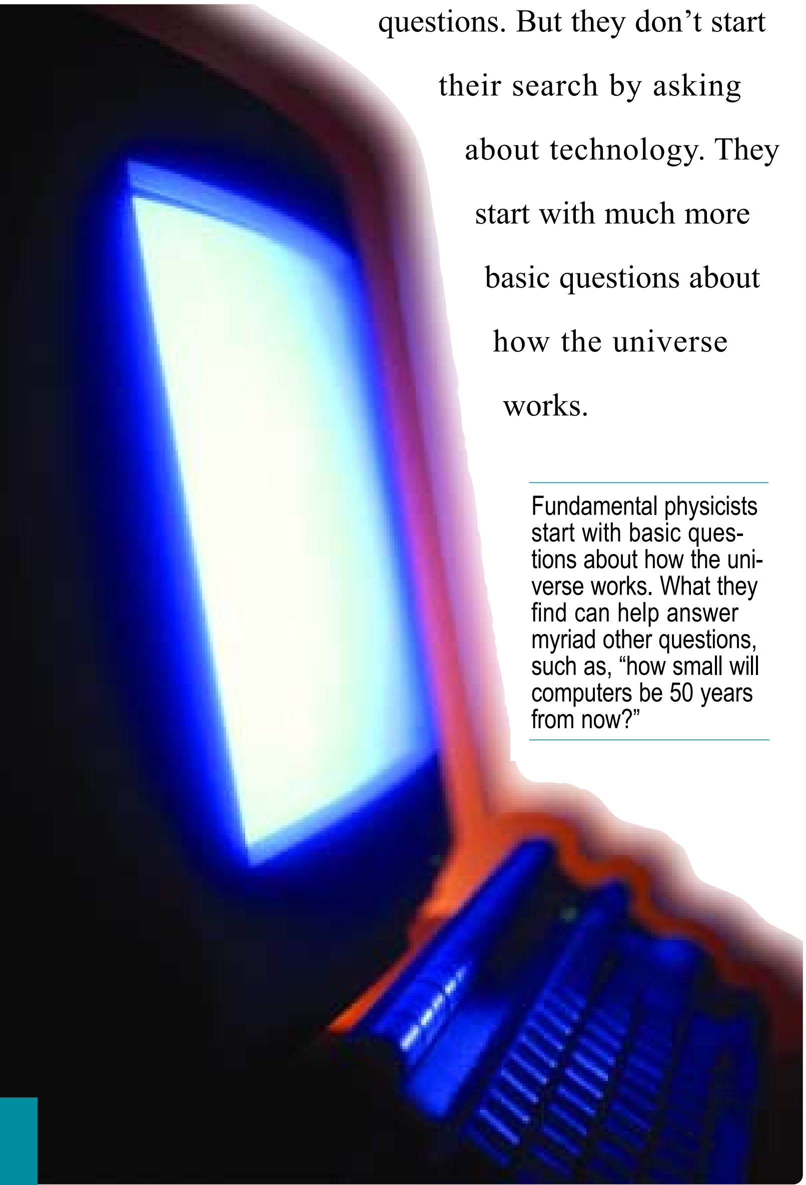
While flying his experiment aboard the KC-135 aircraft in a parabolic pattern in 2000, Dhir discovered something that no one else has studied: that while a single bubble can grow to dangerously large sizes in low gravity, the release of even a few small bubbles can create radically different flow patterns in a liquid, inducing additional bubbles to depart.

Moreover, Dhir's computer simulations show that if the bubbles are neatly lined up like beads on a string, they have little effect on each other. But if their positions are staggered, they merge and induce circulation and lift forces that move other bubbles away from the heating surface as well. To Dhir, this discovery suggests that patterning a surface with deliberate, microscopic variations might induce proper boiling in a low-gravity heat-transfer system.

To find out, Dhir will need to run his experiment in a long-term microgravity environment onboard the ISS. Then, in 5 to 10 years, Dhir expects that the result of a successful ISS investigation could be design codes that engineers would use to optimize surfaces in a boiling system for a range of applications both on Earth and in space. Such understanding could help thermal engineers design space applications ranging from nuclear electric propulsion systems powering space vehicles between planets to electrical power plants and cooling systems operating efficiently in the fractional gravities on other planets.

OVERVIEW

Do you ever wonder how small a computer will be 50 years from now? Or what new tools a doctor will have to detect cancer? Or what new technology might replace CD players? Or if we will have the instruments we need to make deep space exploration possible? Fundamental physicists are the people finding the answers to these questions. But they don't start their search by asking about technology. They start with much more basic questions about how the universe works.

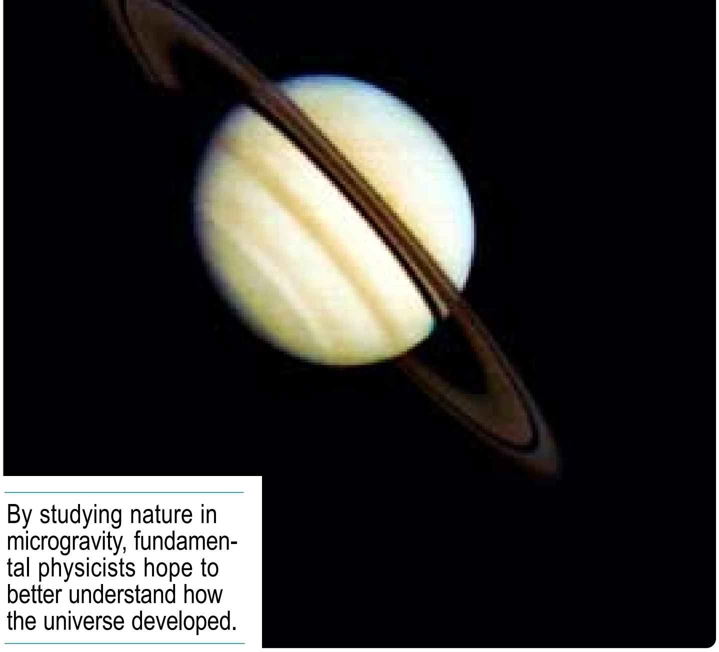


Fundamental physicists start with basic questions about how the universe works. What they find can help answer myriad other questions, such as, "how small will computers be 50 years from now?"

Science is driven by human curiosity about nature. In the study of fundamental physics, scientists wish to uncover and understand the basic underlying principles that govern the behavior of the world around us. Fundamental physics research, therefore, establishes a foundation for many other branches of science and provides the intellectual underpinning needed to maintain and further develop our highly technological society.

Researchers in the discipline have two quests that motivate laboratory studies and experiments in space. One of these quests is to explore and understand the fundamental physical laws governing matter, space, and time. Deep examination of the smallest and largest building blocks that make up the universe will yield a better understanding of the basic ideas, or theories, that describe the world. The space environment provides access to different space-time coordinates and frees experimenters from the disturbing effects caused by gravity on Earth.

The second quest is to discover and understand the organizing principles of nature from which structure and complexity emerge. While the basic laws of nature may be simple, the universe that has



By studying nature in microgravity, fundamental physicists hope to better understand how the universe developed.

arisen under these laws is amazingly complex and diverse. By studying nature apart from the influence of Earth's gravity, we can better understand how the universe developed and how best to employ these principles in service to humanity.

The pursuit of these quests will greatly benefit society in many ways over the long run. For example, the study of physical laws and natural principles with unprecedented precision requires advances in instrumentation that provide the foundation for tomorrow's breakthrough technologies. These advances contribute to the competitiveness of American industry and further support and enhance the presence of humans in space.

To address the two long-term quests of the program, research is currently being pursued in three areas: gravitational and relativistic physics, laser cooling and atomic physics, and condensed matter physics. Gravitational and relativistic physics is the study of gravity's influence on the physical world and of Einstein's Theory of General Relativity, which puts gravity at the heart of the universe's structure. Laser cooling and atomic physics is the study of atoms and how they manifest on a small scale the same fundamental laws that govern the universe on a large scale. Condensed matter physics, in which matter is also studied at an atomic level, specifically examines the properties of atoms in liquids and solids, the states of matter in which atoms are condensed.

Scientists who study condensed matter physics examine the properties of atoms in liquids (such as water) and solids (such as ice), the states of matter in which atoms are condensed. Scientists are drawn to study the transition between states, such as melting or evaporating, because certain universal behaviors are found in the properties of the system as the transition is performed under carefully controlled conditions.

Program Summary

Almost 200 fundamental physicists and other scientists representing 82 universities and 12 countries gathered in Pasadena, California, in May 2001 for the Second Pan-Pacific Basin Workshop on Microgravity Sciences. The workshop was a four-day opportunity for researchers who hailed mostly from countries that border the Pacific Ocean to share their latest work related to microgravity and the space environment. Topics discussed ranged from fundamental research in physical, chemical, and biological processes to cross-discipline research and applied technology innovations. Participants also attended outreach events at the California Science Center, in Los Angeles, and learned firsthand how education and outreach can play a key role in explaining the benefits of their work to the public.

This year's workshop, the largest-ever gathering of microgravity scientists from the Pacific Rim, was hosted by the Association of Pacific Rim Universities, the National Society of Microgravity Science and Application of China, and the Japan Society of Microgravity Application. Other participating organizations included NASA, the National Space Development Agency of Japan, the Chinese Academy of Sciences, the Canadian Space Agency, and the Russian Space Agency.

The workshop also served as the annual meeting for the microgravity fundamental physics program, giving investigators within the discipline an opportunity to present research developments and results and to share ideas with others in the field, especially with many international colleagues. Leading off the plenary talks, Principal Investigator (PI) David Lee, of Cornell University, Ithaca, New York, described the excitement of the 1970s race to discover superfluidity in liquid helium-3. PI Randall Hulet of Rice University, in Houston, Texas, presented the final plenary talk, discussing his recent observation of Fermi pressure in ultracold lithium-6 atoms and showing pictorially the differing behaviors of bosons and fermions (two isotopes of the element). Charles Elachi, newly installed as the director of the Jet Propulsion Laboratory (JPL) in Pasadena, California, described during his address at the conference banquet how the microgravity fundamental physics program fits into JPL's ambitious plans for space exploration. The fundamental physics sessions educated attendees about techniques for using liquid helium as a test bed for fundamental theories, observations of quantum behavior in clouds of atoms cooled to within a millionth of a degree of absolute zero, and funding for research to explore fundamental physics.

The 2002 NASA Workshop for Fundamental Physics in Space was held May 9–11 in Dana Point, California. More than 75 scientists attended the workshop to report on progress in their research and to learn about new opportunities for research funding. Mark C. Lee, the enterprise scientist for fundamental physics at NASA headquarters, described the discipline as currently the strongest he has ever known it, based on the large number of proposals in each subdiscipline that had been received in response to the 2001 NASA Research

credit: NASA

Ketterle Awarded Nobel Prize

Principal Investigator Wolfgang Ketterle, of the Massachusetts Institute of Technology, was awarded the 2001 Nobel Prize for physics for his research involving ultracold atoms that form a new type of matter. The physicist shared the prize with Eric Cornell and Carl Wieman, both of the Joint Institute of Laboratory of Astrophysics and the National Institute of Standards and Technology, in Boulder, Colorado.

The award cites the researchers' achievements and fundamental studies of Bose-Einstein condensates, a peculiar form of matter predicted by Albert Einstein based on research by Indian physicist Satyendra Nath Bose. The Royal Swedish Academy of Sciences, which awards the Nobel Prize, said the three scientists have caused atoms to "sing in unison." Through their research, atomic particles were induced to have the same energy and to oscillate together in a controlled fashion. Laser light has these qualities, but researchers have struggled for decades to make other matter behave this way. The breakthrough research has potential uses for extremely precise measurements and may lead to microscopic computers and ultraprecise gyroscopes that could dramatically improve aircraft guidance and spacecraft navigation. Ketterle's award brings the number of Nobel laureates presently working in NASA's fundamental physics program to eight.

Announcement sponsored by NASA's Office of Biological and Physical Research. He explained that such announcements would occur each year to permit scientists to enter the program at short intervals, with each year's announcement focusing on a slightly different theme in fundamental physics. The theme for the 2001 announcement was gravitational and relativistic physics, laser cooling and atomic physics, and low temperature and condensed matter physics.

Fundamental Physics Discipline Scientist Ulf Israelsson, of JPL, followed Lee's remarks by outlining the changes in the NASA and JPL organizations that will affect the discipline. He described how the new team of the Office of Biological and Physical Research (OBPR), now headed by Mary Kicza, is interpreting the recommendations of the Research Maximization and Prioritization task force, which assembled in 2001 to assess priorities for all OBPR-funded research. Additionally, Israelsson promoted the guest investigator opportunity for fundamental physics scientists, which provides for invited scientists to participate in already-approved flight experiments, including the development of a flight instrument's mission.

PI David Lee presented results from his group's measurements of decay times for species of impurities trapped in a matrix of solid helium. At the low temperatures involved in the measurements, the change of populations observed implies that the reactions take place by quantum tunneling mechanisms, rather than by normal chemical reactions. The results demonstrate the possibility of developing valuable energy storage methods in these systems.

PI John Thomas, of Duke University, Durham, North Carolina, described his team's efforts to cool clouds of Fermi atoms into a state of degeneracy, characterized by atoms that are stripped of their electrons and by very great density. The research group hopes that the proper conditions can be reached to initiate a pairing of the Fermi atoms that will cause the clouds to become superfluid.

Many additional topics of considerable interest were described in the presentations. Attendees at the workshop heard about progress on the Primary Atomic Reference Clock in Space flight experiment, several techniques useful for studying laser-cooled atom samples, mass interferometry methods for measuring the gravitational constant G and for developing sensitive gyroscopes and gravity gradiometers, and phase transitions in an array of ultracold atomic spins. These and other investigations discussed were funded through NASA Research Announcements (NRAs).

NASA releases announcements of opportunities for new research grants at regular intervals to maintain a productive research community working at the cutting edge of the science topics in fundamental physics. New ideas for research broaden the topics and update the standing of the supported experiments. An NRA (NRA-00-HEDS-02) soliciting proposals in fundamental physics was released in February 2000, and selections for funding were announced in November 2000, at the beginning of fiscal year (FY) 2001.

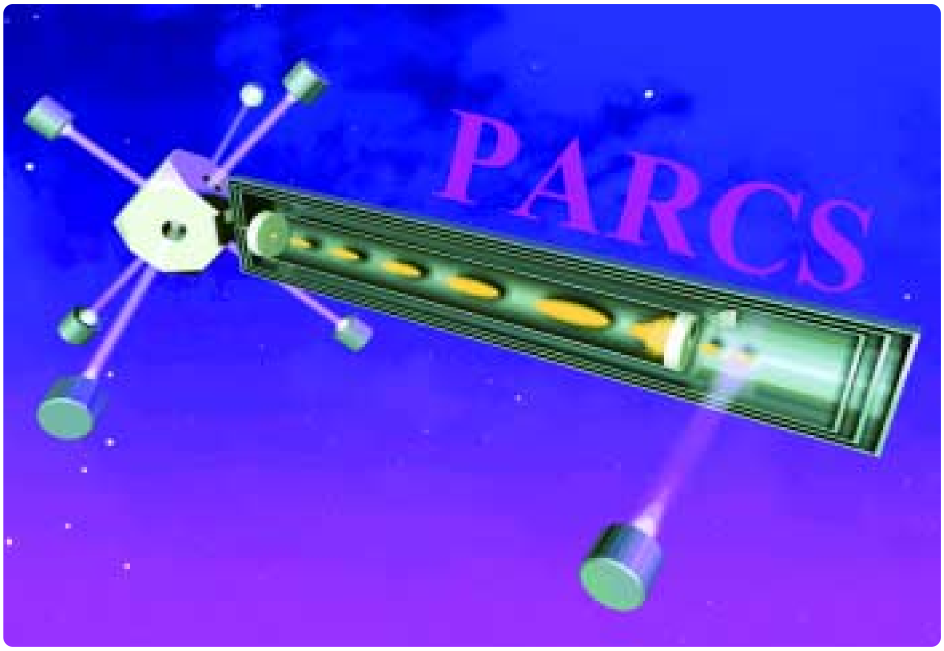
Based on peer review of the 109 proposals submitted in response to the 2000 NRA, 36 ground-based investigations were selected for funding, with seven of those in the new area of biological physics. In addition, five flight-definition investigations were chosen for development. These flight projects included two guest investigations for the first mission of the Low Temperature Microgravity Physics Facility on the International Space Station (ISS), one investigation in gravitational physics, and two experiments in laser cooling and atomic physics. A complete list of the 42 selected research projects from the 2000 NRA can be found on the World Wide Web at *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2000/00-183a.txt*.

An NRA for subsequent funding (NRA-01-OBPR-08-E) was released in January 2001. The announcement solicited research seeking knowledge that will expand understanding of space, time, and matter and enhance understanding of physical, biological, and chemical processes associated with fundamental physics. Proposals were due in April 2002, and selections of investigations to be funded will be announced in early 2003.

The fundamental physics program supported a total of 53 ground-based investigations and 14 flight investigations in FY 2001 and 67 ground-based investigations and 13 flight investigations in FY 2002.

Flight Experiments

The flight program in fundamental physics achieved several milestones this year. As development of the Low Temperature Microgravity Physics Facility (LTMPF) planned for the ISS progressed, experiments slated to fly in the facility also moved forward. For its first mission, scheduled for 2008, the LTMPF will accommodate experiments that investigate superfluid helium. When helium is cooled to extremely low temperatures (nearing absolute zero, –273°C) it remains in a liquid state but exhibits some very unusual properties. For instance, it has no resistance to flow, so it can leak through tiny holes that even gaseous helium cannot penetrate, and it demonstrates infinite heat conductivity. Helium in this state is called a superfluid. Studying the critical point for superfluidity, the conditions of temperature and pressure at which the transition occurs, has



credit: NASA

Diagram of the proposed PARCS laser-cooled space clock. Atoms in the source (atom-preparation) region are cooled and trapped and then launched through the cavity region. The microgravity condition keeps the atoms flowing straight to the detection region.

proved the transition to be an excellent model of the physics of other transitions between states, such as the liquid-gas critical point.

The Critical Dynamics in Microgravity Experiment (DYNAMX), scheduled for the first LTMPF mission, will study how liquid helium becomes a superfluid while being driven far from equilibrium by a heat current. In FY 2001, DYNAMX passed its preliminary design review and was granted limited authority to proceed. Only minor design changes remained before the detailed design definition of the flight hardware would be complete. In FY 2002, the final DYNAMX flight prototype and flight hardware were designed, and the drawings and flight assembly procedures were more than half complete.

The Microgravity Scaling Theory Experiment (MISTE), also planned for the first LTMPF mission, will test scaling law predictions for thermophysical properties of systems near liquid-vapor critical points. During FY 2001, MISTE passed its preliminary design review, and the MISTE team began fabricating an engineering model of the flight hardware for testing. The team continued its collaboration with Mission Research Corporation on developing a small, pneumatic low-temperature valve for repeated actuation at liquid helium temperatures. The ground-based experimental cell was redesigned to permit more accurate measurements, and a MISTE web site (*http://miste.jpl.nasa.gov*) was created for outreach purposes. In FY 2002, the MISTE team developed a novel low-temperature valve to meet flight requirements. The team also acquired new data using the redesigned ground-based experimental cell. Based on these data, they revised their mathematical model, and predictions are now being tested against experimental measurements.

Two other superfluid helium experiments will be conducted during the first LTMPF mission. The Enhanced Heat Capacity of 4He Near the Superfluid Transition (CQ) experiment and the Coexistence Boundary (COEX) experiment will use the DYNAMX flight instrument and the MISTE instrument, respectively, in different ways from their primary experiments to maximize scientific return on the instruments. The CQ experiment will explore the effect of heat flux on the superfluid transition of helium. In FY 2001, the experiment was approved and funded as a guest experiment with DYNAMX. In FY 2002, the flight definition of the CQ experiment was completed, and the review board of the CQ requirements definition review recommended that CQ receive authority to proceed to flight.

COEX measures densities of a sample of helium-3 as it approaches very near to the vapor-liquid critical point. The data should help to determine precisely the parameters for the theoretical description of the properties of that critical point. In FY 2001, COEX was accepted by NASA as a guest experiment using the MISTE flight hardware, and the COEX team determined preliminary data. In FY 2002, the COEX science requirements document and experiment implementation plan were prepared.

The science concept review and requirements definition review were held in April 2002.

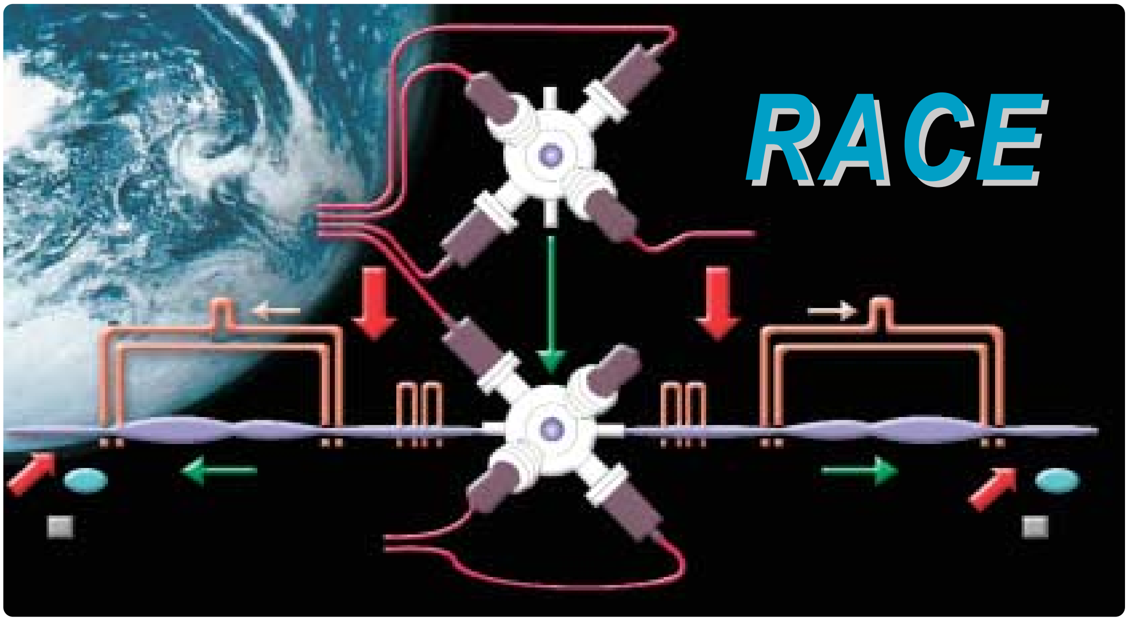
Experiments have also been selected for the second LTMPF mission, planned for 2010: The Boundary Effects on the Superfluid Transition (BEST) experiment will determine the effects of boundaries on the thermal conductivity of superfluid helium near the critical transition, and the Superconducting Microwave Oscillator (SUMO) is a project to develop an oscillator that will be used to test theories about relativity and in other applications.

The program currently supports two flight experiments to develop atomic clocks using laser-cooled atoms. Atomic clocks are the most accurate timekeepers on Earth, but gravity limits their performance. Development of a laser-cooled atomic clock that could take advantage of a microgravity environment would enable an improvement in accuracy by perhaps as much as a hundredfold. An atomic clock on the ISS could serve as a primary frequency standard, providing labs around the world with the premier definition of the second and perhaps enabling experiments in fundamental physics that were not possible previously. Such a clock also could aid in deep space navigation and navigation on Earth by improving the accuracy of the Global Positioning System (GPS).

Scientists working on the Primary Atomic Reference Clock in Space (PARCS) project are developing a cesium-beam atomic clock to operate on the ISS. In this clock, atoms of cesium will be made to oscillate between energy states by exposure to a specific microwave frequency. To precisely measure the atoms' oscillation, or "ticking," they will be slowed by extreme cooling and trapped within the instrument by the microgravity environment of orbit.

In December 2000, the PARCS project passed its requirements definition review, which involved defining the engineering aspects of conducting the experiment in space. Also, a number of components have been either designed or fabricated in prototype form. The shutters for the atom beam, which are critical to operation of the PARCS clock, have been fabricated, and preliminary testing of them has begun. These shutters must be nonmagnetic, produce a minimum of vibration, have an aperture larger than 1 cm, operate at a rate of at least 1 hertz (one cycle per second), and should survive more than 1 million usages. In addition, collimators (devices for the trapping and detection of lasers), plus a prototype trapping chamber, have been constructed of titanium, and a prototype for the clock is under development. A microwave synthesizer with a performance that meets the need for the PARCS instrument has been constructed, and measurements of phase noise are under way. A second synthesizer design, which incorporates features that better match it to PARCS and uses a number of space-qualified components, is nearing completion.

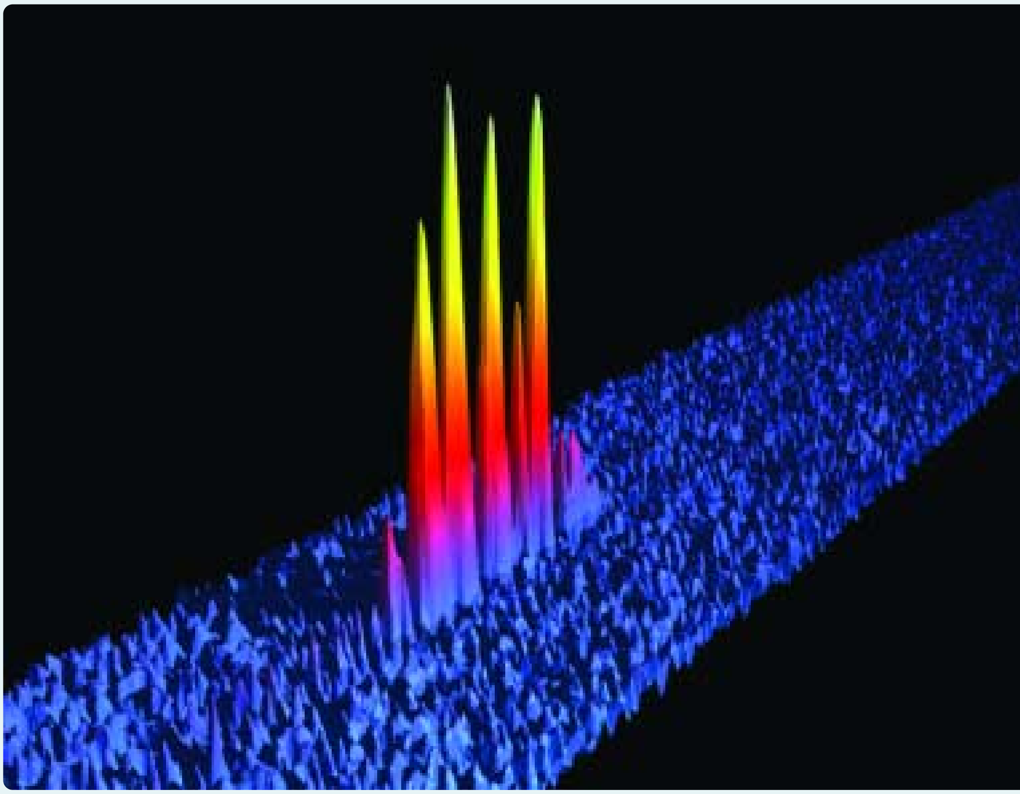
The team of scientists working on the Rubidium Atomic Clock Experiment (RACE) is attempting to further improve the accuracy of laser-cooled microgravity



credit: NASA, redrawn by Jacky Edwards

A new design for the RACE rubidium microgravity clock was developed this year. This design, shown in the figure above, simplifies the trapping and shutter mechanisms while maintaining a high throughput of cold atoms, minimizes the requirements on the local oscillator, and eliminates errors due to vibrations.

clocks. By using rubidium instead of cesium, this experiment addresses one of the largest sources of errors in a cesium clock: the frequency shift of atoms caused by cold collision. The collision shift of rubidium is 50 times smaller than that of cesium, allowing for better stability and thus more accurate determination of the frequency required to cause the atoms to oscillate between energy states. The team has also developed a technique to cause the atoms to be launched in quick succession from the base of the clock, pass through one microwave region, where their energy state is measured, continue toward the top, and pass through another microwave region, where they are remeasured before they fall again. The short-term stability of the atoms' oscillation before they collide is proportional to the launch rate, so juggling the atoms allows a higher accuracy to be maintained. In FY 2002, the RACE team rebuilt the clock to improve its energy state detection system.



credit: Randall Hu

This is a three-dimensional rendering of an image of a matter-wave soliton train. Each peak in the train is Bose-Einstein condensate, a collection of atoms cooled to a temperature of nearly absolute zero. Soliton are localized bundles of waves, constrained to move in only one dimension, which propagate without spreading. Advanced optical communications systems employ solitons because ordinary light pulses spread and require frequent signal boosters. The atom-wave solitons shown in the figure may someday useful as the atom laser input to an atom interferometer.

An experiment in condensed matter physics, the second Critical Viscosity of Xenon Experiment, CVX-2, was manifested on space shuttle mission STS-107. The experiment, which measures the change in viscosity of a fluid near its critical point, is laying the groundwork for a method of predicting the viscosity of various fluids. Work progressed on readying the CVX-2 hardware for integration into the shuttle. This experiment builds on results from a previous successful flight on shuttle mission STS-85 in August 1997.

Highlights

Glimpses of Cold Stars and New Laser Power

Scientists have successfully used lasers to cool a cloud of lithium atoms sufficiently to observe unusual quantum properties of matter, including some that could shed light on the behavior of stars or lead to improved tools for space navigation. Randall Hulet and his team at Rice University watched as an extremely cold lithium cloud resisted condensation in much the same way that stars will collapse to a certain point and no further after they have used up their fuel and succumbed to gravity. The scientists also have been able to make the atoms in a lithium cloud move in perfect, nondissipating waves, one atom following after another, which could be an important first step in making an atom laser for clock and navigation applications.

Both of these observations were made as the team attempted to achieve the unique conditions that would induce lithium atoms to behave collectively, or as a quantum system. Under certain conditions, atoms exhibit wavelike behavior, that is, sometimes an atom exists not as an object occupying a single point but rather is spread out over a region of space, known as the wavelength of the atom. Since atoms of the same material all display the same type of wave, under unique conditions of very low temperature, the waves lock together and move almost like troops marching in formation. In this state, the cold and dense cloud of atoms is known as a Bose-Einstein condensate (BEC), and it exhibits unusual properties similar to those of a superfluid, another quantum state of atoms.

Although a number of elements have been found to undergo this transition, lithium is of particular interest because it exists in two different forms, or isotopes: lithium-7, which consists of atoms known as bosons, and lithium-6, which has atoms known as fermions. Bosons, it turns out, reach the BEC transition at higher temperatures than fermions. Hulet's challenge was to cool the fermions to temperatures low enough to reach the BEC state. In an inspired technique, Hulet and his team cooled a cloud that was a mixture of the two isotopes so that the bosons, which readily respond to cooling, acted as refrigerants, further cooling the fermions.

While trying to achieve a BEC using this mixture of lithium atoms, the team got a surprising snapshot of a phenomenon that occurs in stars — Fermi pressure. Named for Enrico Fermi, a Nobel Laureate noted for his contributions in nuclear physics, Fermi pressure has been theorized as the mechanism for star stabilization that keeps white dwarfs and neutron stars from collapsing past a certain point. These stars are dense, compact objects created when normal stars use up their fuel, cool, and succumb to the forces of gravity.

As the Rice team cooled the lithium cloud to 500 nanokelvins (500 billionths of a degree above absolute zero, –273°C), the bosons compressed, because multiple atoms can occupy the same energy level. However, the fermions resisted being crowded together and did not condense further, confirming the theory that they cannot occupy the same energy level due to Fermi pressure. Thus, Hulet's tiny atom cloud became a quantum model for star behavior, even though the atoms in the two systems exist in vastly different spatial and energy scales. Images of the lithium cloud have revealed some fascinating insights into this force responsible for stabilizing stars.

Hulet has also documented another quantum effect with a cooled cloud of lithium-7 atoms. The Rice group manipulated the cold atoms to form tidy bundles of waves, called solitons, which retained their shape and strength. Normally, when a wave forms — whether in water, light, or clouds of atoms — it tends to spread out as it travels. Not so with a soliton wave, which maintains its perfect shape without spreading.

In their laboratory, Hulet and his team confined lithium atoms with magnetic fields, cooled them with lasers to one billion times colder than room temperature, and confined them in a narrow beam of light that pushed them into a single-file formation. The atoms formed a Bose-Einstein condensate, and Hulet's team was able to observe a "soliton train" of multiple waves. The soliton train produced by Hulet's team comprised individual segments of this condensate that continued to preserve their quantum mechanical phase with respect to each other, despite being segmented. The atom-wave solitons that the Rice University scientists observed could be used in advanced atom lasers, which have beams made of atoms instead of light photons.

Hulet says atom lasers might have many applications that few have envisioned, such as improving instruments that study gravity variations to locate and measure underground water, minerals, oil, caves, and volcanic magma on Earth. By measuring levels of underground magma, for example, scientists may be able to predict volcanic eruptions. The technology could also be used on a spacecraft to map the ocean believed to lie beneath the icy crust of Europa, one of Jupiter's six known moons.

Atom lasers could also lead to other advances, including improvements in atomic clocks and computers. New clocks could be designed using the ultracold lithium atom beams so that the atoms collide less frequently, which would allow even greater accuracy. More precise clocks would help digital communications systems and improve deep space navigation. Using an atom laser to fabricate computer chips with single atomic layer control would make computers run faster.

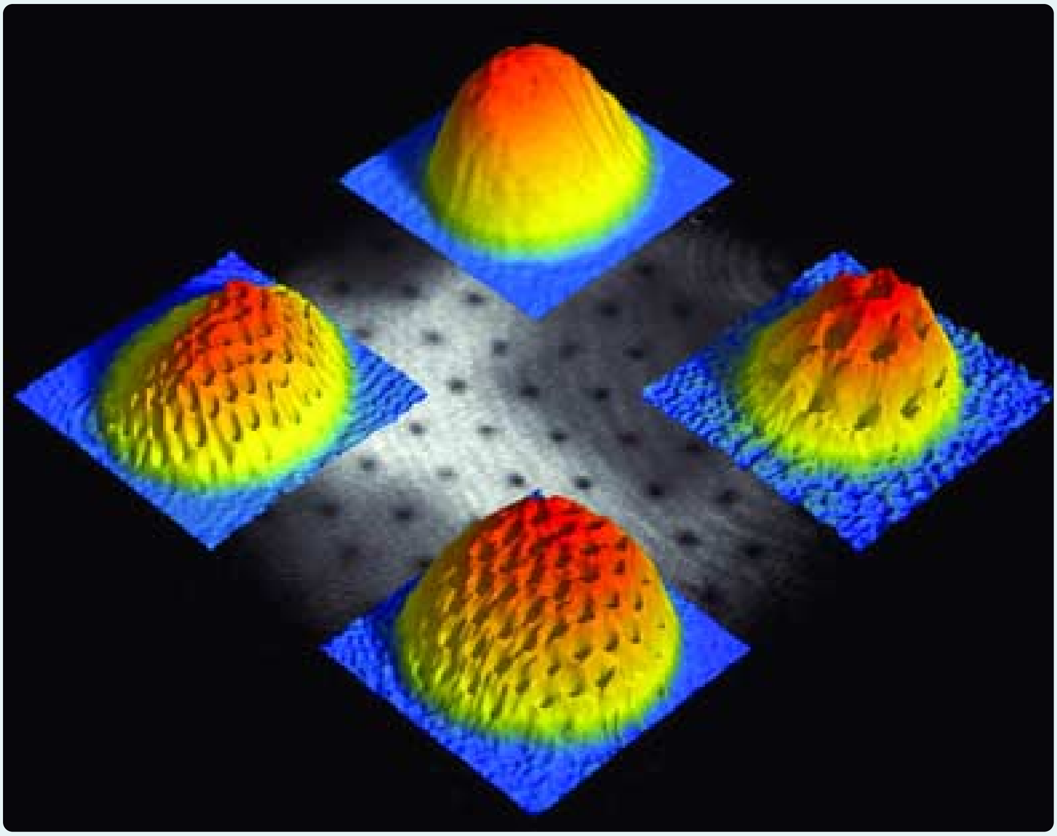
Starquakes on Your Lab Bench, Anyone?

Spinning ultracold sodium gas in the laboratory, scientists at the Massachusetts Institute of Technology (MIT) created a gas cloud that is a model of some quirky pulsar star behavior. As the atom cloud spins, it becomes riddled with tiny whirlpools, like those suspected of causing "starquakes" in space.

The laboratory demonstration of these vortex structures in ultracold atom clouds is related to puzzling glitches observed by astronomers in the otherwise smooth, rapid rotation of pulsars. A pulsar is a type of neutron star, a remnant of a dying star, one of the densest objects in the universe. Glitches in pulsar rotation are called starquakes and may occur when whirlpools, or vortices, form or decay.

Because the gas cloud observed in the laboratory was 100,000 times thinner than air, while a pulsar is about ten thousand trillion times denser than air, one might expect different behavior from the two systems. But both the sodium gas cloud and pulsars are superfluids, a state of matter in which a substance can flow without friction. Scientists know that as superfluids rotate, they form quantum whirlpools that reflect the smallest possible increase in rotation for the gas cloud or for the pulsar.

Previously, scientists in laboratories had seen only one or a few whirlpools in a superfluid; Wolfgang Ketterle, a physics professor at MIT, and his research



credit: Wolfgang Ketterle

The picture above shows images of the gas clouds in four different states of rotation. The spinning sodium gas cloud, with a volume of one-millionth of a cubic centimeter, much smaller than a raindrop, developed a regular pattern of more than 100 whirlpools.

team made the first direct observation of so many vortices. Ketterle described the moment as "breathtaking." The team was amazed as hundreds of whirlpools were created in the ultracold, fragile gas and the cloud remained stable.

To achieve the star model, Ketterle and his team cooled the sodium gas to less than one millionth of a degree above absolute zero (-273°C). At such extreme cold, the gas cloud converts to a peculiar form of matter called a Bose-Einstein condensate, which was predicted 75 years ago by Albert Einstein. No physical container can hold such ultracold matter, so Ketterle's team used magnets to keep the cloud in place. They then used a laser beam to make the gas cloud spin, a process Ketterle compares to stroking a ping-pong ball with a feather until it starts spinning. The spinning sodium gas cloud, with a volume of one-millionth of a cubic centimeter, much smaller than a raindrop, developed a regular pattern of more than 100 whirlpools.

Once the quantum system was achieved, team members were challenged by how to photograph the whirlpools, which were too small to be seen except with special magnification. They switched off the magnets containing the gas cloud, allowing it to expand to 20 times its original size. This made the whirlpools large enough to be photographed. As the cloud expanded, however, gravity made it fall, and the team had to take the pictures quickly. These gravitational limitations would be absent in the microgravity environment that is available to researchers on the International Space Station.

The sodium cloud is an example of a designer quantum system that scientists can use to model something in the laboratory that doesn't occur naturally on Earth. Astronomers had observed the glitches in pulsar rotation, but had no opportunity to explore or manipulate them until now.

How Fast Does the World Turn?

A discovery that may someday help measure how clouds and earthquakes change Earth's rotation has come from an experiment that made friction-free helium whistle. By manipulating ultracold liquid helium-3 in a hollow, doughnut-shaped container, NASA-funded scientists at the University of California (UC), Berkeley, produced a whistling sound that got louder or quieter depending on the container's orientation relative to the North Pole and Earth's rotation. In principle, small changes in Earth's daily rotation rate will also vary the volume of the whistle. Although Earth completes its rotation every 24 hours, clouds and the motion of Earth's crust can make any given day slightly longer or shorter. These findings might provide an unusual new way to measure such changes.

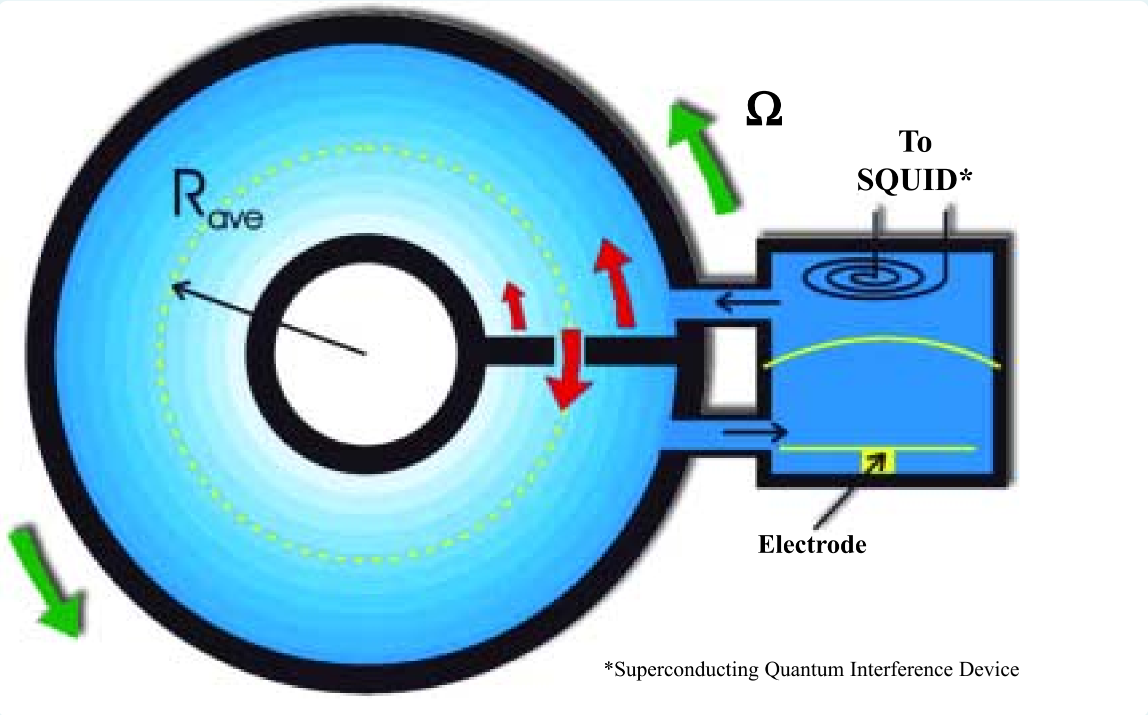
The Berkeley team, led by PI Richard Packard and Co-Investigator Séamus Davis, both professors at UC Berkeley, cooled the vessel filled with liquid helium-3 to a temperature nearly 1 million times colder than room temperature. At this temperature, the liquid helium becomes a superfluid, a state of matter in which a substance experiences no friction, so the liquid can flow continuously inside the vessel. The liquid in the doughnut-shaped container acts like a single, supergiant atom with behavior that is dictated by the strange rules of quantum physics.

This latest discovery that the helium can act as one giant atom builds on the team's previous research. In 1997, they discovered the quantum whistle when they pushed helium through a single perforated membrane between two superfluid-filled chambers. This experiment demonstrated a phenomenon called the Josephson effect: as they tried to push the fluid through the holes, each 1/500th as wide as a human hair, the fluid jiggled to and fro. The vibration frequency increased as they pushed harder on the fluid. They used the world's most sensitive microphone and ordinary headphones to hear the vibrations, which made an oscillating, whistling sound.

In their latest research, the researchers put two thin membranes, each with an array of more than 4,000 tiny holes, at opposite sides of the doughnut to divide the superfluid. When they tried to push the fluid through the holes with electrostatic pressure, it did not flow in the direction they were pushing. Instead, it flowed in a strange, oscillating pattern, again producing a whistle. As the fluid flowed through the doughnut-shaped vessel, the whistle got louder or softer, depending on the vessel's orientation with respect to Earth's axis of rotation.

In essence, the team has demonstrated that two weak links (established by the two perforated membranes) behave as one weak link (established by the single membrane) whose properties are influenced by Earth's rotation. The successful demonstration of this effect has been a goal of low-temperature physicists for more than 35 years. The promising new research might lead to extremely precise gyroscopes to help navigate future NASA spacecraft. This experiment used a tiny amount of helium-3, but by using a much larger amount, an ultrasensitive gyroscope might be created.

Earth is probably too noisy an environment to realize the full potential of this technology, and Packard looks forward to maybe one day listening to his quantum whistle in the best possible environment for the experiment — a free-floating satellite, which could have zero vibration.



credit: NASA

Doughnut-shaped hardware for this experiment included two thin membranes, each with thousands of tiny holes, at opposite sides of the doughnut to divide the fluid. When researchers tried to push the fluid through the holes with electrostatic pressure, it flowed in a strange, oscillating pattern, producing a whistle.

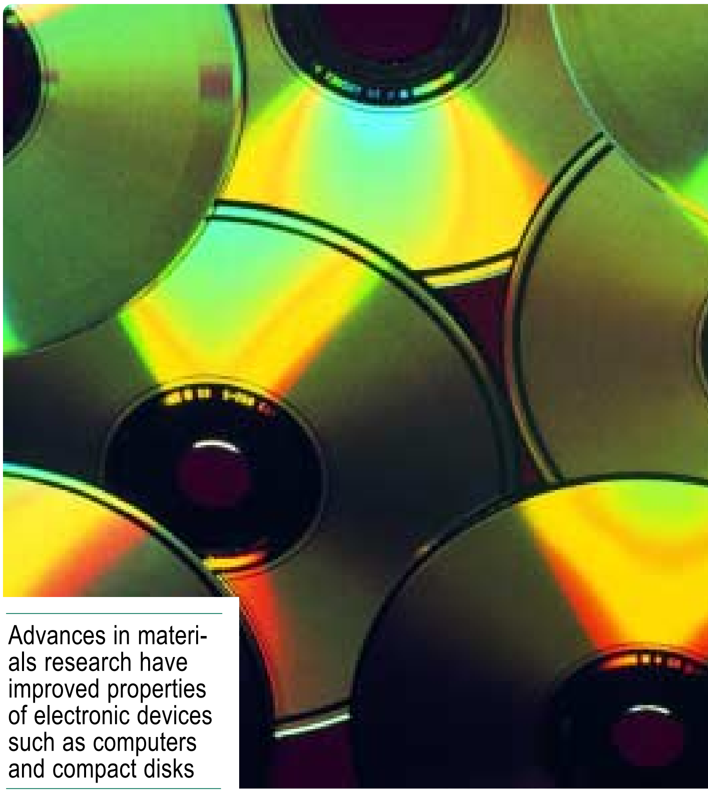
OVERVIEW

The metal alloys used to build airplanes, the circuits in a computer, the plastic used for a heart valve, the composite metallic-ceramic materials used in industrial turbine blades — all of these materials have specific properties that make them the right choice for the products in which they are used. Materials scientists are always on the lookout for ways to improve the properties of materials and to create materials that have new properties for new purposes.

Materials scientists are on a never-ending quest to take existing materials such as glass, metals, or ceramics and make them stronger, lighter, cheaper, or better. Microgravity research is helping researchers understand the fundamentals of materials and enabling them to develop novel solutions to technology challenges in industry and in the space program.

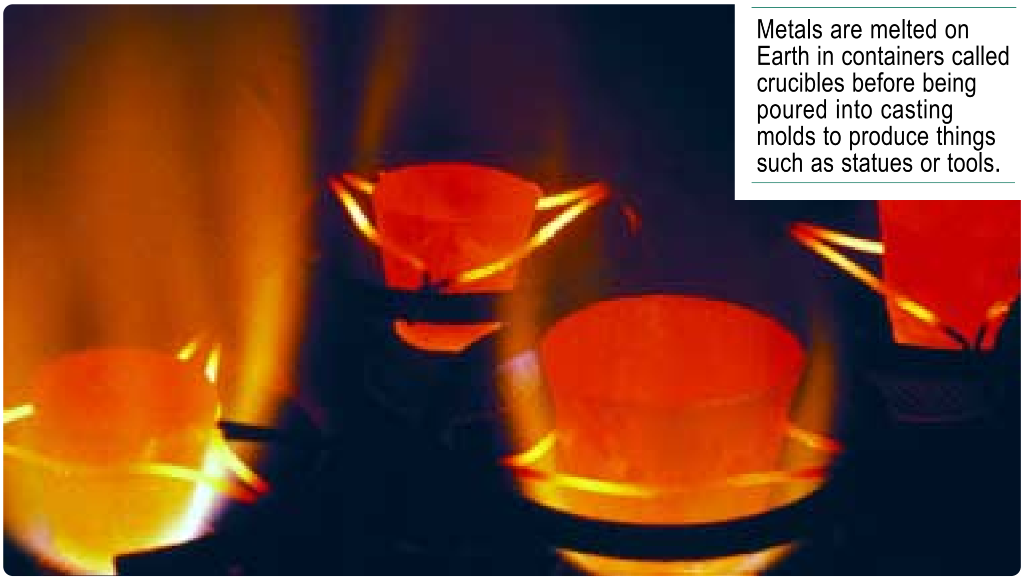
A material's properties, such as how strong, how durable, or how poor or efficient a conductor it is, are determined by not only by its chemical composition but also by its crystalline structure. The crystalline structure is established as a result of the method and conditions under which the material is produced. For example, if a mixture of liquid metal and ceramic particles is solidified at one speed, those ceramic particles may congregate in undesired ways, causing the processed material to crack easily or be brittle. If, on the other hand, the same molten mixture is solidified at a different speed, the ceramic particles may be more evenly distributed throughout the solidified material, lending it desirable strength. By learning how to alter the conditions of material processing to get desired properties, investigators may be able to manufacture materials with more useful properties than are currently available.

Because most solid materials are formed from a liquid melt or a vapor, the production processes for most materials include steps that are very heavily influenced by the force of gravity. Typical gravity-related effects that take place in materials processing include buoyancy-driven convection (fluid flow caused by temperature-driven density differences in a material), sedimentation (settling of different materials, liquid and/or solid, into distinct layers), and hydrostatic pressure (differences in pressure within a quantity of material due to the material at the top weighing down on the material at the bottom). Observing, monitoring, and studying material production in microgravity is beneficial because it allows researchers to isolate some of the underlying mechanisms that govern how materials are formed and to determine how those mechanisms affect the structure and properties of the material. This can increase our fundamental understanding of materials and possibly result in improved methods for processing materials on Earth.



Advances in materials research have improved properties of electronic devices such as computers and compact disks

During fiscal years (FYs) 2001 and 2002, three new research initiatives were proposed for the microgravity materials science program: radiation shielding, advanced space propulsion, and in-space fabrication and repair for long-distance space exploration. Fundamental research in the areas of metals and alloys, electronic and photonic materials, ceramics, glasses, and polymers continues.



Metals are melted on Earth in containers called crucibles before being poured into casting molds to produce things such as statues or tools.

Program Summary

As NASA continues on its path toward long-term, crewed space missions, each discipline is challenged to develop the technology necessary to make exploration beyond low Earth orbit possible. To provide solutions to the new problems such missions will pose, the three new research topics of radiation shielding, advanced space propulsion, and in-space fabrication and repair for long-distance space exploration were added to the materials science program and included in NASA Research Announcements (NRAs) in FYs 2001 and 2002. Researchers from universities, industries, and government laboratories across the country compete for funding in the materials science program by submitting research proposals in response to NRAs. Each proposal is evaluated by a peer review committee and selected on the bases of scientific merit, applicability of the project to NASA's goals, and feasibility.

Learning how to protect astronauts from the increased exposure to harmful radiation outside Earth's sheltering atmosphere will be critical to spaceflights to other planets and habitation on those planets. Materials science is contributing to this effort through research aimed at understanding the radiation shielding effectiveness of existing materials, as well as through research focused on developing new materials. An NRA (NRA-01-OBPR-05) was released August 24, 2001, soliciting proposals for ground-based research opportunities in radiation shielding and biomaterials. Proposals were due November 27, 2001. Another NRA (NRA-02-OPBR-02) highlighting ground-based research opportunities in space radiation biology and space radiation shielding materials was issued August 30, 2002, with proposals due November 25, 2002. Selections for both NRA grants will be posted on the World Wide Web (WWW) at *http://spaceresearch.nasa.gov/research_projects/selections.html*.

The advanced space propulsion initiative is focused on identifying materials that will meet the challenging requirements of the high-temperature and high-energy systems needed to carry vehicles deeper into space. These advanced propulsion systems may involve chemical, nuclear, electromagnetic, magnetic, solar thermal, directed plasma, and photonic components. The research initiative for in-space fabrication and repair supports NASA's plans for construction in space and on other planets. The goals of this effort are to reduce the mass of materials carried into space, to create designs that will enable and facilitate the fabrication of large

credit: NASA

Sharon Cobb of Marshall Space Flight Center in Huntsville, Alabama, shows how a cylindrical sample will be inserted into the Materials Science Research Rack-1 furnace for processing aboard the International Space Station. This rack is being developed to provide a flexible, permanent platform for conducting materials science experiments in the U.S. Laboratory on the space station.

structures in space, and to learn how to use naturally occurring resources on other planetary bodies as building materials.

A general NRA covering all the disciplines within the Physical Sciences Research Division (NRA-01-OBPR-08) was issued December 21, 2001. It included materials science opportunities (NRA-01-OBPR-08-F) and a special solicitation of proposals for developing materials for advanced space propulsion (NRA-01-OBPR-08-G). Proposals for the NRA in microgravity materials science were due July 16, 2002, with selections to be made in December 2002. Proposals for the propulsion NRA were due October 1, 2002, with selections to be made in spring of 2003.

A total of 89 principal investigators (PIs) received research grants for FY 2001–2002. A list of all ongoing materials science research projects, along with the names of the investigators conducting the research, is provided in Appendix A. A complete list of funded projects may also be found on the WWW at *http://research.hq.nasa.gov/code_u/code_u.cfm*.

A new cycle of NRA preparation began at the Fifth NASA Microgravity Materials Science Conference, held June 25–26, 2002, in Huntsville, Alabama. The conference attracted more than 268 attendees and served to spark further scientific interest in materials research in microgravity. Papers and posters featuring work currently sponsored by the program were presented. The two NRAs released in 2001 and the upcoming NRA due to be released in December 2002 were discussed. Oral presentations were selected to highlight mature research and the new research directions in the program.

These new research directions or initiatives are prompted by NASA's vision of future space exploration. If long-duration, crewed space flights are to be made possible, new or improved technology will be needed for each initiative. The FY 2002 NRA includes a special focus theme of Materials Science for Advanced Space Propulsion. This technology will help NASA's vision become a reality. Ron Litchford, of the Marshall Space Flight Center (MSFC) Transportation Directorate highlighted this announcement at the conference in a plenary address. The importance of supporting the NASA and MSFC program in propulsion was further emphasized to all conference attendees in the banquet speech by Michael Houts, also of the MSFC Transportation Directorate, which focused on materials requirements for nuclear-fueled space missions.

Workshops in FY 2001–2002 were also organized to support the new research themes. The Materials Science for Advanced Space Propulsion Workshop was held October 8–10, 2001, in Huntsville, Alabama, to provide input for the propulsion NRA. Attendees brainstormed possible materials needed to develop new propulsion systems that will enable the space program to expand the frontiers of space.

credit: NASA

Designed to isolate experiments inside the Microgravity Science Glovebox, the g-LIMIT apparatus will protect physical sciences research that is very sensitive to vibrations and accelerations on the space station.

The Space Radiation Shielding Materials Workshop took place April 3–5, 2002, at Langley Research Center in Hampton, Virginia. Experts in engineering, space and nuclear physics, technology, materials science, and radiation safety gathered to develop a comprehensive understanding of design methods and requirements related to the design of advanced spacecraft and space habitat radiation shielding.

The In-Space Manufacturing of Space Transportation Infrastructure Workshop was held June 11–13, 2002, at MSFC in Huntsville, Alabama. Sponsored by the NASA Exploration Team, the workshop brought together a variety of engineering and manufacturing specialists, aerospace contractors, and members of the academic science community to address strategies for developing a robust in-space transportation infrastructure that might eventually include permanent refueling stations and maintenance platforms in space. Attendees analyzed NASA's goals to determine its needs for materials advances.

Several notable invitations were extended to participants in the microgravity materials science program in FY 2002. In August, Ken Kelton, of Washington University, St. Louis, Missouri, was invited to deliver a plenary lecture at the 11th International Conference on Rapidly Quenched Metals, at Oxford University, Oxford, England. His research deals with the solid-state precipitation process of oxygen, one of the major impurities in electronic grade silicon, and as such, one of the remaining limiting factors to further progress of the advancement of personal computers. In his lecture, to be published in the Philosophical Transactions of the Royal Society, Kelton outlined a new theory of so-called coupled-flux nucleation. Kelton is using nucleation in liquids held below their freezing points to validate his theories, and the work will culminate in experiments on the International Space Station (ISS). Preparatory ground-based research is being done in the electrostatic levitator at MSFC. The importance of the work is further demonstrated by the fact that, in addition to NASA, the National Science Foundation and industry partners are helping to sponsor this work.

Narayanan Ramachandran, of MSFC, gave an invited talk at the International Symposium on Optical Science and Technology on “Magnetic Microspheres for Therapeutical Applications” in July 2002. Co-authored by Konstantin Mazuruk, Universities Space Research Association, the paper dealt with the possible use of magnetic microspheres for *in-situ* hyperthermia therapy for cancerous tumors.

Maria Zugrav and William Carswell, both of the University of Alabama, Huntsville, gave a conference presentation at the Microgravity Transport Processes in Fluid, Thermal, Biological, and Materials Sciences Conference II held in Banff, Alberta, Canada, September 30–October 5, 2001. The presentation, titled “Vapor Transport Growth of Organic Solids in Microgravity and Unit Gravity: Some Comparisons and Results to Date,” summarized and reviewed four years’ worth of work studying materials for potential applications in the emerging field of optoelectronics. This exciting area of research is the merging of physical, optical, electronic, chemical, and materials sciences to develop newer, faster, and more efficient ways of exploiting the properties of light. Advances can be seen in areas as diverse as telecommunications, manufacturing, aerospace, medicine, and entertainment. Zugrav and Carswell are co-PIs for this investigation.

Notable papers published during FYs 2001 and 2002 included “Crystal Engineering: From Structure to Function,” by Mark Hollingsworth, of Kansas State University, Manhattan, which appeared in *Science 295*(5564), 2410–13. The paper discussed modern crystal engineering, which allows chemists to control the internal structure and symmetry of crystals and produce materials with useful chemical and physical properties. Another paper, titled “Triggered Nucleation in $Ni_{60}Nb_{40}$ Using an Electrostatic Levitator,” by Tom Rathz et al., was accepted for publication in the *Journal of Materials Science Letters*. The article describes the first occasion in which a levitated molten metal drop was forced to solidify by being touched or triggered by an external probe. The purpose of the study is to establish the variety of new and potentially useful structures that can be produced by such techniques.

Flight Experiments

The materials science program conducted its first experiments aboard the ISS in FY 2002. The investigations were carried out in the Microgravity Science Glovebox (MSG), a small, contained unit shared among all the disciplines. Construction of the MSG was completed during FY 2001 by the European Space Agency (ESA). The facility was launched to the space station in June 2002 and began operations in July 2002.

The first investigation conducted in the MSG facility was Solidification Using a Baffle in Sealed Ampoules (SUBSA). SUBSA is designed to test whether the addition of a baffle, a device used to regulate the flow of the liquid metal in the sample, to the directional solidification process, in which the liquid is frozen from one end of the container to the other, will significantly reduce convection that naturally occurs in the melt and result in better-mixed, less-segregated alloy materials with improved properties. Aleksander Ostrogorsky, of Rensselaer Polytechnic Institute, Troy, New York, is the PI for SUBSA.

Once SUBSA was completed, the Pore Formation and Mobility Investigation (PFMI) was installed in the MSG, and its series of experiments was initiated. PFMI investigates the formation of undesirable holes, or pores, in a material as it solidifies. The experiment was performed using a transparent material called succinonitrile; the transparency of the sample allows the researchers to directly observe and record how the pores are formed and how they move during processing. PFMI was led by PI Richard Grugel, of MSFC.

During FYs 2001 and 2002, integration activities were under way for a series of experiments to be conducted in the MSG in FY 2003. These included four experiments from ESA plus four new NASA-sponsored experiments. The NASA experiments are the Investigation of the Structure of Paramagnetic Aggregates From Colloidal Emulsions, the Coarsening in Solid-Liquid Mixtures-2 experiment, the Fiber Supported Droplet Combustion experiment, and the Glovebox Integrated Microgravity Isolation Technology (g-LIMIT) apparatus. Following its on-orbit characterization and testing, the g-LIMIT device will be made available to any future MSG experiments that have a particular sensitivity to low-level vibrations and require special vibration isolation.

In addition to the MSG, the Materials Science Research Rack-1 (MSRR-1) will house microgravity materials science experiments in the Destiny laboratory module of the ISS. The MSRR-1 continued to make progress toward completion and installation on the space station, as did experiment modules designed for the facility. The MSRR-1 is scheduled for launch to the ISS in 2005. For more details about the MSRR-1 and its associated modules, see the International Space Station section of this report.

During FY 2002, final preparations were completed for integrating the Mechanics of Granular Materials (MGM) investigation on the STS-107 space shuttle flight, scheduled for launch in January 2003. This experiment is a continuation of earlier studies regarding properties of granular materials for the advancement of soil science. The microgravity environment provides data on granular materials that cannot be collected on Earth, where gravity collapses the materials so quickly that scientists cannot take measurements. Knowledge derived from the MGM experiments will further the understanding of design models for soil movement under confinement and various stresses. These models can be applied to strengthening building foundations, managing undeveloped land, and handling powdered and granular materials in chemical, agricultural, and other industries. The knowledge obtained is also expected to be valuable in understanding technical issues in fields such as earthquake engineering, terrestrial and planetary geology, mining engineering, and coastal and off-shore engineering.

Highlights

Solidifying the Future

The beautiful structure of a snowflake is a well-known example of the way tiny water droplets freezing into ice form branching crystals. Such branching crystals are called "dendrites" from an ancient Greek word for tree. As a puddle freezes, however, a continuing dendritic network of ice crystals forming across its surface traps air within the water, bubbles that remain when the puddle is frozen solid.

Many metals and alloys also have dendritic structures. When molten metals or alloys are solidified for commercial applications, uniformly distributing the dendrites and controlling or eliminating gas pockets are crucial to ensuring the materials' strength.

credit: NASA

Principal Investigator Richard Grugel examines his Pore Formation and Mobility Investigation apparatus inside the Microgravity Science Glovebox. The project melted samples of a transparent modeling material to observe how bubbles form in the samples and study their movements and interactions.

Richard Grugel at Marshall Space Flight Center, investigator for the Microgravity Science Glovebox (MSG) on the International Space Station (ISS), is seeking to understand the subtle forces that act on gas bubbles in molten metals and alloys. Grugel and his team have created the Pore Formation and Mobility Investigation (PFMI) to study how bubbles move and interact with one another as a material is melted and solidified in microgravity.

On Earth, gravity-driven buoyancy allows the bubbles that form in most liquids to rise quickly to the surface, pop, and disappear. But in cooling molten metal, bubbles can become trapped in the solid when they are caught between dendrites or under the solidifying skin on the top of a casting. Such bubbles become pores, or trapped pockets of gas — defects that undermine the material's strength. Gravity-driven buoyancy so dominates the behavior of bubbles on Earth that it hinders scientists from observing slighter influences on bubble dynamics. In microgravity, however, buoyancy is minimized, and bubbles do not rise and disappear, allowing for a more complete study of their subtler behavior.

The PFMI apparatus flew to the ISS aboard space shuttle mission STS-111 in June 2002. The PFMI thermal chamber, the experiment cameras, and other data-collecting devices were installed in the Microgravity Science Glovebox.

The experiment consists of the controlled melting of a transparent material that is structurally similar to metals, in this case, succinonitrile and succinonitrile mixed with a small amount of water. The samples are processed inside a thermal chamber installed in the glovebox's workspace. As the sample melts, video cameras record bubble formation and movement near the liquid-solid interface.

Once a sample is loaded into the chamber, an ISS crewmember starts the experiment with the glovebox laptop computer and inserts a videocassette into a VCR to record the experiment. As the temperature of a movable heater at the far end of the glass tube heats the sample to a maximum of 130°C (266°F), the succinonitrile material at the end of the sample melts. The heater is then moved down the length of the tube, melting the solid in a controlled manner. During this step most of the bubble activity is observed and recorded. Then the direction is reversed, and the tube moves through a cold section of the thermal furnace (the succinonitrile solidifies at about 13°C [55°F]) where the liquid is directionally resolidified. Each experimental run lasts 10 to 12 hours.

Video plays a crucial role in this experiment, providing a visual record of the way bubbles form, move, and interact as the sample melts and later resolidifies. The science team hypothesized that the bubbles would travel to the hotter end of the sample through the applied temperature gradient, with bigger bubbles moving faster than the smaller ones. The video confirmed their hypothesis, recording the movement of bubbles emerging from the "centerline crack" during melting. During the solidification portion of the experiment, bubble generation between dendrites was observed as well as the formation of defects known as "rat tails."

The PFMI investigation, with its ability to control and visualize melting and solidification over a wide range of temperature gradient and translation parameters, is enhancing our knowledge of bubble movement and porosity, liquid-solid interface dynamics, and solidification phenomena. Results from this ongoing study are expected to benefit materials scientists on Earth as well as future flight experiment investigators.

This is the first use of the PFMI apparatus in the ISS glovebox facility. It has well demonstrated its capability, and Grugel believes its generic design makes it a potential candidate for use in future investigations.

Baffling Flows in Microgravity

Better semiconductors could mean improvements and innovations in technologies for a range of fields from telecommunications to medicine to manufacturing. An experiment recently conducted on the ISS may play a role in helping industry to grow better crystals of semiconductors and bring about a new generation of semiconductor capability.

On Earth, buoyancy forces cause a fluid motion called convection that can be undesirable during materials processing. During semiconductor crystal growth in particular, buoyancy forces can cause an uneven distribution of dopants, or impurities used to control the properties of the crystals. If dopants are not properly distributed in the crystal as it grows, the electronic and optical properties of the semiconductor are degraded, potentially reducing their ability to transmit signals using electrons and photons. In microgravity, these buoyancy forces can be reduced by a factor of up to 1 million. Nevertheless, analyses of crystals previously grown in space have indicated that a weak motion can still persist in a melt even in microgravity, interfering with the hypothetical convection-free process. SUBSA experiment, run by PI Aleksandar Ostrogorsky, of Rensselaer Polytechnic Institute, Troy, New York, tests the use of a submerged baffle during the solidification of semiconductor crystals from a melted material to further reduce or control convection in microgravity.

For this investigation, tellurium and zinc are added as dopants to molten indium antimonide specimens that are cooled by directional solidification to form a single solid crystal. The baffle placed inside the melt limits the length of the solidifying liquid column and aids in reducing convective motion, while microgravity further helps to establish an extremely calm environment that can provide scientific data of high precision. After growth, the distribution of the dopants will be measured and can indicate the degree of convection that existed during the growth process. The microgravity environment will enable scientists to enhance their theoretical knowledge of the crystal growth process.

From July 11 to September 10, 2002, Expedition Five's Science Officer Peggy Whitson conducted a series of experiment runs for the SUBSA investigation on the ISS. SUBSA has the distinction of being the first investigation to be conducted in the Microgravity Science Glovebox after its installation in the Destiny laboratory module on the space station. During experiment operations, a real-time video camera was focused on transparent ampoules containing samples that were melted in the SUBSA furnace. The camera sent images to Earth so that the progress of the experiment could be observed directly by the investigator and his team. Thus, during the melting of the material, the movement of the liquid-solid interface toward a solid single crystal seed could be observed and crystal growth initiated on command when a small amount of the seed had melted. Movement of the interface in the material was observed during both heating and cooling cycles, and appropriate actions were taken by the experimental team through the command capability of the Telescience Support Center.

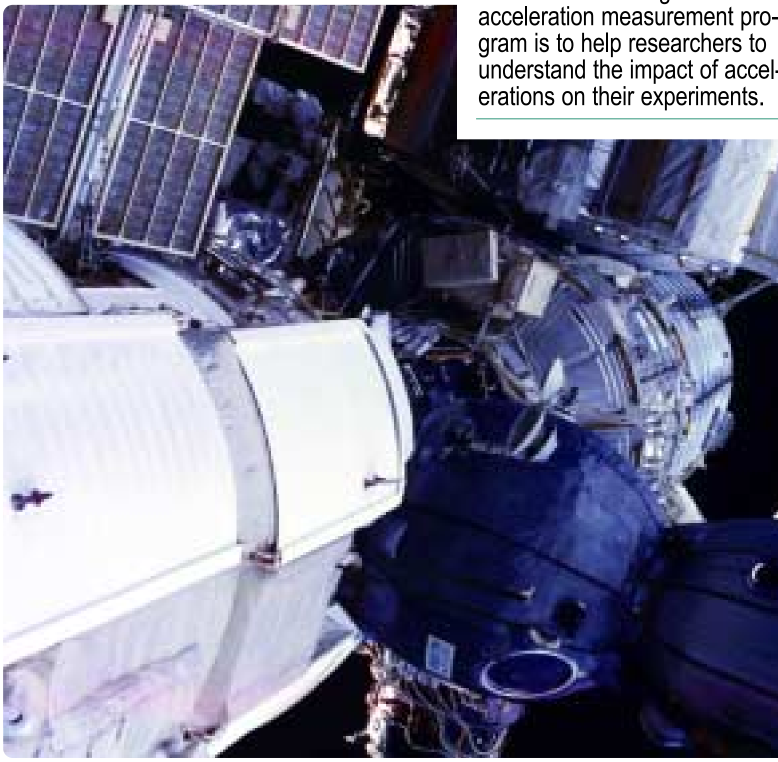
With the return of the samples to Earth, the effectiveness of the baffle will be determined after the samples have been comprehensively analyzed. As a bonus to the management of the crystal seeding, the real-time images allowed scientists to make a direct measurement of the solidification rate, leading to more accurate data. The information obtained during the SUBSA experiments will increase the knowledge and understanding of the solidification process in microgravity and determine how effective baffles can be in producing quality semiconductors in orbit. Furthermore, data will be used as a guide for future ground-based research. If the experiments yield the expected results, directional solidification with the baffle may become a useful technique for future crystal growth in space.

credit: NASA

One of the first materials science experiments on the space station, the Solidification Using a Baffle in Sealed Ampoules investigation was also the first experiment to be run in the newly installed Microgravity Science Glovebox. Principal Investigator Aleksandar Ostrogorsky examines one of the sealed ampoules.

OVERVIEW

For many ISS experiments constant microgravity conditions are essential. Disturbances such as those created by a Soyuz spacecraft docking with the space station can affect experiment results. The goal of the acceleration measurement program is to help researchers to understand the impact of accelerations on their experiments.



credit: NA

Variations in the quality of a microgravity environment can have an adverse effect on experiment results. Sometimes the very tools that enable an experiment to be conducted in microgravity can be responsible for these variations. Experiment hardware, crewmembers, and even the flight vehicle itself can cause accelerations, commonly known as vibrations, that affect microgravity levels and disturb sensitive experiments. Because accelerations can cause convection, sedimentation, and mixing in microgravity science experiments — effects that researchers experimenting in microgravity generally wish to avoid — information about accelerations is critical to the interpretation of science experiment results. Acceleration measurement is the process by which data that describe the quality of a microgravity environment are acquired, processed, and analyzed. The data are then passed on to microgravity principal investigators (PIs) to aid them in analyzing the results of their own investigations.

Experiments are usually conducted in microgravity to avoid the by-products of gravity, such as buoyancy-driven convection and sedimentation; however, accelerations can strongly influence fluid motion and the motion of particles or bubbles in fluids. For example, in materials science experiments, heavier elements such as mercury tend to settle out of solution when subjected to steady accelerations. Such settling can also damage protein crystals grown in biotechnology experiments. Convection due to low-frequency accelerations tends to cause hot gases in combustion experiments to move. Fluid movement due to accelerations may mask fluid characteristics, such as surface tension forces, that the experimenter wishes to observe. Mechanical vibrations over a wide range of frequencies may cause drastic temperature changes in low-temperature physics experiments, where the samples are at temperatures close to absolute zero.

Program Summary

Accurate measurement of the microgravity conditions during a spaceflight is crucial. PIs use acceleration data to determine the influence of accelerations on their experiments in order to gain a more accurate picture of the phenomena under observation. The primary objective of the acceleration measurement program is to characterize the reduced-gravity environment of the various experiment carriers, such as the space shuttle; Russia's former space station, *Mir*; sounding rockets; parabolic flight aircraft; drop towers; and the International Space Station (ISS).

Devices used to measure the quality of a microgravity environment onboard the various experiment carriers are known as accelerometers. Several different accelerometer units have been developed to meet the requirements of a wide range of experiments and, initially, to fly aboard different experiment carriers. Although developed separately, the systems all complement each other in their measurements. Quasisteady sensors measure the microgravity environment for low-frequency accelerations. Vibratory sensors measure higher-frequency accelerations (up to 400 hertz, Hz).

Current Space Acceleration Measurement Sensors (SAMS) operational systems include the following:

• Remote Triaxial System (RTS) — an ISS vibratory system (0.01–400 Hz). There is an RTS in every EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Rack with Active Rack Isolation System capability and in the Microgravity Science Glovebox (MSG), and there are two RTS Drawers in EXPRESS Rack 1.

• Microgravity Acceleration Measurement System (MAMS) — an ISS system using a quasisteady sensor (direct current to 1 Hz) and a vibratory sensor (0.01–100 Hz). It is deployed in EXPRESS Rack 1.

• Triaxial Sensor Head–Free Flyer (TSH–FF) — used to support ground facilities and aircraft operations (0.01–400 Hz).

• Parabolic Acceleration Rating System (PARS) — deployed on the KC-135, PARS provides a rating number to the pilots and acceleration data to the researchers. It utilizes a TSH–FF sensor head.

• Triaxial Sensor Head–Ethernet/Standalone (TSH–ES) — will be deployed for the first time on the Fluids and Combustion Facility and the Combustion Integrated Rack on the ISS. It greatly reduces the size and power required by the RTS with the same performance.

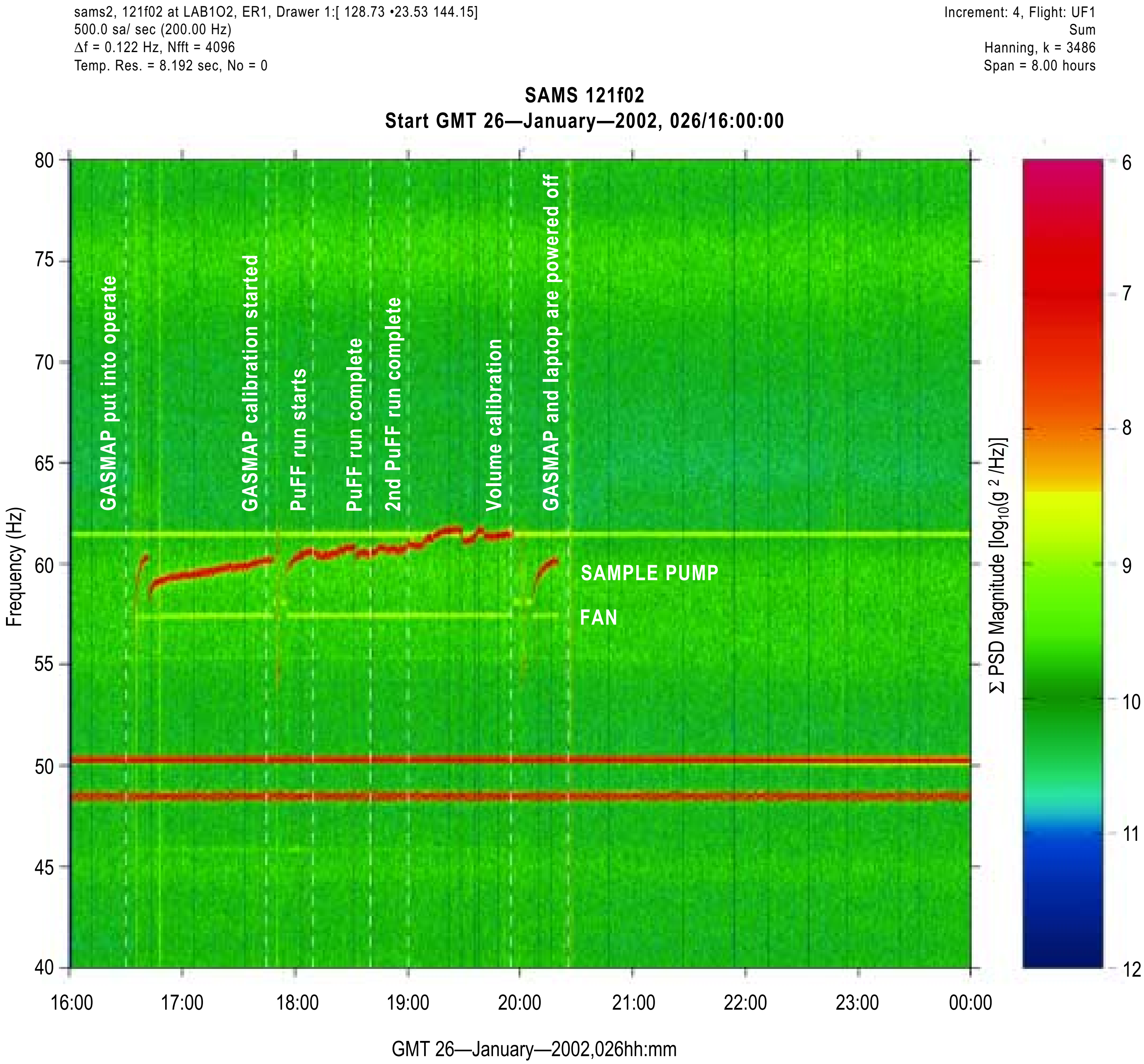
• Roll Rate Sensor (RRS) — enables the measurement of rotational accelerations by using a fiber optic gyroscope. It has been used on sounding rocket and space shuttle flights.

Helping researchers better understand the microgravity environment that their experiments will be exposed to and teaching them how to quantify and analyze the impact of such an environment on their experiments is the goal of the acceleration measurement program's Microgravity Environment Interpretation Tutorial. For the fourth and fifth consecutive years, the acceleration measurement program offered its tutorial to PIs and project scientists in the Physical Sciences Research Division during three-day sessions in Cleveland, Ohio, March 6–8, 2001, and March 5–7, 2002. The tutorials covered topics in accelerometer instrumentation, data collection and analysis techniques, the quality of the microgravity environment on NASA's various carriers, and the implications of those environments for microgravity experiments. A 500-page reference book provided participants with a guide to maximizing the success of their microgravity research.

PIs were also invited to attend the 20th International Microgravity Measurements Group meeting, held August 7–9, 2001, in Cleveland. During the meeting, talks about the ISS, the effects of microgravity accelerations on scientific experiments, the various acceleration measurement systems, and analysis of acceleration environment data were presented to U.S. and international representatives from each of the physical science disciplines and to other ISS program participants. Proceedings were made available on CD-ROM.

In addition to sharing information with investigators, the acceleration measurement program educates astronauts about the microgravity environment. On January 28, 2002, Principal Investigator Microgravity Services (PIMS), a team that supports researchers with data analyses of the microgravity environment, conducted a training session with the astronaut candidate class at Johnson Space Center (JSC) in Houston, Texas.

Seventeen astronaut candidates attended and learned about the effect of accelerations on experiment results, sources of disturbances to the environment, means of maintaining the desired environment, and methods PIMS uses to analyze and present the environment data. The session leaders also explained how the astronauts themselves contribute to the environment (e.g., by exercising) and offered suggestions for how astronauts can minimize the generation of vibrations as they work in spacecraft. Crews for ISS increments 2–9 were also trained in the operation of SAMS and SAMS subsystems as well as in interpretation of the data.



credit: NASA

PIMS takes data from SAMS and MAMS and displays it in a format that shows researchers when and at what frequency vibrations occur on the ISS. Here the vibrations associated with the use of Human Research Facility Gas Analyzer System for Metabolic Analysis Physiology (GASMAP) hardware to study the effects of space walks and long-term exposure to microgravity on pulmonary function (PuFF) are presented.

A one-day introductory Microgravity Environment Interpretation Tutorial was held October 10, 2002, and the 21st International Microgravity Measurements Group meeting was held October 11, 2002, as associated events of the World Space Congress in Houston, Texas. The training was a condensed version of the regular three-day training offered by PIMS. The meeting of the International Microgravity Measurements Group included presentations on predictions of ISS microgravity conditions in given situations, improvements to space accelerometers, and environment concerns of experiments, as well as discussions by members of the International Partners program. Offering the training and holding the meetings during the World Space Congress — a once-a-decade event attended by thousands of scientists, engineers, and space science–interested public from around the world — made the events more accessible to many more international participants.

Flight Experiments

In fiscal year (FY) 2001, operation of accelerometers aboard the ISS began. SAMS subsystems — MAMS, the RTS, and the Interim Control Unit (ICU) — were ferried to the ISS on STS-100 in April 2001 and installed. The MAMS subsystem began operations in May, and the RTS and ICU subsystems began operation in June. The SAMS subsystems have operated on ISS with very little need for diagnostics or corrective actions. Most operational trouble has been related to rack or ISS subsystem problems associated with the growing pains of operating new equipment on a new space platform.

The PIMS project has analyzed thousands of hours of SAMS and MAMS data from the ISS. Analyses have included the following activities and conditions: space shuttle dockings to the ISS; *Progress* dockings to the ISS; ISS systems and subsystems operations; science experiment operations; crew exercise, nominal operations, and sleep periods; ISS vehicle attitudes and methods of control; and extravehicular activity for ISS assembly and maintenance.

Tasks for the project team supporting these instruments for the first year and a half of operations have included monitoring flight and ground systems, maintaining continuous contact with JSC and Marshall Space Flight Center employees by using pagers, maintaining console operations on an as-needed basis, archiving instrument health and status data, and supporting increment transitions.

In June 2002, space shuttle mission STS-111 delivered two sensor head electronic enclosures to the ISS. They were installed in the MSG and EXPRESS Rack 3, facilities that support investigations in a variety of disciplines on the ISS.

A new SAMS vibratory sensor head to simplify the installation and operation in users' equipment was designed in FY 2002. The new sensor head will become the primary sensor for vibratory acceleration measurement, with the same or better performance capabilities, but in a smaller package. In an effort to further reduce resources for acceleration measurement systems, a TSH-MEMS concept was developed during FYs 2001 and 2002. This head will provide acceleration measurement from 1 to 400 Hz and will complement the TSH-ES.

The acceleration measurement program analyzes the actual microgravity environment during space missions, but it also helps to predict what that environment will be. In 2001, the Engineering Design and Analysis Division at Glenn Research Center (GRC) in Cleveland, Ohio, acquired the function of producing predictive analyses of the ISS microgravity environment. This effort contributes to ensuring that the ISS and its payloads will be creating a world-class microgravity acceleration environment for the science experiments conducted onboard. Support and assistance to PIs is also offered through experiment modeling and the division's experience in how science experiments can impact and be impacted by the microgravity environment.

Before experiments and equipment are installed on the ISS, their effect on the environment can be tested. GRC's Microgravity Emissions Laboratory (MEL) is a one-of-a-kind laboratory that simulates and verifies acceleration emissions generated by ISS payloads and their components, including disk drives, pumps, motors, solenoids, fans, and cameras.

MEL uses a low-frequency acceleration measurement system for the characterization of rigid body inertial forces generated by various operating components of the ISS. Twenty-six tests in MEL between May 2000 and December 2002 have included ISS subsystem components, payload rack subsystem components, payload components, and entire payloads. The weight capacity of the facility has been increased to accommodate tests of equipment at an ISS rack–level weight. The Physics of Colloids in Space (PCS) experiment hardware was tested in MEL May 4–10, 2000. The Zeolite Crystal Growth (ZCG) flight hardware was tested January 23–26, 2001, and backup flight hardware was tested April 15–19, 2001. The wire rope isolators with the air thermal control unit fans and housing assembly of the Fluids and Combustion Facility were tested in MEL on November 1, 2001. The Lord isolators for the Light Microscopy Module were also tested in MEL June 2–14, 2002.

The PCS and ZCG experiments were tested in the emissions laboratory to define on-orbit vibratory disturbance predictions. The PCS and ZCG tests were successful, and payload integrators were provided with

credit: NASA

It is important for ISS crewmembers to exercise to maintain their health in a microgravity environment. Crewmembers also participate in biomedical research experiments by jogging on treadmills and undertaking other exercise-related activities. The acceleration measurement program records and analyzes the small vibrations caused by such necessary activities and makes the data available to researchers.

the necessary information to determine their compliance to ISS requirements. The MEL test data of the PCS experiment apparatus has been validated against flight measurements of SAMS data from ISS operations.

The Fluids and Combustion Facility and Light Microscopy Module projects have both used the MEL laboratory to demonstrate the effectiveness of vibration isolators for their projects. MEL was utilized to define the most effective isolator treatments during the design phase of the engineering level hardware. Flight design changes were implemented due to the initial MEL characterization of the vibration response expected from component hardware. Both of these projects have also utilized the MEL component data to predict flight rack–level vibratory disturbances.

On January 5–16, 2001, MEL contributed to NASA's goals for future space exploration by providing transmissibility characterization of two opposing Stirling Technology Company's 55-Watt Technology Demonstration Converters that are to be installed into a power system for onboard electric power for NASA deep space missions. The MEL testing was a part of a successful technology advancement of the development of these power converters.

Highlights

Minimizing Shake, Rattle, and Roll

Most of the experiments aboard the ISS are there to take advantage of the microgravity environment afforded by low Earth orbit. But even the smallest motions, such as the subtle vibrations created by movement of the crew or hardware (such as the robotic arm), can affect those experiments by changing the microgravity environment aboard the ISS. The Active Rack Isolation System (ARIS) is designed to mitigate the effects of such vibrations by absorbing the shock of motion and thereby protecting experiments from that motion.

Currently operating on the ISS, the ARIS system is connected to Rack 2 of the EXPRESS program, a facility that is accommodating early ISS investigations in a variety of disciplines. The ability of ARIS to isolate the experiments in EXPRESS Rack 2 from minor disturbances and vibrations is being analyzed in an experiment of its own called the ARIS ISS Characterization Experiment (ICE).

ARIS operates by using sensors that detect disturbances on the ISS. When a disturbance is detected, the ARIS actuators deliver a reactive force to the rack to counter the effects detected by the sensors. In effect, ARIS acts as a shock absorber for EXPRESS Rack 2.

credit: NASA

This shaker device was used to create known distubances in EXPRESS Rack 2 to test the Active Rack Isolation System (ARIS).

ARIS, however, is much more complex than the shock absorbers that you might find on your car. ARIS components include accelerometer assemblies that measure disturbances and send that information to the electronic unit, “push rods” that apply force against the ISS framework, and a microgravity rack barrier that prevents accidental crew disturbances of the ARIS rack. During ICE, the on-orbit vibration-reduction capabilities of the ARIS system will be examined. ICE in part involves the use of a shaker unit that has been installed in EXPRESS Rack 2. The shaker unit provides a precise, measurable disturbance that will allow ground controllers to evaluate the efficacy of ARIS.

NASA expects ARIS to play a key role in the successful completion of a number of biological, chemical, and physical science experiments that depend on a microgravity environment for obtaining useful data. Through its ability to help maintain a disturbance-free microgravity environment aboard the ISS, ARIS will contribute to the advancement of scientific knowledge on Earth and to the success of the ISS as a space-based scientific laboratory.

Team Develops Award-Winning Software

Innovative software developed by the Principal Investigator Microgravity Services (PIMS) team received a Space Act Award and was a first runner-up for the Software of the Year Award in 2002.

The new Microgravity Analysis Software System collects, archives, and processes acceleration data on a continuous, untended basis and broadcasts uninterrupted analyses of the microgravity environment on the Internet so that PIs in the ISS program and other interested parties have real-time access to data. The group has developed new techniques appropriate for analyzing the vast amount of microgravity acceleration environment data being acquired from the complex ISS vehicle and its variety of operational modes.

The PIMS team provides critical support to PIs and other Physical Sciences Research Division participants in spaceflight missions, such as vibration isolation programs. To do this, PIMS must provide acceleration analyses both in real time during missions and after spaceflight, as well as respond to requests to analyze specific aspects of the microgravity environment from archived data. In addition to real-time analyses, PIMS publishes Increment Reports describing the ISS microgravity environment for periods of several months at a time and prepares custom reports or data sets specifically requested by individual researchers.

The International Space Station (ISS) provides researchers with a permanent orbiting laboratory in space where one of the fundamental forces of nature — gravity — is greatly reduced. Conducting research in this facility will enable world-class scientists from a variety of discrete fields, as well as across a wide range of multidisciplinary pursuits, to obtain research results that are impossible to reproduce in any other venue. The benefits of a permanent human presence in space aboard the space station are expected to be infinite in scope, enhancing our understanding of fundamental scientific processes and bringing exciting new applications to benefit humans both on Earth and in their exploration of space.

The physical sciences division will contribute enormously to these discoveries through the development of science experiments that can benefit from the unique environment the ISS provides and through the application of knowledge gained about the microgravity environment to exploration initiatives planned by NASA. To that end, the Physical Sciences Research Division has designed several multiuser experiment facilities specifically for long-duration scientific research aboard the ISS. To obtain an optimal balance between science capabilities, costs, and risks, facility requirements definitions have been aligned with evolving space station capabilities. These facilities are the Biotechnology Facility (BTF); the EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Racks; the Fluids and Combustion Facility (FCF); the Low-Temperature Microgravity Physics Facility (LTMPF); the Materials Science Research Rack-1 (MSRR-1); and the Microgravity Science Glovebox (MSG). Their descriptions appear below.

Space Station Facilities for Microgravity Research

Biotechnology Facility (BTF)

The Biotechnology Facility is designed to meet the requirements of the science community for conducting

credit: NA

The International Space Station provides a unique environment in which scientists from a variety of disciplines can conduct research nearly free from the effects of gravity.

low-gravity, long-duration biotechnology experiments. The facility is intended to serve biotechnologists from academic, governmental, and industrial venues in the pursuit of basic and applied research. Changing science priorities and advances in technology are easily accommodated by the BTF's modular design, allowing experiments in cell culture, tissue engineering, and fundamental biotechnology to be supported by this facility.

The BTF brings space science forward from the era of the space shuttle payload to the new age of the long-term space laboratory and will elevate space research productivity to a level that is consistent with the productivity of ground-based laboratories. The BTF will be operated continuously on the ISS. It is a single-rack facility with several separate experiment modules that can be integrated and exchanged with each space shuttle flight to the ISS. The facility provides each experiment module with power, gases, thermal cooling, computational capability for payload operation and data archiving, and video signal handling capabilities. Able to process 3,000 to 5,000 specimens a year, the BTF will provide sufficient experimental data to meet demands for objective analysis and publication of results in relevant journals. Careful design of experiments can result in the publication of two to five primary articles per year. Validation of BTF concepts and operations were successfully completed onboard the Russian space station, *Mir*, using the Biotechnology System (BTS). The BTS served as an important risk-mitigation effort for the BTF, demonstrating the technology and systems that will support biotechnology investigations for long-duration operations.

In fiscal year (FY) 2002, the BTF project team initiated the requirements definition phase, which involves defining the engineering aspects of operating the facility in space. A system requirements review (SRR) was held in July 2002, and the science requirements and system specifications were baselined later in the year. Currently, preparations for the facility's preliminary design review (PDR) are under way. The scheduled launch date for the first phase of the BTF facility is late 2006.

Biotechnology research during the early phases of the ISS will be conducted using a modular accommodations rack system known as the EXPRESS Rack. The EXPRESS Rack requires individual experiments to develop additional capabilities and involves science implementation trade-offs. The EXPRESS Rack will hold currently existing biotechnology equipment previously flown on the space shuttle and on *Mir*. It will also accommodate the first operation of equipment built specifically to meet space station requirements.

EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Racks

The EXPRESS Rack is the standardized payload rack system that transports, stores, and supports ISS experiments. The EXPRESS Rack is housed in an International Standard Payload Rack (ISPR) — a refrigerator-sized container that provides the shell for the EXPRESS Rack — and supplies standard interfaces between the space station and the payload. EXPRESS Rack payloads can be operated from the payload front panel, from the EXPRESS Rack front control panels, by the ISS crew, or from the ground.

The EXPRESS Rack includes both elements that remain on the ISS and elements that travel to and from the ISS. While the racks remain on the ISS, experiments may be changed out as needed. Payloads may use the entire rack or a portion of the rack. If more than one payload is included in one rack, the payloads can be operated individually. By providing a design into which research modules can be integrated, the rack helps to reduce the cost in money, time, and complexity of developing payloads, thereby making the microgravity environment of low Earth orbit more accessible to researchers from academia, government, and industry. When construction on the ISS is completed, a total of six EXPRESS Racks will be included on board.

The EXPRESS Racks support payloads from a variety of research disciplines, including biology, physics, chemistry, ecology, and medicine. Various modules that have been designed for use in the EXPRESS Racks are described in the following paragraphs.

The Apparatus for the Study of Material Growth and Liquids Behavior Near Their Critical Point (DECLIC) facility is being developed by the French space agency (CNES) in cooperation with Glenn Research Center (GRC) in Cleveland, Ohio, to provide a compact autonomous or tele-operated capability for fluids research. The facility consists of two middeck lockers that will fit into an EXPRESS Rack. It will support research on fluids near the critical point and transparent materials systems during solidification, as well as other fluids experiments that are compatible with available imaging, interferometric, and light scattering diagnostics. Through cooperative interagency agreements signed in early 2000, NASA will provide launch, integration, and resources for DECLIC and will share in the utilization of the facility.

An experiment-specific insert is being developed for the DECLIC facility to support research related to testing the theories that describe nontraditional forces at the diffusive interface in flow regimes. The insert is expected to be operational in 2006.

Fluids and Combustion Facility (FCF)

The Fluids and Combustion Facility is a modular, multiuser facility that will be located in Destiny, the U.S. laboratory module of the ISS, and will accommodate sustained, systematic microgravity experimentation in both the fluid physics and combustion science disciplines. The FCF flight unit consists of two powered racks called the Combustion Integrated Rack (CIR) and the Fluids Integrated Rack (FIR). The CIR, to be deployed to the ISS in FY 2004, and the FIR, to be deployed to the ISS in FY 2005, will be linked by fiber optic cable to provide direct communication between the two racks, resulting in a fully integrated FCF system. The two racks will operate together with payload experiment equipment, ground-based operations facilities, and the FCF ground unit. The facility will also support experiments from science disciplines other than fluids and combustion and commercial and international investigations.

The FCF is being developed at GRC. A contract called the Microgravity Research Development and Operations Contract was initiated by GRC in FY 2000 for primary development of the FCF by Northrup Grumman, who will also develop, integrate, and support the operation of the initial FCF combustion science and fluid physics payloads. The FCF preliminary design review was successfully accomplished in FY 2001, which led to the completion of engineering model designs. In FY 2002, the FCF successfully finished the assembly and checkout of the CIR and FIR engineering model units. Results of environmental and performance testing of the CIR and FIR engineering model units are being used to finalize the flight design in preparations for the FCF critical design review in early FY 2003.

The Granular Flow Module (GFM) is a minifacility initially designed to conduct three microgravity granular experiments in the FIR on the ISS. Granular materials, such as dry sand, soil, and powders, exhibit flow characteristics that are similar to those of liquids in some ways, but quite different in other ways. The microgravity environment provides data on granular materials that cannot be collected on Earth, where gravity collapses the materials so quickly that scientists cannot take measurements of their movement. Studying the flow of granular materials will further the understanding of design models for soil movement under confinement and various stresses, including shear stress, which is the force that causes two objects (e.g., grains of sand) to slide relative to each other in a direction parallel to their plane of contact. These models can be applied to strengthening building foundations, managing undeveloped land, and handling powdered and granular materials in chemical, agricultural, and other industries.

The GFM will provide three experiment shear apparatuses; a multispeed low/high-frame-rate camera; the ability to supply and remove the spheres used to model granular flow; and systems to control the rotation of the boundaries, stress measurement, and nitrogen flow.

The GFM will allow for on-orbit operations through imbedded software. The software will control the experiment operations, data collection, and data transfer to the ground. The module will also allow for ground control. The GFM will permit on-orbit reconfiguration and maintenance that can support follow-on experiments. The ISS and the FIR will provide many significant functions and resources to the GFM. The ISS will provide the space platform and communication to ground for the FIR. The FIR supplies an environmentally controlled space, an optic bench, power, cooling fluid and gas, vacuum exhaust, avionics, image processing, data storage, and additional science diagnostic hardware. The facility is designed to minimize vibration transmission to the experiment shear apparatus, the FIR, and the ISS, as well as to minimize crew time, power requirements, and mass.

The Light Microscopy Module (LMM) will be the first integrated payload into the FIR aboard the ISS. The development of the LMM, an automated, remotely controllable microscope for experiments in complex fluids, has made tremendous progress toward the critical design of the spaceflight hardware. The LMM is planned as a subrack facility, allowing flexible scheduling and operation of fluids and biotechnology experiments.

The LMM flight unit features a modified commercial off-the-shelf Leica RXA microscope, which is enhanced to operate automatically with some interaction from the ground support staff or the astronaut crew. A researcher can choose from six objective lenses of different magnifications and numerical aperture to obtain the required science data. In addition to video microscopy techniques used to record sample features, including basic structures and crystal growth dynamics, the microscope is modified and enhanced to provide the following additional capabilities: interferometry to measure vapor bubble thin-film thickness, laser tweezers for sample particle manipulation and patterning, confocal microscopy to provide three-dimensional visualization of sample structures, and spectrophotometry to measure photonic properties. This suite of measurements allows a very broad characterization of fluids, colloids, and two-phase media, including biological samples. The LMM will use cameras and light sources provided by the FIR to accomplish these imaging techniques.

The LMM will receive power, communications, air and water cooling, vacuum exhaust, avionics, image processing, data storage, and additional science diagnostic hardware from the FIR rack. The LMM will be installed while the ISS is in orbit, and will remain in the FIR for a period of 30 months performing five separate fluid physics experiments.

Low-Temperature Microgravity Physics Facility (LTMPF)

The Low-Temperature Microgravity Physics Facility is a complete cryogenic laboratory that will be attached to the Japanese Experiment Module–Exposed Facility (JEM-EF) on the ISS. The LTMPF consists of two identical dewars, each of which can support two experiments in parallel operations. The facility is designed for studies of low-temperature (as low as 1.6 kelvins) and condensed matter physics.

The LTMPF project made significant progress in finalizing the critical design of the facility subsystems for its first mission (M1). In preparation for a system critical design review previously scheduled for November 2002, the project successfully held a series of thorough and in-depth technical peer reviews for all subsystems and M1 instruments during September and October 2002. The peer reviews validated critical designs in all key areas and examined the plans and readiness for flight fabrication, integration, and test. Schedule-critical hardware development is well under way, with substantial progress made in the areas of flight dewar fabrication, dewar welding, flight computer and key electronics boards, M1 flight instrument sensor packages, and common flight hardware such as superconducting quantum interference device sensors.

A two-year delay of the JEM-EF launch and budget reductions had a significant adverse impact on the LTMPF's development. Critical flight design and development were scaled back, and the project went through a major replanning process at the end of calendar year 2002. As a result, the LTMPF will not be available for use by researchers until July 2007. Other major milestones for the M1 mission are delayed accordingly, with the system's critical design review now scheduled in September 2003. Additional options for attaching the LTMPF to the ISS are also being considered.

Materials Science Research Rack-1 (MSRR-1)

The MSRR-1 is being developed to provide a flexible, permanent platform in the U.S. Laboratory module dedicated to investigations in materials science. This facility will support research on a range of materials, including metals and alloys, glasses, electronic materials, ceramics, polymers, and other special purpose materials. The MSRR-1 will be composed of experiment modules and module inserts that can be delivered to the ISS by the space shuttle, then integrated and exchanged by crew members aboard the station. In its initial configuration, the MSRR-1 will house two independent experiment modules, each designed for different materials processing techniques. Both experiment modules can operate simultaneously, sharing common subsystems and interfaces required for the operation of experiment hardware. This design concept avoids the need for developing and deploying redundant support systems for each type of investigation. The MSRR-1 is being developed to provide cost-effective, productive near-term and long-range approaches for performing science investigations in the microgravity environment on the ISS.

credit: N

With its standardized hardware interfaces streamlined approach, the EXPRESS Ra enables quick, simple integration of mult payloads aboard the International Space Station.

The MSRR-1 successfully passed the phase 2 flight safety review conducted by Johnson Space Center's (JSC's) Payload Safety Review Panel in September 2001. This significant milestone clears the way for construction of ground and flight hardware to proceed. MSRR-1 also completed the integrated payload critical design review in June 2002 and the Marshall Space Flight Center's (MSFC's) Systems Management Office independent annual review in June 2002. The MSRR-1 is currently scheduled for launch in July 2005.

The first experiment module planned for use in the MSRR-1 is the Materials Science Laboratory (MSL), which is being developed by the European Space Agency (ESA). Occupying approximately one-half of the rack, the MSL module will be launched and integrated into the MSRR-1 unit in August 2003. The MSL will accommodate materials processing inserts that contain experiment-specific hardware.

NASA is building a furnace for the MSL called the Quench Module Insert (QMI). The QMI is a high-temperature, Bridgman-type furnace with an actively

credit: NASA

During Expedition 5, Peggy Whitson completes the installation of the Microgravity Science Glovebox in the Destiny module and prepares it for the first series of experiments.

cooled cold zone. It is being designed to create an extremely high-temperature gradient for the directional solidification processing of metals and alloys. Directional solidification is a process by which a long, thin sample is melted, then slowly solidified, starting at one end of the ampoule and proceeding to the other. This technique is useful for studying the solidification behavior of materials and for the growth of high-quality single crystals.

The QMI also has a feature known as "quench capability." This allows the furnace to rapidly freeze the sample at the liquid-solid interface, where most of the interesting science takes place during directional solidification. Quenching preserves this liquid-solid interface, allowing scientists to examine it carefully when the samples are returned to Earth, where researchers can develop models that recreate and explain exactly what was happening during solidification. The QMI successfully completed its phase 2 flight safety review by the JSC's Payload Safety Review Panel in August 2001.

In addition to NASA's QMI, two module inserts are being developed by ESA for the MSL, the Low Gradient Furnace (LGF) and the Solidification and Quenching Furnace (SQF). Both furnaces can accommodate processing temperatures up to 1600°C. The LGF is primarily intended for crystal growth experiments requiring directional solidification processing in which precise temperature requirements and control of translation speed are needed. The SQF will be used for metallurgical experiments requiring large thermal gradients and rapid quenching of samples. Additional module inserts can be developed and processed over the lifetime of the MSL and the MSRR-1.

The second experiment module, completing the initial MSRR-1 configuration, is a commercial research facility: the Space Product Development furnace. This commercial furnace will be replaced in orbit with other NASA materials science modules after approximately one year.

Microgravity Science Glovebox (MSG)

The MSG facility enables scientists from multiple disciplines to participate actively in the assembly and operation of experiments in space with much the same degree of involvement they have in their own research laboratories. Developed by ESA and integrated by MSFC, the MSG was launched to the ISS in June 2002. This facility offers an enclosed work area that is accessible to the crew through sealed glove ports and to ground-based scientists through real-time data links and video. Because the MSG work area can be sealed and held at a negative pressure, the crew can manipulate experiment hardware and samples without the potential hazard of small parts, particulates, fluids, and gases escaping into the open laboratory module.

For conducting investigations, each experiment apparatus is mounted to the floor of the MSG working area (approximately 90 cm x 50 cm) and connected on the back wall to standard utilities such as power, computer communications, and control units. The work area unit is designed to slide forward on rails that can extend out of the volume of the rack. This forms an enclosed "table-top" for experiment containment and operation.

A notable feature of the MSG system is its substantial video, data acquisition, and command and control capabilities. Up to four color cameras are available for viewing and recording experiment processes. Flat-screen monitors can display views of any two of these cameras and simultaneously share the views with the investigator on the ground. The entire system is controllable through computer interfaces either with the onboard MSG computer or via the ISS data system from the ground. These resources allow researchers to adjust experiment processes as they occur, based on the results of their observations.

To facilitate the use of the MSG by the scientific community, MSFC maintains an active group of managers, engineers, and support personnel to assist investigators with the complex task building and operating an experiment in space. Construction of the MSG was completed by ESA in 2001, and the facility was subsequently launched and integrated into the ISS. Prior to the end of FY 2002, the unit had been successfully used to conduct a series of materials science experiments in two different investigations, Solidification Using a Baffle in a Sealed Ampoule and the Pore Formation and Mobility Investigation. In both cases, the teamwork concept inherent in the MSG design demonstrated that enhanced scientific return is possible when the crew and scientists can easily interact.

For future MSG experiments that are particularly sensitive to low-level vibrations, a new device, the Glovebox Integrated Microgravity Isolation Technology (g-LIMIT) apparatus, is undergoing final phases of development and testing. After the g-LIMIT unit has been delivered to the ISS and has completed on-orbit characterization and testing, vibration-sensitive experiments will be mounted to an electromagnetically levitated top plate of the g-LIMIT unit. Specially designed umbilicals will connect experiments to the MSG utilities. Additional experiments, sponsored by both NASA and ESA, are planned for FY 2003. These new experiments will extend the use of the MSG unit to additional disciplines, including biotechnology, combustion, and fluid science.

Table 8 — ISS Flights Significant to the Physical Sciences Research Division

Milestone	Assembly Flight	STS Flight	Launch Date*
U.S. Laboratory Delivery	5A	STS-98	February 20
U.S. Laboratory Outfitting	5A.1	STS-102	March 200
First two EXPRESS Racks, Microgravity Capability	6A	STS-100	April 2001
Phase Two Complete	7A	STS-104	July 2001
U.S. Laboratory Outfitting, Two Additional EXPRESS Racks	7A.1	STS-105	Aug 2001
Utilization Flight	UF-1	STS-108	Dec 2001
Utilization Flight, Fifth EXPRESS Rack, Microgravity Science Glovebox (MSG) Rack	UF-2	STS-111	June 2002
First Utilization & Logistics Flight	ULF-1	STS-114	Under Revi
Spacehab Flight, Continued U.S. Laboratory Outfitting	12A.1	STS-116	Under Revi
Spacehab Flight, Continued U.S. Laboratory Outfitting	13A.1	STS-118	Under Revi
ISS U.S. Core Complete, Node 2	10A	STS-120	Under Revi
Utilization & Logistics Flight, Sixth EXPRESS Rack	ULF-2	STS-121	Under Revi
European Space Agency (ESA) Laboratory (Columbus Module)	1E	STS-122	Under Revi
Utilization Flight, Combustion Integrated Rack (CIR)	UF-3	STS-123	Under Revi
Utilization Flight	UF-4	STS-125	Under Revi
Utilization Flight, Fluids Integrated Rack (FIR), and First Materials Science Research Rack (MSRR-1)	UF-5	STS-126	Under Revi
Utilization Flight, EXPRESS Pallet-1 Alpha Magnetic Spectrometer (AMS)	UF-4.1	STS-127	Under Revi
Utilization Flight	UF-6	STS-128	Under Revi
EXPRESS Pallet-2	1 J/A	STS-129	Under Revi
Japanese Experiment Module (JEM) Laboratory	1 J	STS-130	Under Revi
Utilization & Logistics Flight, Biotechnology Facility (BTF) Science	ULF-3	STS-131	Under Revi
Utilization Flight	UF-7	STS-133	Under Revi
JEM Exposed Facility (JEM-EF)	2 J/A	STS-134	Under Revi
Utilization & Logistics Flight, Seventh EXPRESS Rack	ULF-5	STS-135	Under Revi
EXPRESS Pallet-3 (EP3) Low-Temperature Microgravity Physics Facility (LTMPF)	14A	STS-136	Under Revi

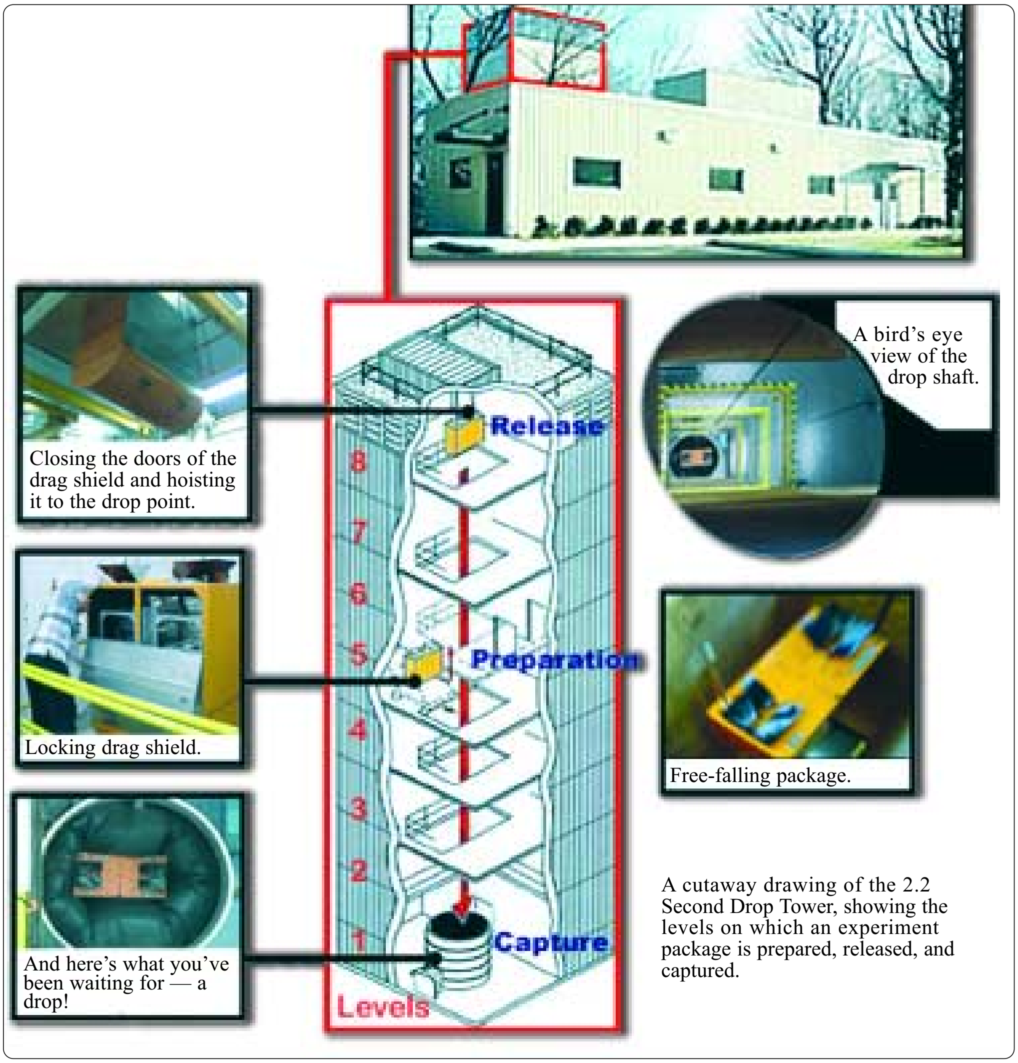
* Launch dates subject to cha

Schedule of Flights

Approximately 25 flight opportunities have been planned to date for the delivery of the U.S. Laboratory module of the ISS and its components (including the microgravity facilities described above), the utilization of the space station for microgravity experiments, and the delivery of modules and racks developed by NASA and its international partners. A list of milestones, flights, and dates significant to the Physical Sciences Research Division are listed in Table 8. Descriptions of flight hardware to support microgravity experiments are listed in Appendix B.

In fiscal years (FYs) 2001 and 2002, NASA continued to maintain very productive ground facilities for reduced-gravity research. These facilities included KC-135 parabolic flight aircraft, the 2.2 Second Drop Tower, and the Zero Gravity Research Facility. The reduced-gravity facilities at Glenn Research Center (GRC) and Johnson Space Center (JSC) have supported numerous investigations addressing a variety of processes and phenomena in several research disciplines. Microgravity, a state of apparent weightlessness, can be created in these facilities by executing a freefall or semi-freefall condition, where the force of gravity on an object is offset by its linear acceleration during a "fall" (a drop in a tower or a parabolic maneuver by an aircraft).

Even though ground-based facilities offer relatively short experiment times of less than 25 seconds, this available test time has been found to be sufficient to advance the scientific understanding of many phenomena. Experiments scheduled to fly on the space shuttle and the International Space Station are frequently tested and validated in the ground facilities prior to being conducted in space. Experimental studies in a low-gravity environment can enable new discoveries and advance the fundamental understanding of science. Many tests performed in NASA's ground-based microgravity facilities, particularly in the disciplines of combustion science and fluid physics, have resulted in exciting findings that are documented in a large body of literature.



credit: NASA

Glenn Research Center's 2.2 Second Drop Tower has a normal throughput capacity of 12 tests per day. Its ease of operation makes it an attractive and highly utilized test facility, particularly for performing evaluation and feasibility tests. The drop tower is able to provide gravitational levels ranging from 1 percent of Earth's gravitational acceleration to 0.01 percent.

JSC's KC-135 is NASA's primary aircraft for ground-based reduced-gravity research and is the only facility that can provide partial-gravity environments similar to those found on the Moon or Mars. The KC-135 can accommodate several experiments during a single flight. Low-gravity conditions can be obtained for approximately 18–25 seconds as the aircraft traces a parabolic trajectory. The trajectory begins with a shallow dive to increase air speed, followed by a rapid climb at up to a 45- to 50-degree angle. The low-gravity period begins with the pushover at the top of the climb and continues until the pullout is initiated when the aircraft reaches a 40-degree downward angle. During the parabola, an altitude change of about 1,800 meters (approximately 6,000 feet) is experienced. More than 50 parabolas can be performed in a single flight. In FY 2001, 36 experiments were performed during 1,604 trajectories over 80 flight hours. Of the 36 experiments supported, 6 were

Table 9 — Use of Ground-Based Low-Gravity Facilities in FY 2001/2002

	KC-135	2.2 Second Drop Tower	Zero Gravity Research Facility
Investigations supported	36/59	25/29	8/10
Drops or trajectories	1,604/1,871	1,241/1,024	174/148
Flight hours	80/108	N/A	N/A

combustion experiments, 29 were fluid physics experiments, and 1 was an exploration research experiment. In FY 2002, 59 experiments were performed during 1,871 trajectories over 108 flight hours. Of these 59 experiments, 24 were in combustion, 30 were in fluid physics, 3 were in materials science, 1 was in fundamental physics, and 1 was in exploration research.

The GRC 2.2 Second Drop Tower offers a shorter test time than the KC-135, but its simple mode of operation and normal throughput capacity of 12 tests per day make it an attractive and highly utilized test facility, particularly for performing evaluation and feasibility tests. The drop tower is able to provide gravitational levels that range from 1 percent of Earth's gravitational acceleration to 0.01 percent. More than 23,000 tests have been performed in the drop tower to date. In FY 2002, the number of drop tests conducted averaged more than 80 per month.

Reduced-gravity conditions in the drop tower are created by dropping an experiment contained within an enclosure known as a drag shield, which isolates the test hardware from aerodynamic drag during a 24-meter freefall in an open environment. Twenty-five experiments were supported during 1,241 drops performed in FY 2001, and 29 experiments were supported during the 1,024 drops performed in FY 2002. As in the past, several of these experiments were aiding the development of research that will be conducted in space. The steady utilization of the drop tower is expected to continue, as many new experiments are in the design and fabrication phases of development for the coming years.

credit: NASA

Investigators can fly experiments aboard NASA's KC-135 turbojet transport, which flies parabolic arcs to produce 20 to 25–second periods of microgravity. This platform allows the investigators to prepare their experiments for the microgravity environment of low Earth orbit.

The Zero Gravity Research Facility at GRC, a registered U.S. national landmark, provides a quiescent low-gravity environment for a test duration of 5.18 seconds as experiments are dropped in a vacuum chamber that goes 132 meters (432 feet) underground. Aerodynamic drag on the freely falling experiment is nearly eliminated by dropping in a vacuum. This procedure restricts drop tests to two per day, resulting in fewer projects supported in this facility than in the 2.2 Second Drop Tower. However, the relatively long test time and excellent low-gravity conditions more than compensate for the lower test throughput rate. In FY 2001, 8 major projects were supported as 174 test drops were executed. In FY 2002, 10 major projects were supported with 148 test drops being completed.

Getting the word out about what microgravity researchers do and why they do it is crucial to maintaining the strength and relevance of the science program. The Physical Sciences Research (PSR) Division outreach and education efforts target a broad audience. That audience includes researchers who have not yet considered the benefits of conducting experiments in microgravity, scientists and engineers in industry, students of all grade levels, instructors and administrators in a variety of educational settings, and the lay public.

credit: NASA

Participants from NASA's Educator Resource Centers receive training in the use of the microgravity demonstrator, also known as the mini drop tower.

credit: NASA

One of NASA's newest educa
tion publications, *How High Is*
made its debut at the annual
National Council of Teachers o
Mathematics conference in Ap
2001. An educator's guide wit
activities focused on scale mo
els of distances was presente
by author Carla Rosenberg, w
led teachers in several hands-
activities from the guide durin
the conference.

Methods for communicating the substance of the program are as varied as the audiences served. Microgravity researchers and support personnel are involved in a number of outreach activities that include visiting classrooms; staffing exhibits at national technical, educational and public outreach conferences; offering tours and open houses at microgravity science facilities; and sponsoring student researchers at NASA centers. In addition, print and World Wide Web (WWW) publications highlighting specific research projects allow the PSR Division to share its information worldwide.

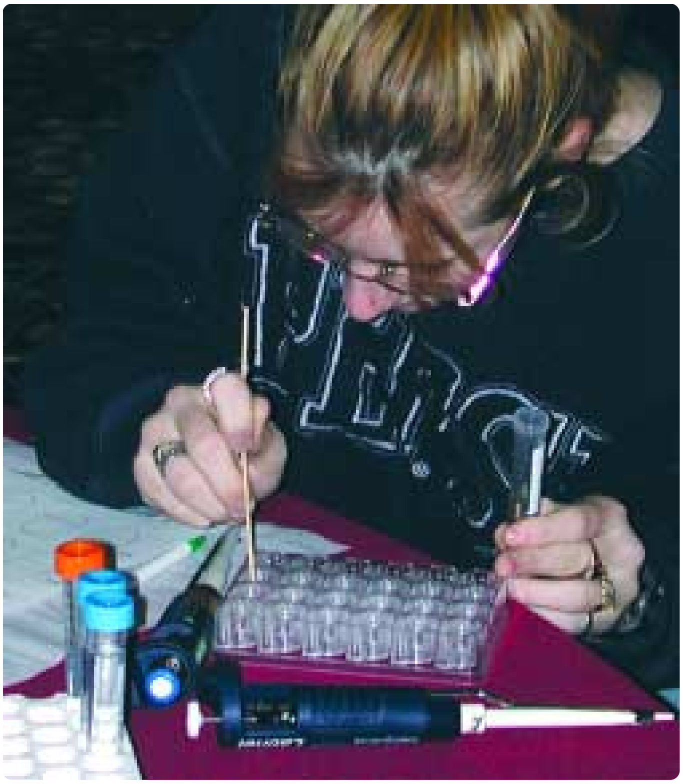
Who said science can't be fun? Students participating in the second DIME competition assemble a plastic pipe structure under water in a scuba exercise similar to the training astronauts receive at Johnson Space Center in Houston, Texas.

credit: NASA

Program Summary

The outreach and education team for microgravity research in the physical sciences has continued to communicate how the microgravity research mission benefits life on Earth and advances the capability of long-term human exploration. In fiscal years (FYs) 2001 and 2002, the outreach and education program supported 24 major educational, scientific, and public outreach conferences with speakers, materials, and exhibits. Some events supported include the Aerospace Science Meeting and the national meetings of the American Institute of Aeronautics and Astronautics and American Association for the Advancement of Science. Outreach and education team members also made many visits to schools, museums, and science centers throughout the country.

Major national educator conferences give NASA the opportunity to demonstrate new ways to teach students about the importance of microgravity research. More than 75,000 elementary and secondary school (K–12) teachers and administrators attended annual meetings of the National Science Teachers Association, the National Council of Teachers of Mathematics, the International Technology Education Association, the National Association of Biology Teachers, and the American Association of Physics Teachers, all of which featured booths staffed by PSR Division personnel. Microgravity science and mathematics posters, teacher's guides, mathematics briefs, microgravity demonstrator manuals, microgravity technology guides, microgravity mission and science lithographs, and WWW microgravity resources sheets were distributed to teachers at these conferences.



credit: NASA

West Virginia students worked with NASA and university scientists to load biological samples for an International Space Station experiment as part of the Student Access to Space program. Once delivered to the space station, the samples thawed and formed crystals to be returned to Earth for further study. The space experiment and the educational workshops were sponsored by NASA's Marshall Space Flight Center in Huntsville, Alabama, and the University of California, Irvine.

The National Center for Microgravity Research K–12 Outreach Program had 12 new educational products in process during FY 2001–2002, including three educator guides. Two of the guides, *How High Is It?* and *Amusement Park Physics With a NASA Twist*, are for middle school teachers and were evaluated in pilot programs. The finalized publications will become available in the spring of 2003. The third educator guide, *Science in a Box: NASA Glovebox Activities in Science, Mathematics, and Technology*, is for high school teachers. This guide contains schematics for fabricating a wooden glovebox with camera, lighting, fan, and power systems. The students can then conduct experiment activities based on either actual glovebox flight investigations or microgravity research in biology, physics, and chemistry.

The PSR Division, along with the Office of Biological and Physical Research (OBPR) and its other research divisions, initiated a formal collaborative effort with the National Association of Biology Teachers (NABT) in FY 2001. The PSR Cell Sciences Program at Johnson Space Center in Houston, Texas, and the Physical Sciences Outreach and Education Program at Marshall Space Flight Center in Huntsville, Alabama, developed a bioreactor education guide targeting high school biology classes. The curriculum supplement, which demonstrates the unique cell and tissue culture research possible using NASA's rotating wall vessel bioreactor, was featured in an NABT workshop. Wayne Carley, executive director of the NABT, commented, "We see NASA research as an incredibly engaging way to bring people into the world of science." Carley finds the cutting-edge fundamental biology research conducted by NASA especially valuable to NABT members: "We have members who teach subjects such as neurobiology and human performance who could use direct examples of space research in these areas in their lesson plans."

The Student Access to Space Program, founded by Alexander McPherson of the University of California, Irvine, teaches students how to perform crystallization experiments in the classroom and on the International

Microgravity News, a quarterly newsletter that covered physical sciences research, was redesigned and renamed *Space Research*. The newsletter now covers all four research divisions of the Office of Biological and Physical Research.

Space Station (ISS). The program uses the Enhanced Gaseous Nitrogen (EGN) Dewar project, an inexpensive, simple, high-capacity system for the crystallization of different samples in space aboard the ISS. Teachers attend workshops where they learn about a classroom version of the experiment and curriculum activities on structural biology. Students also compete to participate in the Protein Crystals in Space Program, where they attend a Student Flight Sample Workshop. They prepare and load actual flight samples into the EGN-Dewar facility, are present at launch, and receive their samples back after flight. This program seeks to reach underserved inner-city and rural schools, special needs and gifted students, and mainstream schools. Approximately 58,000 students and almost 1,200 teachers have been involved in this program so far. Of those, more than 420 students and 260 teachers have been involved in the Student Flight Sample Workshops.

Microgravity News, the quarterly newsletter reporting on microgravity research in the physical sciences, was redesigned and expanded in FY 2001 to cover activities in all four research divisions of the OBPR enterprise. Now called *Space Research*, the newsletter continues to reach thousands of K–12 teachers, curriculum supervisors, science writers, university faculty, graduate students, scientists, principal investigators, and technology developers, among others. Each issue of *Space Research* includes a feature on a topic important to the entire enterprise, research updates for each division, spotlights about special events or awards, meetings, research announcements and selections, and a profile of a member of OBPR's research community. At the end of FY 2002, the distribution for each issue totaled about 20,000 copies, almost double that of *Microgravity News*. *Space Research* has a subscriber base of 8,000 and is mailed to 38 countries. A significant rise has been seen in the number of individuals requesting to be added to the mailing list. Both *Space Research* and archived issues of *Microgravity News* are available on the WWW at *http://spaceresearch.nasa.gov/general_info/prespublic.html#newsletters*.

A key element of outreach is the effective use of images. Images are a critical element in telling a compelling and interesting science story, and the PSR Division outreach team continues to improve its repository of still images for this purpose. The microgravity portion of the web-based image archive at *http://mix.msfc.nasa.gov* grows by approximately 250 new physical sciences images each year and was chosen as the basis for an enterprise-wide image archive for the OBPR in FY 2003. Video is also an important means of communicating about microgravity research. In FY 2002, a lending video library was established by Johnson Space Center's Biological Systems Office Outreach and Education department that is available to scientists and outreach staff to support events such as exhibits and lectures. The library is made up of more than 100 items available in VHS, 8 mm, Mini DV, or CD/DVD format. Topics covered include general program information, flight and ground experiments, and hardware tests.

Table 10 - Physical Sciences Outreach and Education Products Downloaded From Spacelink in FY 2001–2002

Month	Microgravity Teacher's Guide	The Mathematics of Microgravity	Microgravity Video Resource Guide	Microgravity Demonstrator	Microgravity — Fall Into Mathematics	Recipe for Protein Crystallography	How High Is It?	NASA Student Glovebox	Microgravity Bookmark
10/2000	8,402	490	62	132	556				
11/2000	18,154	874	34	150	519	570			
12/2000	4,969	288	52	96	440	186			
1/2001	7,544	434	40	130	435	250			
2/2001	6,199	425	82	172	543	254			
3/2001	6,230	452	84	160	509	258			
4/2001	15,910	507	47	173	487	314			
5/2001	7,525	401	44	203	500	217	3,763		
6/2001	14,512	448	53	192	438	264	1,382	252	
7/2001	6,531	370	91	171	401	326	1,655	466	
8/2001	5,458	304	57	155	393	314	1,390	333	
9/2001	14,550	286	43	118	821	264	874	324	
FY 2001	115,984	5,279	689	1,852	6,042	3,217	9,064	1,375	
10/2001	13,205	478	139	193	489	397	1,312	567	
11/2001	15,829	522	97	317	567	406	1,454	879	
12/2001	9,336	491	133	222	511	486	1,101	285	
1/2002	21,868	386	123	314	553	539	1,280	312	
2/2002	7,975	396	80	221	366	522	1,823	618	
3/2002	12,544	502	128	218	481	544	1,146	365	
4/2002	15,693	449	139	218	586	505	1,601	320	
5/2002	17,910	500	144	344	636	444	1,190	514	
6/2002	17,402	394	126	245	473	458	850	336	
7/2002	12,420	620	394	548	710	709	939	592	
8/2002	9,876	628	424	540	783	769	1,669	2,078	545
9/2002	15,384	725	476	521	869	858	1,312	672	472
FY 2002	169,442	6,091	2,403	3,901	7,024	6,637	15,677	7,538	1,017

Sites on the Internet sponsored by the physical sciences research program continue to serve as clearinghouses of information for the science community, the public, and educators. Hundreds of thousands of Internet users visit these program-sponsored sites each year. The PSR Division's primary web site at *http://spaceresearch.nasa.gov/research_projects/microgravity.html* provides detailed information about microgravity research and highlights of current events and milestones as well as links to other important sites under the physical sciences umbrella. The Microgravity Research Program Office's (MRPO's) web page at *http://microgravity.nasa.gov* provides links to news highlights, information about upcoming conferences, and microgravity-related research announcements, as well as enhanced links to microgravity research centers and projects, educational links, and links to the microgravity image archive. A list of microgravity-related web sites sponsored by the program is presented on page 87.

The Internet also continues to be an important distribution method for microgravity outreach and education products. Efforts were ongoing in FYs 2001 and 2002 to make educators aware of all the microgravity research education products that are available online through the MRPO web site, NASA Spacelink, and the NASA CORE (Central Operation of Resources for Educators) education distribution system. The table above lists several K–12 education products and the number of separate "downloads" for each in FY 2001

credit: NASA

Astronaut Clayton Anderson, a graduate of Iowa State University's aerospace engineering program, participated in two Iowa Communications Network sessions for the NASA-Iowa Connection program. A cooperative project between NASA and Iowa Public Television, this program teaches middle school students about science and technology in space.

and FY 2002. This number is considered a more accurate accounting of actual product use than the frequently used number of hits, because it indicates those users who downloaded the PDF files to their computers.

Highlights

Make the Connection

The "NASA-Iowa Connection: International Space Station Project" is bringing rich learning opportunities to Iowa teachers and students through Iowa's fiber optic and broadcast system known as the Iowa Communications Network (ICN). Marshall Space Flight Center's Education Programs Department and Microgravity Research Program Office are participating in this pilot distance-learning project for the educational communities of Iowa. Twila Schneider, an Infinity Technology Inc. employee based in Huntsville, Alabama, supporting the Microgravity Research Program Office, conducted a workshop on February 27, 2002, for Iowa teachers. She presented an introduction to the basic concepts of microgravity and research conducted in the Microgravity Science Glovebox. The teachers received background information regarding ISS physical sciences research and were provided a guide for making their own classroom glovebox using a standard copier paper box.

Middle school students involved in this distance-learning project designed and constructed models of a future space station from everyday household materials. Students also learned about the ISS and other space-related topics, including space food. Several "Ask the Expert" sessions were conducted for the students. One included scientists from the NASA Food Technology Commercial Space Center at Iowa State University (ISU) in Ames, who explained about how space food was manufactured, packaged, and prepared in space. Astronaut and ISU alumnus Clayton Anderson also participated in this session. If this pilot project is successful, it could be conducted in other states with statewide distance-learning networks similar to the ICN.

Question and Answer Sessions About Space

The Physical Sciences Research Division was heavily involved in the Second Pan-Pacific Basin Workshop on Microgravity Science held in Pasadena, California, May 1–4, 2001. Almost 200 scientists representing 82 universities and 12 countries gathered to share their latest research related to microgravity and the space environment. They also learned firsthand how outreach and education can play a key role in explaining the benefits of their work to large numbers of people. Steven Sample, chairman of the Association of Pacific Rim Universities, one of the hosting organizations, said, "We all recognize the common basic need for increased education and knowledge about the effects of gravity and microgravity in countless areas of our lives."

A few of the scientists shared their work with yet a broader audience during two satellite broadcast sessions held at the California Science Center in Los Angeles. More than 800 students and adults participated in real-time discussions about a variety of topics, from why scientists conduct research in microgravity to why astronauts get "Moon face" when in orbit. Participants were all beneficiaries of NASA's efforts to increase awareness of careers in science and mathematics and identify ways in which members of the public can be involved in NASA science programs.

The first session was geared toward encouraging young people to go into careers in science or mathematics. For this event, the science center hosted more than 100 local high school students and three panelists (a materials scientist, a biologist, and a physician who is a former astronaut). Students at the location, as well as

credit: NASA

Marshall Space Flight Center employees visited DuPont Manual High School in Louisville, Kentucky, as part of an outreach session of the Second Annual Pan-Pacific Basin Workshop on Microgravity Science. Materials engineer Chris Cochrane explains the operation of NASA's Mini Drop Tower to demonstrate freefall.

another 200 students at three other science centers across the country, saw presentations by the panelists and then asked them questions about their research and space travel.

The second session was geared toward building interest in microgravity research among the general public. The session featured presentations on atomic clocks and combustion research along with firsthand accounts of travel on a space shuttle. Viewers at two other U.S. science centers and at Flinders University in Adelaide, Australia, could see the presentations in real time and then ask questions of the panelists: a fundamental physicist, a combustion scientist, and Chiaki Mukai, a Japanese physician who is currently an astronaut. The investigators at the science center explained how their microgravity research resulted in commercial products for use on the ground. As well, Mukai, who flew as a payload specialist on space shuttle flight STS-95, described the experience of being in space and how she performed science experiments during her flight. Participants at both sessions also viewed a short video featuring conversations with students and laypeople from countries around the pan-Pacific Basin about their perspectives on space and space travel.

These outreach and education sessions supported the purpose of the conference, which was to go beyond cultural differences to advance microgravity research and promote the understanding of its importance. As Sample noted, "All these [cultural] differences can be and often are obstacles to communication and understanding, but it's important to remember that people on both sides of the Pacific share quite similar fundamental ideas and goals: to build better societies. And these goals can't be reached without building better-educated societies and without the open sharing of knowledge."

Drop a DIME for Education

The NASA Dropping in a Microgravity Environment (DIME) student competition pilot project came to a successful conclusion April 25–27, 2001, at

credit: NASA

A colored oil flow toy was part of a student-designed experiment used in the 2001–2002 program year Dropping in a Microgravity Environment competition held April 23–25, 2002, at NASA's Glenn Research Center (GRC). Two teams from Sycamore High School, Cincinnati, Ohio, one from Bay High School, Bay Village, Ohio, and one from COSI Academy, Columbus, Ohio, competed by running their experiments on GRC's 2.2 second drop tower.

Glenn Research Center (GRC) in Cleveland, Ohio. The competition involved high school–aged student teams who developed concepts for microgravity experiments and prepared experiment proposals. A team of NASA scientists and engineers evaluated the student team proposals and selected two teams. Mentored by NASA scientists, the two student teams — one from COSI Academy, sponsored by the Columbus, Ohio, Center of Science and Industry (COSI), and the other from Sycamore High School in Cincinnati, Ohio — designed microgravity experiments, fabricated the experimental apparatus, and visited GRC to operate their experiments in the 2.2 Second Drop Tower.

The COSI Academy team investigated the effects of density and phases of matter in a microgravity environment by observing the interaction of soybeans in small bottles of ginger ale. The Sycamore High School team investigated the effects of microgravity on the combustion of cotton — an experiment developed after the team discovered that NASA astronaut clothing is often made of 100 percent cotton. While the pilot year involved teams based in Ohio, for school year 2001–2002, teams based in Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin are eligible. In future years, teams from the 50 U.S. states, Washington, D.C., and Puerto Rico will be eligible.

Microgravity World Wide Web Sites

NASA
http://www.nasa.gov/
NASA current events and links to NASA Strategic Enterprise sites.

NASA Office of Biological and Physical Research
http://spaceresearch.nasa.gov/
Goals and organization of Biological and Physical Research Enterprise, and links to research opportunities.

Microgravity Research Program Office
http://microgravity.nasa.gov/
Information about microgravity research activities with links to an image gallery and related science and technology web sites.

Space Research
http://spaceresearch.nasa.gov/general_info/spaceresearchnews.html
Online issues of *Space Research*, a quarterly newsletter about research in microgravity.

Microgravity Research Task Book and Bibliography
http://microgravity.nasa.gov/tb.html
Descriptions of research funded by the program.

Microgravity Meetings
http://zeta.grc.nasa.gov/ugml/ugmltext.htm
List of meetings, conferences, and symposia related to microgravity research topics.

Marshall Space Flight Center (MSFC)
http://www.msfc.nasa.gov
Information about MSFC, including ongoing research and facilities at the center.

Glenn Research Center (GRC)
http://www.grc.nasa.gov
Information about GRC, including ongoing research and facilities at the center.

Microgravity Science Division at GRC
http://microgravity.grc.nasa.gov
Descriptions of microgravity projects and facilities sponsored by GRC.

Jet Propulsion Laboratory (JPL)
http://www.jpl.nasa.gov/
Information about JPL, including ongoing research and facilities at the center.

Microgravity Fundamental Physics (JPL)
http://funphysics.jpl.nasa.gov
Contains background material, descriptions, and results for fundamental physics experiments funded by the program.

Johnson Space Center (JSC)
http://www.jsc.nasa.gov
Information about JSC, including ongoing research and facilities at the center.

NASA Science News
http://science.nasa.gov
Breaking news stories about NASA science research.

National Center for Microgravity Research on Fluids and Combustion
http://www.ncmr.org/
Information about research and events sponsored by the center.

Microgravity Experiment Data and Information Archives
http://mgravity.itsc.uah.edu/microgravity_experiment_archive.html
Provides searchable information about NASA microgravity flight experiments.

KC-135 Reduced Gravity Research Program
http://jsc-aircraft-ops.jsc.nasa.gov/kc135/
Overview of the program, which uses the KC-135 aircraft to provide brief periods of microgravity for research.

Spacelink – Microgravity Educational Products
http://spacelink.msfc.nasa.gov/
NASA education information, materials, and services.

NASA Human Spaceflight
http://spaceflight.nasa.gov/
Information about all of NASA's spaceflight programs.

Space Shuttle Flights
http://spaceflight.nasa.gov/shuttle/
http://www.ksc.nasa.gov/shuttle/index.htm
Information on the space shuttle missions.

International Space Station (ISS)
http://spaceflight.nasa.gov/station/
http://scipoc.msfc.nasa.gov/factchron.html
Information about the development of the ISS, including links to recent news, details of assembly, and images.

Student Access to Space
http://spacecrystal.nasa.gov
Source for teachers and students interested in the Student Access to Space program.

Microgravity Sciences and Applications Department at MSFC
http://msad.msfc.nasa.gov
Information on projects and events within the department.

NASA Kids
http://www.nasakids.com/
Student-oriented educational guide to space exploration.

Appendix A: Fiscal Years 2001 and 2002 Grant Recipients, by State

(includes some continuing projects at no additional cost)

ALABAMA

J. Barry Andrews
University of Alabama, Birmingham; Birmingham, AL
Coupled Growth in Hypermonotectics
Materials Science
2001–2002

J. Barry Andrews
University of Alabama, Birmingham; Birmingham, AL
The Effect of Convection on Morphological Stability During Coupled Growth in Immiscible Systems
Materials Science
2001–2002

John Baker
University of Alabama, Tuscaloosa; Tuscaloosa, AL
Magnetically-Assisted Combustion Experiment (MACE)
Combustion Science
2001–2002

R. M. Banish
University of Alabama, Huntsville; Huntsville, AL
Self-Diffusion in Liquid Elements
Materials Science
2001

R. M. Banish
University of Alabama, Huntsville; Huntsville, AL
Thermophysical Property Measurements of Te-Based II-VI Semiconductor Compounds
Materials Science
2001–2002

Daniel Carter
New Century Pharmaceuticals, Inc., Huntsville, AL
Neutron Diffraction: Microgravity Applications in Structure-Guided Drug Development
Biotechnology
2001–2002

Daniel Carter
New Century Pharmaceuticals, Inc., Huntsville, AL
Protein Crystal Growth Facility–Based Microgravity Hardware
Biotechnology
2001–2002

Alexander Chernov
Universities Space Research Association, Huntsville, AL
Origin of Imperfections and Convection in Macromolecular Crystal Perfection
Biotechnology
2001

Alexander Chernov
Universities Space Research Association, Huntsville, AL
Morphological Stability of Stepped Interfaces Growing From Solution
Materials Science
2001–2002

Alexander Chernov
Universities Space Research Association, Huntsville, AL
The Role of Impurities and Convection in Macromolecular Crystal Perfections
Biotechnology
2002

Krishman Chittur
University of Alabama, Huntsville; Huntsville, AL
Infrared Signatures for Mammalian Cells in Culture
Biotechnology
2001

Ewa Ciszak
Universities Space Research Association, Huntsville, AL
Crystal Structure of Human Pyruvate Dehydrogenase Complex Facilitated by Microgravity
Biotechnology
2001

Ewa Ciszak
University of Alabama, Huntsville; Huntsville, AL
Crystal Structure of Human Pyruvate Dehydrogenase Complex Facilitated by Microgravity
Biotechnology
2002

Lawrence J. DeLucas
University of Alabama, Birmingham; Birmingham, AL
Microgravity Studies of Medically Relevant Macromolecules
Biotechnology
2001–2002

Lawrence J. DeLucas
University of Alabama, Birmingham; Birmingham, AL
Protein Crystal Growth in Microgravity
Biotechnology
2001–2002

Edwin Ethridge
Marshall Space Flight Center, Huntsville, AL
Mechanism for the Crystallization Studies of ZBLAN
Materials Science
2001–2002

Alexandre I. Fedoseyev
University of Alabama, Huntsville; Huntsville, AL
Theoretical and Experimental Investigation of Vibrational Control of the Bridgman Crystal Growth Experiment
Materials Science
2001

Donald C. Gillies
Marshall Spaceflight Center, Huntsville, AL
Solidification of II-VI Compounds in a Rotating Magnetic Field
Materials Science
2001

Donald C. Gillies
Marshall Spaceflight Center, Huntsville, AL
Use of Computed Tomography for Characterizing Materials Grown Terrestrially and in Microgravity
Materials Science
2001–2002

Russell A. Judge
University of Alabama, Huntsville; Huntsville, AL
Macromolecule Nucleation and Growth Rate Dispersion Studies: A Predictive Technique for Crystal Quality in Microgravity
Biotechnology
2001–2002

Craig E. Kundrot
Marshall Space Flight Center, Huntsville, AL
Optimizing the Use of Microgravity to Improve the Diffraction Quality of Problematic Biomacromoleclar Crystals
Biotechnology
2001–2002

Sandor L. Lehoczky
Marshall Spaceflight Center, Huntsville, AL
Crystal Growth of II-VI Semiconducting Alloys by Directional Solidification
Materials Science
2001–2002

Sandor L. Lehoczky
Marshall Spaceflight Center, Huntsville, AL
Growth of Solid Solution Single Crystals
Materials Science
2001–2002

Daniel W. Mackowski
Auburn University, Auburn, AL
Coupled Radiation/Thermophoresis Effects in Sooting Microgravity Flames
Combustion Science
2001-2002

Jimmy Mays
University of Alabama, Birmingham; Birmingham, AL
Controlled Synthesis of Nanoparticles Using Block Copolymers: Nanoreaction in Microgravity Conditions
Materials Science
2001

Konstantin Mazuruk
Universities Space Research Association, Huntsville, AL
Effects of Traveling Magnetic Field on Dynamics of Solidification
Materials Science
2001–2002

Robert J. Naumann
University of Alabama, Huntsville; Huntsville, AL
Control of Transport in Protein Crystal Growth Using Restrictive Geometries
Biotechnology
2001–2002

Robert J. Naumann
University of Alabama, Huntsville; Huntsville, AL
Reduction of Convection in Closed-Tube Vapor Growth Experiments
Materials Science
2001–2002

Marc L. Pusey
Marshall Space Flight Center, Huntsville, AL
A Diffractometer for Reciprocal Space Mapping of Macromolecular Crystals to Study Their Microstructure
Biotechnology
2001–2002

Marc L. Pusey
Marshall Space Flight Center, Huntsville, AL
The Role of Specific Interactions in Protein Crystal Nucleation and Growth Studied by Site-Directed Mutagenesis
Biotechnology
2001–2002

Marc L. Pusey
Marshall Spaceflight Center, Huntsville, AL
The Study and Optimization of Flow in Solution Biological Crystal Growth
Fluid Physics
2001–2002

Narayanan Ramachandran
Marshall Space Flight Center, Huntsville, AL
Study of Fluid Flow Control in Protein Crystallization Using Strong Magnetic Fields
Fluid Physics
2002

Robert C. Richmond
Marshall Space Flight Center, Huntsville, AL
Heterozygous Ataxia-Telangiectasia Human Mammary Cells as a Microgravity-Based Model of Differentiation and Cancer Susceptibility
Biotechnology
2001–2002

Edward H. Snell
Universities Space Research Association/Marshall Spaceflight Center, Huntsville, AL
Cool Crystals — A Physical and Biochemical Study of Macromolecular Crystal Cyropreservation
Biotechnology
2001–2002

Robert Snyder
New Century Pharmaceuticals, Inc., Huntsville, AL
Electrophoretic Focusing
Biotechnology
2001–2002

Doru Stefanescu
University of Alabama,Tuscaloosa; Tuscaloosa, AL
Particle Engulfment and Pushing by solidifying Interfaces (PEP)
Materials Science
2001–2002

Ching-Hua Su
Marshall Spaceflight Center, Huntsville, AL
Crystal Growth of Zn-Se and Related Ternary Compound Semiconductors by Vapor Transport
Materials Science
2001–2002

Ching-Hua Su
Marshall Space Flight Center, Huntsville, AL
Structural Fluctuations and Thermophysical Properties of Molten II-VI Compounds
Materials Science
2001–2002

Frank R. Szofran
Marshall Spaceflight Center, Huntsville, AL
Reduction of Defects in Germanium-Silicon (RDGS)
Materials Science
2001–2002

William Witherow
Marshall Space Flight Center, Huntsville, AL
A New Ultra-High Resolution Near-Field Microscope for Observation of Protein Crystal Growth
Biotechnology
2001

Maria I. Zugrav
University of Alabama, Huntsville, AL
Ground-Based Experiments in Support of Microgravity Research Results — Vapor Growth of Organic Nonlinear Optical Thin Film
Materials Science
2001–2002

ARIZONA

James P. Allen
Arizona State University, Tempe, AZ
Crystallization Mechanisms of Membrane Proteins
Biotechnology
2001

Cho Lik Chan
University of Arizona, Tucson, AZ
Resonance Effects in Single- and Double-Diffusive Systems Under Gravity Modulation
Fluid Physics
2001–2002

Kenneth A. Jackson
University of Arizona, Tucson, AZ
Growth of Rod Eutectics
Materials Science
2001–2002

Jeffrey W. Jacobs
University of Arizona, Tucson, AZ
An Experimental Investigation of Incompressible Richtmyer-Meshkov Instability
Fluid Physics
2002

Pierre Meystre
University of Arizona, Tucson, AZ
Atom Optics in Controlled and Microgravity Environments
Fundamental Physics
2001

David Poirier
University of Arizona, Tucson, AZ
Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments
Materials Science
2001–2002

Peter Smith
University of Arizona, Tucson, AZ
Mars Atmospheric Dust in the Optical and Radio (MATADOR)
Fluid Physics
2001–2002

K. R. Sridhar
University of Arizona, Tucson, AZ
Modeling of Transport Processes in a Solid Oxide Electrolyzer Generating Oxygen on Mars
Fluid Physics
2001

K. R. Sridhar
University of Arizona, Tucson, AZ
Development of Superior Materials for Layered Solid Oxide Electyrolyzers Based on Mechanical and Thermal Failure Testing and Analysis
Materials Science
2001–2002

Bruce Towe
Arizona State University, Tempe, AZ
A Microfluidic Bioreporter for Exploratory Probes
Biotechnology
2001–2002

CALIFORNIA

Guenter Ahlers
University of California, Santa Barbara; Santa Barbara, CA
The Superfluid Transition of 4He Under Unusual Conditions
Fundamental Physics
2001–2002

Guenter Ahlers
University of California, Santa Barbara; Santa Barbara, CA
Boundary Effects on Transport Properties and Dynamic Finite-Size Scaling near the Superfluid Transition Line of 4He
Fundamental Physics
2001–2002

Ralph Curtis Aldredge
University of California, Davis; Davis, CA
Flame Propagation in Low-Intensity Turbulence Under Microgravity Conditions
Combustion Science
2001–2002

Eduardo A. C. Almeida
Ames Research Center, Moffett Field, CA
Biosensor Nanovesicles
Biotechnology
2002

Mark S. Anderson
Jet Propulsion Laboratory, Pasadena, CA
Biomolecular Imaging with Atomic Force Microscope-Mediated Raman Spectroscopy
Biotechnology
2002

Sanjoy Banerjee
University of California, Santa Barbara; Santa Barbara, CA
Direct Numerical Simulation of Turbulent Flows with Phase Change in Microgravity
Fluid Physics
2001–2002

Martin Barmatz
Jet Propulsion Laboratory, Pasadena, CA
Microgravity Test of Universality and Scaling Predictions near the Liquid-Gas Critical Point of 3He
Fundamental Physics
2001–2002

Josette Bellan
Jet Propulsion Laboratory, Pasadena, CA
High-Pressure Transport Properties of Fluids: Theory and Data From levitated Drops at Combustion-Relevant Temperatures
Combustion Science
2001–2002

Subrata Bhattacharjee
San Diego State University, San Diego, CA
Dynamics of Flame Spread in Microgravity Environment
Combustion Science
2001–2002

Linda G. Blevins
Sandia National Laboratories, Livermore, CA
Carbon Monoxide and Soot Formation in Inverse Diffusion Flames
Combustion Science
2001–2002

John F. Brady
California Institute of Technology, Pasadena, CA
Dispersion Microstructure and Rheology in Ceramics Processing
Materials Science
2001–2002

John F. Brady
California Institute of Technology, Pasadena, CA
Inertial Effects in Suspension Dynamics
Fluid Physics
2001–2002

David S. Cannell
University of California, Santa Barbara; Santa Barbara, CA
Gradient-Driven Fluctuations
Fluid Physics
2001–2002

Geoffrey Chang
Scripps Research Institute, La Jolla, CA
Crystallization of Integral Membrane Proteins Using

Microgravity
Biotechnology
2001–2002

Jyh-Yuan Chen
University of California, Berkeley; Berkeley, CA
Numerical Study of Bouyancy and Differential Diffusion Effects on the Structure and Dynamics of Triple Flames
Combustion Science
2001–2002

Robert K. Cheng
Lawrence Berkeley National Laboratory, Berkeley, CA
Field Effects of Gravity on Lean Premixed Turbulent Flames
Combustion Science
2001–2002

Talso C. Chui
Jet Propulsion Laboratory, Pasadena, CA
Heat Current Effects on the Superfluid Transition
Fundamental Physics
2001–2002

Vijay K. Dhir
University of California, Los Angeles; Los Angeles, CA
Investigation of Mechanisms Associated With Nucleate Boiling Under Microgravity Conditions
Fluid Physics
2001–2002

Vijay K. Dhir
University of California, Los Angeles; Los Angeles, CA
Transition From Pool to Flow Boiling–The Effect of Reduced Gravity
Fluid Physics
2001–2002

Derek Dunn-Rankin
University of California, Irvin; Irvine, CA
Applications of Electric Field in Microgravity Combustion
Combustion Science
2001–2002

Douglas J. Durian
University of California, Los Angeles; Los Angeles, CA
Foam Optics and Mechanics
Fluid Physics
2001

Douglas J. Durian
University of California, Los Angeles; Los Angeles, CA
The Melting of Aqueous Foams
Fluid Physics
2002

John K. Eaton
Stanford University, Stanford, CA
Attenuation of Gas Turbulence by a Nearly Stationary Dispersion of Fine Particles
Fluid Physics
2001–2002

Fokion N. Egolfopoulos
University of Southern California, Los Angeles, CA
Detailed Studies on the Structure and Dynamics of Reacting Dusty Flows at Normal- and Microgravity
Combustion Science
2001–2002

Fokion N. Egolfopoulos
University of Southern California, Los Angeles, CA
Quantitative Studies on the Propagation and Extinction of Near-Limit Flames Under Normal- and Microgravity
Combustion Science
2001–2002

James W. Evans
University of California; Berkeley, Berkeley, CA
Exploiting the Temperature Dependence of Magnetic Susceptibility to Control Convection in Fundamental Studies of Solidification Phenomena
Materials Science
2001–2002

Francis Everitt
Stanford University, Stanford, CA
Satellite Test of the Equivalence Principle (STEP)
Fundamental Physics
2002

Robert Feigelson
Stanford University, Stanford, CA
Investigation of the Crystal Growth of Dielectric Materials by the Bridgeman Technique Using Vibrational Control
Materials Science
2001–2002

Robert Feigelson
Stanford University, Stanford, CA
Laser Scattering Tomography for the Study of Defects in Protein Crystals
Biotechnology
2001

Carlos A. Fernandez-Pello
University of California; Berkeley, Berkeley, CA
Flammability Diagrams of Combustible Materials and Microgravity
Combustion Science
2001–2002

Carlos A. Fernandez-Pello
University of California; Berkeley, Berkeley, CA
Fundamental Study of Smoldering Combustion in Microgravity
Combustion Science
2001–2002

Carlos A. Fernandez-Pello
University of California; Berkeley, Berkeley, CA
Two Dimensional Smoldering and Its Transition in Flaming in Microgravity
Combustion Science
2001–2002

John Frangos
University of California, San Diego; San Diego, CA
Novel Strategy for Tridimensional In-Vitro Bone Induction
Biotechnology
2001–2002

Curtis W. Frank
Stanford University, Stanford, CA
Production and In-Flight Regeneration Active Biological Membranes
Biotechnology
2001–2002

Michael Y. Frenklach
University of California, Berkeley; Berkeley, CA
Microgravity Production of Nanoparticles of Novel Materials Using Plasma Synthesis
Fundamental Physics
2001–2002

Alice P. Gast
Stanford University, Stanford, CA
Anisotropic Colloidal Self-Assembly
Fluid Physics
2001

Joe D. Goddard
University of California, San Diego; San Diego, CA
Vibratory Dynamics and Transport of Granular Media at Various g Levels
Fluid Physics
2001–2002

David L. Goodstein
California Institute of Technology, Pasadena, CA
The CQ Experiment
Fundamental Physics
2001–2002

Harvey Allen Gould
Lawrence Berkeley National Laboratory, Berkeley, CA
Electron Electric Dipole Moment Experiment with Laser-Cooled Atoms in a Microgravity Environment
Fundamental Physics
2001–2002

Inseob Hahn
Jet Propulsion Laboratory, Pasadena, CA
Coexistence Boundary Experiment
Fundamental Physics
2001–2002

Michael H. Hecht
Jet Propulsion Laboratory, Pasadena, CA
Compatibility Assessment (MECA)
Materials Science
2002

Lawrence H. Heilbronn
Lawrence Berkeley National Laboratory, Berkeley, CA
Radiation Transmission Properties of In Situ Metals
Materials Science
2001–2002

George Homsy
University of California, Santa Barbara; Santa Barbara, CA
Microgravity Fluid Mechanics:g-Jitter Convection and the Mechanics of Fluidized Beds
Fluid Physics
2001–2002

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Lawrence Berkeley National Laboratory, Berkeley, CA
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Materials Science
2001

Melany L. Hunt
California Institute of Technology, Pasadena, CA
Granular Materials Flows With Interstitial Fluid Effects
Fluid Physics
2001–2002

Ulf E. Israelsson
Jet Propulsion Laboratory, Pasadena, CA
Dynamic Measurements Along the Lambda Line of Helium in a Low-Gravity Simulator on the Ground
Fundamental Physics
2001–2002

Farrokh Issacci
Honeywell International, Torrance, CA
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Fluid Physics
2001–2002

William Johnson
California Institute of Technology, Pasadena, CA

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Materials Science
2001–2002

Frances Jurnak
University of California, Irvine; Irvine, CA
Stabilization and Preservation of Crystals for X-Ray Diffraction Experiments
Biotechnology
2001–2002

Ian Kennedy
University of California, Davis; Davis, CA
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Combustion Science
2001–2002

Edgar Knobloch
University of California, Berkeley; Berkeley, CA
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Fluid Physics
2002

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KLA-Tenor, San Jose, CA
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Materials Science
2001–2002

Melora E. Larson
Jet Propulsion Laboratory, Pasadena, CA
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Fundamental Physics
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Jet Propulsion Laboratory, Pasadena, CA
Experiments Along Coexistence Near Tricriticality (EXACT)
Fundamental Physics
2001–2002

L. Gary Leal
University of California, Santa Barbara; Santa Barbara, CA
Interaction Forces and the Flow-Induced Coalescence of Drops and Bubbles
Fluid Physics
2001

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Ames Research Center, Moffett Field, CA
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2002

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Stanford University, Stanford, CA
A Test of Supersymmetry Theory By Searching for Anomolous Short-Range Forces
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Stanford University, Stanford, CA
Testing the Renormalization Group Theory of Matter Near the Superfluid Transition of Helium on the Space Station
Fundamental Physics
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Tests of Universality and Confinement Near the Lambda Point
Fundamental Physics
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2001–2002

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High-Resolution Study of the Critical Region of Oxygen Using Magnetic Levitation
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2001–2002

Feng-chuan Liu
Jet Propulsion Laboratory, Pasadena, CA
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Fundamental Physics
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Jing Liu
California State University, Long Beach, CA
Magnetorheological Fluids: Rheology and Nonequilibrium Pattern Formation
Fluid Physics
2001

Yuanming Liu
Jet Propulsion Laboratory, Pasadena, CA

Effects of Heat Current on the Superfluid Transition in a Low-Gravity Simulator
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John R. Marshall
SETI Institute, Mountain View, CA
Microgravity Experiments to Evaluate Electrostatic Forces in Controlling Cohesion and Adhesion of Granular Materials
Fluid Physics
2001–2002

Tony Maxworthy
University of Southern California, Los Angeles, CA
The Dynamics of Miscible Interfaces: A Spaceflight Experiment
Fluid Physics
2001–2002

Christopher P. McKay
Ames Research Center, Moffett Field, CA
Fluorometric Detection of Microorganisms on Sterilized Surfaces
Biotechnology
2002

Alexander McPherson Jr.
University of California, Irvine; Irvine, CA
An Observable Protein Crystal Growth Flight Apparatus
Biotechnology
2001–2002

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University of California, Irvine; Irvine, CA
Enhanced Dewar Program
Biotechnology
2001–2002

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University of California, Santa Barbara; Santa Barbara, CA
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Fluid Physics
2001–2002

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Fluid Physics
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Ames Research Center, Moffett Field, CA
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Biotechnology
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Jack Miller
Lawrence Berkeley National Laboratory, Berkeley, CA
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Materials Science
2001–2002

Carlo D. Montemagno
University of California, Los Angeles; Los Angeles, CA
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Biotechnology
2001–2002

Zuhair A. Munir
University of California, Davis; Davis, CA
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Combustion Science
2001–2002

Jay L. Nadeau
Jet Propulsion Laboratory, Pasadena, CA
Miniature Electronic Dynamic Ion Channel Sensor (MEDICS)
Biotechnology
2002

Cun-Zheng Ning
Ames Research Center, Moffett Field, CA
Technology Development of Miniaturized Far-Infrared Sources for Biomolecular Spectroscopy
Biotechnology
2002

Douglas Dean Osheroff
Stanford University, Stanford, CA
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Fundamental Physics
2001

Richard E. Packard
University of California, Berkeley; Berkeley, CA
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Fundamental Physics
2001–2002

Andrew Pohorille
Ames Research Center, Moffett Field, CA
Computational Techniques for Reconstruction and Discovery of Metabolic, Signal Transduction, and Evolutionary Pathways
Biotechnology
2002

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Ames Research Center, Moffett Field, CA
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Biotechnology
2002

Adrian Ponce
Jet Propulsion Laboratory, Pasadena, CA
Biomimetic Self-Assembly of Mesostructures in Microgravity: The Nature of the Capillary Bond
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University of California, Davis; Davis, CA
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University of California, San Diego; San Diego, CA
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Leslie Eileen Prufert-Bebout
Ames Research Center, Moffett Field, CA
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University of California, Los Angeles; Los Angeles, CA
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California Institute of Technology, Pasadena, CA
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Materials Science
2001–2002

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Ames Research Center, Moffett Field, CA
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Fundamental Physics
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University of Southern California, Los Angeles, CA
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Materials Science
2001–2002

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University of Southern California, Los Angeles, CA
Studies of Premixed Laminar and Turbulent Flames at Microgravity
Combustion Science
2001–2002

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University of Southern California, Los Angeles, CA
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Combustion Science
2001–2002

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University of Southern California, Los Angeles, CA
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Materials Science
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University of Southern California, Los Angeles, CA
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Materials Science
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University of California, San Diego; San Diego, CA
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Biotechnology
2001–2002

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University of California, San Diego; San Diego, CA
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2001–2002

Eric S. G. Shaqfeh
Stanford University, Stanford, CA
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2002

Benjamin D. Shaw
University of California, Davis; Davis, CA
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Combustion Science
2001–2002

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University of California, Davis; Davis, CA
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Combustion Science
2001–2002

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Jet Propulsion Laboratory, Pasadena, CA
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Biotechnology
2002

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SRI International, Menlo Park, CA
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Combustion Science
2001–2002

Owen I. Smith
University of California, Los Angeles; Los Angeles, CA
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Combustion Science
2001

Viktor Stolc
Ames Research Center, Moffett Field, CA
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Biotechnology
2002

Viktor Stolc
Ames Research Center, Moffett Field, CA
Solid-Surface DNA Sequencing Array
Biotechnology
2002

Donald Strayer
Jet Propulsion Laboratory, Pasadena, CA
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Fundamental Physics
2001

David P. Summers
SETI Institute, Mountain View, CA
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Biotechnology
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Henryk Szmacinski
Microcosm, Inc., El Segundo, CA
Cellular Oxygen and Nutrient Sensing in Microgravity Using Time-Resolved Fluorescence Microscopy
Biotechnology
2001–2002

Peter Taborek
University of California, Irvine; Irvine, CA
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Fluid Physics
2001–2002

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University of California, Irvine; Irvine, CA
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Edwards Air Force Base, CA
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University of California, Santa Barbara; Santa Barbara, CA
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2001–2002

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University of California, Santa Barbara; Santa Barbara, CA
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Fluid Physics
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James Trolinger
MetroLaser, Inc., Irvine, CA
Investigate the Influence of Microgravity on Transport Mechanisms in a Virtual Spaceflight Chamber
Biotechnology
2001

James Trolinger
MetroLaser, Inc., Irvine, CA
Spaceflight Holography Investigation in a Virtual Apparatus (SHIVA)
Materials Science
2001–2002

Forman A.Williams
University of California, San Diego; San Diego, CA
High-Pressure Combustion Experiment (DCE/DCE-2)
Combustion Science
2001–2002

Forman A.Williams
University of California, San Diego; San Diego, CA
High-Pressure Combustion of Binary Fuel Sprays
Combustion Science
2001–2002

Cary J. Zeitlin
Lawrence Berkeley National Laboratory, Berkeley, CA
Measurement of Charged-Particle Interactions in Spacecraft and Planetary Habitat Shielding Materials
Materials Science
2001–2002

Fang Zhong
Jet Propulsion Laboratory, Pasadena, CA
Measurement of the Thermal Conductivity Near the Liquid-Vapor Critical Point of He-3 and He-4
Fundamental Physics
2001

COLORADO

John Alford
TDA Research, Inc., Wheat Ridge, CO
Formation of Carbon Nanotubes in a Microgravity Environment
Combustion Science
2001–2002

Melvyn C. Branch
University of Colorado, Boulder; Boulder, CO
Combustion of Metals in Reduced-Gravity and Extraterrestrial Environments
Combustion Science
2001–2002

Noel A. Clark
University of Colorado, Boulder; Boulder, CO
Structure and Dynamics of Freely Suspended Liquid Crystals
Fluid Physics
2001–2002

Joshua Colwell
University of Colorado, Boulder; Boulder, CO
Collisions into Dust Experiment 2
Fluid Physics
2001–2002

Joshua Colwell
University of Colorado, Boulder; Boulder, CO
Dusty Plasma Dynamics Near Surfaces in Space
Fluid Physics
2001–2002

Joshua Colwell
University of Colorado, Boulder; Boulder, CO
Physics of Regolith Impacts in Microgravity Environment (PRIME)
Fluid Physics
2001–2002

Joshua Colwell
University of Colorado, Boulder; Boulder, CO
Dynamics of Charged Dust Near Surfaces in Space
Fluid Physics
2002

Robert H. Davis
University of Colorado, Boulder; Boulder, CO
Surface Collisions Involving Particles and Moisture (SCIP'M)
Fluid Physics
2001–2002

Robert H. Davis
University of Colorado, Boulder; Boulder, CO
Thermocapillary-Induced Phase Separation of Dispersed Systems With Coalescence
Fluid Physics
2001–2002

Alan Greenberg
University of Colorado, Boulder; Boulder, CO
Influence of Solutocapillary Convection of Macrovoid Defect Formation in Polymeric Membranes
Materials Science
2001–2002

John L. Hall
Joint Institute of Laboratory Astrophysics and University of Colorado, Boulder; Boulder, CO
Fundamental Physics Using Frequency-Stabilized Lasers as Optical "Atomic Clocks"
Fundamental Physics
2001

John L. Hall
Joint Institute of Laboratory Astrophysics and University of Colorado, Boulder; Boulder, CO
Ultrastable Local Oscillator
Fundamental Physics
2001–2002

John E. Hart
University of Colorado, Boulder; Boulder, CO

Stratified Taylor-Couette Flow With Radial Buoyancy
Fluid Physics
2001–2002

David W. M. Marr
Colorado School of Mines, Golden, CO
A Novel Colloidal Microfluidics Platform for Spaceborne Micro Total Analysis Systems
Biotechnology
2001–2002

John J. Moore
Colorado School of Mines, Golden, CO
A Fundamental Study of the Combustion Synthesis of Ceramic-Metal Composite
Combustion Science
2001–2002

Jacques I. Pankove
Astralux, Inc., Boulder, CO
Optoelectric Neural System
Biotechnology
2001–2002

Stein Sture
University of Colorado, Boulder; Boulder, CO
Mechanics of Granular Materials
Fluid Physics
2001–2002

Mark M. Weislogel
TDA Research, Inc.; Wheat Ridge, CO
Capillary Flow in Interior Corners
Fluid Physics
2001

CONNECTICUT

Robert Apfel
Yale University, New Haven, CT
Novel Concepts in Acoustopheresis for Biotechnology Applications
Biotechnology
2001–2002

Robert Apfel
Yale University, New Haven, CT
Nucleation and Growth Mechanisms Underlying the Microstructure of Polymer Foams Produced By Dynamic Decompression and Cooling
Materials Science
2001

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Yale University, New Haven, CT
Studies of the Dynamics, Control, and Evaporation of Three-Dimenstional Droplet Arrays
Fluid Physics
2001–2002

Jerzy Blawzdziewicz
Yale University, New Haven, CT
Drop Coalescence: Drainage and Stabilization of Thin Liquid Films
Fluid Physics
2002

Amir Faghri
University of Connecticut, Storrs, CT
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Fluid Physics
2001–2002

Juha Javanainen
University of Connecticut, Storrs, CT
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Yale University, New Haven, CT
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Fundamental Physics
2001–2002

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Yale University, New Haven, CT
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Fluid Physics
2001–2002

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Yale University, New Haven, CT
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Fluid Physics
2001–2002

Daniel E. Rosner
Yale University, New Haven, CT
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Combustion Science
2001–2002

Mitchell D. Smooke
Yale University, New Haven, CT
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Combustion Science
2001–2002

DELAWARE

Robert E. Akins
A. I. duPont Hospital for Children, Wilmington, DE
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Biotechnology
2001–2002

Siu-Tat Chui
University of Delaware, Newark, DE
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Fundamental Physics
2001–2002

Eric W. Kaler
University of Delaware, Newark, DE
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Fluid Physics
2001

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University of Delaware, Newark, DE
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Biotechnology
2001–2002

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University of Delaware, Newark, DE
Surfactant Structures Guide Membrane Protein Crystallization
Biotechnology
2001–2002

Leonard W. Schwartz
University of Delaware, Newark, DE
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Fluid Physics
2001

Hai Wang
University of Delaware, Newark, DE
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Combustion Science
2001–2002

FLORIDA

Reza Abbaschian
University of Florida, Gainesville, FL
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Materials Science
2001

Reza Abbaschian
University of Florida, Gainesville, FL
Morphological Stability of Faceted Interfaces
Materials Science
2001–2002

Timothy Anderson
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Jeanne L. Becker
University of South Florida, Tampa, FL
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Biotechnology
2001–2002

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University of South Florida College of Medicine, Tampa, FL
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Biotechnology
2001–2002

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Florida State University, Tallahassee, FL
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Fluid Physics
2001

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Florida Institute of Technology, Melbourne, FL
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Biotechnology
2001–2002

Luca Inverardi
Diabetes Research Institute, Miami, FL
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Biotechnology
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University of Florida, Gainesville, FL
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Fluid Physics
2001–2002

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Fundamental Physics
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Ranga Narayanan
University of Florida, Gainesville, FL
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University of South Florida College of Medicine, Tampa, FL
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University of Florida, Gainesville, FL
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Materials Science
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Biotechnology
2001–2002

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Emory University, Atlanta, GA
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Biotechnology
2001–2002

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Georgia State University, Atlanta, GA
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Georgia Institute of Technology, Atlanta, GA
VIBE Technology for Microgravity Heat Transfer Applications
Fluid Physics
2002

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Emory University, Atlanta, GA
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Fluid Physics
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Northwestern University, Evanston, IL
The Evolution of Dendrite Morphology During Isothermal Coarsening
Materials Science
2001–2002

Hassan Aref
University of Illinois, Urbana-Champaign; Urbana, IL
Fluid Physics of Foam Evolution and Flow
Fluid Physics
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John Buckmaster
University of Illinois, Chicago, IL
Smolder-Edge-Waves and Edge-Flames
Combustion Science
2001–2002

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University of Illinois, Urbana-Champaign; Urbana, IL
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Fundamental Physics
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Materials Science
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Northwestern University, Evanston, IL
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Fluid Physics
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Finch University of Health Sciences/The Chicago Medical School, Chicago, IL
Crystallization of the Mitochondrial Metabolite Transport Proteins
Biotechnology
2001–2002

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Combustion Science
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Illinois Institute of Technology, Chicago, IL

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Biotechnology
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Northwestern University, Evanston, IL
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Fluid Physics
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Mary Silber
Northwestern University, Evanston, IL
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Fluid Physics
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Northwestern University, Evanston, IL
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Combustion Science
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Peter Voorhees
Northwestern University, Evanston, IL
Coarsening in Solid-Liquid Mixtures (CSLM)-2
Materials Science
2001–2002

John S. Walker
University of Illinois, Urbana-Champaign; Urbana, IL
Models of Magnetic Damping for Bridgman Semiconductor Crystal Growth in Microgravity
Materials Science
2001–2002

John S. Walker
University of Illinois, Urbana-Champaign; Urbana, IL
Models to Optimize the Benefits of Rotating Magnetic Fields for Semiconductor Crystal Growth in Space
Materials Science
2001–2002

Richard Weber
Containerless Research, Inc., Evanston, IL
Microgravity Studies of Liquid-Liquid Phase Transitions in Undercooled Alumina-Yttria Melts
Materials Science
2001–2002

Richard Weber
Containerless Research, Inc., Evanston, IL
Process-Property-Structure Relationships in Complex Oxide Melts
Materials Science
2001–2002

Charles Zukoski
University of Illinois, Urbana-Champaign; Urbana, IL
Particle Interaction Potentials and Protein Crystal Quality
Biotechnology
2001–2002

INDIANA

Hsueh-Chia Chang
University of Notre Dame, Notre Dame, IN
Microcirculation Anomalies in Microgravity Blood Flow
Fluid Physics
2002

James A. Glazier
University of Notre Dame, Notre Dame, IN
Diffusive Coarsening of Liquid Foams in Microgravity
Fluid Physics
2001–2002

Barbara L. Golden
Purdue University, West Lafayette, IN
Engineering a Ribozyme for Diffraction Properties
Biotechnology
2001–2002

David R. Johnson
Purdue University, West Lafayette, IN
Experimental and Numerical Investigations of Growth Morphologies of Peritectic Reactions
Materials Science
2001–2002

V. Alan Kostelecky
Indiana University, Bloomington; Bloomington, IN

Theoretical Studies of Lorentz and CPT Symmetry
Fundamental Physics
2001–2002

Issam Mudawa
Purdue University, West Lafayette, IN
Investigation of Critical Heat Flux in Reduced Gravity Using Photomicrographic Techniques
Fluid Physics
2001–2002

Shripad T. Revankar
Purdue University, West Lafayette, IN
Study of Co-Current and Counter-Current Gas-Liquid Two-Phase Flow Through Packed Bed in Microgravity
Fluid Physics
2002

Yudaya R. Sivathanu
En'Urga, Inc., West Lafayette, IN
Fan Beam Emission Tomography for Non-Symmetric Laminar Fires
Combustion Science
2001–2002

Paul Todd
Space Hardware Optimization Technology Inc., Floyd Knobs, IN
Preparation and Analysis of RNA Crystals
Biotechnology
2001–2002

Christie Marie Traycoff
Indiana University School of Medicine, Indianapolis, IN
Self-Renewal Replication of Hematopoietic Stem Cells in Microgravity
Biotechnology
2001–2002

Arvind Varma
University of Notre Dame, Notre Dame, IN
Mechanic Studies of Combustion and Structure Formation During Synthesis of Advanced Materials
Combustion Science
2001–2002

Carl R. Wassgren
Purdue University, West Lafayette, IN
Granular Flow Around Immersed Objects
Fluid Physics
2002

IOWA

Mark Arnold
University of Iowa, Iowa City, IA
Real-Time Monitoring of Protein Concentration in Solution to Control Nucleation and Crystal Growth
Biotechnology
2001

Mark Arnold
University of Iowa, Iowa City, IA
Noninvasive Near-Infrared Monitors for Protein Crystallization and Biomedical Systems
Biotechnology
2001–2002

Christoph Beckermann
University of Iowa, Iowa City, IA
Dendritic Alloy Solidification Experiment (DASE)
Materials Science
2001–2002

Christoph Beckermann
University of Iowa, Iowa City, IA
Equiaxed Dendritic Solidification Experiment (EDSE)
Materials Science
2001–2002

Amitava Bhattacharjee
University of Iowa, Iowa City, IA
Theory and Simulation of Ground-Based and Microgravity Dusty Plasma Experiments
Fluid Physics
2001–2002

Lea Dur Chen
University of Iowa, Iowa City, IA
Reflight of ELF (Enclosed Laminar Flames) Investigation
Combustion Science
2001–2002

Gerald M. Colver
Iowa State University, Ames, Iowa
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Combustion Science
2001–2002

John A. Goree
University of Iowa, Iowa City, IA
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Fluid Physics
2001–2002

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Optically Excited Waves in 3-D Dusty Plasmas
Fluid Physics
2002

Jeffrey S. Marshall
University of Iowa, Iowa City, IA
Rivulet Dynamics With Variable Gravity and Wind Shear
Fluid Physics
2001–2002

David W. Murhammer
University of Iowa, Iowa City, IA
Monitoring and Control of Rotating Wall Vessels and Application to the Study of Prostate Cancer
Biotechnology
2001–2002

Tonya Peeples
University of Iowa, Iowa City, IA
Extremophilic Interfacial Systems for Waste Processing in Space
Biotechnology
2001–2002

Victor Rodgers
University of Iowa, Iowa City, IA
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Biotechnology
2001–2002

Rohit Trivedi
Iowa State University, Ames, IA
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Materials Science
2001–2002

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Iowa State University, Ames, IA
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Materials Science
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John M. Wiencek
University of Iowa, Iowa City, IA
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2001–2002

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2001–2002

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Mark D. Hollingsworth
Kansas State University, Manhattan, KS
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Materials Science
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Kenneth J. Klabunde
Kansas State University, Manhattan, KS
Nanocrystal Superlattices: Synthesis and Properties
Materials Science
2001–2002

Christopher Sorensen
Kansas State University, Manhattan, KS
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Lori Wilson
Eastern Kentucky University, Richmond, KY
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Biotechnology
2001–2002

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Donald P. Gaver
Tulane University, New Orleans, LA
Investigations of the Influence of Air-Liquid Interfacial Stresses on Pulmonary Epithelial Cells in a Microgravity Environment
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John J. Hegseth
University of New Orleans, Lakefront, LA
Geophysical Flow Experiment in a Rotating Spherical Capacitor
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2001–2002

Timothy G. Hammond
Tulane University Health Sciences Center, New Orleans, LA
Transcription Factors Mediating Gene Expression Changes During Renal Cell Rotating Wall Vessel Culture
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2001–2002

Larry W. Mason
Lockheed Martin Space Systems Company, New Orleans, LA
CO_2 Acquisition Membrane (CAM)
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Cheryl A. Nickerson
Tulane University Health Sciences Center, New Orleans, LA
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Kim C. O'Connor
Tulane University Health Sciences Center, New Orleans, LA
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Robert F. Berg
National Institute of Standards and Technology, Gaithersburg, MD
Critical Viscosity of Xenon 2 (CVX-2)
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Kim D. Collins
University of Maryland Medical School, College Park, MD
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University of Maryland, College Park, MD
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University of Maryland, College Park, MD
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D. Travis Gallagher
Center for Advanced Research in Biotechnology, Rockville, MD
Protein and DNA Crystal Lattice Engineering
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Ashwani K. Gupta
University of Maryland, College Park, MD
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Combustion Science
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Anthony Hamins
National Institute of Standards and Technology, Gaithersburg, MD
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James L. Harden
Johns Hopkins University, Baltimore, MD
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Leo W. Hollberg
National Institute of Standards and Technology, Gaithersburg, MD
Advanced Optical Frequency Standard for Space
Fundamental Physics
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National Institute of Standards and Technology, Gaithersburg, MD
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Combustion Science
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National Institute of Standards and Technology, Gaithersburg, MD
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University of Maryland, College Park, MD

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Wolfgang Losert
University of Maryland, College Park, MD
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Richard Maurer
Johns Hopkins University, Baltimore, MD
Development of a Neutron Spectrometer to Asses Biological Radiation Damage Behind Spacecraft Materials
Materials Science
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National Institute of Standards and Technology, Gaithersburg, MD
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Materials Science
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National Institute of Standards and Technology, Gaithersburg, MD
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National Institute of Standards and Technology, Gaithersburg, MD
Acoustic Study of Critical Phenomena in Microgravity
Fluid Physics
2001–2002

George W. Mulholland
National Institute of Standards and Technology, Gaithersburg, MD
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Combustion Science
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Hasan N. Oguz
Johns Hopkins University, Baltimore, MD
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Ho Jung Paik
University of Maryland, College Park, MD
Search for Spin-Mass Interaction With a Superconducting Differential Angular Accelerometer
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William D. Phillips
National Institute of Standards and Technology, Gaithersburg, MD
Condensate Laboratory Aboard the Space Station (CLASS)
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National Institute of Standards and Technology, Gaithersburg, MD
Evaporative Cooling and Bose Condensates in Microgravity: Picokelvin Atoms in Space
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Andrea Prosperetti
Johns Hopkins University, Baltimore, MD
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Fluid Physics
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Johns Hopkins University, Baltimore, MD
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Kathleen J. Stebe
Johns Hopkins University, Baltimore, MD
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2001–2002

Donald Sullivan
National Institute of Standards and Technology, Gaithersburg, MD
Primary Atomic Reference Clock in Space (PARCS)

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2001–2002

Jose L. Torero
University of Maryland, College Park, MD
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Combustion Science
2001–2002

Denis Wirtz
Johns Hopkins University, Baltimore, MD
Novel Microgravity Optical Technique for Molecularly Engineering Electrophoretic Media
Biotechnology
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George Benedek
Massachusetts Institute of Technology, Cambridge, MA
Kinetic Evolution of Stable and Metastable States in Protein Solutions
Materials Science
2001–2002

Peggy Cebe
Tufts University, Medford, MA
Study of Development of Polymer Structure in Microgravity Using Ellipsometry
Materials Science
2001–2002

Michael Cima
Massachusetts Institute of Technology, Cambridge, MA
Forces During Manufacture and Assembly of Microscale Discrete Electronic Components
Materials Science
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Merton C. Flemings
Massachusetts Institute of Technology, Cambridge, MA
The Role of Convection and Growth Competition on Phase Selection in Microgravity
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Seth Fraden
Brandeis University, Waltham, MA
Nucleation of Colloidal and Protein Crystals in the Vicinity of a Metastable Critical Point
Fluid Physics
2001–2002

Lisa E. Freed
Massachusetts Institute of Technology, Cambridge, MA
Microgravity Tissue Engineering
Biotechnology
2001–2002

Alice P. Gast
Massachusetts Institute of Technology, Cambridge, MA
Anisotropic Colloidal Self Assembly
Fluid Physics
2002

James C. Hermanson
Worcester Polytechnic Institute, Worcester, MA
Stability and Heat Transfer Characteristics of Condensing Films in Reduced Gravity
Fluid Physics
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Worcester Polytechnic Institute, Worcester, MA
Combustion Characteristics of Fully Modulated, Turbulent Diffusion Flames in Reduced Gravity
Combustion Science
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Boston University, Boston, MA
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Fluid Physics
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Rheology of Foam Near the Order-Disorder Transition
Fluid Physics
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David L. Kaplan
Tufts University, Medford, MA
Hierarchical Assembly of Collagen
Materials Science
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Alain S. Karma
Northeastern University, Boston, MA
Phase-Field Simulations of Dendritic Growth at Low Undercooling: Confronting Theory and Experiment
Materials Science
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Northeastern University, Boston, MA
The Role of Dynamic Nucleation at Moving Boundaries in Phase and Microstructure Selection
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Wolfgang Ketterle
Massachusetts Institute of Technology, Cambridge, MA
Towards Precision Experiments with Bose-Einstein Condensates II
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2001–2002

Matthew B. Koss
College of the Holy Cross, Worcester, MA
Transient Dendritic Solidification Experiment (TDSE)
Materials Science
2001–2002

Gareth H. McKinley
Massachusetts Institute of Technology, Cambridge, MA
An Interferometric Investigation of Contact-Line Dynamics in Spreading Polymer Melts and Solutions
Fluid Physics
2001–2002

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Massachusetts Institute of Technology, Cambridge, MA
Resin-Spinning of Synthetic Polymer Fibers With Silk-Like Properties
Biotechnology
2001–2002

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Massachusetts Institute of Technology, Cambridge, MA
Extensional Rheology Experiment (ERE)
Fluid Physics
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Keith E. Oslakovic
Molecular Geodesics, Inc., Boston, MA
Functionally Adapted Biomimetic Material for Space Exploration
Biotechnology
2001–2002

W. Terry Rawlins
Physical Sciences Inc., Andover, MA
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Combustion Science
2001-2002

Thomas Russell
University of Massachusetts, Amherst, MA
Capillary Wavelengths at Interfaces: The Role of Gravity and Electric Field Enhancement
Materials Science
2001–2002

Albert Sacco
Northeastern University, Boston, MA
Modeling of Macroscopic/Microscopic Transport and Growth Phenomena in Zeolite Crystal Solutions Under Microgravity
Materials Science
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Donald Sadoway
Massachusetts Institute of Technology, Cambridge, MA
From Oxygen Generation to Metal Production: In Situ Resource Utilization by Molten Oxide Electrolysis
Materials Science
2001–2002

William J. Schwartz
University of Massachusetts Medical School, Worcester, MA
Microgravity and the Biology of Neural Stem Cells
Biotechnology
2001–2002

Irwin Shapiro
Smithsonian Astrophysical Observatory, Cambridge, MA
Test of the Equivalence Principle in an Einstein Elevator
Fundamental Physics
2001

Frans Spaepen
Harvard University, Cambridge, MA
Kinetics of Nucleation and Growth From Undercooled Melts
Materials Science
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Frans Spaepen
Harvard University, Cambrdige, MA
Glass Formation, Nucleation, and Diffusion in Metallic Melts
Materials Science
2001–2002

Arthur J. Sytkowski
Beth Israel Deaconess Medical Center, Boston, MA
Growth Factor Receptor Function and Cell Differentiation in a Low-Shear Environment
Biotechnology
2001–2002

Gretar Tryggvason
Worcester Polytechnic Institute, Worcester, MA
Computations of Boiling in Microgravity
Fluid Physics
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Worcester Polytechnic Institute, Worcester, MA
Computational Modeling of the Effect of Secondary Forces on the Phase Distribution in Dispersed

Multiphase Channel Flows
Fluid Physics
2001–2002

Michael Tsapatsis
University of Massachusetts, Amherst, MA
Thin-Film Molecular Sieve Synthesis: Processing-Microstructure Relationships and the Effect of Gravity on Microstructure
Materials Science
2001–2002

Ronald L. Walsworth
Smithsonian Astrophysical Observatory, Cambridge, MA
Ground-Based Investigations With the Cryogenic Hydrogen Maser
Fundamental Physics
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Smithsonian Astrophysical Observatory, Cambridge, MA
Probing Planck-Scale Physics With a 21Ne-3He Zeeman Maser
Fundamental Physics
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David A. Weitz
Harvard University, Cambridge, MA
Fabrication of Photonic Structure With Colloid Engineering
Fluid Physics
2001–2002

David A. Weitz
Harvard University, Cambridge, MA
Physics of Colloids in Space (PCS)
Fluid Physics
2001–2002

David A. Weitz
Harvard University, Cambridge, MA
Engineering of Novel Biocolloidal Suspensions
Fluid Physics
2002

August Witt
Massachusetts Institute of Technology, Cambridge, MA
Identification and Control of Gravity-Related Defect Formation During Melt Growth of Electro-optic Single Crystals: Sillenites ($Bi_{12}SiO_{20}$, BSO)
Materials Science
2001–2002

MICHIGAN

Arvind Atreya
University of Michigan, Ann Arbor, MI
Radiant Extinction of Gaseous Diffusion Flames
Combustion Science
2001–2002

Andre Benard
Michigan State University, East Lansing, MI
Investigation of Solidification Processes With Convection Using Meshless Methods and Quantitative Experimental Verification
Materials Science
2001–2002

Thomas Courtney
Michigan Technological University, Houghton, MI
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Materials Science
2001–2002

Werner Dahm
University of Michigan, Ann Arbor, MI
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Biotechnology
2001

James F. Driscoll
University of Michigan, Ann Arbor, MI
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Combustion Science
2001–2002

Gerard M. Faeth
University of Michigan, Ann Arbor, MI
Flow/Soot-Formation in Nonbouyant Laminar Diffusion Flames
Combustion Science
2001–2002

Gerard M. Faeth
University of Michigan, Ann Arbor, MI
Investigation of Laminar Jet Diffusion Flames in Microgravity
Combustion Science
2001–2002

James B. Grotberg
University of Michigan, Ann Arbor, MI
Capillary-Elastic Instabilities in Microgravity
Fluid Physics
2001

James B. Grotberg
University of Michigan, Ann Arbor, MI
Fluid Dynamics and Interfacial Stability of Pulmonary Airway Closure and Reopening in Microgravity
Fluid Physics
2002

Ronald G. Larson
University of Michigan, Ann Arbor, MI
Microscopic Visualization of Fluid Flow in Evaporating Droplets and Electro-Osmotic Flow
Fluid Physics
2001

Ronald G. Larson
University of Michigan, Ann Arbor, MI
Microfluidic and Dielectric Processing of DNA
Fluid Physics
2002

Laura R. McCabe
Michigan State University, East Lansing, MI
Microgravity Regulation of Oncogene Expression and Osteoblast Differentiation
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2001–2002

Marc Perlin
University of Michigan, Ann Arbor, MI
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Fluid Physics
2001–2002

Michael J. Solomon
University of Michigan, Ann Arbor, MI
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Fluid Physics
2001–2002

Indrek S. Wichman
Michigan State University, East Lansing, MI
Investigation of Diffusion Flame Tip Instability in Microgravity
Combustion Science
2001–2002

MINNESOTA

Jeffrey Derby
University of Minnesota, Minneapolis, MN
Atomistic Simulations of Cadmium Telluride: Toward Understanding the Benefits of Microgravity Crystal Growth
Materials Science
2001

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University of Minnesota, Minneapolis, MN
First Principles Calculations of Molten II-VI Compounds and Their Solidification Behavior
Materials Science
2001–2002

Jeffrey Derby
University of Minnesota, Minneapolis, MN
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Materials Science
2001–2002

MISSISSIPPI

John Pojman
University of Southern Mississippi, Hattiesburg, MS
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Materials Science
2001–2002

Joe B. Whitehead
University of Southern Mississippi, Hattiesburg, MS
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2001–2002

W. W. Wilson
Mississippi State University, Starkville, MS
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Biotechnology
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W. W. Wilson
Mississippi State University, Starkville, MS
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Richard L. Axelbaum
Washington University, St. Louis, MO
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Combustion Science
2001–2002

Delbert E. Day
University of Missouri, Rolla; Rolla, MO
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Materials Science
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Kenneth F. Kelton
Washington University, St. Louis, MO

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Materials Science
2001

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Washington University, St. Louis, MO
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Materials Science
2001–2002

MONTANA

Kenneth L. Nordtvedt
Northwest Analysis, Bozeman, MT
Optimizing Science From a STEP Mission
Fundamental Physics
2001

NEVADA

Garcia Almeida-Porada
University of Nevada, Reno, NV
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NEW HAMPSHIRE

Christopher J. Crowley
Creare, Incorporated, Hanover, NH
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2001

Ursula Gibson
Dartmouth College Hanover, NH
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Paul M. Chaikin
Princeton University, Princeton, NJ
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Edward L. Dreizin
New Jersey Institute of Technology, Newark, NJ
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Rutgers University, Piscataway, NJ
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David G. Keil
Titan Corporation, Princeton, NJ
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Harry Kojima
Rutgers University, Piscataway, NJ
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Chung K. Law
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Combustion Science
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Combustion Science
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Dudley A. Saville
Princeton University, Princeton, NJ
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Fluid Physics
2001–2002

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Princeton University, Princeton, NJ
Electrohydrodynamics of Suspensioons
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Alex V. Babkin
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Fundamental Physics
2001–2002

Stephen Boyd
University of New Mexico, Albuquerque, NM
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Eichi Fukushima
New Mexico Resonance, Albuquerque, NM
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Joel A. Silver
Southwest Sciences, Inc., Santa Fe, NM
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City College of the City University of New York, New York, NY
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City College of the City University of New York, New York, NY
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Cornell University, Ithaca, NY
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NYS Department of Health, Albany, NY
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Biotechnology
2001–2002

Morris A. Benjaminson
NSR-Touro Applied Bioscience Research Consortium, Bay Shore, NY
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Hauptman-Woodard Medical Research Institute, Buffalo, NY
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Biotechnology
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Joel Koplik
City College of the City University of New York, New York, NY
Molecular Dynamics of Fluid-Solid Systems
Fluid Physics
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David J. Larson
NASA Headquarters/State University of New York, Stony Brook, NY
Defects Numerically Decreased (DENUDE)
Materials Science
2001–2002

David Lee
Cornell University, Ithaca, NY
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Sung P. Lin
Clarkson University, Potsdam, NY
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2001–2002

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Materials Science
2001–2002

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2001–2002

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Syracuse University; Syracuse, NY
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2001–2002

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National Center for Microgravity Research on Fluids and Combustion, Cleveland, OH
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Thomas Jefferson University, Philadelphia, PA
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Materials Science
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Combustion Science
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2001–2002

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Brown University, Providence, RI
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University of Rhode Island, Kingston, RI
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Adam Smolka
Medical University of South Carolina, Charleston, SC

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Vanderbilt University, Nashville, TN
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Vanderbilt University, Nashville, TN
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University of Houston, Houston, TX
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James J. Riley
University of Washington, Seattle, WA
Investigation of the Liftoff and Blowout of Transitional and Turbulent Jet Flames
Combustion Science
2001–2002

Ward TeGrotenhuis
Battelle Pacific Northwest National Laboratory, Richland, WA
Microchannel Phase Separations for In-Situ Resource Utilization
Fluid Physics
2002

Viola Vogel
University of Washington, Seattle, WA
Motor Proteins as Shuttles for Directed Transport in Synthetic Matrices
Biotechnology
2001–2002

WEST VIRGINIA

Thomas Meloy
West Virginia University, Morgantown, WV
Mars Environmental Compatibility Assessment (MECA)
Biotechnology
2001

WISCONSIN

Reid Cooper
University of Wisconsin, Madison, WI
Dynamic Reduction and the Creation of Fine-Grained Ceramics From Inviscid Oxide/Silicate Melts
Materials Science
2001–2002

Sindo Kou
University of Wisconsin, Madison, WI
Physical Simulation of Marangoni Convection in Weld

Pools
Materials Science
2001–2002

John Perepezko
University of Wisconsin, Madison, WI
Analysis of Containerless Solidification Microstructures in Undercooled Melts and Composite Systems
Materials Science
2001–2002

Eric E. Rice
Orbital Technologies Corporation, Madison, WI
Carbon-Based Reduction of Lunar Regolith
Materials Science
2001

Eric E. Rice
Orbital Technologies Corporation, Madison, WI
Development of Methods of Producing and Utilizing Alternate Fuel/Oxidizer Combinations
Combustion Science
2001–2002

Thad G. Walker
University of Wisconsin, Madison, WI
All-Optical High-Density Atom Sources
Fundamental Physics
2001

DISTRICT OF COLUMBIA

Alexander Malkin
Naval Research Laboratory, Washington, DC
Growth Processes and Defect Structure of Macromolecular Crystals
Biotechnology
2001–2002

Gopal Patnaik
Naval Research Laboratory, Washington, DC
Unsteady Multidimensional Numerical Simulations of Flame Vortex Interactions in Microgravity
Combustion Science
2002

John Milburn Jessup
Georgetown University Medical Center,
Washington, D.C.
Gene Expression of Human Colorectal Carcinoma in Microgravity
Biotechnology
2001–2002

John Milburn Jessup
Georgetown University Medical Center,
Washington, D.C.
Use of NASA Biorector to Study Cell Cycle Regulation
Biotechnology
2001–2002

Glenn R. Joyce
Naval Research Laboratory, Washington, DC
Modeling Dusty Plasmas in Microgravity
Fluid Physics
2001–2002

Wu Ma
Naval Research Laboratory, Washington, DC
Neurogenesis in Cell-Hydrogel-Bioreactor System Forming Neuronal Networks in Microgravity
Biotechnology
2001–2002

Keith Ward
Naval Research Laboratory, Washington, DC
Investigation of the Particle Dynamics in the Vicinity of Crystal Surfaces: Depletion Zone Dynamics
Biotechnology
2001–2002

Flights to the International Space Station

Below are two lists of selected payloads for the International Space Station (ISS) and the associated EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Racks and microgravity facilities in the order of their flight to the station. Early on, microgravity research will consist of EXPRESS payloads, Microgravity Science Glovebox investigations, and Combustion Integrated Rack payloads, as reflected in the first list, which includes investigations currently manifested. The second list comprises payloads in development that are candidates for later flights.

Protein Crystal Growth–Enhanced Gaseous Nitrogen Dewar (PCG-EGN): This apparatus is a gaseous nitrogen dewar that can maintain samples at cryogenic temperature for about 10 days. Frozen liquid-liquid diffusion and batch protein crystal growth experiments are launched in a dewar and then allowed to thaw to initiate the crystallization process in a microgravity environment. The dewar houses a protein crystal growth insert typically holding approximately 500 protein samples. (First flight: 2A.2B)

Microgravity Acceleration Measurement System (MAMS): MAMS provides measurement of quasi-steady-state microgravity acceleration levels at low frequencies (0.01 to 2 hertz) with extreme accuracy. It is an enhanced version of the Orbital Acceleration Research Experiment system used on the space shuttle. Using MAMS data, the microgravity level at any point in the U.S. Laboratory or on the ISS can be calculated using a transformation matrix and a known center of gravity for the station. (First flight: 6A)

Space Acceleration Measurement System, Second Generation (SAMS-II): The SAMS-II instrument is an early addition to the ISS and will most likely remain onboard for the life of the station. SAMS-II measures vibratory accelerations (transients) in support of a variety of microgravity science experiments. It also characterizes the ISS microgravity environment for future payloads. (First flight: 6A)

Protein Crystal Growth–Single Thermal Enclosure System (PCG-STES): The PCG-STES hardware is a single EXPRESS locker that provides a controlled temperature environment within ± 0.5°C of a set point in the range from 4–40°C. The PCG-STES houses a variety of protein crystal growth apparatus, including the Second-Generation Vapor Diffusion Apparatus, the Diffusion-Controlled Crystallization Apparatus for Microgravity, and the Protein Crystallization Apparatus for Microgravity. (First flight: 6A)

Protein Crystal Growth–Biotechnology Ambient Generic (PCG-BAG): This apparatus flies Second-Generation Vapor Diffusion Apparatus, Diffusion-Controlled Crystallization Apparatus for Microgravity, or Protein Crystallization Apparatus for Microgravity hardware as ambient stowage items within a middeck locker or Cargo Transfer Bag. (First flight: 7A)

Vapor Diffusion Apparatus, Second Generation (VDA-2): VDA-2 uses the vapor-diffusion method (hanging drop technique) for protein crystal growth in order to produce large, high-quality crystals of selected proteins. The 20 growth chambers need to be activated to start the process and deactivated to stop it. The PCG-STES holds four VDA-2 trays; the PCG-BAG holds six trays. (First flight: 6A, as part of the PCG-STES)

Protein Crystallization Apparatus for Microgravity (PCAM): PCAM uses the vapor-diffusion method to produce large, high-quality crystals of selected proteins. Each PCAM is a cylindrical stack of nine trays, each with seven chambers, providing 63 chambers for protein crystal growth. The PCG-STES holds six cylinders; the PCG-BAG holds eight. (First flight: 6A, as part of the PCG-STES)

Physics of Colloids in Space (PCS): The PCS experiment hardware supports investigations of the physical properties and dynamics of formation of colloidal superlattices and large-scale fractal aggregates using laser light scattering. PCS advances understanding of fabrication methods for producing new crystalline materials. (First flight: 6A)

Dynamically Controlled Protein Crystal Growth (DCPCG): The DCPCG apparatus comprises two components: the control locker and the vapor locker. The command locker controls experiment processes in the vapor locker. It also collects data, performs telemetry functions, and is programmable from the ground. The vapor locker holds 40 protein samples. (First flight: 7A.1)

Cellular Biotechnology Operations Support System (CBOSS): This hardware provides a platform for the study of basic cell-to-cell interactions in a quiescent cell culture environment and the role of these interactions in the formation of functional cell aggregates and tissues. The Biotechnology Specimen Temperature Controller (BSTC) operates primarily in the incubation mode. The Biotechnology Refrigerator, Biotechnology Cell Science Stowage, and the Gas Supply Module support BSTC research. (First flight: 7A.1)

Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions (InSPACE): InSPACE hardware was designed to be accommodated by the Microgravity Science Glovebox (MSG). Observations of three-dimensional microscopic structures of magnetorheological fluids in a pulsed magnetic field will be made. (First flight: UF-2)

Pore Formation and Mobility Investigation (PFMI): This investigation promotes understanding of detrimental pore formation and mobility during controlled directional solidification processing in a microgravity environment. This MSG investigation utilizes a transparent material, succinonitrile, so that direct observation and recording of pore generation and mobility during controlled solidification can be made. (First flight: UF-2)

Solidification Using a Baffle in Sealed Ampoules (SUBSA): This investigation will test the performance of an automatically moving baffle in microgravity and determine the behavior and possible advantages of liquid encapsulation in microgravity conditions. This low-cost MSG experiment will resolve several key technological questions and lessen the risk and uncertainties of using a baffle and liquid encapsulation in future major materials science facilities. (First flight: UF-2)

Coarsening of Solid-Liquid Mixtures-2 (CSLM-2): This MSG investigation is designed to obtain data on steady-state coarsening behavior of two-phase mixtures in microgravity. For the first time, coarsening data with no adjustable parameters will be collected and then directly compared with theory. This will allow a greater understanding of the factors controlling the morphology of solid-liquid mixtures during coarsening. (First flight: 11A)

Diffusion-Controlled Crystallization Apparatus for Microgravity (DCAM): The DCAM system can use the liquid-liquid diffusion or dialysis method of protein crystal growth to produce high-quality single crystals of selected proteins. Three DCAM trays, each with 27 chambers, are flown per PCG-STES or PCG-BAG. (First flight: 11A)

Capillary Flow Experiment (CFE): The CFE hardware consists of two modules that have identical fluid injection mechanisms and similarly sized test chambers. The experiment can be performed in the MSG or as a stand-alone experiment. Its purpose is to provide fundamental insight into the mechanics of capillary flow that can be immediately applied by designers of low-gravity fluids systems. Specifically, the experiment will produce conclusive data about large-length-scale capillary flows, flow phenomena in complex geometries, and critical damping resulting from moving contact lines. The fluids used are benign, flight-qualified silicone oil and immersion oil. (First flight: 12P)

In Space Soldering Investigation (ISSI): This investigation will study surface tension–driven convection phenomena as well as the microscale physics of the interfacial zone of molten metals. The soldering experiments will consist of systematically investigating a number of key solidification/fabrication parameters. (First flight: 12P)

Miscible Fluids in Microgravity (MFMG): The objectives of this investigation are twofold: 1) to determine whether isothermal miscible fluids can exhibit transient interfacial phenomena similar to those observed with immiscible fluids; and 2) to determine whether miscible fluids in a thermal gradient can exhibit transient interfacial phenomena similar to those observed with immiscible fluids. (First flight: 12P)

Glovebox Integrated Microgravity Isolation Technology (g-LIMIT): G-LIMIT hardware is being developed to provide attenuation of unwanted accelerations within the MSG; to characterize the MSG acceleration environment; and to demonstrate high-performance, robust control technology. It will also be available to provide vibration isolation and measurement to other MSG investigations. (First flight: ULF-1)

Physics of Colloids in Space Plus (PCS+) Experiment: This investigation complements and extends the research begun with the original PCS investigation, flown on flight 6A. The PCS+ hardware consists of an avionics section, a test section, auxiliary hardware, operating system hard drives, and mass data storage hard drives. It utilizes light scattering and rheological measurements to investigate colloidal hard sphere disorder-order transitions as well as the properties of the resulting ordered phase. (First flight: 12A.1)

Fiber Supported Droplet Combustion-3 (FSDC-3): The objective of this investigation, utilizing the MSG, is to provide critical data on multicomponent droplet combustion, which will enable the development of theoretical models for use in multidroplet (spray) applications. The FSDC-3 hardware consists of an experiment module, liquid fuel syringes, deployment needles, droplet tethers, igniters, nozzles, diagnostics, and a computer control interface. (First flight: 12A.1)

Observable Protein Crystal Growth Apparatus (OPCGA): The OPCGA flight investigation hardware comprises three major components: the mechanical system, the optical system, and the video data acquisition and control system. The OPCGA hardware also provides 96 individual experiment cells with the capability to collect optical data on 72 cells. (First flight: 12A.1)

Metastable Solution Structure in Protein Crystal Growth (XLINK): The XLINK consists of the Low-Temperature, Low-Energy Carrier and Group Activation Pack hardware. The objective of XLINK is to study the presence and distribution of aggregates in solutions that lead to crystal growth of lysozyme and insulin. The experiment will investigate the effects of gravity on the formation of aggregates, the size distribution of and/or average size of aggregates, and the transport of the aggregates to the crystal surface. (First flight: 12A.1)

Delta-L: The Delta-L investigation will replace hardware previously known as the Interferometer for Protein Crystal Growth. This MSG investigation will study the crystal growth characteristics of biological macromolecules in microgravity. Data from Delta-L will be used to verify the theory that growth rate dispersion plays a role in crystal quality improvement in microgravity. (First flight: 13A.1)

Smoke Points in Coflow Experiment (SPICE): This investigation, using the MSG, evaluates the effect of oxidizer and fuel velocities on the laminar smoke point (the propensity of flames to emit soot). The SPICE hardware consists of an experiment module, 12 gaseous fuel bottle assemblies, igniters, nozzles, and a video camera. (First flight: 13A.1)

Shear History Extensional Rheology Experiment (SHERE): SHERE will study the effects of pre-shear on the transient evolution of the microstructure and viscoelastic tensile stresses for viscoelastic polymer solutions. The SHERE hardware consists of a rheometer assembly, a camera arm, and a fluid module tray containing 25 fluid modules. Each fluid module contains a single sample for testing. (First flight: 15A)

Droplet Combustion Experiment-2 (DCE-2): DCE-2 will study single pure fuel droplet combustion in microgravity to better understand combustion kinetics through droplet combustion extinction diameter measurements. It will also improve the understanding of transient liquid and gas phase phenomena. DCE-2 will be conducted in the Combustion Integrated Rack (CIR) designed specifically to support advanced combustion research in the microgravity environment. DCE-2 is the first of four experiments to use the Multiuser Droplet Combustion Apparatus (MDCA) in the CIR. (First flight: ULF-2)

Bi-Component Droplet Combustion Experiment (BCDCE): BCDCE will study bi-component fuel droplet combustion in microgravity, where spherical symmetry is approached in both gas and liquid phases of the droplet, to better understand the transient buildup of the less volatile component on the liquid side of the liquid/gas interface. BCDCE will be conducted in the CIR. BCDCE is the second experiment to use the MDCA in the CIR. (First flight: ULF-2)

Candle Flames in Microgravity-2 (CFM-2): CFM-2 will exploit candle geometry as a platform for fundamental science and educational outreach to determine the limiting oxygen concentration for a microgravity candle, whether a steady microgravity candle flame can exist in air, if the microgravity flame will oscillate for a prolonged period, and the interactions and extinction behavior between two neighboring flames. CFM-2 will be operated in the MSG. (First flight: ULF-2)

Microheater Boiling Experiment (MABE): This experiment determines boiling heat transfer mechanisms and tests the hypotheses that bubble coalescence is the primary bubble removal mechanism, heat is transferred by small satellite bubbles, and heat transfer from the small bubbles is not affected by gravity level. Specific experiment hardware consists of a set of miniature heaters and heater controllers installed in the Boiling Experiment Facility (BXF). The BXF itself will be operated in the MSG. (First flight: ULF-2)

Nucleate Pool Boiling Experiment (NPBX): The objective of this experiment is to validate boiling models with descriptions of such aspects as bubble growth and departure at single nucleation sites, as well as bubble merger, bubble-bubble interaction and vapor removal from predesigned cavities on a heater surface during quasistatic conditions. This experiment, like MABE, will be performed in the BXF in the MSG. (First flight: ULF-2)

Physics of Colloids in Space-3 (PCS-3): PCS-3 is a follow-on to the PCS and PCS+ experiments. Using the same techniques of light scattering, PCS-3 will address fundamental questions about nucleation, growth, morphology, and dynamics of binary colloidal crystal alloys, colloid-polymer gels, fractals, anisometric colloids, and colloidal glasses. It will examine samples provided by three separate principal investigators. (First flight: ULF-2)

Payloads that are planned and/or in development and that have not yet been manifested are listed below in alphabetical order.

Binary Colloidal Alloy Test-3 (BCAT-3): BCAT-3 is being developed with the heritage from BCAT and BCAT-2. BCAT-3 is designed to operate as a stand-alone experiment in the ISS's Maintenance Work Area. In BCAT-3, the long-term behavior of crystals of binary colloidal alloys will be studied in a microgravity environment, where the effects of sedimentation and convection are greatly reduced, to allow a better understanding of colloids and how to engineer their properties. The experiment's predecessor, BCAT-2, was flown on the Russian space station, *Mir*.

Biotechnology Facility (BTF): BTF, the next generation of on-orbit cellular biotechnology hardware, serves as a new platform for cellular research. BTF automates many of the functions performed by the crew during the earlier CBOSS experiments and allows for increased science throughput. The Phase I BTF is a two-rack facility that includes three Automated Stationary Culture System units for processing various types of cells as supported by two Gas Supply Module units to supply carbon dioxide–enriched medical-grade air, and an Automated Culture Water Assembly to create cell growth media. BTF also provides cold storage at 4 °C, -80 °C, and -180 °C. The Phase II BTF will add a Multivessel Rotating Bioreactor and data analysis equipment.

Buoyancy-Driven Instabilities in Single-Bubble Sonoluminescence (BDISL): This experiment will quantify buoyancy-induced instabilities that may play a dominant role in the mechanism for sonoluminescence extinction. The influence of chemical instabilities will be tested by using different gas-water concentrations. BDISL will be operated in the MSG.

Colloidal Disorder-Order Transition-3 (CDOT-3) Apparatus: This hardware fits in a glovebox and is used to photograph samples of dispersions of very fine particles as they form various crystalline or gel structures. This hardware was flown previously on the second United States Microgravity Laboratory payload and on STS-95.

Coupled Growth in Hypermonotectics (CGH): Hypermonotectic alloys consist of two separated phases not only in the solid, but also in the liquid. With liquids of different densities, sedimentation of the denser phase takes place on the ground. This Materials Science Research Rack (MSRR) payload will help in elucidating the theory behind the formation, and hence will improve our ability to produce the desired structures on the ground.

Chain Aggregation Investigation by Scattering (CHAINS): This experiment will investigate the fluctuations and dynamics responsible for the cross-linking of dipolar chains in magnetorheological fluids. CHAINS will be operated in the MSG.

Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments (CSS): The primary purpose of this MSRR payload is to compare the structure and segregation in binary metallic alloys that are directionally solidified in terrestrial and low-gravity environments.

Constrained Vapor Bubble (CVB): This experiment will investigate heat conduction in microgravity as a function of liquid volume and heat flow rate to determine, in detail, the transport process characteristics in a curved liquid film. CVB is being developed to run in the Light Microscopy Module (LMM) in the Fluids Integrated Rack (FIR).

Dynamical Selection of Three-Dimensional Interface Patterns in Directional Solidification (DSIP): The objective of this investigation is to establish fundamental principles that govern the spatial-temporal evolution of cellular and dendritic interface patterns in directional solidification. Low-gravity experiments will be used to validate a rigorous numerical model of pattern evolution dynamics that are currently being developed using the phase-field approach.

Dynamics of Droplet Combustion and Extinction (DDCE): This experiment will investigate the effects of small convective flows on burning droplets to better define the influences of such flows on the extinction process. DDCE extends the knowledge generated in the study of droplet combustion by DCE-2 and BCDCE before it. DDCE is the fourth experiment to use the MDCA in the CIR.

Dynamics of Miscible Interfaces (MIDAS): This experiment will investigate the dynamics of miscible interfaces, as well as document flow fields and concentration gradients near an evolving fluid interface within a precisely controlled, two-fluid flow system. MIDAS will be operated in the DECLIC facility, developed by the French space agency (CNES), in an EXPRESS Rack.

Foam Optics and Mechanics (FOAM): This experiment is being designed by the European Space Agency (ESA) for operation in the ESA-developed Fluid Science Laboratory. The objective of FOAM is to understand the unusual nature of foam rheology in terms of behavior at the bubble scale, the packing structure, the rearrangement dynamics, and the coarsening of foams via gas diffusion. Video microscopy, multiple light scattering, and rheology techniques will be employed to examine foams as a systematic function of liquid content, shear rate, and foam age.

Forced Ignition and Spread Test (FIST): This experiment will validate a proposed new flammability test methodology for homogeneous and composite materials under environmental conditions found only in crew-occupied spacecraft or extraterrestrial habitats. FIST will be conducted in the CIR. FIST is the first of at least five experiments to use the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS) in the CIR.

Gravitational Effects on Distortion in Sintering (GEDS): The GEDS apparatus will use the Low Gradient Furnace (LGF). The microgravity Liquid Phase Sintering (LPS) experiments contained in the GEDS apparatus are designed to isolate gravity-porosity interactions with respect to densification, component distortion, and underlying microstructure evolution. Findings from this research will be used to improve modeling of LPS by including gravity-porosity effects.

Interface Pattern Selection Criteria for Cellular Structures in Directional Solidification (IPSIDS): The objective of this MSRR payload is to obtain benchmark data on cellular and dendritic growth under conditions that produce negligible convection. Precise measurements of interface shape, cell/dendrite tip radius, tip composition, and tip temperature as functions of composition, growth rate, and thermal gradient will be carried out. These measurements will be used to characterize conditions for the planar to cellular, shallow cells to deep cells, and deep cells to dendrites transition.

Kinetics of Nucleation and Crystal Growth in Glass Forming Melts in Microgravity (CROMIS): CROMIS will investigate why glass forms more easily and is more chemically homogeneous in microgravity than on Earth. The flight experiment will include melting lithium disilicate, a glass with well-known properties, then treating it at selected temperatures for different amounts of time at each temperature. Measurements of the rates of nucleation and crystal growth in microgravity will be compared to those on Earth.

Levitation Observation of Dendrite Evolution in Steel Ternary Alloy Rapid Solidification (LODESTARS): This payload will help to develop a better understanding of how nucleation and growth of the austenitic phase affect phase selection in ternary steel alloys following formation of a primary metastable ferritic dendritic array.

Light Microscopy Module (LMM): LMM is a remotely controllable, automated, on-orbit microscope, allowing flexible scheduling and control of physical science and potential biological science experiments within the FIR on the ISS. Its key features include video microscopy, confocal microscopy, laser tweezers, an oil immersion system, thin-film interferometry, and spectrophotometry.

Particle Engulfment and Pushing by Solidifying Interfaces (PEP): This investigation, which flew previously in the Middeck Glovebox, will study the effects when two nonmixing alloys (immiscibles such as oil and water) are stirred and frozen in normal gravity and then melted and resolidified in microgravity. PEP will be conducted in the MSG.

Physics of Colloids in Space-2 (PCS-2): The objective of PCS-2 is to carry out further investigation of critical fundamental problems in colloid science and to fully develop the evolving field of "colloid engineering," as well as to create materials with novel properties using colloidal particles as precursors. PCS-2 is being developed to run in the LMM in the FIR.

Physics of Hard Spheres-2 (PHaSE-2): This experiment will investigate the growth, structure, and properties of hard sphere colloidal crystals in microgravity and how applied fields affect these systems. PHaSE-2 is being developed to run in the LMM in the FIR.

Quasicrystalline Alloys for Space Investigation (QUASI): This payload will perform studies of aluminum-thulium and titanium/zirconium-thulium liquids to better understand the local atomic structure of phases in relation to undercooled liquids, the growth mechanism for complex periodic and ordered nonperiodic phases, and nucleation when the composition of initial and final phases are different.

Quench Module Insert (QMI): QMI is being designed for materials science research inside the Materials Science Laboratory in MSRR-1. QMI is a high-temperature, Bridgman-type furnace with an actively cooled cold zone. The apparatus will create an extremely high-temperature gradient for the directional solidification processing of metals and alloys. It is also capable of rapidly freezing (quenching) samples at the liquid-solid interface, where most of the science takes place during directional solidification.

Radiative Enhancement Effects on Flame Spread (REEFS): This experiment will investigate the transport and chemical effects of various atmospheres on flame spread over solid fuel beds with emphasis on radiative enhancements likely to be present in fires that may occur in microgravity. REEFS is the second experiment to use the FEANICS in the CIR.

Reduction of Defects in Germanium-Silicon (RDGS): The RDGS experiment will likely be conducted in the LGF. RDGS investigates the mechanism leading to detached crystal growth in the Bridgman configuration and determines the parameters essential for the controlled use of the furnace for detached growth. A comparison of processing-induced defects in Bridgman, detached Bridgman, and float-zone growth configurations in germanium-silicon crystals will be made. A determination as to whether detached Bridgman or float-zone processing can produce germanium-silicon crystals with fewer defects will also be made, and any differences will be quantified.

Smoke: Increasing mission durations and the expanded size of habitable space aboard spacecraft require enhanced fire detection capability. This experiment will improve the ability to detect spacecraft fires by studying the particle size distribution of smoke generated in microgravity. Results from research conducted as part of the United States Microgravity Payload in 1996, indicate that smoke structure changes significantly in low gravity. Current ISS and space shuttle smoke detectors were designed based upon data collected in Earth's gravity. The Smoke experiment is being designed for operation in the MSG.

Sooting and Radiation Effects in Droplet Combustion (SEDC): This experiment will investigate the effects of sooting and radiation influences on the overall burning behavior of droplets by means of optical and intrusive techniques. SEDC extends the knowledge generated in the study of droplet combustion by DCE-2 and BCDCE before it. SEDC is the third experiment to use the MDCA in the CIR.

Spaceflight Holography Investigation in a Virtual Apparatus (SHIVA): SHIVA will record particle motion in a fluid using holographic data. SHIVA plans to use the MSG and possibly g-LIMIT.

Transient Interfacial Phenomena in Miscible Polymer Systems (TIPMIPS): This experiment will measure the fluid flow induced by a temperature gradient along the interface between a polymer and its monomer and the fluid flow induced by a variation in the initial width of the interface between a polymer and its monomer. TIPMIPS will also determine if Marangoni instability can occur at a miscible interface and if a bubble driven by a temperature gradient penetrates a miscible interface.

Ultraviolet-Visible-Infrared Spectrophotometer (UVIS): This experiment will provide spectrophotometry capabilities from 200 nanometers to 2,400 nanometers to determine the photonic band structures of crystals and support future fluid physics and biotechnology experiments. UVIS will be operated in the MSG.

Water Mist: This experiment will investigate how different sizes and concentrations of droplets will affect a thin layer of flame, known as a laminar flame. The Water Mist investigation is developed by the Center for Commercial Applications of Combustion in Space and will be conducted in the CIR.

Wetting Characteristics of Immiscibles (WCI): The WCI investigation, which flew previously in the Middeck Glovebox, will study the effects when two non-mixing alloys are stirred and frozen in normal gravity and then melted and resolidified in microgravity. WCI will be conducted in the MSG.

The Physical Sciences Research Division currently has two unpressurized payload candidates in addition to the Low-Temperature Microgravity Physics Facility. These payloads are described below.

Primary Atomic Reference Clock in Space (PARCS): The PARCS investigation will measure various predictions of Einstein's Theory of General Relativity, including gravitational frequency shift and the local position invariance on the rate of clocks. PARCS will also achieve a realization of the second, a fundamental unit of time, as a function of the energy difference between two atomic levels in a cesium atom at an order of magnitude better than that achievable on Earth.

Rubidium Atomic Clock Experiment (RACE): The RACE investigation will interrogate rubidium (87Rb) atoms one to two orders of magnitude more precisely than Earth-based systems, achieving frequency uncertainties in the 10^{-16} to 10^{-17} range. RACE will improve clock tests of general relativity, advance clock limitation, and distribute accurate time and frequency from the ISS.

The following international payloads are planned for the ISS.

Apparatus for the Study of Material Growth and Liquids Behavior Near Their Critical Point (DECLIC): The DECLIC facility is being developed by CNES in cooperation with Glenn Research Center in Cleveland, Ohio, to provide an autonomous or tele-operated capability at middeck locker–scale to accommodate research on high-pressure samples of fluids near their critical points, transparent materials systems during solidification, and other fluids experiments that are compatible with available diagnostics. Through cooperative interagency agreements (signed in 2000), NASA will provide launch, integration, and resources for DECLIC and will share in the utilization of the facility.

Fluid Science Laboratory (FSL): The FSL is part of ESA's Microgravity Facilities for Columbus Programme. It will support basic and applied research in fluid physics under microgravity conditions. The design provides easy exchange of FSL modules in the case of upgrades and modifications. The facility can be operated in fully automatic mode, following a preprogrammed sequence of commands, or in semiautomatic telescience mode, enabling the user to interact with the facility in quasi–real time from the ground. This will allow scientists to follow the evolution of their experiments and to provide feedback on the data they receive at the ground station.