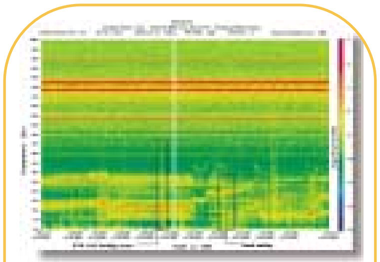
NASA'S PHYSICAL SCIENCES RESEARCH PROGRAM

ANNUAL REPORT 2000

National Aeronautics and
Space Administration

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

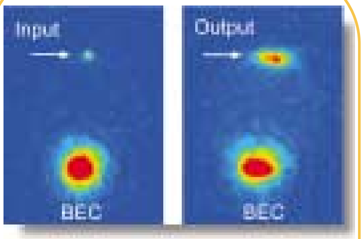


A sample color spectrogram of acceleration data obtained during a shuttle docking with the space station.

See page 51

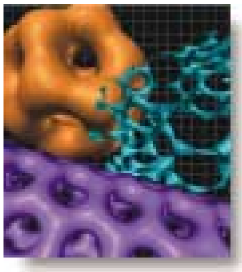
Conducting research aboard the ISS will enable world-class scientists from a variety of discreet fields.

See page 54



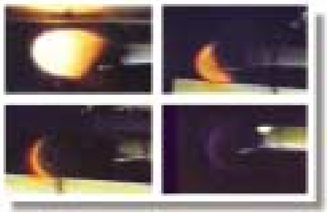
An atom beam amplified: The left image shows the shadow of the initial (or input) beam of atoms. The right image shows the shadow of the output beam.

See page 41



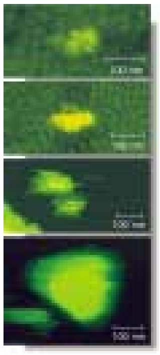
Pictured here are computer models of a nanotube and a fullerene, materials with unique properties that formed from carbon molecules.

See page 43



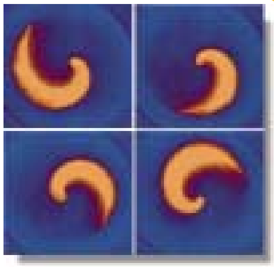
Researchers working on fire safety issues in space need to understand the flammability characteristics of materials that are commonly used aboard spacecraft.

See page 24



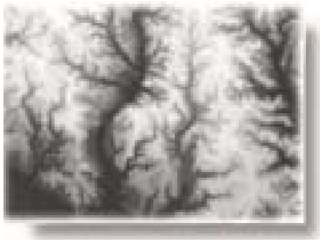
Watching molecules of apoferritin come together to form a nucleus reveals some interesting behavior.

See page 12



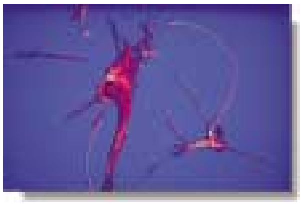
Researchers found these (false-color) spiral flames when they ignited a spinning plastic disk suspended horizontally in air.

See page 27



A new method for predicting the path of rivers relies on elevation data from satellites and mathematics.

See page 33



Pictured here are red blood cells, nerve cells, and tissue from the trachea and lungs.

See page 14

1		Cover images	
1		Table of Contents	
1		For More Information	
2		Introduction	pg 1
3		Biotechnology	pg 4
4		Combustion Science	pg 22
5		Fluid Physics	pg 28
6		Fundamental Physics	pg 36
7		Materials Science	pg 42
8		Acceleration Measurement	pg 50
9		International Space Station	pg 54
10		Ground-Based Microgravity Facilities	pg 58
11		Outreach and Education	pg 60
12		Program Resources	pg 66
13		Appendices	
		A Grant Recipients	pg 67
		B Microgravity Experiment Hardware	pg 98

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 Microgravity Research Program 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, which is conducting business better, cheaper, and faster through cooperative ventures and other streamlined practices.

By disseminating knowledge and transferring technology among private industries, universities, and other government agencies, the Microgravity Research Program 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 and *Mir* 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 paving the way for long-duration microgravity science on the International Space Station.

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

The Physical Sciences Division
NASA Headquarters
300 E Street, S.W.
Washington, DC 20546-0001
Phone: (202) 358-1490
Fax: (202) 358-3091
World Wide Web addresses:
http://spaceresearch.nasa.gov
http://microgravity.hq.nasa.gov
http://microgravity.msfc.nasa.gov

At the close of fiscal year 2000, the Office of Life and Microgravity Sciences and Applications became the Office of Biological and Physical Research under the newly formed Biological and Physical Research Enterprise (BPRE). This organizational restructuring reflects the increasing recognition of the importance of the scientific research role played by the nascent International Space Station (ISS) and of the leadership responsibility that this new research enterprise must carry out. Within this new NASA research enterprise, the Microgravity Research Division (MRD) remains an integral unit, with a change of name. The MRD is now the Physical Sciences Research Division (PSRD). The BPRE, which will continue to sponsor cutting-edge interdisciplinary research, has marked the year 2000 by introducing new programs such as biomolecular physics and chemistry, nanoscience, and advanced applications of biotechnology on Earth.

This division's principal objectives are to carry out multidisciplinary basic research, enabled by the space environment, to accomplish NASA's goal of advancing and communicating knowledge and to develop a rigorous cross-disciplinary scientific capability, bridging physical sciences and biology to address NASA's human and robotic space exploration goals. Further, the division is in the process of establishing the ISS facilities as unique on-orbit science laboratories that will target scientific and technological issues of high significance.

In 2000, the program has continued to build an outstanding peer-reviewed research program by selecting new flight and ground-based investigations in the disciplines of fundamental physics (41 tasks) and combustion research (26 tasks). The biotechnology, materials science, and fluid physics disciplines will issue proposal calls in 2001. A memorandum of understanding has been signed between NASA and the National Cancer Institute for collaboration on advanced research in ground-breaking biomolecular systems technology targeting distributed and miniaturized medical sensors to detect early signs of cancer and any negative physiological impact of long-term exposure to the space environment. A joint announcement of opportunity will solicit research proposals early in 2001 for awards to be made in fall 2001.

The ground-based research program has continued to increase its productivity through generating a large number of peer-reviewed publications and by organizing and hosting workshops in fluid physics, fundamental physics, and materials science. The division has begun a reassessment of the planned ISS flight program in which the priority of the various discipline-dedicated ISS research facilities under development will be addressed. One of the objectives has been to implement the recommendations contained in the National Research Council report on *Future Biotechnology Research on the International Space Station*. Other major motivations have been to enhance the interdisciplinary research component of the program and to optimize the productivity of planned on-orbit research facilities.

This year was a year of research discipline expansion, strategic replanning, and managerial restructuring to build an essential component of a new NASA research enterprise. We believe that we have the opportunity to mold a cutting-edge, cross-disciplinary research program that will stand out among all federal research agencies and will bring to fruition the promises of the microgravity environment.

— Eugene Trinh
Director, Physical Sciences Division

Table 1 — Microgravity Research Program Overview			
	1998	1999	2000
Research tasks	465	485	584
Principal investigators	377	409	455
Co-Investigators	446	487	667
FY budget ($ in millions)	100.4	113.7	108.7

Table 2 — Program Bibliographic Listings			
	1998	1999	2000
Journal articles	683	905	904
Presentations	823	962	1,062
Proceeding papers	305	350	422
NASA technical briefs	31	30	13
Books/chapters	26	33	50
Total	1,868	2,280	2,451

Table 3 — Grant Statistics			
	1998	1999	2000
Students funded	853	969	1,146
Degrees granted	277	368	457
Patents applied for	8	26	22

Table 4 — Glenn Research Center Task Summary			
	1998	1999	2000
Ground-based	152	163	189
Flight program	44	43	55
Total	196	206	244

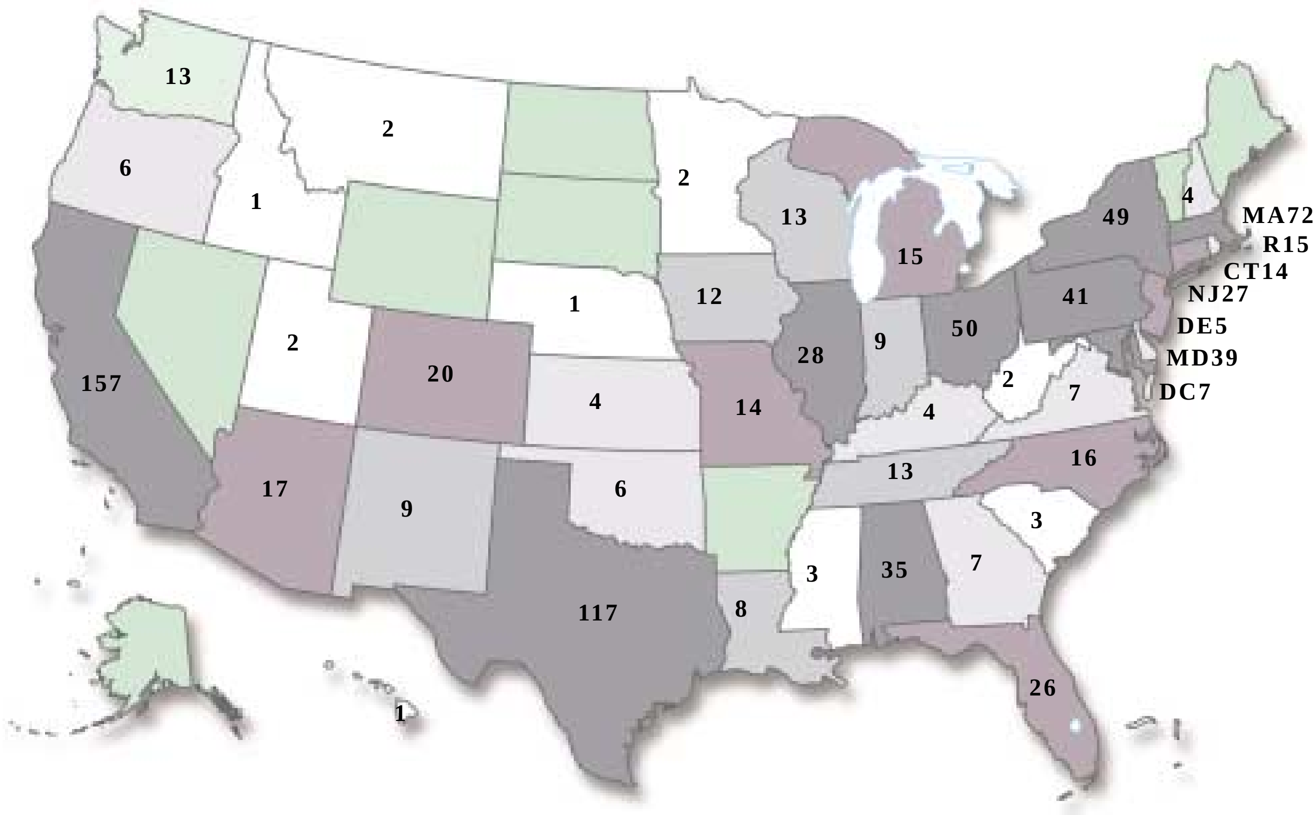
Table 5 — Jet Propulsion Laboratory Task Summary			
	1998	1999	2000
Ground-based	42	40	40
Flight program	9	9	9
Total	51	49	49

Table 6 — Johnson Space Center Task Summary			
	1998	1999	2000
Ground-based	37	55	56
Flight program	1	2	2
Total	38	57	58

Table 7 — Marshall Space Flight Center Task Summary			
	1998	1999	2000
Ground-based	127	135	180
Flight program	39	39	46
Total	166	174	226

OFFICE OF BIOLOGICAL AND PHYSICAL RESEARCH (OBPR)

FY00 Total Investigations by State



*886 Investigations funded in
42 States and the District of Columbia

*Includes some investigations that may not have received FY00 funds.

Humans have harnessed biotechnology in its most basic forms to produce goods such as bread, cheese, and wine for human consumption.

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 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, as well as to produce alcohol-based fuels for motorized vehicles. Bacteria have been discovered that can break down oil and petroleum, 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

Biotechnology also allows people to use nature to help solve environmental problems. Microbes are used to process sewage, and scientists have genetically altered bacteria to create microbes that will feed on oil slicks.

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.

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.

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 in Huntsville,

Biotechnological advances have allowed farmers to plant agricultural crops that are more productive, resistant to disease, and able to withstand the herbicides used to control unwanted plants.

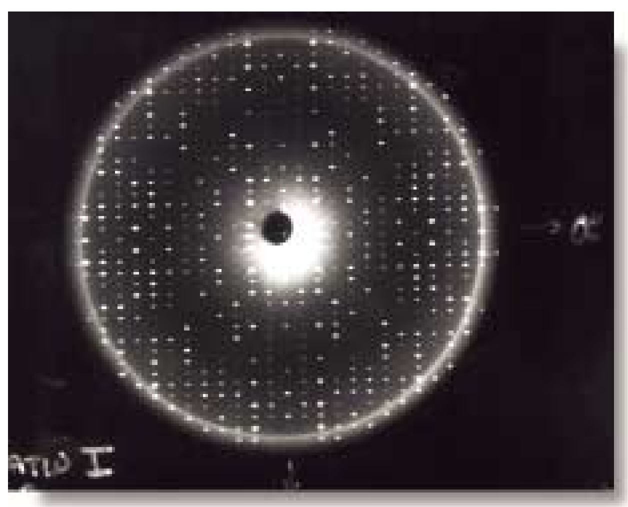
Deoxyribonucleic acid — DNA — carries all the genetic information that allows cells to make proteins and other biological molecules that are necessary to maintain life.

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 aid in fighting infection (antibodies are proteins). 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.

The best-known examples of nucleic acids are ribonucleic acid (RNA) and deoxyribonucleic acid (DNA). Nucleotides, or 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 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.

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



X-ray crystallography is the most commonly used method for studying the structure of biological molecules. X-rays diffracted from a well-ordered protein crystal create sharp patterns of scattered light on film. Computer analysis of these patterns can then be used to generate a model of a protein molecule.

All of the protein and virus crystals depicted in this collage were successfully grown in space and are suitable for X-ray diffraction analysis.

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 are formed of the molecule of interest, and X-rays are passed through the single crystal at various angles. The resulting diffraction patterns are analyzed by using computers to estimate the size, shape, and structure of the molecule. Flawed crystals will yield a blurry diffraction pattern, whereas a well-ordered crystal will yield a sharp diffraction pattern and thus useful information about the structure of the crystal.

A microgravity environment reduces the effects of fluid flows and sedimentation, which can affect the crystal growth process and the quality of the crystal. Crystals are grown in solution. When a crystal begins to form, 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 than the remainder of the solution and therefore has a lower density. This difference in density creates currents next to the growing crystal. Such fluid flows can alter the orientation and position of the biological molecules as they add to the crystal lattice, thereby creating disorder in the crystal.

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, 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.

Large, better structured insulin crystals grown in microgravity (left) reveal their vital form and function to crystallographers and to scientists seeking better treatments for diabetic patients. The same information would be almost impossible to obtain from the smaller, less well-ordered insulin crystals grown on Earth (right).

Program Summary

Following the release in 2000 of the National Research Council's (NRC's) report, *Future Biotechnology Research on the International Space Station*, the biotechnology program implemented the Structural Biology Initiative to enact the recommendations of the NRC panel. 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, provide video microscopy of crystallization experiments, allow new experiments to be set up and manipulated from the ground, and allow cryocooling (cooling to extremely low temperatures) of crystals grown in orbit. The program will also concentrate on enabling iterative biological crystallization, which will allow researchers to conduct several rounds of experiments on the ISS rather than the one round that is possible now. Both of these initiatives will maximize the use of the microgravity environment for structural biology investigations.

Also in response to the NRC panel, the biotechnology program began developing and testing an associate investigator program, which 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/flight_opp.html* on the World Wide Web (WWW).

The NASA Research Announcement (NRA) for macromolecular and cellular biotechnology that was released in August 2000 directly addressed the recommendations contained in 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 research described in the preceding paragraph 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. Research in this area combines molecular biology, physical sciences, and materials engineering. Biomolecular materials have the capability of self-assembling without external intervention, and understanding the processes 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 Human Exploration and Development of Space (HEDS) goals.

Finally, in the area of structural protein-based materials, NASA solicited proposals for the production of protein-based materials or the isolation, in useable form, of such materials from cells. Collagen, keratin, and silk are examples of structural proteins, and they are also characterized by their ability to self-assemble. 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 by using recombinant DNA technology, it is possible to create a uniform and controllable architecture of the resulting material. Such biomaterials could also support HEDS 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. NASA plans to announce selections in spring 2001, with grants and contracts to be awarded shortly thereafter. For additional information on the NRA and selections, visit *http://research.hq.nasa.gov/code_u/nra/current/NRA-00-HEDS-03/index.html* on the WWW.

The Eighth International Conference on Crystallization of Biological Macromolecules was held May 14–19, 2000, in Sandestin, Florida. The meeting was co-chaired by NASA Principal Investigators (PIs) Lawrence DeLucas, director of the Center for Macromolecular Crystallization at the University of Alabama, Birmingham, and Alexander Chernov, of the Universities Space Research Association and Marshall Space Flight Center. Craig Kundrot, biotechnology discipline scientist, presented a talk on NASA-sponsored research at this meeting. Kundrot discussed the character and scope of NASA's macromolecular crystal growth program, as well as the NRC recommendations, and provided information on the types of crystals that had been grown in space, the facilities available for macromolecular biotechnology research on the ISS, and the types of experiments that were being performed.

Kundrot concluded his talk with a description of the ways in which researchers could participate in the macromolecular biotechnology program, including information on the most current NRAs and the Structural Biology Initiative. The initiative supports an effort to produce crystals of important biological macromolecules both on the ground and in microgravity in order to evaluate the efficacy of using the microgravity environment of low Earth orbit to grow such crystals.

The macromolecular biotechnology program sponsored 20 ground-based and eight flight-based researchers in fiscal year (FY) 2000. A listing of all ongoing biotechnology research projects, along with the names of the investigators conducting the research, is provided in the Appendix.

Flight Experiments

Exciting progress on flight projects was made in FY 2000, with one shuttle flight and one ISS research increment carrying experiments from the macromolecular biotechnology program. Significant milestones were also reached in the development of ISS experiment hardware and in the analysis of crystals grown during the NASA shuttle/*Mir* program.

The space shuttle *Atlantis* (STS-101) was launched on May 19, 2000, with 504 samples of 10 varieties of proteins from eight researchers. The samples were contained in a Biotechnology Ambient Generic Protein Crystallization Apparatus for Microgravity (PCAM). The basic PCAM is a self-contained crystal growth apparatus that consists of a plastic tray containing seven sample wells. The sample wells, which each hold a drop of protein solution, are surrounded by a "moat" of absorbent material. 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 into one PCAM cylinder, and six cylinders can be carried in a temperature-controlled locker. Once in orbit, shuttle crewmembers use a wrench to retract metal cams that hold the rubber seals in place, thereby allowing the liquid to evaporate from the protein solution samples and starting the crystallization process. Near the end of the mission, crewmembers crank the cams back into place to reseal the sample wells before returning to Earth.

Crystals of albumin, *E. coli* Gro EL, Eco R1 Endonuclease-DNA complex, lysozyme, and pectate lyase large enough to generate good results from X-ray diffraction were produced during this PCAM experiment (see Table 8). Additionally, hemoglobin C, which did not develop crystals on STS-95, produced large crystals on STS-101. On the basis of estimates of the sizes of crystals at unloading, several other crystals, including those of pectate lyase and S-layer protein from *Bacillus sphaericus*, appeared to have grown larger under microgravity conditions than had previously been attained under the normal-gravity conditions on Earth. Researchers are currently evaluating the crystals that were obtained from the proteins flown on STS-101, a process that can take months.

NASA PI Alexander McPherson, of the University of California, Irvine, led an Enhanced Dewar Program conducted on the ISS during FY 2000. The Enhanced Gaseous Nitrogen Dewar (EGN) is essentially a Thermos in which tubes of flash-frozen biomolecular samples are bundled. The dewar is filled with liquid nitrogen, which maintains the samples in a frozen state prior to arrival in orbit. The enhanced version of the dewar includes devices for recording and storing temperature data from inside the dewar. Once the liquid nitrogen evaporates, the crystallization process begins.

Crystallization may be achieved in two ways. In batch samples, biological macromolecules are mixed in a supersaturated solution from which, after thawing, crystals can be expected to form over time. In liquid-liquid diffusion samples, the material to be crystallized and the precipitant solutions, frozen separately, thaw and diffuse with each other, resulting in crystal formation across the liquid-liquid interface. Under microgravity conditions, crystals of the biomolecular materials form without interference from the container, other crystals, or turbulent flows.

Students from Memphis, Tennessee, prepare samples at the University of Alabama for the first protein crystal growth experiments to be performed aboard the International Space Station.

Because the EGN allows hundreds of samples to be flown at once, researchers can experiment with a variety of conditions to try to determine which conditions will produce the most useful crystals for further analysis. That valuable information can then be used to optimize crystal growth during future protein crystal growth experiments aboard the ISS.

The space shuttle *Atlantis* (STS-106), which launched on September 8, 2000, carried an EGN dewar experiment with 473 samples of 21 different proteins to the ISS. Space shuttle *Discovery* (STS-92) returned the EGN samples to Earth on October 24, 2000. Middle and high school students from Alabama, California, Florida, and Tennessee prepared 150 of the samples for this first EGN experiment aboard the ISS. Nine different proteins were successfully crystallized in the EGN by the PIs and students. Several additional macromolecules were also crystallized by guest investigators. The samples are currently undergoing analysis by X-ray diffraction and atomic force microscopy. For the first time, an excellent recording of the temperature inside the dewar during the entire course of the mission was obtained.

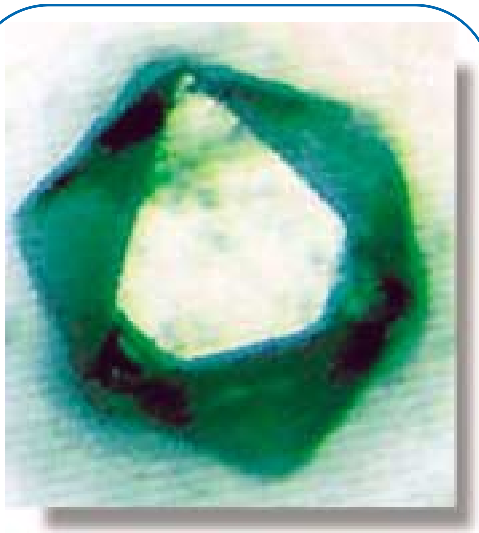
Many biotechnology experiments will make use of the EXpedite PRocessing of Experiments to Space Station (EXPRESS) rack system on the ISS, which features standardized hardware interfaces to enable the integration of payloads, as well as removable experiment subracks that can be exchanged in and out of the EXPRESS racks as needed. One of these subracks is the Single Thermal Enclosure System (STES), which can house several types of equipment used to grow biological crystals in microgravity, including the PCAM, which is scheduled to be carried to the ISS on the STS-100 mission early in 2001. On later ISS research increments, STES will accommodate two other types of crystallization equipment, the Second-generation Vapor Diffusion Apparatus and the Diffusion-Controlled Crystallization Apparatus for Microgravity (DCAM).

A new Dynamically Controlled Protein Crystal Growth (DCPCG) system will allow researchers to access and control the crystallization process aboard the ISS. This system uses controlled dehydration or temperature as a function of time to control crystal growth. The DCPCG system is made of three interfacing lockers: the first locker accommodates crystal growth by allowing evaporation from protein solutions that are held at a constant temperature, the second locker allows crystal growth from a supersaturated solution, and the third locker supplies a subsystem that provides an integral link for nearly immediate experiment evaluation. The system permits ground-to-spacecraft communication, allows video capture of experiments for later evaluation, and stores in-orbit data. The DCPCG system also allows experiment profiles to be controlled from the ground so that several rounds of experiments can be done, with parameters for subsequent experiments being adjustable in response to results from preceding experiments.

PI Alexander McPherson worked on the Observable Protein Crystal Growth Apparatus (OPCGA) during FY 2000. The objective for the OPCGA is to develop a platform that will allow direct observation of crystal growth and provide detailed information of the concentration gradient around the growing crystal. During FY 2000, a preliminary design review was completed and a critical design review was initiated.

Table 8: Proteins Successfully Crystallized Aboard STS-101

Protein	Description/Use
Serum albumin	The most abundant blood serum protein; regulates blood pressure and transports ions, metabolites, and therapeutic drugs.
E. coli Gro EL	One of a class of proteins that assist in making proteins in a cell by folding them into their correct three-dimensional structure.
Eco R1 Endonuclease-DNA complex	An enzyme that cleaves the ends of the DNA sites where they are bound and thus provides information on how proteins discriminate between different DNA sequences.
Lysozyme	Protein isolated from chicken egg white; the first enzyme ever characterized by X-ray crystallography; functions as a bacteriostatic enzyme by degrading bacterial cell walls; used as an excellent model system for better understanding parameters involved in microgravity crystal growth experiments.
Pectate lyase	Protein secreted by plant pathogenic microbes that initiates soft-rot diseases by attacking the pectate component of the plant cell wall.
Hemoglobin C	The second most common hemoglobin (the iron-containing molecule in red blood cells that carries oxygen) variant found in the United States next to sickle hemoglobin.
S-layer protein from *Bacillus sphaericus*	Protein that readily forms two-dimensional crystals which can be used in a variety of nanotechnology applications (e.g., biosensor development).



PI Peter Vekilov and his research team studied the mechanism of formation of apoferritin crystals using atomic force microscopy in a ground-based research study. The apoferritin crystal in this photo was grown under microgravity conditions. Apoferritin is the protein precursor to ferritin, the protein that stores iron in the body and releases it in a controlled fashion.

Highlights

The Birth of a Crystal

If you could witness the beginning of a process that has long been theorized but never seen, you might be surprised by what you saw. This is just what happened to PI Peter Vekilov, at the University of Alabama, Huntsville, and his team of researchers.

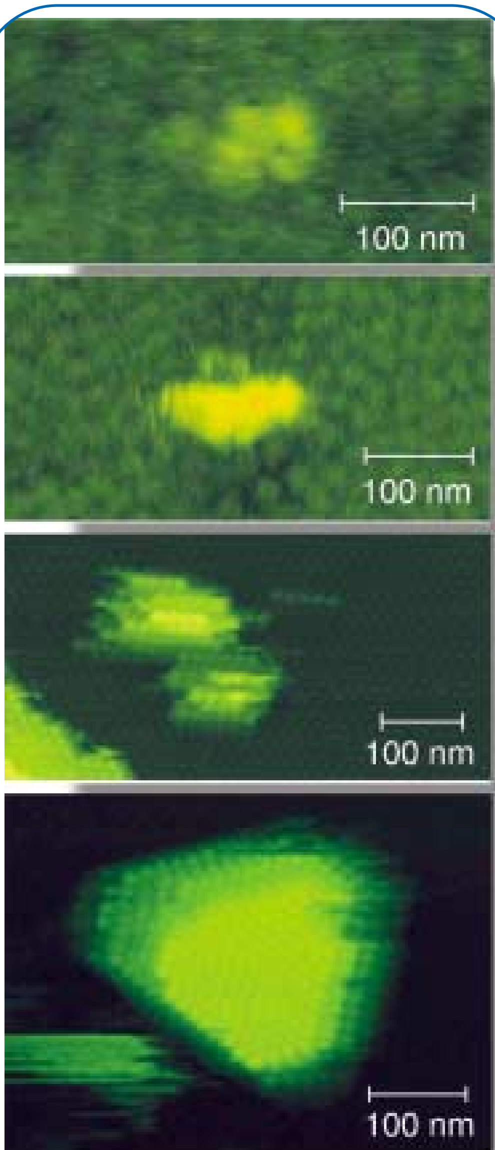
Vekilov's team studies protein solutions as they change from liquids to crystalline solids. They want to know if the protein molecules in solution interact with one another, and if so, what kinetics and thermodynamics are involved and what forces control those interactions. They also study nucleation, the beginning stage of crystallization. It is important to understand the process of nucleation because it sets the stage for crystal growth — it can determine the rate of crystal growth, the number of crystals that will be formed, and the quality and size of the crystals.

The formation of a crystal starts when a small number of molecules bump into each other and their energy is such that it is more favorable for them to come together than to stay apart. These molecules create a new surface in the protein solution, and to continue growing, that surface requires energy. If energy is added, then the structure can continue to attract other molecules to form a crystal. Thus, for nucleation to occur, this surface energy barrier must be overcome.

Observing nucleation is made difficult by the small size of the molecules, the speed at which nucleation occurs, and the ability to pinpoint exactly where in the solution nucleation will occur.

Vekilov and his team studied apoferritin, a protein precursor to ferritin, the protein that stores iron in the body and releases it in a controlled fashion. Apoferritin is a relatively large molecule, approximately 130 angstroms long (a molecule of water is about 2 angstroms long). To locate the site of nucleation, the researchers waited for the nuclei to attach to the bottom of the container holding the protein solution.

Vekilov and Co-Investigator Siu-Tung Yau used atomic force microscopy to create subatomic sequence images showing the behavior of individual molecules as they attach and detach from a crystal or crystalline nucleus. An atomic force microscope has a very sharp tip and a spring mechanism that acts like a cantilever. It works by measuring how much force is pressing



Watching molecules of apoferritin come together to form a nucleus reveals some interesting behavior. In this series of images, researchers observed clusters of four molecules at the corners of a "diamond" (top). As more molecules attach to the cluster, they arrange themselves into rods (second from top), and a raft-like configuration of molecules forms the critical nucleus (third from top), suggesting that crystal growth is much slower than it could be were the molecules arranged in a more compact formation. In the final image, a crystallite consisting of three layers containing approximately 60 – 70 molecules each is formed. Atomic force microscopy made possible visualization of the nucleation process for the first time.

against the tip as the tip passes over the surface to which the crystal nuclei are attached. The deflection of the tip allows the nuclei to be "seen" by the microscope. Molecules enter and leave the crystal nucleus every two or three seconds, which is within the observation capability of an atomic force microscope.

3

What Vekilov and his research team discovered was that crystal growth is not a linear process. Rather, molecules attach and detach from the growing crystal, with crystal growth occurring when attachment events occur more often than detachment events. This discovery allows researchers to directly measure nucleation rates in the smallest of aggregates.

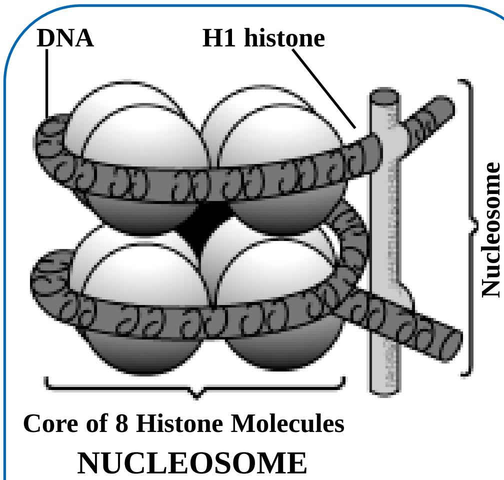
Another surprising discovery was that the crystal nucleus for apoferritin was not spherical, which would be the most energy-efficient shape for crystal formation. Apoferritin nuclei actually had a quasiplanar, or raft-like, shape. The larger surface area of the quasiplanar form requires greater energy input for crystallization to occur, and thus crystal growth occurs much more slowly than it would if the nuclei were spherical.

Vekilov's team has published their work in several recent articles, among them "Quasi-Planar Nucleus Formation in Apoferritin Crystallization," *Nature*, 406: 494–7, August 3, 2000; and "Control of Protein Crystal Nucleation Around the Metastable Liquid-Liquid Phase Boundary," *Proceedings of the National Academy of Sciences*, 97(12): 6277–81, June 6, 2000.

Unraveling the DNA Package

When people think of cells and their genetic material, they tend to think small. The nucleus of a cell, which houses DNA, averages somewhere between 3 and 25 microns in diameter. Yet, the total length of human DNA is a little over a meter. Such a great amount of DNA can be contained in such a small package as the nucleus because of intricate folding of the DNA molecule.

This folding is enabled by the way in which the DNA is grouped together with protein molecules. The structure is very similar to beads on a string. The double helix of DNA is the string, which wraps around groups of eight proteins called histones. Each of these groupings, called a nucleosome, is a bead, and the nucleosomes are connected by lengths of DNA. This structure allows the molecule to fold and coil into strands called chromatin and then ultimately coil into loops, which make up a chromosome. There are 23 chromosomes in a single cell nucleus; the total number of loops in a nucleus is about 50,000.

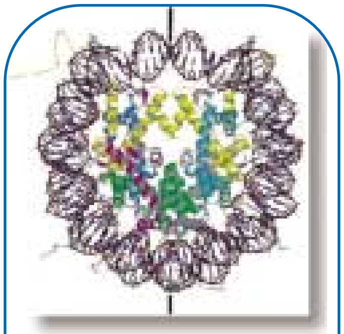


Fitting the long DNA molecule into a cell nucleus is accomplished by an intricate folding mechanism. The basic structure that allows folding resembles beads on a string. This illustration depicts the DNA — the "string" — wrapped around a group of eight histones to form a "bead," which is called a nucleosome.

Nucleosomes, or the beads on the DNA string, are of particular interest to scientists. In addition to their DNA packing function, nucleosomes are strongly involved in the gene expression mechanisms that allow only selected regions of the immense DNA molecule to be read out as a result of specific signaling processes. Packaging DNA functions and supporting gene expression functions require approximately 25 million nucleosomes in each human cell nucleus.

A crystal of the histone octamer that forms the nucleosome core particle around which the DNA molecule is wound to enable the molecule to fit in a cell nucleus.

PI Gerard Bunick, of Oak Ridge National Laboratory, has obtained the most detailed structure to date of the nucleosome. Bunick grew crystals of the nucleosome core particle on several shuttle/*Mir* flights, and on STS-81 in 1997, he obtained large crystals suitable for X-ray diffraction analysis. These space-grown crystals provided 40 percent more data than the best Earth-grown crystals. With them, Bunick was able to obtain a diffraction resolution of 2.5 angstroms (one ten-billionth of a meter), which is better than the diffraction limit for the best available Earth-grown crystals in Bunick's laboratory — approximately 2.8 angstroms.



This computerized rendering of the nucleosome core particle was developed from X-ray crystallographic data obtained on space-grown crystals. The center "ribbon" structure shows the histone octamer, with the DNA molecule wrapped around the outside.

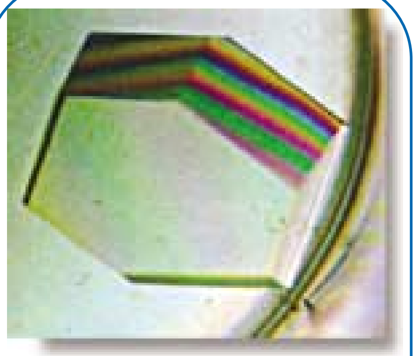
Interestingly, the use of a single space-grown crystal at 2.5-angstrom diffraction resolution revealed more detailed features than another research group's use of 27 Earth-grown crystals of a similar nucleosome core particle at 2.0-angstrom resolution. Because the 2.0-angstrom diffraction limit should have been able to provide 95 percent more data when compared to a 2.5-angstrom diffraction limit, this result provides evidence that crystals grown in a microgravity environment have features that enable them to reveal more structural information than would be expected on the basis of increased diffraction resolution alone.

Bunick's work, "Asymmetries in the Nucleosome Core Particle at 2.5-Angstrom Resolution," was featured on the cover of *Acta Crystallographica*, D56(12): 1513–34, December 2000.

Hydrogen Atoms Unmasked

About one-half of the atoms that make up a protein are hydrogen atoms, and they remain unseen even by the most common method for studying the structure of proteins, X-ray crystallography. In this technique, protein crystals are bombarded with X-rays, which are then 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 isn't a complete 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 structure of the protein, including the positions of the hydrogen atoms, to be determined.

The bonding of hydrogen atoms due to mutual attraction is crucial to protein structure and activity, and thus the capability to determine the positions of hydrogen atoms within a protein can provide important insights into the structure and potential reactivity of the protein, because structure has a bearing on a protein's activity. Neutron diffraction can be used to determine the positions of hydrogen "bridges," which are hydrogen atoms that connect two parts of a structure as a result of their mutual attraction; the conformations of specific hydrogen-containing sections of the molecule; the degree of protection of hydrogen atoms within the protein structure, which affects the ability of the hydrogen atom to undergo a chemical reaction; or the orientations of hydrogen-containing side chains. However, neutron diffraction techniques are not without disadvantages. Although a complete structural analysis can be made using a single crystal, that crystal must be much larger than crystals that are suitable for X-ray analysis.



Researchers used neutron diffraction to determine the structure of lysozyme, including the positions of hydrogen atoms, by analyzing a lysozyme crystal similar to the one shown here. This was one of the few cases in which neutron diffraction has been used to solve a protein structure.

Flight PI Daniel Carter, of New Century Pharmaceuticals, and Co-Investigators Dean Myles, of the Institut Laue-Langevin, in France, and Jean-Paul Declerq, of the Université Catholique de Louvain, in Belgium, grew such a crystal of monoclinic lysozyme in the DCAM on STS-89 as part of the NASA shuttle/*Mir* program. Using this crystal and neutron diffraction at the Institut Laue-Langevin, they were able to determine the structure of the protein, delineating many of the waters and exchangeable hydrogens within the lysozyme crystal. This is one of the few cases in which neutron diffraction has been used to solve a protein structure.

The structures of ferritin, a protein that stores iron and releases it in a controlled fashion, and apoferritin, a protein precursor to ferritin, are also being studied by neutron diffraction. When these studies are completed, the results will represent the largest protein structure determined to date by neutron diffraction.

Carter, Myles, and Declerq described their work in "Neutron Structure of Monoclinic Lysozyme Crystals Produced in Microgravity," which was submitted to the *Journal of Crystal Growth* to be published in summer 2001.

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. These various cells are assembled into a variety of tissues. Pictured here are red blood cells, nerve cells, and tissue from the trachea and lungs.

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.

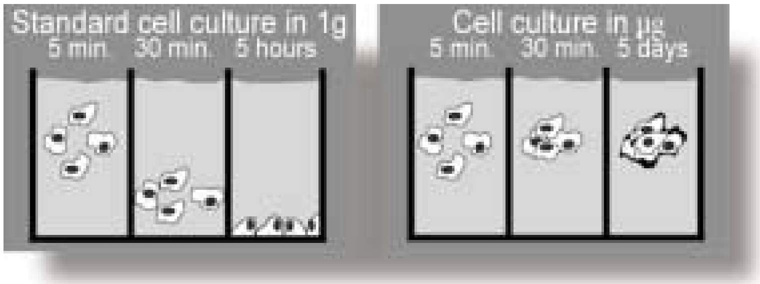
What can be learned about cells depends on the available tools. Culturing (growing) cells is one of the most basic techniques used by medical researchers. The growth of human cells outside the body enables the investigation of the basic biological and physiological phenomena that govern the normal life 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, 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.

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

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, the NASA bioreactor, experiments to form three-dimensional cell formations were confined to the microgravity environment of space.

The NASA bioreactor is an analog of microgravity cell culture that can be used on the ground. The completely 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, the 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 re-engineer defective tissues, and to develop new hypotheses for the emergence of diseases such as cancer. Finally, cells exposed to simulated and true microgravity respond by making novel adaptations that give new insights to 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.



Cells cultured on Earth (left) typically settle quickly on the bottom of culture vessels due to gravity. In microgravity (right), cells remain suspended and aggregate to form three-dimensional tissue.

Program Summary

The annual Cellular Biotechnology Investigators' Working Group (IWG) Meeting, held March 16–18, 2000, in Houston, Texas, was attended by approximately 100 scientists from universities, NASA field centers, the National Institutes of Health, the National Space Biomedical Research Institute, and commercial cell culture enterprises.

Highlights of the 33 presentations made at the meeting included discoveries in the engineering of heart muscle and cartilage, unique gene expression in renal (kidney) cells maintained in microgravity and in space bioreactors, the formation of primitive blood vessel–like structures in cancerous tissue, and a patent application related to the unique glycosylations afforded in bioreactor cell culture. Several issues of the journal *In Vitro* will showcase the NASA-sponsored research in cell-based systems using the bioreactor. Three new bioreactor systems were also unveiled at this meeting: one from Johnson Space Center, one from Ames Research Center, and one from SHOT, Inc.

Under the NRA for cellular and macromolecular biotechnology that was released in August 2000, NASA sought to expand its activities in bioreactor design and tissue engineering, with the goal of developing tissue models for space experiments and biomedical research. Research proposals were solicited in the areas of tissue engineering, tissue models for human disease studies and drug testing, bioreactor design, and changes in gene expression and metabolic function. Additional areas of interest revolved around cell culture technologies, including studying the physical environment within a bioreactor; assessing the value of low-shear and spatial co-location in bioreactors; and studying the effects of culture media, cellular metabolism, and waste accumulation to facilitate tissue growth and differentiation. NASA also sought research in the area of biomaterials and scaffolds for tissue engineering, and research to support the development of technologies (e.g., biosensors for pH, glucose, and oxygen levels) and maintenance strategies for three-dimensional culture to allow long-term automation and improvement of the culturing process.

Notices of intent for this NRA were due on September 6, 2000, and 225 proposals were received by the October 27, 2000, due date. NASA plans to announce selections in spring 2001, with grants and contracts to be awarded shortly thereafter. For additional information on the NRA and selections, visit *http://research.hq.nasa.gov/code_u/nra/current/NRA-00-HEDS-03/index.html* on the WWW. In addition, a listing of all ongoing biotechnology research projects, along with the names of the investigators conducting the research, is provided in the Appendix.

The cellular biotechnology program was reviewed by the National Research Council in 2000. The NRC report, *Future Biotechnology Research on the International Space Station*, recommended that the cellular biotechnology program should more closely coordinate its research strategies and work with NASA's Life Sciences Division to take advantage of overlapping interests between the two programs.

In response to this recommendation, the cellular biotechnology program is planning for its 2001 IWG Meeting to be a landmark meeting — the first agency-wide cell science conference, open to all investigators conducting cell-based space research. The meeting will be sponsored jointly by the cellular biotechnology program at Johnson Space Center (JSC) and the fundamental biology program at Ames Research Center. In an effort to foster coordination and collaboration between these programs, both flight- and ground-based research will be presented in sessions covering tissue modeling, immunology, cell culture technology, biological response to physical forces, cell proliferation and differentiation, research models in lower organisms (e.g., bacteria and insects), cell movement and the cytoskeleton (the protein fibers composing the structural framework of the cell), and gene expression.

Another exciting development is NASA's groundbreaking agreement with the private sector to explore a new frontier in biotechnology. A Space Act Agreement was signed with Fisk Ventures to explore the use of JSC-developed biotechnology. This is a first-of-its-kind agreement between NASA, the private venture capital firm, and a newly established biotechnology joint venture company, StelSys, Inc., of Baltimore, Maryland. This agreement for commercial use of NASA's bioreactor technology is a joint effort involving an extensive market-driven study of both what is technically possible and what is most likely to be commercially successful. This unprecedented private-sector investment is expected to open the door to a new frontier in medical research, which may one day lead to new treatment options for patients facing organ transplant surgery. Areas of focus include infectious disease research, developing a liver-assist device for patients in need of transplant surgery, and potentially faster drug testing and approval.

Celdyne Corporation has been awarded a patent license to manufacture the hydrofocusing bioreactor (HFB), a bioreactor technology that was developed at JSC. The HFB enables three-dimensional cell culture and tissue engineering research on Earth and in space. It provides a reduction in shear forces exerted on cell aggregates in culture as compared with other systems, thereby permitting the development of larger cell aggregates. Using this bioreactor technology will help researchers to increase their understanding of basic cell function and three-dimensional tissue engineering as they relate to the basis of disease, tissue modeling, and drug development.

Flight Experiments

FY 2000 was a year of advances for the cellular biotechnology flight program. One experiment in renal tissue culturing flew this year on the shuttle, and preparations for four future shuttle flight experiments in microencapsulation processing are under way. Development of the Biotechnology Facility for the International Space Station progressed along with some new technology to aid in flight experiments.

On shuttle mission STS-106, Principal Investigator Timothy Hammond, of Tulane University Medical Center, ran a follow-up experiment to his STS-90 investigation, in which microgravity was found to cause large-scale alterations in renal cell gene expression. The follow-up experiment examined how microgravity alters the gene expression in renal cells that ultimately enables kidneys to develop and function normally.

Cells grown in suspension in space or in a bioreactor on Earth can join together and form three-dimensional tissues similar to their counterparts in an intact organ. These tissues are difficult to produce in Earth's gravity because even in a bioreactor, once the aggregates grow large enough, they become too heavy to remain suspended and so fall to the bottom of the bioreactor and cease to grow. Renal cells were grown both on STS-106 and on the ground. Controls included samples grown under conditions to simulate the increased gravitational forces and vibrations experienced during shuttle launch, as well as cells grown under optimal conditions in the rotating wall vessel. Cells were fixed two hours into the flight, RNA was extracted upon return to Earth, and gene array analyses were performed. Preliminary analyses from both flight and control renal cells show that mechanical conditions did affect the types of nuclear proteins that were produced by the renal cells — specific clusters of genes changed over time. Some of these changes were unique to the microgravity environment, but others were the result of mechanical culture conditions. The researchers observed an array of transcription factors that they are now attempting to identify. (Transcription is the process of converting DNA into RNA.) Hammond and his co-investigators hope to identify which transcription factors change which cluster of genes.

To fly Hammond's experiment on STS-106, three separate NASA programs worked together: the fundamental biology program, the microgravity cellular biotechnology program, and the Division of Research Integration, the NASA division that oversees commercial research. Hammond hopes that the outcome of his research will have direct clinical applications. For example, together with commercial partner StelSys, Inc., Hammond has patented a method to produce vitamin D using the rotating wall vessel bioreactor. People on kidney dialysis need vitamin D, but it is expensive to make and difficult to purify. StelSys hopes to use the bioreactor to mimic natural vitamin D production in the kidney cells with the hope of producing the vitamin easily and inexpensively.

Preparations for the flight of the microgravity encapsulation and drug delivery system continued in FY 2000. The Microencapsulation Electrostatic Processing System

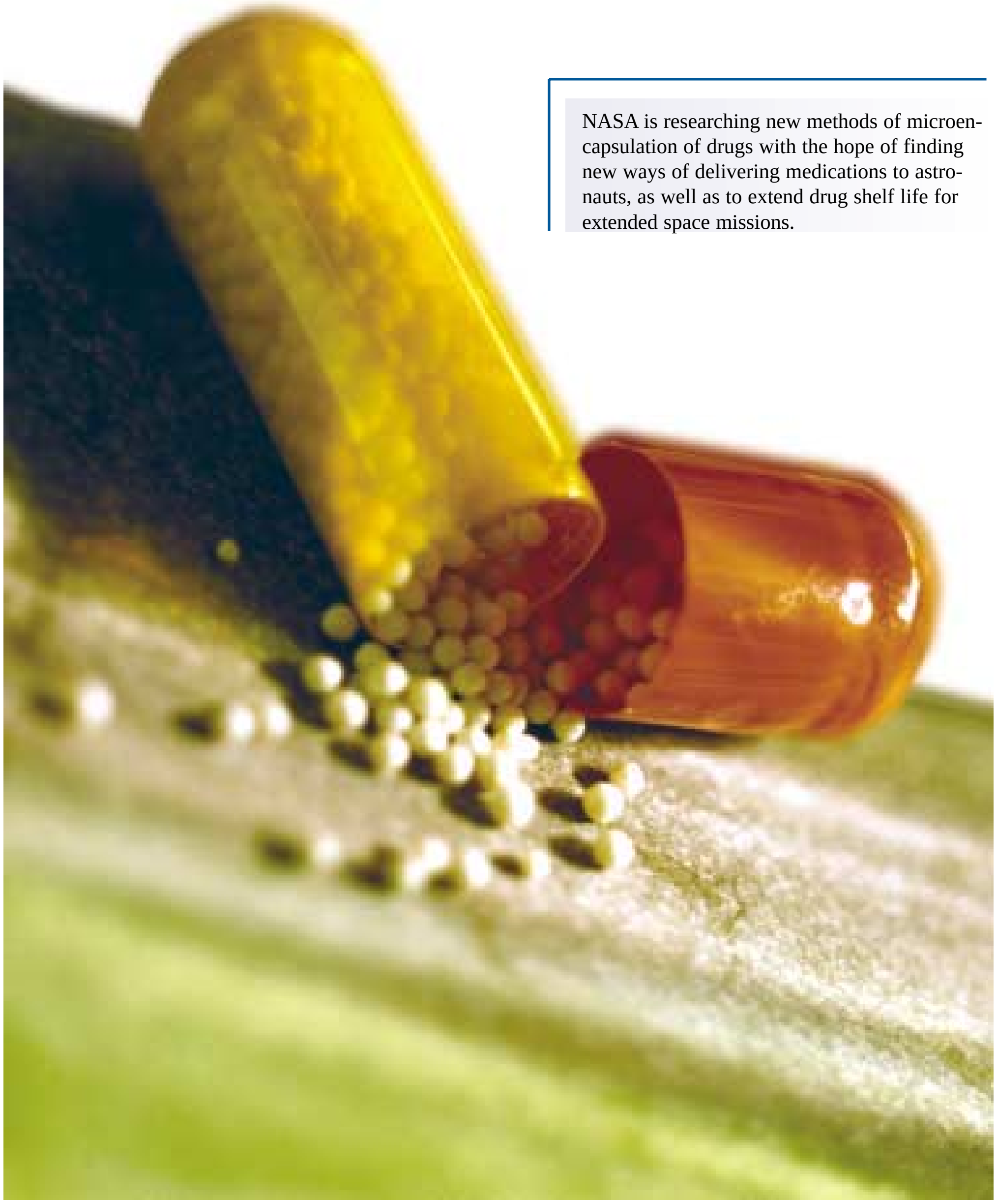
Renal cortical (outer surface) cells have been cultured successfully in the microgravity environment of space. Kidney cells are being cultured in space so that researchers may study the expression of proteins that may be useful for the treatment of kidney disease.

(MEPS-II) will be used to form and harvest microcapsules. This facility uses electrostatic fields to add coatings to make the microcapsules more effective. Researchers are exploring "multilayered" microcapsules as a new way of combating cancer, improving chemotherapy treatments, and delivering drugs to astronauts, for whom ingestion or injection of medications is not always possible (one possible method for delivery of the microcapsules is intranasally).

NASA is also enhancing its commercial biotechnology research on the MEPS-II under an expanded program with two research centers at Texas A&M University. The drug encapsulation effort at JSC focuses on novel drug delivery systems for crewmembers and methods to extend drug shelf life for extended space missions.

MEPS-II will fly on STS-108 near the end of 2001. Ten microencapsulation experiments will be performed on each of four flights (STS-108, STS-109, STS-110, and STS-111) during 2001 and 2002. This year, MEPS-II has been reconfigured so that it can be operated without using the ISS cabin air system, and an internal process control computer has been added.

Space station research plans are moving ahead, with a major program review for the Biotechnology Facility (BTF) planned for January 22–24, 2001. The review will include participants from JSC Life Sciences and Engineering, the International Space Station Program, the Microgravity Research Program Office, and NASA headquarters. The BTF is a one-rack, continuously operated facility for the ISS in which separate experiment modules will be integrated and adapted as needed. The facility was conceptualized in 1992,



NASA is researching new methods of microencapsulation of drugs with the hope of finding new ways of delivering medications to astronauts, as well as to extend drug shelf life for extended space missions.

and an operating concept was demonstrated from 1994 to 1998 on the Russian space station, *Mir*. Lessons learned from space shuttle flights and *Mir* increments led to completion of the requirements for a continuously operating BTF for the ISS. This concept was endorsed by the NRC nonadvocate review meeting in July 1999.

The science requirements for high throughput necessitate that the facility aboard the ISS have a major proportion of the experiment hardware in residence and that specimens (rather than equipment) be shuttled to and from the facility. The BTF raises space science from the shuttle "payload" mentality to the new age of the space laboratory and elevates space research productivity to a level that is consistent with the productivity of ground-based laboratories. The BTF will make it possible for researchers to decrease the time from experiment inception to publication of results to as little as three years, compared with the traditional seven-to-eleven-year time frame. The BTF can also accommodate the accelerated approaches often sought by commercial developers conducting pathfinding research.

The cell- and tissue-based research that will be enabled by the BTF is critical to the Human Exploration and Development of Space and Bioastronautics initiatives. The cellular biotechnology program will facilitate basic and applied research in cell biology, tissue engineering, and related sciences for peer-reviewed investigators from the world science and industrial communities by providing the technology and resources for the conduct of ground-based and flight experiments. The BTF will provide the continuum of research activity that meets the needs of investigators seeking the microgravity environment as a means to achieve scientific goals.

Growth of long-duration mammalian cell and tissue cultures in spaceflight bioreactor systems requires automated monitoring of culture parameters such as pH and glucose concentration. In support of this, the cellular biotechnology program has developed a noninvasive optical sensor to measure the pH of bioreactor cell culture media. This is the first such sensor to successfully operate for 120 days continuously and without recalibration over the biological pH range of 6.5 to 7.5.

Highlights

The Beat Goes On

A properly functioning heart is vital to an organism's health and survival. More than five million Americans suffer from heart failure — a leading cause of death in developed countries. NASA PI Lisa Freed and Co-Investigator Gordana Vunjak-Novakovic, both of the Massachusetts Institute of Technology (MIT), believe that they can use engineered cardiac tissue to study the function of heart muscle and perhaps devise intervention methods to help people with heart disease. In fact, their efforts have paid off with the first-ever laboratory observation of the beating of engineered cardiac tissue, with the tissue showing spontaneous contractions at a rate of 70 beats per minute. With this achievement, Freed and Vunjak-Novakovic have taken the first steps toward developing tissue that could one day be used to patch damaged human hearts.

To date, researchers are capable of engineering only very thin patches of heart muscle, but they are working toward the even greater challenges of creating in vitro thick, vascularized tissue. Here, a transmission electron micrograph shows a number of important landmarks present in functional heart tissue: (a) well-organized myofilaments (Mfl), z-lines (Z), and abundant glycogen granules (Gly); and (b) intercalcated disc (ID) and desmosomes (DES).

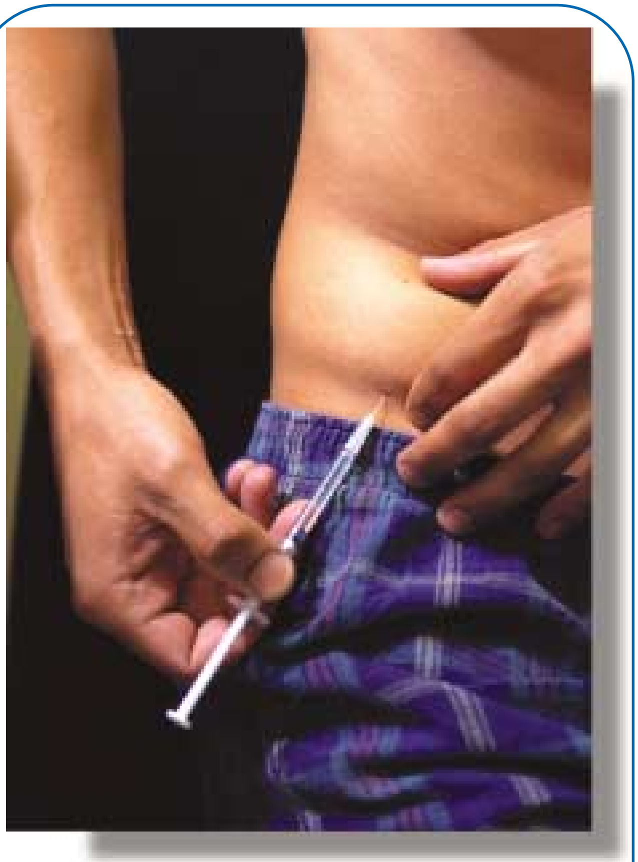
Freed and Vunjak-Novakovic's team attached heart cells isolated from very young rats to polymer scaffolds, which were then placed in a NASA rotating wall bioreactor along with a solution of nutrients and a membrane for gas exchange. It took about a week of just the right conditions for the more than 5 million (on average) cells to begin to form connections among themselves and to begin to contract in unison as a piece of functional tissue. The ability to conduct electrical signals is possible only if the cells are functionally connected, and the first goal of the research is to reconstruct the cardiac cells' native tissue.

More than five million Americans suffer from heart failure, which is a leading cause of death in developed countries. While heart transplants can save some lives, researchers hope they can use engineered heart tissue to help patients with heart disease.

The second goal of Freed and Vunjak-Novakovic's research is to characterize the engineered heart tissues to learn about their electrophysiological, histological, and molecular properties. Using an electrode array, they can study the propagation of electrical waves through the tissue, command the tissue to beat at a prescribed rate, and study the range of frequencies that can be used to pace the tissue, the way a pacemaker implanted in a human heart patient is used to control the heart.

This research team's successes are exciting, but a long road must still be traveled before engineered heart muscle patches are ready to help patients in need. The MIT team has made only the muscle component, and even that muscle is very thin. To obtain a real piece of implantable cardiac tissue, that cardiac muscle has to be integrally fed by a system of blood vessels. Additionally, Freed and Vunjak-Novakovic's team must move from studies of rat cells to studies using human cells. They are now in the beginning stages of such studies.

Freed, Vunjak-Novakovic, and their team of researchers have published their findings in two articles: "Cardiac Muscle Tissue Engineering: Toward an In-Vitro Model for Electrophysiological Studies," *American Journal of Physiology*, 227 (Heart Circ. Physiol. 46): H433–44, 1999; and "Cardiac Tissue Engineering: Cell Seeding, Cultivation Parameters, and Tissue Construct Characterization," *Biotechnology and Bioengineering*, 64: 580–9, 1999.



Diabetes is among the top ten causes of death by disease in the U.S. and is the leading cause of blindness and kidney failure. One alternate treatment regimen to insulin injection for diabetics is pancreatic islet transplantation. Pancreatic islet cells are responsible for the production of insulin in the body. Researchers are working toward a viable method for growing islet cells in vitro.

Seeking Insulin Independence

Diabetes is among the top ten leading causes of death by disease and is the leading cause of blindness and kidney failure in the United States, as well as a major risk factor for heart disease. More than 20 million people in the United States are diabetic, and diabetes contributes significantly to the health care costs in this country. In Type I diabetes, previously known as juvenile diabetes, the body is unable to produce insulin, which is necessary for control of glucose levels in the blood. Excess levels of glucose in the blood result in the disease processes associated with diabetes.

An intensive treatment regimen can reduce some of the risk associated with the disease, but because it involves testing blood sugar levels four or more times a day; multiple daily insulin injections or use of an insulin pump; adjustment of insulin doses according to food intake and exercise; diet and exercise plans; and monthly visits to a health care team that can be composed of a physician, a nurse educator, a dietitian, and a behavioral therapist, the number of people who can follow the regimen with success is limited.

One alternate treatment to a regimen of insulin injections is pancreatic islet cell transplantation. Insulin is made by the beta cells in pancreatic islets, small "islands" of hormone-producing cells in the pancreas. In Type I diabetes, the beta cells in the pancreas are destroyed at an early age, possibly by the body's own immune system. In an islet cell transplantation procedure, islet cells are taken from a deceased donor's pancreas and are transplanted into the patient's liver using a catheter. The islets cells will, after a time, attach to the blood vessels and begin to produce insulin. Rejection of donor tissue is one complication of this procedure, and transplant recipients must take anti-rejection drugs to ensure that the islet cells will continue to function. Lack of a reliable source for transplantable tissue is another major barrier to transplantation.

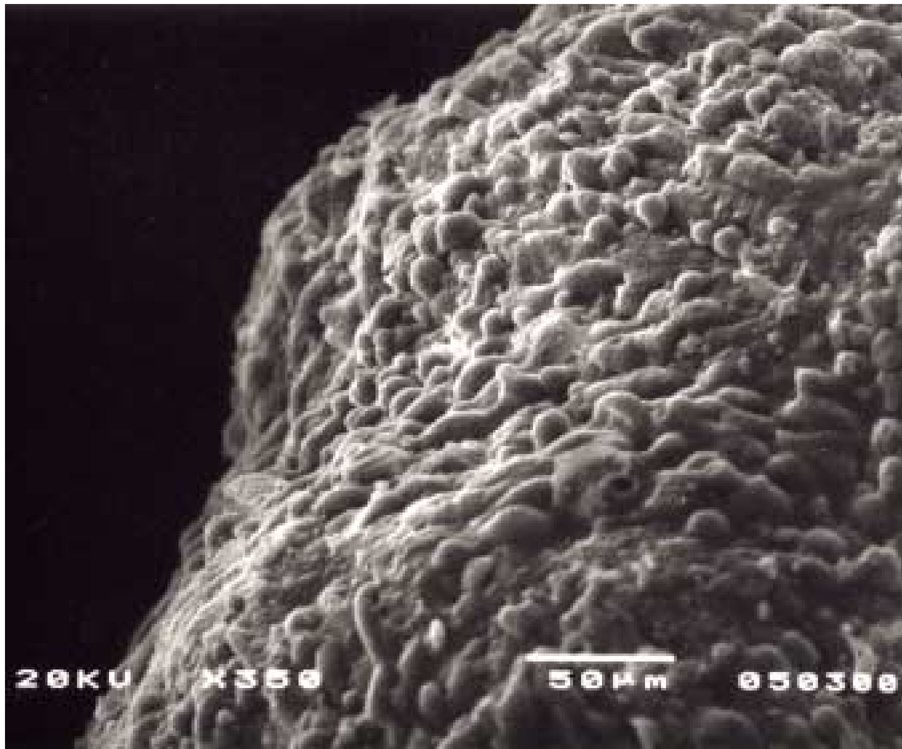
Overcoming this barrier is the research goal of NASA PI Arun Rajan of Baylor College of Medicine. Rajan is working toward a viable method for growing islet cells in vitro. He and his team began working with endocrine tissue from rats. To create a limitless supply of normally functioning islet cells in vitro, the researchers used a genetic engineering strategy. With gene transfer, the researchers were able to confer tumorlike immortal properties on the cells, which allowed them to grow in culture. The team also incorporated a gene sequence that would allow the transferred genes to be removed so as not to allow growth into tumors.

These islet cells were then placed in a NASA rotating wall bioreactor. Rajan and his team developed a modified rotating wall bioreactor prototype that would allow the assembling islets to grow and be fed without physically disturbing the culture itself. The islet cells assembled in the bioreactor into islet-like aggregates that exhibited natural islet structure and function. Said Rajan, "The non-random arrangement of the artificial islets compares well with natural islets." In fact, the researchers were able to show that their artificial islets did indeed produce insulin, a big step toward the goal of developing a paradigm for human islet expansion. Success with rat islet cells moves researchers closer to being able to generate an unlimited number of safe, normally functioning islet cells for human transplantation.

Rajan and his co-workers have published their experimental results in "Microgravity Tissue Engineering of Pancreatic Islets," *Diabetes*, 48 (Supp. 1): 1487, A340, 1999.

Prostrating Prostate Cancer

Prostate cancer is the most commonly diagnosed cancer in men in North America, striking approximately 200,000 men every year, and is the second leading cause of cancer death. While prostate cancer does have a propensity to metastasize (spread) to the bones, it is easily treated if diagnosed early. Unfortunately, because of the potential unpleasant side effects to early treatment of the disease, many men put off being tested. Once the cancer spreads to the bones, it is inevitably fatal, killing 40,000 men in the United States each year. The public health cost of prostate cancer in the United States is more than $2 billion per year.



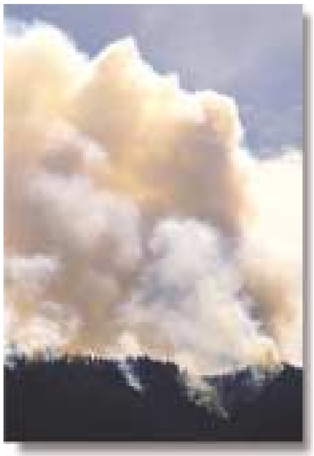
Prostate cancer can be easily treated if diagnosed early, but it does have a propensity to metastasize to the bones if left untreated. Once the cancer spreads to the bones, it is inevitably fatal. Researchers are using the NASA bioreactor to grow three-dimensional prostate cancer tissue for use in developing a co-targeting approach to destroying cancer cells as well as their neighboring supporting bone cells.

Recognizing that no effective therapies exist for prostate cancer that has spread, PI Leland Chung and his team at the University of Virginia undertook the development of an in-vitro model of prostate cancer metastasis to the skeleton. This model would enable researchers to better study the spreading and growth process, as well as allow them to test and assess potential therapies.

Chung and his team started their research by developing three different prostate cancer cell sublines from a parent prostate cancer cell line. To make sure these cells would indeed metastasize to the skeleton, the team tested them in vivo in mice and confirmed that the cells traveled to the bone and formed tumors there. The next step was to grow these prostate cancer cell lines and bone-forming cells (called osteoblasts) together, or co-culture them, to try to replicate the type of tumor growth found in the skeleton. The team tried traditional two-dimensional methods for cell culturing and found that the traditionally grown cells did not possess the properties of in-vivo tissue. They then co-cultured the cells in the NASA rotating wall bioreactor, which allowed the cells to grow under gentle suspension. The result was the formation of three-dimensional tissues, or organoids, that were composed of proliferating prostate cancer cells and osteoblasts. The organoids will make study of metastasized prostate cancer and potential treatments easier.

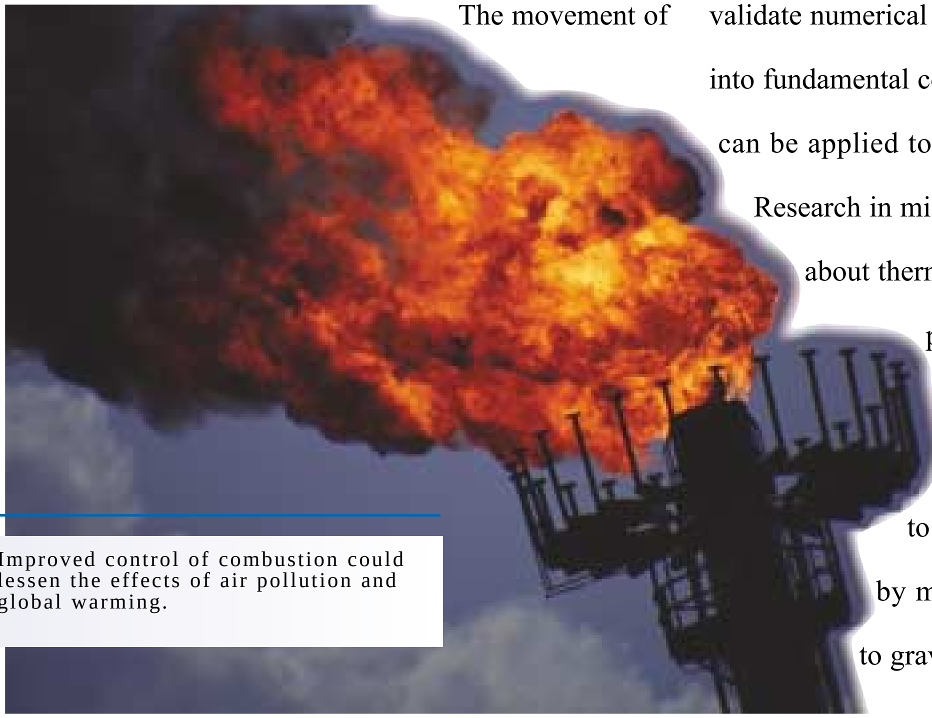
The researchers have found that some of the observable and genetic changes of the prostate cancer cells grown in the bioreactor were induced by specific three-dimensional conditions under the influence of neighboring prostate or bone stromal cells. (Stromal cells make up the supporting framework of an organ — in this case, bone.) This result suggests that there is some signaling process between prostate cancer cells and their microenvironment. In fact, Chung and his team have observed that once the prostate cancer cells have moved to the skeleton they begin to mimic some of the properties of bone cells. This indicates that the prostate cancer cells are receiving a signal from the bone cells. A strategy that Chung is investigating is to develop a co-targeting approach, which would destroy cancer cells as well as their neighboring supporting bone cells. Although these studies were ground-based, Chung hopes to continue his research aboard the ISS. Chung and his co-workers will publish a paper, "A Conditional Replication-Competent Adenoviral Vector, Ad-OC-E1a, to Cotarget Prostate Cancer and Bone Stroma in an Experimental Model of Androgen-Independent Prostate Cancer Bone Metastasis" in *Cancer Research* in August 2001.

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. Improved control of combustion would be of great benefit to society, yet is impeded by a lack of fundamental understanding of combustion processes.



Combustion research is hampered by the effects of gravitational forces on Earth. Gravity causes hot, lightweight gases produced during combustion to rise. The movement of the gases generates airflows that produce flames which are unsteady and nonsymmetric, like flames produced by a campfire. These flames are almost impossible to characterize because their shifting movements and shapes make it difficult for scientists to solve the equations that describe them mathematically. Combustion theories, therefore, are often based on steady, symmetrical flames. 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, for example, that play a role in flame propagation and extinction. These processes, while present on Earth, are difficult to observe because they are often hidden by more dominant reactions attributable to gravity.



Improved control of combustion could lessen the effects of air pollution and global warming.

Program Summary

In fiscal year (FY) 2000, 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 added a more applications-based focus to aid NASA in developing solutions for crew health and safety issues. The microgravity combustion science program funded new and ongoing research projects for 78 principal investigators (PIs) working on 19 flight investigations and 59 ground-based projects. A listing of all ongoing combustion science research projects, along with the names of the investigators conducting the research, is provided in the Appendix.

The newest group of research grants resulted from a combustion science NASA Research Announcement (NRA) released to the combustion research community in November 1999. Peer-review panels evaluated and ranked the 119 proposals received, of which 28 were ultimately selected for either ground-based or flight-definition research. Six of the 28 selected proposals address critical, recently identified 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 new Bioastronautics initiative, will focus on generating specific, attainable, applications-based solutions to NASA's fire safety issues for crewmembers living and working aboard spacecraft. A workshop planned for the spring of 2001 will assist in sharpening that focus. Also selected for funding were investigations in gaseous flames, droplets and sprays, combustion synthesis, and surface combustion. A complete list of funded projects may be found on the World Wide Web at *http://peer1.idi.usra.edu/peer_review/press/mg/pr00-03.htm*.

The ground-based microgravity combustion science program provides insight into fundamental combustion phenomena. The results obtained are crucially important to scientifically challenging missions that NASA hopes to pursue. This year, ground-based combustion researchers continued to add to the increasing body of knowledge in the field. Emerging areas of ground-based study include research in understanding the process of the combustion synthesis of nanoparticles and nanotubes; both areas hold promise for customizing material properties for high-strength aerospace applications.

In FY 2000, 15 ground-based research investigations from the 1995 NRA process concluded their studies in the areas of diffusion and premixed gas flames, droplets and sprays, surface combustion, propellants, and combustion synthesis processes. The ongoing 1997 NRA grant pool of 40 ground-based investigations also continues to bear fruit. In combination with the 1995 NRA grants, the 55 investigations generated 76 journal articles and contributed 52 papers to published conference proceedings. More than 100 presentations based on research to date were delivered in FY 2000 at national and international forums. Contributions to five books were made last year as a result of our investigators' work.

Flight Experiments

Experiments in space further refine and validate combustion theories and extend our understanding of combustion phenomena that are obscured by gravity. The extended times in microgravity and the generally higher-quality microgravity conditions that can be obtained in space 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 terrestrial facilities.

In FY 2000, investigators continued preparations for 19 flight research projects that require the advantages offered by the microgravity conditions available in orbit. Five of the investigations have near-term flight opportunities aboard the space shuttle or on a sounding rocket. The remaining 14 investigations continued with their research formulation and hardware implementation paths toward flight opportunities within the Combustion Integrated Rack (CIR) aboard the International Space Station (ISS). (For more detailed information about the CIR, see p.55.)

Flight-definition activities, which determine the objectives of flight experiments and detail the hardware necessary to conduct those experiments in space, continued for nine investigations, one of which passed its first peer review with exceptional praise from the panel. The Cool Flames investigation team, headed by PI Howard Pearlman, of Glenn Research Center (GRC), who received the 1999 Presidential Early Career Award for Scientists and Engineers, will begin its engineering development in 2001 for a journey toward flight.

Although no new flight research results were obtained this year, mission hardware preparations were completed for three projects encompassing four flight investigations that will be conducted aboard a sounding rocket; in two autonomous, shuttle-based, Get Away Special (GAS) canisters; and within the Combustion Module (CM) facility onboard a shuttle flight. The Spread Across Liquids experiment concluded preparations for its sixth sounding rocket flight, which is scheduled for launch in the early months of 2001. The Microgravity Smoldering Combustion Reflight Experiment has prepared two GAS systems for flight aboard the space shuttle and continues to await flight manifesting. The CM-1 system, which flew aboard the Microgravity Science Laboratory–1 (MSL–1) mission on STS-83 and STS-94, has been refurbished as CM-2 and is integrated with the SPACEHAB carrier for a flight aboard STS-107 in the spring of 2002.

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 FY 2000. In conjunction with the preparation of the CIR portion of the Fluids and Combustion Facility, the combustion science program worked to ready a number of experiments for upcoming research flights to the space station. Detailed engineering of both a Multiuser Droplet Combustion Apparatus (MDCA) and a solids-based apparatus known as FEANICS (Flow Enclosure Accommodating Novel Investigations in Combustion of Solids) is under way.

The MDCA will enable droplet combustion research to be conducted in the CIR and will be the first research payload in the CIR. Multiuser hardware such as the MDCA allows more effective resource utilization of the ISS and CIR. Research on the combustion of fuel droplets is important because of the many kinds of practical devices that deliver fuel to combustors in droplet form, including diesel engines and industrial turbine engines. Studies in microgravity allow researchers to investigate spherical fuel droplets, which are much easier to model mathematically than gravitationally influenced tear-shaped droplets. Four investigators have been identified to conduct an initial set of research utilizing the combined capabilities of the CIR and MDCA systems. The investigations are the Droplet Combustion Experiment-2, the Bi-Component Droplet Combustion Experiment, Sooting and Radiation Effects in Microgravity Droplet Combustion, and the Dynamics of Droplet Combustion and Extinction experiment. The MDCA will also remain available for use with new droplet investigations that may be proposed in the future.

A second group of investigations, which will be conducted in the FEANICS apparatus aboard the ISS, will concentrate on the phenomena of solids combustion. These investigations are highly relevant to the understanding of fire ignition, the sustenance of combustion flames in real materials, and fire extinction. All such topics are crucial to the increased understanding of terrestrial and spacecraft fire safety activities. The investigations are titled Solid Inflammability Boundary at Low Speed, Transition From Ignition to Flame Growth Under External Radiation in Three Dimensions, Flammability Diagrams of Combustible Materials in Microgravity, Radiative Enhancement Effects on Flame Spread, and Investigation of Diffusion Flame Tip Instability.

In addition to these already selected investigations, two new investigations are being considered for early deployment on the ISS. These investigations focus on the spacecraft fire safety element of the Bioastronautics initiative and will make use of the Microgravity Science Glovebox (MSG). (For more information on the MSG, see page 57.)

Previous flight investigation results were analyzed and published in FY 2000. These publications included final reports from an international cooperative research project involving NASA and the Keldysh Research Center of Moscow, Russia. The reports follow the investigation of the flammability of three types of plastic materials aboard the Russian space station, *Mir*.

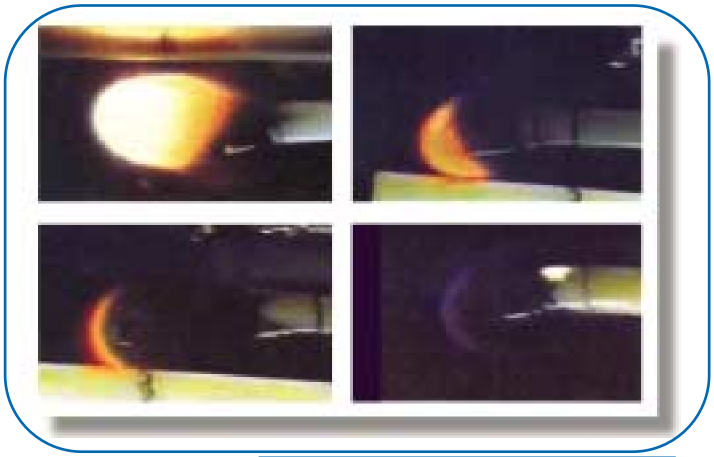
Highlights

Setting Fires to Prevent Fire in Space

Many materials that we come into contact with every day will burn given the right set of circumstances: proper airflow, fuel, and a spark to get it all started. That's a problem in space, where resources for dealing with an accidental fire are limited. Researchers working on fire safety issues for crews in space want to reduce opportunities for accidental fires as much as possible.

One way to do that is to understand the flammability characteristics of some of the most commonly used materials in space, like plastics and composite materials, which are used for everything from water storage to vital spacecraft components.

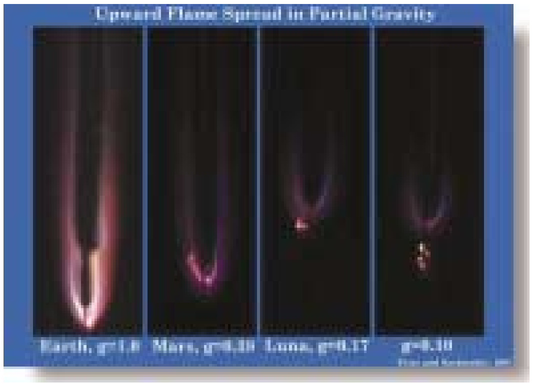
To address this issue, an international cooperative research project involving scientists at GRC, NASA's White Sands Test Facility, and the Keldysh Research Center in Moscow, Russia, set out to investigate the flammability of three plastic materials supplied by the United States: polymethyl methacrylate, known as Plexiglas; high-density polyethylene, used in plastic milk bottles and food storage containers; and Delrin, a very strong plastic used in valve bodies and piping seals.



Researchers working on fire safety issues in space need to understand the flammability characteristics of materials that are commonly used aboard spacecraft. Experiments performed on *Mir* revealed that there was a critical minimum airflow necessary to burn materials in low gravity. Polyethylene rods (a common component in plastic milk bottles) are shown burning on *Mir* at different airflow velocities (from left to right, top to bottom: 8.5 cm/sec, 4.0 cm/sec, 2.0 cm/sec, and 1.0 cm/sec).

Material tests in microgravity were performed on the Russian space station, *Mir*, over a three-day period in October 1998. Researchers gathered data on airflow rates and air composition as samples of the three plastic materials were burned. Video provided information on flame size and rate of flame spread. Reference testing of the flammability, heat release, thermal properties, and combustion products of identical materials was also conducted in terrestrial laboratories at both the Keldysh Research Center and the White Sands Test Facility. What the tests revealed was that with a critical minimum airflow, these materials would burn in low gravity, though they would not burn in quiescent air. These findings confirm the theory that materials that are found to be flame-resistant on Earth may in fact burn in certain low-gravity conditions in space.

The Russian contribution to the project concluded with the publication and distribution of the final report as a NASA Contractor's Report. The report summarizes the findings of the *Mir* tests, discusses the fire safety implications of the minimum airflow required for flame propagation, and describes the nature of recommended further research. A separate final report from the White Sands Test Facility presented the results of flammability measurements on the ground for the test materials and proposed a simple model to predict the minimum airflow for flame propagation.



A fire on the Moon or Mars behaves differently than it would on Earth because of differences in the amounts of gravitational force on these planets. Upward flame spreading over paper samples at four different gravity levels is shown in these images. Varying gravity levels were obtained using NASA's KC-135 aircraft as it maneuvered through a parabolic flight path. As gravity is reduced, the buoyant, upward motion of air is slowed and the flames become shorter and spread more slowly.

Fire in the Sky

Would a fire on the Moon or Mars burn the same as a fire on Earth? Not if the gravitational forces are different. That's because gravity, which causes hotter, less dense gases to rise and cooler, heavier gases to sink, creates airflows around a flame that can work to either impede or enhance a fire. Since the force of gravity on the Moon and on Mars is less than on Earth, fires there will behave very differently than they do on Earth. Just how differently is what PI Kurt Sacksteder, of GRC, is investigating.

In tests conducted on NASA's KC-135 aircraft, which produces microgravity and partial-gravity conditions while flying in parabolic trajectories, Sacksteder observed the effects of varying amounts of gravity on material flammability and flame spreading characteristics over solid fuels. His experiments have provided the first observations of quasi-steady upward flame spreading in partial-gravity environments, including lunar and martian gravitational values. Earlier tests considered downward spreading in partial gravity and indicated that materials have a state of maximum flammability at a gravity level between 0 g and 1 g. Findings from Sacksteder's research have important implications for missions to other gravity environments where fire detection and suppression may require different methods than are required on Earth.

Fire by the Numbers

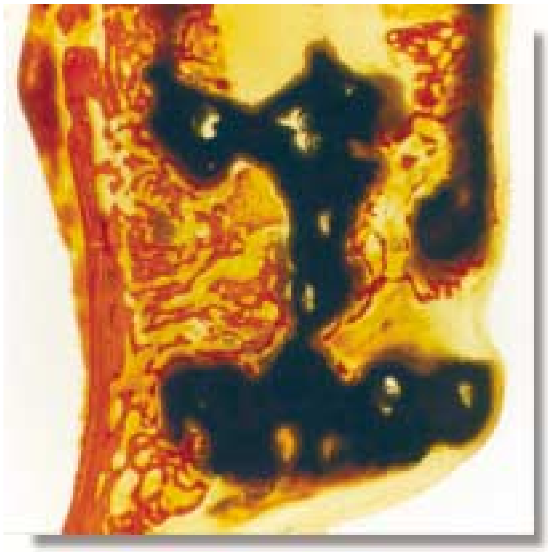
Fires that keep industrial boilers stoked and provide power to jet aircraft don't always stay where they are supposed to. Turbulence can cause flames to lift off their burners (hence, the phenomenon called lifted jet flames) and can temporarily interrupt the steady operation of these machines. Stabilizing jet flames is therefore crucial to the optimal function of these devices. By studying lifted jet flames, which can occur without the flame going completely out, researcher Jyh-Yuan Chen, of the University of California, Berkeley, hopes to discover valuable information on jet flame stability.

The stability of jet flames may be due to something known as a "triple flame," which is a three-pronged flame structure found at the base of a lifted jet flame. Experimental and numerical studies suggest that triple flames may also play a role in promoting flame propagation. Chen hopes that studying the influence of gravity on triple flames, which affects propagation speed as well as flame structure, will enhance understanding of flame spreading and stabilizing mechanisms. Depending on the conditions, gravity can either augment or attenuate triple flame propagation, causing the flame to become unstable and lose its ability to propagate or, under favorable gravity conditions, to accelerate the rate of propagation.

Chen is approaching the problem of triple flame stability and propagation numerically. Computer simulations of triple flames have begun to reveal a picture of the dominant structures and the underlying physics of gravity that affect flame propagation. Two-dimensional models of the combustion reaction, including data on heat, fuel, and oxidizer transport, allow Chen to experiment with flames under a wide range of conditions and have begun to reveal valuable information on a number of phenomena critical to flame stability.

As Good As Bone in a Fraction of the Time

Bones take years to grow. Therefore, to correct damage due to injury, disease, or genetic defects, sometimes bone replacement is the best option. Synthesized bone for replacement



Combustion synthesis can be used to fabricate bone to be used as temporary inserts that are absorbed by the body or as permanent implants supporting healthy bone growth. Combustion synthesized materials are easy to produce and can be manufactured to mimic the porosity characteristics of natural bone. This image of rat skull tissue shows the ingrowth of new bone into a porous titanium boride implant.

procedures has been made from such diverse materials as ground, sintered coral and hydrated calcium phosphate, but none of these materials can be produced as quickly and precisely as the products of combustion synthesis that are being investigated by PI John Moore, of the Colorado School of Mines.

Combustion-synthesized bone can be fabricated in a matter of seconds and shaped to resemble the natural bone being replaced. In combustion synthesis, the burning of two or more reactive materials results in a new compound — in this case, a porous material similar to natural bone. Recent research results show that combustion-synthesized materials are relatively easy to form, and that porosity mimicking natural bone can be precisely controlled. Compression tests, which determine the strength of the synthesized bone material, have also revealed that the mechanical properties of these materials can be improved to a high enough level to make them ideal replacements for natural bone.

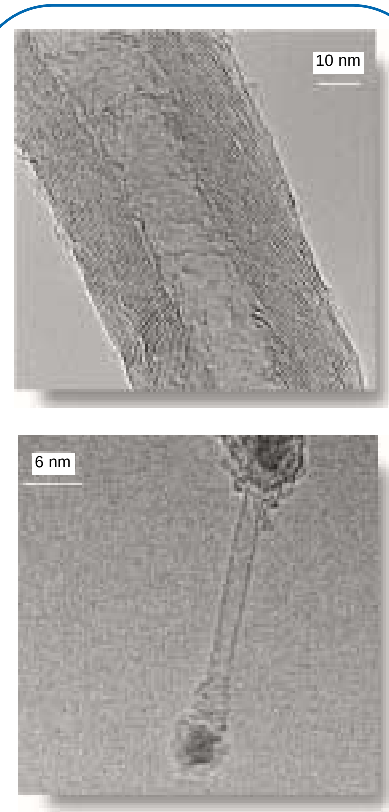
Understanding the structure of the combustion-synthesized materials is the key to maximizing their strength and functionability for bone replacement. Gravity controls pore size and the degree of porosity in a given material. In low-gravity experiments conducted on NASA's KC-135 aircraft, Moore is working to produce "foamed," or porous, composites from a wide range of advanced materials, including ceramics, intermetallics, metal matrix composites, and ceramic matrix composites. He is also attempting to vary the size of the pores and the degree of porosity. The porous materials may eventually be used as permanent implants supporting healthy bone growth through the pores, or as temporary inserts until healthy bone can grow and the replacement bone can be absorbed by the body.

But are these materials safe? Biocompatibility and bioactivity of the replacement materials is measured using cytotoxicity and in-vivo biocompatibility tests. These tests ensure that no harm is caused to the body from the introduction of foreign material. Recent cytotoxicity tests conducted by Sulzer Medica, Inc., a commercial company, on samples produced by Moore of titanium reinforced with titanium boride and nickel-titanium compounds show that the materials are not toxic to the body's natural cells.

The Biggest News Is Little Carbon Fibers

With applications ranging from electronics to pharmaceuticals, tiny, hollow cylinders formed from a single atomic layer of graphite may just be the most versatile material around. These highly ordered carbon structures, called nanotubes, are thought to be the strongest materials known. Randall Vander Wal, of the National Center for Microgravity Research on Fluids and Combustion, is looking for ways of producing them in quantity for use in industry.

Although these fibers are very small (on the order of a nanometer, a billionth of a meter), the most common methods for fabricating them are costly; therefore, it is unclear whether carbon nanotubes can be produced commercially on a large scale. Vander Wal is investigating a method of producing the nanotubes by combusting reactive materials in a process called flame synthesis.



Known for their versatility and strength, carbon nanotubes could be of great use to industries as far ranging as electronics and pharmaceuticals. Producing the fibers on a commercial scale is expensive. Flame synthesis offers an economical way of producing the fibers in large quantities. Samples of multi-walled (top) and single-walled (bottom) carbon nanotubes have been produced using flame synthesis techniques.

Flame synthesis has proven to be an economical means of producing in bulk a variety of aerosol materials such as carbon black. Flame synthesis of carbon nanotubes on a large scale could enable their use in structural materials for aerospace applications.

Vander Wal has successfully fabricated single-walled nanotubes in a laboratory on Earth using the flame synthesis method. In these experiments, catalyst particles were seeded into the flame. Upon reaching a suitable temperature within the flame, the catalyst particles initiated nanotube formation.

The resulting nanotubes were sampled using a probe, which was rapidly inserted into and retracted from the flame. Buoyancy-induced convection, however, limited the growth of the nanotubes, as the catalyst particles remained within the flame for less than one-tenth of a second (the particle's residence time within the flame) before they were carried away. Vander Wal hopes that experiments conducted in a low-gravity environment will aid in understanding the limitations imposed by such short residence times upon nanotube growth and structure.

Spirals Turn Up in Unusual Places

Spiral patterns are known to exist in a range of chemical and biological systems, including the electrical signals generated in heart muscles, but no one expected to find them in flames propagating on a moving surface. What PIs Vedha Nayagam, of GRC, and Forman Williams, of the University of California, San Diego, did expect to find when they ignited a spinning plastic disk suspended horizontally in air were flat, circular flames.

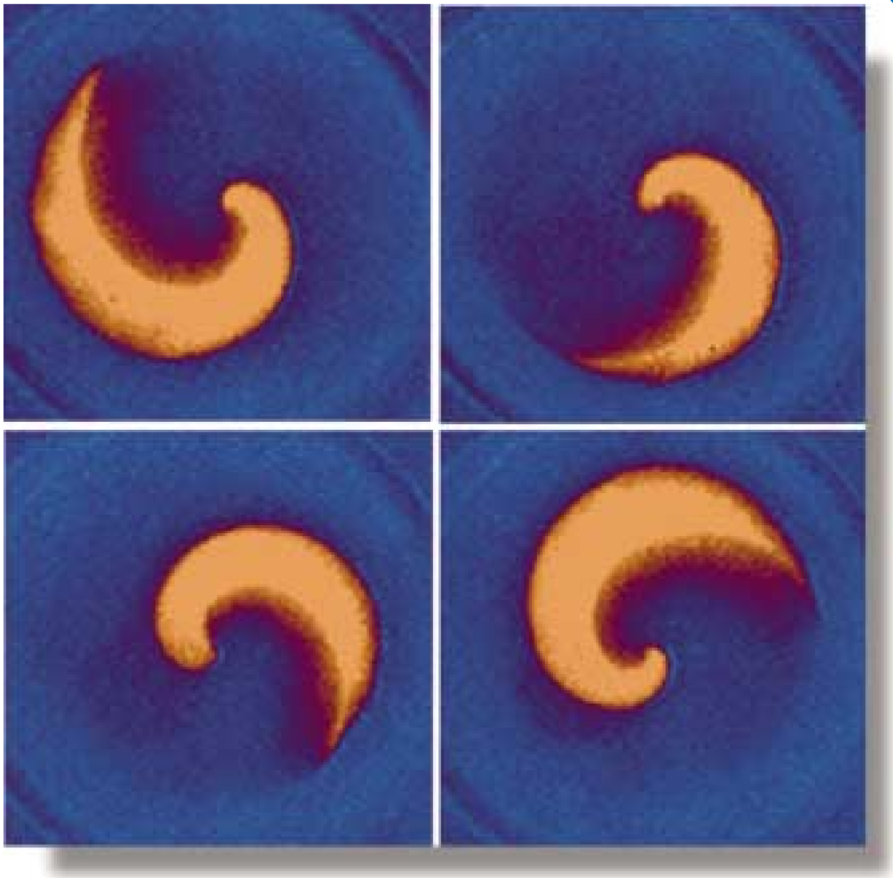
Instead, after using a blowtorch to ignite a spinning plastic disk about one and a half times the size of an audio compact disc, Nayagam and Williams observed a complex spiral pattern that advanced around the disk in the opposite direction from the disk's rotation.

A delicate balance between the swirling motion of the air near the disk surface and the propagation speed of the flame as it advanced toward new sources of fuel is responsible for the unusual pattern.

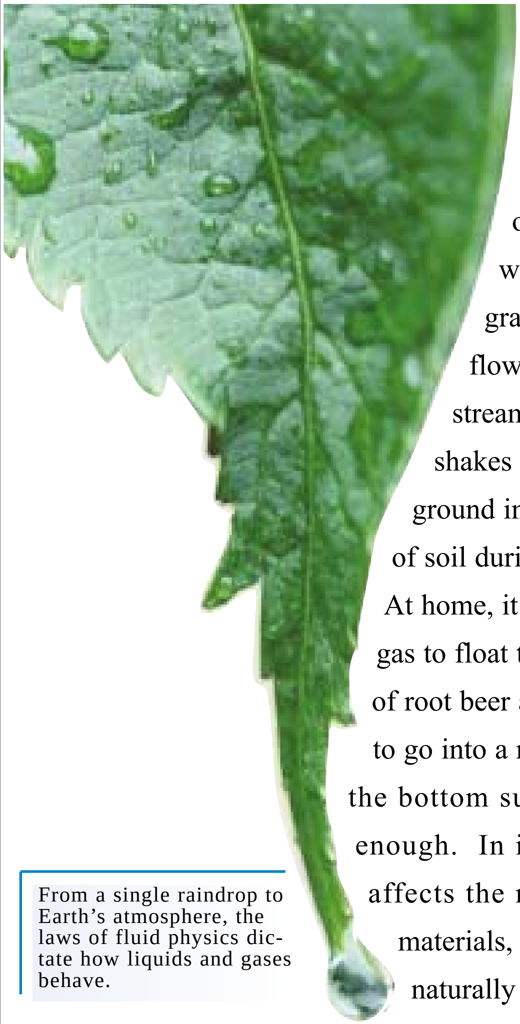
Nayagam and Williams discovered the spiral shape in experiments where the disk was not quite hot enough to sustain burning for more than a minute.

As the fuel (vaporized molecules of plastic from the disk) and oxygen were depleted by the combustion reaction at a given point on the disk, the flame dissipated until the spinning disk circled around, bringing more vaporized plastic molecules and oxygen.

Nayagam and Williams are looking to basic physics principles to provide an explanation for the occurrence of these spiral patterns. Their work on this unusual phenomenon has been published in the January 2000 issue of *Physical Review Letters* (vol. 84, p. 479) in an article titled "Rotating Spiral Edge Flames in Von Karman Swirling Flows." This article has also appeared in the May 12, 2000, issue of *NASA Science News*



Researchers found these (false-color) spiral flames when they ignited a spinning plastic disk suspended horizontally in air. A delicate balance between the swirling motion of air near the disk surface and the propagation speed of the flame as it advances toward new sources of fuel is responsible for the unusual pattern.



From a single raindrop to Earth's atmosphere, the laws of fluid physics dictate how liquids and gases behave.

Evidence of gravity's sway over the movement of fluids here on Earth is everywhere. In nature, gravity guides the flow of rainwater into streams and rivers and shakes seemingly solid ground into rippling waves of soil during an earthquake. At home, it causes bubbles of gas 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 that affect fluid behavior.

Physicists in the microgravity fluid physics program conduct studies under conditions that minimize the effects of gravity so they can see the effects of other phenomena such as surface tension and capillary flow. Through their studies, these scientists are striving to improve the ability to predict and control the behavior of all fluids, including gas, liquid, plasma (a gas containing free ions and electrons, and therefore capable of conducting electric currents), and, in some circumstances, solids.

Their work covers five main areas: complex fluids, interfacial phenomena, dynamics and stabilities, biological fluid physics, and multiphase flows and phase changes. Research in complex fluids involves gases or liquids that contain particles of other substances dispersed within them. These include colloids, which are systems of fine particles suspended in a fluid. Orange juice and paint are examples of colloids. Another complex 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 understand such occurrences as duck feathers and waterproof tents repelling water or water spontaneously displacing air in the gaps of a sponge.

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. Scientists also are 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.

The area of dynamics and stability includes research in drop dynamics, capillarity, and magneto/electrohydrodynamics. The study of drop dynamics deals 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. And 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.

A microgravity environment allows scientists to probe such complex phenomena as how a liquid wets a surface like a windshield or how bubbles of gas form. The study of fluid physics in space is even teaching researchers about fluid systems within the body.

Program Summary

In support of research in these five areas, the microgravity fluid physics program funded a total of 115 experiments during fiscal year (FY) 2000. Of these experiments, 75 were new, including 61 ground-based research projects and 14 projects that were selected for flight definition. The new investigations were chosen in January 2000 from among 297 proposals submitted in response to a NASA Research Announcement (NRA) released in November 1998.

For a list of selectees, visit the World Wide Web at *http://microgravity.hq.nasa.gov/archives/98-HEDS/-03_selections.htm*. In addition, a listing of all ongoing fluid physics research projects, along with the names of the investigators conducting the research, is provided in the Appendix.

Researchers learned about new funding opportunities through NASA and new directions and advances in microgravity fluid physics research when they gathered for the Fifth Microgravity Fluid Physics and Transport Phenomena Conference August 9–11, 2000, in Cleveland, Ohio. At the conference, which is held every two years, the director of the Microgravity Research Division, Eugene Trinh, introduced a new and evolving cross-disciplinary structure for the program, which included the addition of biological sciences research. He also explained the expanded opportunities for funding that will become available as scientists from different disciplines work together on projects, making all researchers involved eligible for funding from all disciplines involved in a project.

Attendees also learned about the new International Announcement of Opportunity, a research announcement that was released in November 1999. The opportunity invited researchers across all microgravity physical science disciplines around the world to collaborate on research on the International Space Station (ISS). The announcement was designed to coordinate parallel research being conducted in different countries in order to maximize resources planned for the ISS and to avoid duplicated efforts.

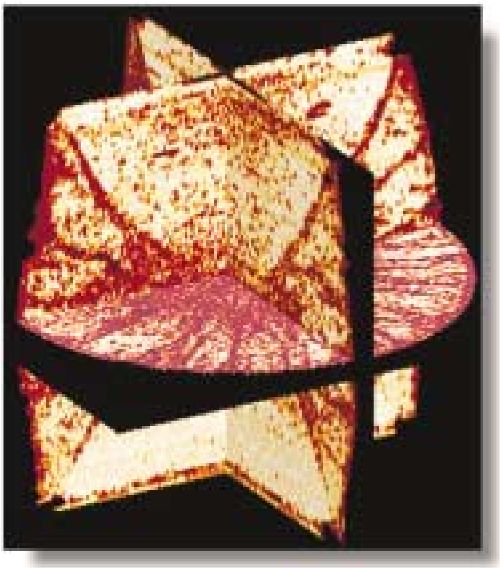
Current and potential researchers also learned about the schedule for the NRA in microgravity fluid physics, to be released in January 2001, as well as the latest advances in research in their discipline, which were shared by current principal investigators (PIs). In addition, they found out that the goal of future fluid physics research is to gain deeper fundamental knowledge in order to permit the design and development of systems for safe, long-term, crewed exploration of space and to enhance NASA's ability to impact Earth-based applications in industry, the environment, and health-related issues.

Fluid physicists also participated in the Workshop on Research Needs in Space Thermal Systems and Processes for Human Exploration of Space in July 2000. Temperature control of thermal systems involves many aspects of fluid physics, such as the flow of liquid fuel, and condensation and evaporation at gas-liquid interfaces. Attendees posed and addressed a number of questions relating to fluid dynamics, including where the liquid is in systems in microgravity, how the liquid moves, how thermocapillarity influences flow field in a large tank, and when gravity is an important variable. Their report is available on the workshop's World Wide Web site at *http://microgravity.grc.nasa.gov/6712/thermal/workshop.html*.

Several notable papers describing the work of fluid physics PIs were published in prestigious journals in FY 2000, including *Nature*, *Science*, and *Physical Review Letters*. Of particular note were a paper published by researchers Zhengdong Cheng, William Russel, and Paul Chaikin, all of Princeton University, titled "Controlled Growth of Hard-Sphere Colloidal Crystals" (*Nature*, vol. 401, October 1999); an article by Dudley Saville, of Princeton University, titled "Electrophoretic Assembly of Colloidal Crystals With Optically Tunable Micropatterns" (*Nature*, vol. 404, March 2000); and an article by John Hegseth, of the University of New Orleans, titled "Thermalization of a Two-Phase Fluid in Low Gravity: Heat Transferred From Cold to Hot" (*Physical Review Letters*, vol. 84, May 2000).

Flight Experiments

This was a year of significant advances for a new remotely controllable microscope and experiments in complex fluids, all of which are scheduled for flight on the ISS.



The Mechanics of Granular Materials is a spaceflight experiment that is shedding light on fine grain systems that behave like fluids under stress. Scans of samples of sand (above) subjected to varying stress in microgravity may reveal clues for how soil behaves during earthquakes (right).

Because the new Light Microscopy Module (LMM) can be controlled from Earth, it will allow flexibility in scheduling experiments for the Fluids Integrated Rack, the fluid physics facility to be installed in the Destiny laboratory of the ISS. (For more information about the Fluids Integrated Rack, see p.55.) The LMM, based on a commercially available upright microscope, offers several key capabilities: video microscopy to observe a sample's features, including basic structures and dynamics; interferometry to measure the thickness of the thin liquid film that surrounds a bubble; laser tweezers for colloidal particle manipulation and patterning; confocal microscopy for providing enhanced three-dimensional visualization of colloidal structures; and spectrophotometry for measuring colloidal crystal photonic properties. Although the LMM has been designed for complex fluids experiments, it can also be used for study of biological samples at the cellular and tissue levels.

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; Physics of Colloids in Space-2, led by David Weitz of Harvard 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 three 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 first microgravity fluid physics experiment to fly on the ISS will be Physics of Colloids in Space (PCS). The experiment, conceived by PI David Weitz and Co-Investigator (Co-I) Peter Pusey, of the University of Edinburgh, involves selected binary colloidal crystals (formed from colloids with particles of two different sizes), which may help explain the behavior of alloys; colloid and polymer mixtures (gels and crystals), which can make the colloids slightly attractive, such as when polymers stabilize the ingredients in salad dressing; and fractal colloidal gels (gels that form highly disordered networks), like the fractal network that holds Jell-O together. These elements will be used to study fundamental colloid physics questions, colloid engineering (using colloids as precursors for building new materials), and the properties of new materials and their precursors.

The experiment will be conducted on the EXpedite PRocessing of Experiments to Space Station (EXPRESS) rack, and testing of the integrated PCS/EXPRESS rack was completed this year. In addition, the flight experiment hardware has been assembled and turned over to Kennedy Space Center. Integration of flight samples into the flight hardware is under way, and final hardware performance tests have been initiated. PCS is scheduled to fly on STS-100 in April 2001.

Scheduled to fly on the ISS in summer 2002 is the experiment Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions (InSPACE). InSPACE will be conducted in the Microgravity Science Glovebox (MSG) and is scheduled for launch on the first Utility Flight (UF-1) in June 2002. (For more information about the MSG, see p.57.)

In SPACE, led by Alice Gast, of Stanford University, seeks to determine the effects of particle concentration, field strength, and frequency on the lowest energy structural configuration in a magnetorheological fluid. This research will add to our understanding of the complex properties of magnetorheological fluids, enabling methods of improving their characteristics and their implementation. Researchers want to know how a pulsed magnetic field will affect the fluid suspension. Three different particle concentrations will be tested during nine test runs each, for a total of 27 test runs. The MSG will provide cameras and video recorders to view and store the science data. Assembly of flight hardware for InSPACE is expected to be completed in February 2001, followed by verification and environmental testing.

Scheduled to fly on the space shuttle in August 2001 is the third Mechanics of Granular Materials (MGM-III) experiment. 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, which occur during earthquakes and landslides when compacted soil loosens and flows much like a liquid.

In MGM's two previous flights, 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, investigators 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 strong ground motions observed during earthquakes.

The science team will also employ a new specimen-reforming technique, which will provide great benefit to future space station research as it enables the reuse and retesting of the same sample many times under controlled initial conditions. 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 Collisions Into Dust Experiment-2 (COLLIDE-2), led by Joshua Colwell, of the University of Colorado, Boulder, studies the effects of low-velocity particle collisions, which are believed to be responsible for the formation of planetary rings and protoplanetary disks. For the experiment, data are collected 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 an absence of any significant dust ejecta in the collisions studied. For COLLIDE-2, which is scheduled for launch on STS-108 in October 2001, researchers will expand the space where the data are collected in order to find the transition from impacts that are purely the result of the increase of particles to impacts with some dust ejecta. They also hope to characterize the velocity of ejecta as a function of impact velocity and energy. Hardware design modifications and testing for the second flight have been completed and the flight hardware is in storage.

The Extensional Rheology Experiment (ERE), led by Gareth McKinley, of the Massachusetts Institute of Technology, is intended to provide accurate measurements of extensional (stretching) viscosity for a family of polymer fluids and to examine the relaxation of polymer chains within the fluid following the stretching of the fluid. Preflight testing of the ERE flight hardware was completed in February 2000, and the hardware was integrated with the launch vehicle systems in March for the sounding rocket flight of the experiment. Final integration tests on the payload were also completed.

Although originally scheduled for launch in May 2000, the experiment's launch was delayed until July 2000 due to launch failures that occurred with vehicles similar to the one being used for ERE. In July, researchers discovered several problems that occurred during flight that minimized the desired scientific return from the experiment. Postflight hardware testing is in progress and corrective measures are being developed to be implemented when future flight opportunities become available.

Highlights

A New Window for Viewing Particles in Motion

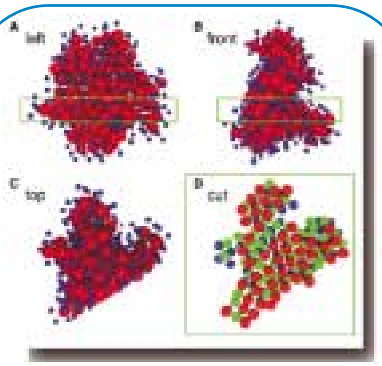
Believe it or not, the windows through which we view the world are structurally more like a fluid than a solid — that is, on the microscopic scale, the particles of which they are composed move, albeit very, very slowly.

Researchers are interested in this movement because many glass-forming liquids behave similarly when cooled, appearing to freeze into a solid-like structure, but retaining many of their fluid-like properties. Theories of the glass transition in supercooled fluids attempt to explain how the molecules in the fluid move, but little is known about the spatial structures they take on because researchers have been unable to directly observe the behavior of the particles in motion in three dimensions.

Recently, PI David Weitz and his team of researchers began using a confocal microscope to observe the three-dimensional dynamics of particles in supercooled colloidal fluids and colloidal glasses. The minimal interactions that take place between hard-sphere colloid particles suspended in a fluid make them excellent models for real systems. The hard-sphere colloids are the simplest systems in which a transition from a fluid to a glass takes place. The confocal microscope allows Weitz to view the movement of individual particles in a fluid sample and to obtain three-dimensional images of the structures they form as they approach the glass transition.

The microscope works by showing researchers one thin cross section of the colloid sample at a time. With this tool, Weitz is able to see exactly what is happening in the colloid sample as it crystallizes or turns into glass, which is something like being able to see how water in a lake freezes as the temperature drops. In the case of the colloids, the volume of solid particles in the liquid, not the temperature, drives crystallization. Volume fraction here is analogous to the temperature in real systems like the freezing lake. First, you might see individual ice crystals forming on the surface of the water, and if you could see each layer of the water, you would witness how the crystals begin to attach to other crystals until the entire lake freezes.

By witnessing these types of events in colloid samples, Weitz will be able to determine what conditions trigger the glass transition. In previous experiments involving two-dimensional, time-resolved images, researchers were able to observe some of the cooperative motion of the particles that is responsible for the glass transition, but were unable to gain insight into the structure and distribution of particle clusters that



Colloid samples consisting of a liquid containing hard spherical particles make good models for the transition that occurs when a fluid becomes a glass. A colloid sample viewed from different angles (labeled A, B, C, and D) shows the arrangement of particles into an ordered "glass" state. Determining what conditions trigger the glass transition may help researchers to design new materials with specific properties.

form as the sample is cooled. Likewise, three-dimensional static images can provide only limited insight into how the structures form.

Using the confocal microscopy technique, Weitz and his team have followed the motion of several thousand colloidal particles and have characterized the size and structures of large, extended clusters that form as the glass transition is approached. Weitz witnessed long chains of colloid particles moving randomly in the sample fluid. Then, as the fluid approached transition, a number of crystal clusters formed, creating obstacles for the long chains and thereby arresting any further movement.

A discussion of the methods and results using this microscopy technique was published in the January 28, 2000, issue of *Science*.

Geology Through a Physicist's Eyes

Most people think of a compass, a chisel, and hiking boots as tools for geology. But PI Jayanth Banavar, of Pennsylvania State University, is putting some rather nontraditional tools to work to predict river networks. Banavar is using computers and elevation data from satellites to determine the path of river networks mathematically, a procedure that focuses on general properties of mathematics and physics rather than on the traditional forces — such as weather, erosion, and sedimentation over millions of years — geologists look at to explain natural landscapes. Banavar's research may make it possible to aid land usage planners and natural disaster trackers in predicting changes that will occur to a landscape such as landslides, floods, and erosion.

Banavar's research capitalizes on the many general patterns of river networks that are discernible over a range of landscapes. He and his colleagues have discovered that wherever the location of a river basin — be it the Nile, the Mississippi, or the Thames — universal laws of physics define the path of the water flow and the dendritic design of tributaries, tributaries' tributaries, and so on. Water sculpts the rugged landscape in similar ways, no matter where in the world it begins its course, and smaller portions of a basin mimic the pattern of the whole. Traditional tools of geology have been unable to explain these recurring designs. Applying physical principles such as the path of least resistance may hold the key to explaining some of these behaviors. These principles can then be translated into the language of physicists and mathematicians — mathematical equations.

Satellite data that can provide point-by-point elevation measurements are fueling Banavar's discoveries. In the past, the best way to gather this kind of data was on foot and by using airplanes. Satellite data increase the accuracy of the measurements and allow mapping of large expanses much more quickly. The data are computed, and from the results, one can discern innumerable paths that water can follow down a basin during a storm. Banavar and his colleagues are hoping to find some overriding principle that can explain the patterns.

Banavar's research, as well as the work of geologists and physicists using satellite-made digital maps, is discussed in a November 23, 1999, article in *The New York Times* titled "Physicists Invading Geologists' Turf," which is available to visitors to the *Times*' web site at *http://www.nytimes.com/library/national/science/112399sci-environ-geology.html*.

Shedding Light on the Smallest Invaders

What if ophthalmologists had a tool that would allow them to detect the buildup of tiny particles in the fluid in the lens of the eye — particles so small as to be undetectable by any other method? What if this tool could also tell doctors if treatments designed to prevent or slow the growth of cataracts were effective? Hoping to give doctors a leg up on treating and preventing cataracts, PI Rafat Ansari and his colleagues at the National Center for Microgravity Research on Fluids and Combustion, have been hard at work on a state-of-the-art instrument to do just that.

A new method for predicting the path of rivers relies on elevation data from satellites and mathematics. This calculated schematic of a river network may allow researchers to begin to determine general, universal patterns of water flow that can be applied to river networks everywhere.

Banavar's river network research may eventually aid in predicting changes to the landscape, such as floods, landslides, and erosion.

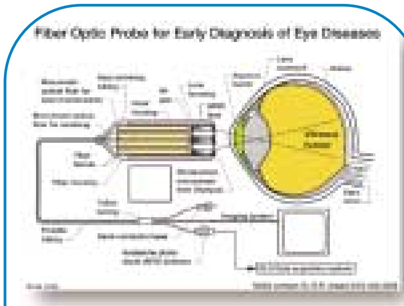
This year, researchers came one step closer to this goal with the completion of successful human clinical trials of the NASA-sponsored technology.

Patented in the fall of 1999, a fiber-optic eye probe developed by Ansari and postdoctoral fellow Kwang Suh uses laser technology to find cataracts in their earliest stages, when there's still time to arrest progress of the disease, or in some cases, to reverse damage. The fiber-optic probe uses laser light–scattering technology to scan an area of the eye's lens for tiny crystallines of protein molecules. Laser beams aimed at the lens undergo the Doppler effect, diffracting at different wave lengths when they encounter protein crystallines, thereby revealing the lens' opacity. A fiber-optic receiver collects the scattered light and carries it to a photodetector, which amplifies the signal and transforms it into electronic signals. These, in turn, are sent to a laptop computer that is programmed to use the data to compute the particle size.

The probe is able to detect particles with diameters ranging from 1 nanometer (about the width of five atoms) to a few microns (about the width of a human hair). Any cataracts detected in these early stages can undergo anti-cataract treatment, which could reverse, delay, or prevent the onset of cataracts.

The real promise of this technology is that it can read the exact same area of a patient's lens in repeated tests. Ansari and his team are working to demonstrate the ability of the probe to reproduce reliable data. If effective, this technology could be used to track changes in a patient's eye over time. Given this ability, doctors could assess the efficacy of a variety of cataract inhibitors designed to prevent or slow the development of cataracts.

Behind these advances in cataract detection and the development of sophisticated tools for tracking changes in a patient's eye are more than a decade of fundamental studies in fluid dynamics conducted on the Russian space station, *Mir*, and on the space shuttle. In the microgravity environment of space, Ansari began observing the link between the motion of very small particles in fluid and the fluid dynamics in the lens of the eye. He applied the same light-scattering tools that are used to measure the size and motion of particles in microgravity to the eye. This allowed Ansari and research partners at the National Eye Institute of the National Institutes of Health to track development of cataracts in their incipient stages.



The fiber optic probe pictured in this schematic uses laser light–scattering technology developed for spaceflight experiments to scan the eye's lens for tiny crystallites.

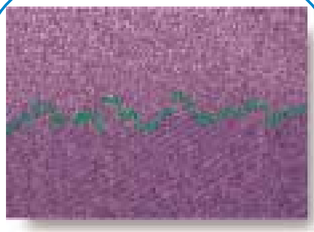
Results of Ansari's research on cataract detection using the light-scattering technology have been published and reported on in the *Review of Ophthalmology.*

Cataracts are the leading cause of blindness worldwide and affect 50 million people each year. A tool to help ophthalmologists detect the earliest stages of cataracts may give doctors a chance to arrest the progress of the disease.

Separating Order From Disorder

Accolades from the technology world are heralding the invention of an automated technique for discriminating between the disorderly liquid phase and the orderly crystalline phase in high–volume fraction colloid systems. These systems are solutions in which small particles make up more than 50 percent of the total volume. A better understanding of how the change between the crystalline and liquid phases occurs in these solutions can eventually lead to understanding how to engineer new materials.

The promising new technique to determine when the phase change occurs was developed by Mark McDowell and his team of researchers at Glenn Research Center (GRC). It is expected to save researchers countless hours in the laboratory. McDowell and his team were honored for their work with the Imaging Solution of the Year 2000 award, given by *Advanced Imaging*, a leading publication in the imaging field.



A compact microscope imaging system saves researchers countless hours in the laboratory in search of the transition between disorderly liquid phases and orderly crystalline phases in high volume fraction colloid systems. Developers of the system received the Year 2000 Imaging Solution award.

All of the excitement is over the use of a compact microscope imaging system that can be tailored to a data set of image frames with minimal input from the user. Until now, researchers had to look at thousands of images of colloid suspensions frame by frame to determine when the phase change from liquid to crystalline solid began. The work of McDowell's team lays the foundation for the application of intelligent processing algorithms for both ongoing ground-based colloid research at GRC and upcoming microgravity experiments on the ISS.

Some Assembly Required

You might call PIs David Weitz, of Harvard University, and Arjun Yodh, of the University of Pennsylvania, tinkerers of sorts. They have long been interested in the kinds of materials that form when particles of different sizes are mixed together in a colloid solution or when polymers (long, chain-like molecules) are added to colloid solutions. When particles of different sizes are mixed, novel structures often result that have completely different properties than any of the constituent parts.

Given a little bit of direction from the researchers, the particles can be encouraged to form in specific patterns and to yield particular crystalline structures. Weitz and Yodh have succeeded in forming a rich variety of two-dimensional fluid-like and solid-like structures using one- and two-dimensional templates. By stacking layer upon layer of the template material, the researchers have obtained symmetrical cubic crystals more than 30 layers thick.

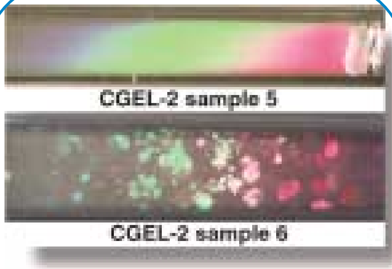
Templates with a series of indentations help Weitz and Yodh direct the assembly of their colloid particles into desired structures. They are aided in this maneuvering by the interactions that take place between particles of different diameters. Strangely enough, the smaller particles in these mixtures command the movement of the larger particles, herding them into the indentations on the template. Weitz and Yodh take advantage of this behavior, using small particles that won't stick to the larger particles to push the larger particles into place. What results is an ordered structure comprising only the large colloid particles.

Weitz' and Yodh's research is fueled by fundamental studies of the dynamics of crystal-forming colloid solutions. More than 15 years of research has gone into studying the kinds of structures that form when particles in various proportions and of various diameters are mixed in a fluid solution. Although scientists are closing in on the ability to predict the kind of structures that will form from particular combinations of particles, gravity introduces a degree of uncertainty in studies performed in laboratories on Earth.

There can be large density differences between the particles and the surrounding fluid. This can cause the particles to sink in the liquid rather than remain suspended, which ultimately alters the kind of structures that will form. In microgravity, the particles tend to stay suspended in the fluid, which makes it possible for researchers to predict the outcome of their experiments and eventually to obtain materials to meet specific needs.

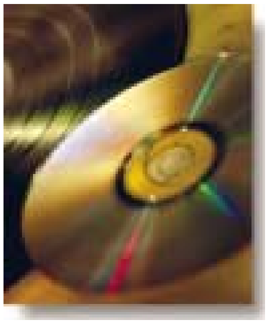
Microgravity has also revealed the importance of understanding how crystalline structures form. By observing the particles during the assembly process, which often determines the properties of the resulting material, researchers are discovering that colloid particles can achieve their final ordered state in somewhat unexpected ways. Understanding why the particles behave in a particular way and the influence that behavior has on their structures may help researchers manipulate the outcomes in order to develop useful new materials.

An article on Weitz' and Yodh's research titled "Entropically Driven Colloidal Crystallization on Patterned Surfaces" appeared in the August 21, 2000, issue of *Physical Review Letters*, vol. 85(8), pp. 1770–3.



More than 15 years of research has gone into studying the kinds of structures that form when particles in various proportions and of various diameters are mixed in a fluid solution. These colloid samples were grown on the space shuttle and contain particles of two different sizes. Growing samples in microgravity yields much better-defined crystals than can be obtained on Earth, allowing their properties to be studied in detail. In the future, researchers hope to be able to predict the kinds of structures that will form from particular combinations and concentrations of particles.

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.

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.

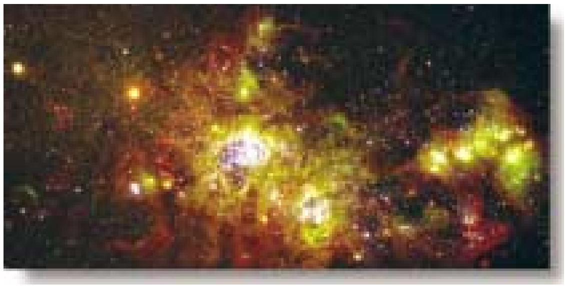
Researchers in the discipline have two quests that motivate laboratory studies and experiments in space. One of these quests is to explore and understand the fundamental physical laws governing matter, space, and time. Deep examination of the smallest and largest building blocks that make up the universe 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.

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

Fundamental physics probes the basic nature of our universe on both a cosmic and atomic scale. Though investigations in this field generate, explore, and confirm scientific theories, like Einstein's theory of General Relativity, they also provide the foundation for future technologies that will become part of our everyday lives. Computers, CD players, and MRIs are all commonplace technological tools that had their beginnings in a physicist asking a fundamental question about the world around us.

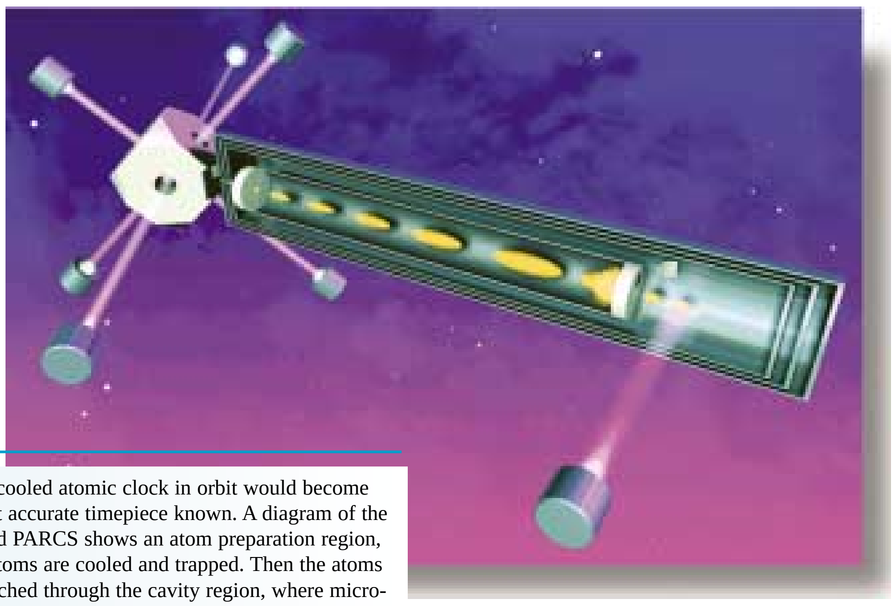
The pursuit of these quests will greatly benefit society in many ways over the long run. For example, the study of physical laws and natural principles with unprecedented precision requires advances in instrumentation that provide the foundation for tomorrow's breakthrough technologies. These advances 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 four areas: gravitational and relativistic physics, laser cooling and atomic physics, condensed matter physics, and biological 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 structure of the universe. Laser cooling and atomic physics is the study of atoms and how they manifest on a microscopic 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 the atoms are condensed. Biological physics explores the boundary between biology and physics.



Program Summary

A NASA Research Announcement (NRA) soliciting new proposals for research in microgravity fundamental physics was released in February 2000. The NRA reflected the program's continuing commitments to engage the best researchers working in the established areas within the discipline and to seek out new areas of study that may benefit from a microgravity environment. The 2000 NRA also solicited research in biological physics, a newly established area of the fundamental physics program. As the understanding of many biological activities requires an understanding of underlying physics principles, the time was ripe to encourage work that links and supports both physics and biology.



A laser-cooled atomic clock in orbit would become the most accurate timepiece known. A diagram of the proposed PARCS shows an atom preparation region, where atoms are cooled and trapped. Then the atoms are launched through the cavity region, where microgravity conditions keep the atoms flowing straight to the detection region.

Based on peer review of the 109 proposals submitted in response to the NRA, 36 ground-based investigations were selected for funding, with seven of those in the new area of biological physics. In addition, five investigations were chosen for development as flight experiments. These flight projects included two guest investigations for the first mission of the Low Temperature Microgravity Physics Facility (LTMPF) on the International Space Station (ISS), one investigation in gravitational physics, and two experiments in laser cooling and atomic physics that will be natural follow-ups to flight experiments in atomic clocks currently slated for the ISS. A complete list of selected research projects can be found on the World Wide Web at *http://peer1.idi.usra.edu/peer_review/press/ls/pr00-02.htm*. In addition, a listing of all ongoing fundamental physics research projects, along with the names of the investigators conducting the research, is provided in the Appendix.

The progress to date of ongoing research projects was presented at the annual NASA/Jet Propulsion Laboratory (JPL) Investigators' Workshop on Fundamental Physics, which took place in Solvang, California, June 19–20, 2000. The workshop was an opportunity for investigators in the program to present research developments and results and to share ideas with others in the field. At the 2000 workshop, 33 oral presentations and 18 poster presentations were given.

The workshop also focused on future developments in the program, including the reorganization of the microgravity research effort at NASA headquarters and some changes in organization at JPL. Special planning sessions were held regarding collaborative work on the development of atomic clocks, experiments that are potential candidates for flight on the space shuttle, and the International Announcement of Opportunity for proposals for research to be conducted on the ISS. The fundamental physics program supported a total of 36 ground-based investigations and 10 flight investigations in fiscal year (FY) 2000.

Flight Experiments

The flight program in fundamental physics achieved several milestones this year. As development of the LTMPF planned for the ISS progressed, experiments slated to fly in the facility also moved forward. The LTMPF will be able to maintain two experiments at a time at temperatures below 2 kelvins for up to six months. A nonadvocate science panel and a nonadvocate engineering panel reviewed six candidate LTMPF experiments for their science significance, need for microgravity, science requirements, and experiment implementation plans. Based on those reviews, four experiments in condensed matter physics were selected for flight on the first two LTMPF missions.

Three of the four experiments chosen explore the properties of superfluid helium. Helium, when cooled to very low temperatures (2.17 kelvins), transitions from a liquid to a superfluid, a state of matter that exhibits unusual properties. Studying the conditions of temperature and pressure at which the transition occurs, called the critical point for superfluidity, has proven the helium 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, which is scheduled for the first LTMPF mission, will explore the properties of superfluid helium as it is subjected to a heat flux, and the Microgravity Scaling Theory Experiment will test scaling law predictions for thermophysical properties of systems near critical points. The Boundary Effects on the Superfluid Transition experiment, scheduled for the second LTMPF mission, will determine the effects of boundaries on the thermal conductivity of superfluid helium. Also chosen for the second mission, the Superconducting Microwave Oscillator is a project to develop an oscillator that will support highly stable atomic clocks that can be used to test theories about relativity and in other applications (For more details on the LTMPF, see p.55).

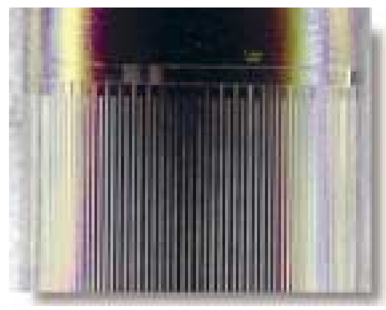
Work advanced this year on two flight experiments to develop atomic clocks using laser-cooled atoms. Atomic clocks are the most accurate timekeepers on Earth, but gravity limits their performance. Development of an atomic clock that could take advantage of a microgravity environment would enable an improvement 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).

One of the atomic clock projects, the Primary Atomic Reference Clock in Space (PARCS), is developing a cesium-beam atomic clock for the ISS. This year, the PARCS team at the National Institute for Standards and Technology (NIST), in collaboration with JPL, developed a novel technique using phase modulation interrogation to eliminate most of the clock's sensitivity to vibration. The technique proved successful in the ground-based clock at NIST. Other technical progress included the design of a nonmagnetic shutter and a laser system, along with studies of using GPS techniques to transfer the time determined by the ISS clock to ground laboratories.

The other project, the Rubidium Clock Experiment (RACE), passed a milestone science review this year, and the RACE team developed a new method for eliminating a major source of error in atomic clocks — frequency shift of the atoms due to cold collisions. In atomic clocks, lasers are used to slow the fast movement of gas atoms so that more accurate measurement of them can be made. However, one problem with slowing the atoms is that they expand and run into each other, which can interfere with the accuracy of the clock. The method to cancel the frequency shift caused by collisions that do occur was developed and tested by the RACE team at Yale University. A summary of the results, authored by Chad Fertig and Kurt Gibble, both of Yale University, was published in *Physical Review Letters*, vol. 85, p. 1622 (2000).

Several projects that will be conducted on carriers other than the ISS are also under way. An experiment in condensed matter physics, the second Critical Viscosity of Xenon (CVX-2) experiment, has been manifested on space shuttle mission STS-107, which is scheduled to fly in 2001. Work progressed on readying the CVX-2 hardware for integration in the shuttle. This experiment, which had a successful flight on shuttle mission STS-85 in 1997, measures the change in viscosity of a fluid near its critical point, laying the groundwork for scientists to better understand viscosity.

Technological advances were made on the STEP project this year. Pictured here are the thin-film superconducting magnetic bearing developed for STEP and the aerogel that will restrict the motion of liquid helium in the STEP dewar.



In FY 2000, a baseline design of the science instrument for the Satellite Test of the Equivalence Principle (STEP) was completed and a first set of drawings was released. STEP is a sophisticated scientific test of the equivalence principle, which states that objects of different densities, sizes, and weights should fall at the same rate of acceleration. In the experiment, test masses will be in freefall as they orbit around Earth on a satellite for more than a year. Conducting the experiment in this disturbance-free environment and over such a long fall will yield results that are an order of magnitude more accurate than previous tests of the equivalence principle.

A number of technological problems were resolved this year for STEP, including the superconducting magnetic bearing, which was resolved by using thin-film laser circuitry, and a helium tidal disturbance, which was resolved using aerogel. The European Space Agency (ESA), NASA's partner in the STEP project, completed a feasibility study of a low-cost spacecraft service module with favorable results in April 2000.

Highlights

Superfluids: Keyholes to Super Technologies

When helium is cooled to extremely low temperatures (about 2 kelvins) 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 has infinite heat conductivity. Helium in this state is called a superfluid. Other properties of superfluid helium can provide a window on the quantum world, as quantum effects are often magnified in helium as it nears its transition to a superfluid. The findings of two scientists in the fundamental physics program as they explored some of these exceptional properties of superfluid helium in FY 2000 may prove useful not only in understanding this fascinating state of matter but also in developing new technologies.

The Physics of a Super-Small Chip

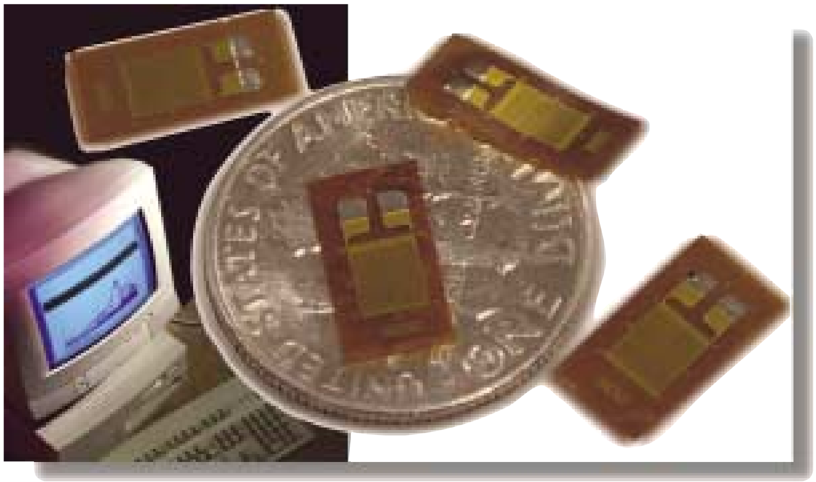
As the quest for miniaturization of devices continues, scientists are asking themselves if size will change the rules for how a sample of matter behaves. For instance, in a transistor circuit on a computer chip, an electron moves around freely in what is called "the bulk" — the interior area of a material — and only occasionally bounces into the surface of the transistor. If that chip is reduced in size, eventually the electron will spend more time hitting the surface than traveling around in the bulk, so the surface will have a greater effect on the electron's behavior. This is called the confinement effect.

Experimentally testing the theory predicting the effect of confinement on the properties of materials is difficult because the samples must be so small that the behavior of the atoms becomes impossible to observe or measure. Superfluid helium provided the answer to this problem. In a very thin sample of helium near the transition to the superfluid state, the effects of confinement become dramatically magnified — by about 10,000 times. The only catch was that gravity causes a pressure difference in the samples because the helium at the top of the sample weighs down upon the helium at the bottom. The nonuniform pressure and the resulting nonuniform density distort results.

John Lipa, of Stanford University, designed an experiment in confinement effects that would be conducted in orbit, where a sample of superfluid helium would be free from the effects of gravity and thus free of the pressure differences found in the earth-bound sample. The Confined Helium Experiment (CHeX) was conducted successfully on the shuttle in 1998, and this year Lipa and his team finished analysis of the CHeX data and published their results in *Physical Review Letters*, vol. 84, p. 4894 (2000). The experiment results agreed well with theoretical prediction of confinement behavior, which should give physicists a good start for designing the ever-smaller circuits and devices of the future.

CHeX was carried in the open cargo bay of the space shuttle during the fourth U.S. Microgravity Payload mission.

Results from a spaceflight experiment called "CHeX" are contributing to the theoretical understanding that will help the engineering of ever-smaller computer chips for new computing systems of the future.



Spin-Doctoring With Super Gyroscopes

What if you were moving, spinning slowly in fact, and had no landmarks or horizon in sight? How could you detect the change in motion? You would need a gyroscope. Gyroscopes are common instruments used in the navigation of ships, planes, and spacecraft. The Russian Space Station *Mir* used 11 gyroscopes to maintain its orientation to the sun for power collection. The GPS also depends on gyroscopes for measurements of the Earth's rotation vectors. Measurements from an ultrasensitive gyroscope could improve the system with resulting benefits for navigation as well as for the prediction of weather patterns, ocean currents, and earthquakes.

A gyroscope developed through fundamental research into the properties of superfluid helium has measured the rotation of the Earth with unprecedented sensitivity.

Richard Packard and his team at Stanford University are using superfluid helium-3 to develop such a highly precise instrument. In their experiment, two baths of superfluid helium are divided by two membranes, thin silicon chips with many tiny holes. In fact, each membrane has 4,225 holes that are each 100 nanometers, or billionths of a meter, in diameter. The membranes allow what are called weak links to be established between the two baths. When pressure is applied across the system, it oscillates, which causes the helium to travel through two established loops, or paths, and through the weak links. As the setup is rotated, the flow of the superfluid through the links is affected. The flow in one loop becomes augmented as the other decreases. The gyroscope can be set to have a specific amplitude of flow, and then if variations are seen, rotation is indicated.

The gyroscope currently is sensitive enough to detect rotation 100 to 1,000 times slower than the daily rotation of the Earth. If the gyroscope were taken to space, where vibrations and other disturbances are eliminated, it is thought that the instrument could be a million times more sensitive.

But this year, Packard's team found that the potential sensitivity might be even greater. They discovered a bistability in the weak links of the experiment, which means that when a specific amplitude of flow is reached, the amplitude suddenly jumps to a higher level. At this level the sensitivity of the gyroscope to rotation doubles. Such an ultrasensitive gyroscope may greatly improve our navigational instruments for ground, air, and space travel. The discovery of bistability was reported in *Physical Review Letters*, vol. 83, p. 3860 (1999).

The Coldest Twosomes Known

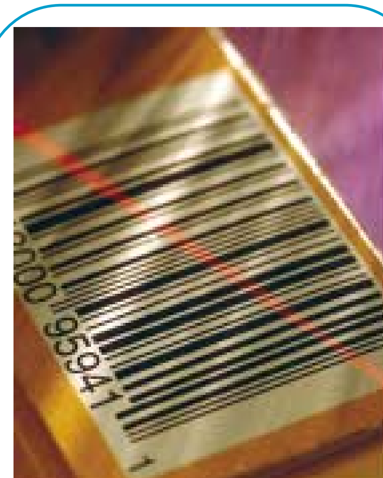
Physicists in recent years have been fascinated by the study of atoms at extremely cold temperatures. They often cool the atoms with laser light, which slows them almost to a standstill, an excellent condition for observation. If the atoms are cooled to low-enough temperatures, they have been observed to rearrange themselves into a highly ordered state, so that their behavior is in a sense magnified.

This new quantum state is called Bose-Einstein condensation. It had previously only been achieved with atoms, but Daniel Heinzen and his science team at the University of Texas have changed all that. They have used lasers to coax some rubidium atoms in a Bose-Einstein condensate (BEC) cloud to pair up to form molecules — the coldest molecules ever achieved in a lab. The ability to observe molecules in a BEC state would open up a new area of investigation with the potential for discoveries about how molecules interact with one another. Heinzen is currently trying to create a whole cloud of BEC molecules.

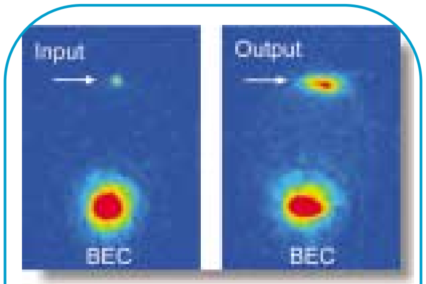
As with BECs of atoms, condensates of molecules would be perfect for observation if gravity didn't cause them to drop out of view of the measuring instruments. Optical and magnetic traps are used to keep the atoms in place in ground-based experiments with condensates, but these methods can interfere with observations. Eventually, the microgravity environment of orbit may hold the key to getting the most out of watching these very still, very cold particles of matter. A report on Heinzen's work appeared in the February 11, 2000, issue of *Science*.

Atom Lasers: May the Force Be Amplified

Lasers have become common tools, used in everything from CD players to grocery store scanners to instruments for surgery and cell manipulation. What seems next on the technological horizon, however, is a beam composed of not photons (light particles) moving in perfect step with each other, but of atoms moving in unison — in essence, an atom laser.



When optical lasers were first developed, everyday uses like grocery store scanners were hard to predict. An atom laser may hold the same potential for unimagined technologies.



An atom beam amplified: The left image shows the shadow of the initial (or input) beam of atoms. The right image shows the shadow of the output beam, obviously amplified after the BEC was illuminated by a pulse of laser light.

Wolfgang Ketterle's team at the Massachusetts Institute of Technology (MIT) created an atom laser in 1997 using the coldest substance on Earth — a BEC. BECs are formed when a gas is cooled to one millionth of a kelvin, or more than a million times colder than interstellar space. At this temperature, a transformation occurs. Rather than moving about independently, the atoms of the gas begin to move or march in lockstep, displaying uniform behavior.

Much as a flash of light is used to stimulate electrons, which in turn give off photons in an optical laser, Ketterle was able to use laser light to stimulate a BEC to create a stream of atoms still in the BEC state. However, the stream was very weak. The question became whether the stream could be amplified in a way similar to the way the emission of photons is amplified inside an optical laser. Indeed, this year, Ketterle's MIT team accomplished just that.

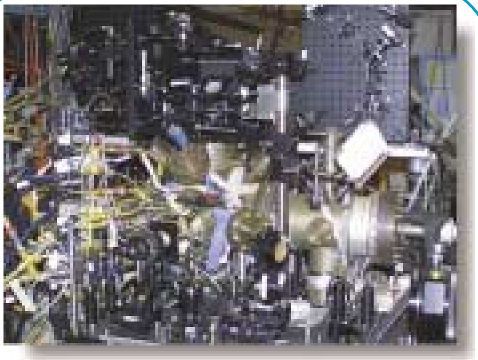
The team used a pulse of laser light to create an initial stream of atoms from a BEC and then a second pulse that excited the BEC and caused some of the atoms to join the initial stream. These added atoms were still in lockstep with the original. Although the resulting beam was very weak due to the current limitation on the size of a BEC sample, the proof that amplification is possible is a very important step in realizing an atom laser for technological purposes. One possible use of an atom laser is to deposit atoms in very controlled ways to create new materials and nanostructures.

A microgravity environment may one day contribute to the creation of larger BEC samples. One of the obstacles to larger samples is the ability to contain or hold in place these very still, very cold atoms. In orbit, samples would not fall through their containers as they do on Earth, which would eliminate the need for optical or magnetic traps that are currently used to suspend the atoms but can also interfere with their behavior. A report on the atom beam amplification technique by Ketterle and his group was published in the December 9, 1999, issue of *Nature.*

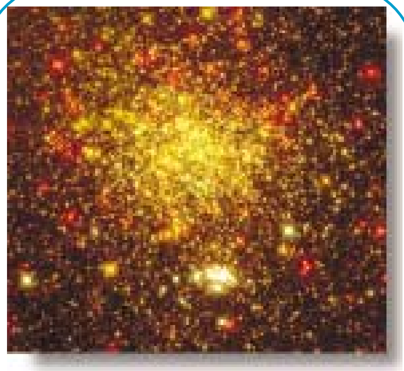
The development of an atom laser amplification device is only the latest in a series of important achievements for Ketterle, starting with his lab's creation of a BEC in 1995 and including subsequent studies of the BEC's properties. In recognition of these accomplishments, in FY 2000 Ketterle was inducted into the American Academy of Arts and Sciences and awarded the Benjamin Franklin Medal in Physics, conferred by the Franklin Institute.

Dynamic Inventions

While working to improve equipment used in his superfluid helium spaceflight experiment, Robert Duncan and his team at the University of New Mexico have developed two new instruments that may one day be of use in different applications. Because the Critical Dynamics in Microgravity experiment measures very slight variations in temperature in samples of superfluid helium, it requires extremely sensitive thermometers. Duncan has used a new metal alloy in the sensing element for these high-resolution thermometers, which have improved the sensitivity of his experiment and opened up possibilities for other uses as well. The sensing element could be used to detect very slight differences in the temperature of tissue in the body, potentially revealing cancerous tissue, and the element might also prove useful in analyzing the light emitted by stars.



The apparatus Ketterle and his team devised to amplify an atom beam.



A sensor developed for a superfluid helium spaceflight experiment may also prove useful in analyzing the light emitted by stars.

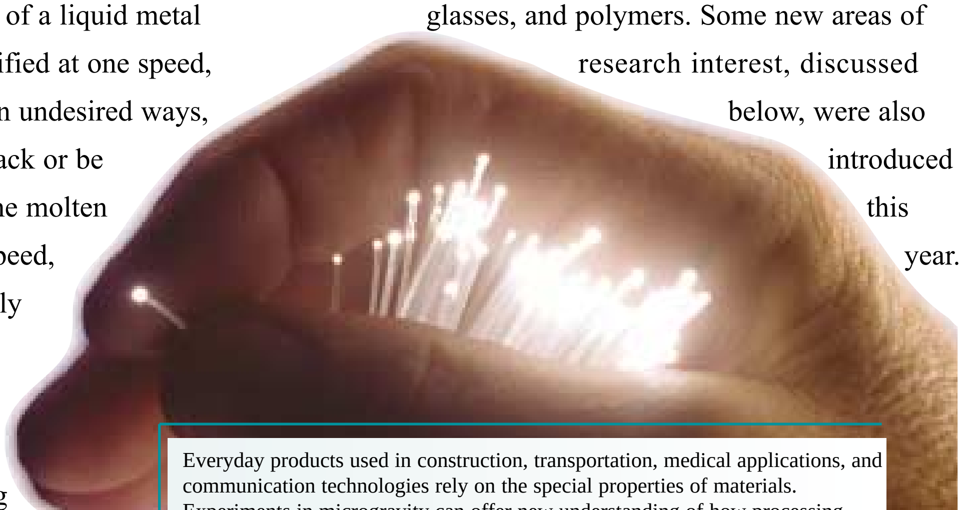
Duncan and his team have also devised an ultraminiature cryogenic valve. Duncan needed the valve to control the liquids involved in the experiment. Because a smaller valve has less impact on the system it regulates, with this miniature valve, Duncan will not have to wait long after an experiment adjustment for the system to reach equilibrium. The valve may prove helpful to many scientists involved in cryogenic research and to engineers developing dilution refrigerators, or refrigerators that hold temperatures of 0.02kelvin.

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 they are used in. 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.

A material's properties, such as how strong, how durable, or how poor or efficient a conductor it is, are determined by the material's molecular structure. The molecular structure is determined by the method and conditions under which the material is produced. For example, if a mixture of a liquid metal containing ceramic particles is solidified at one speed, those ceramic bits may congregate in undesired ways, causing the processed material to crack or be brittle. If, on the other hand, the same molten material is solidified at a different speed, the ceramic parts 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 learn how 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.

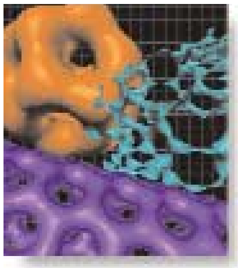
The microgravity materials science program currently sponsors research in the areas of metals and alloys, electronic and photonic materials, ceramics, glasses, and polymers. Some new areas of research interest, discussed below, were also introduced this year.



Everyday products used in construction, transportation, medical applications, and communication technologies rely on the special properties of materials. Experiments in microgravity can offer new understanding of how processing conditions affect the properties of materials and offer insight into the development of novel materials for new applications.

Program Summary

Researchers from universities, companies, and organizations across the country compete for funding in the materials science program by submitting research proposals in response to biennial NASA Research Announcements (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. Fiscal year (FY) 2000 saw the end of one round of this cyclical process with the implementation of all of the grants and contracts for the 65 research proposals selected as a result of the 1998 microgravity materials science NRA. Sixty of the grants funded ground-based research, and the remaining five were flight-definition tasks. A list of selected researchers and their investigation titles is available on the World Wide Web *http://microgravity.hq.nasa.gov/archives/98-HEDS-05_selections.htm.* With the addition of these research projects to ongoing investigations, a total of 163 principal investigators (PIs) and 302 co-investigators participated in the program during FY 2000. A listing of all ongoing materials science research projects, along with the names of the investigators conducting the research, is provided in the Appendix.



Nanotechnology, a focus of the materials program, may provide new miniature technologies for space exploration. Pictured here are computer models of a nanotube and a fullerene, materials with unique properties formed from carbon molecules.

A new cycle of NRA preparation began at the Fourth NASA Microgravity Materials Science Conference, sponsored by the Microgravity Research Division and held June 6–8, 2000, in Huntsville, Alabama. The conference attracted more than 325 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, and the next microgravity materials science NRA, which will be released in the spring of 2001, was discussed.

Some new areas in materials science deserving of heightened focus were presented at the conference. These areas, which could provide fundamental knowledge that may contribute to NASA's long-term exploration goals, include nanotechnology, biomaterials, and materials for radiation protection. Nanotechnology involves the creation and study of materials and systems that operate on the scale of a billionth of a meter. Understanding such systems may hold the key to miniaturization, which is desirable for long-term missions, as it could lower the weight and volume, and therefore the cost, of mission payloads. The development of biomaterials, materials that are inspired by or derived from biological systems, could be beneficial to crew health monitoring or spacecraft systems maintenance over long durations. And materials to protect crewmembers from solar radiation, a danger to which they could be exposed for longer periods than ever before on missions to Mars, for example, are of paramount importance to ensure astronaut health. (Radiation protection materials were also the focus of two other workshops this year; these workshops are described below.)

An In-Situ Resource Utilization (ISRU) Workshop was held in conjunction with the conference. Because it would be extremely impractical for astronauts to bring everything they need with them for stays of more than a year on another planet, it is important that the potential uses of resources and materials available in situ, or at the site, be maximized. Examples of ISRU include harvesting breathable oxygen from other atmospheres, recovering minerals from martian soil, and even making fuel for a return trip to Earth from materials found at a spacecraft's destination site. The workshop provided a forum for researchers to evaluate and prioritize materials processing issues in lunar- and martian-type environments. Invited speakers and investigators funded by the microgravity materials science program under the Human Exploration and Development of Space (HEDS) initiative were featured.

One of the two workshops exploring issues related to radiation held during FY 2000 was the Radiation Shielding Materials Workshop, which took place August 8–9, 2000, in Berkeley, California. The focus of this workshop was threefold: to develop a roadmap to bring transport code development for radiation shielding materials to a successful conclusion, to recommend research to be solicited in the next NRA, and to suggest some measures as goals for radiation protection for future missions. The other workshop, Revolutionary Concepts of Radiation Shielding for Human Space Exploration, was held September 18–19, 2000, at Marshall Space Flight Center (MSFC). At this meeting, NASA

Administrator Daniel Goldin was briefed on the findings of an assessment of revolutionary physical sciences radiation protection strategies. Those findings included a breadth of ideas, from revolutionary materials to magnetic fields to hitching rides on asteroids.

Two notable invitations were extended to participants in the microgravity materials science program in FY 2000. In July 2000, Donald Gillies, of MSFC, gave an invited talk at the Gordon Conference on High-Temperature Materials, Processes, and Diagnostics. The presentation covered those high-temperature materials science experiments slated for the International Space Station (ISS). The experiments Gillies discussed covered glasses, metal strengthening, growing electronic crystals, thermophysical property measurement, and transparent analog materials.

Jennifer Lewis, of the University of Illinois, Urbana-Champaign, was invited to write a centennial feature on "Colloidal Processing of Ceramics" for the *Journal of the American Ceramic Society*. The article was published in October 2000 and was featured on the cover of the issue. Lewis is the PI for the experiment Colloidal Stability in Complex Fluids.

Other notable papers published during FY 2000 included "Polarity Effects of Substrate Surface in Homoepitaxial ZnO Film Growth," written by Shen Zhu, of MSFC, et al., which appeared in the *Journal of Crystal Growth*. The paper discusses the effects of two polar surfaces that used zinc oxide single-crystal substrates for homoepitaxial film growth. Another, titled "The Effect of Microgravity on the Growth of Silica Nanostructures," was accepted for publication in *Langmuir*, a journal published by the American Chemical Society. The work represents a collaboration between NASA-funded investigators at Rice University, Lawrence Berkeley National Laboratory, and MSFC.

Flight Experiments

Many materials science experiments slated to be performed aboard the ISS made significant progress toward their goals this year. The materials science discipline will have two primary facilities for conducting experiments on the station: the Microgravity Science Glovebox (MSG), a small, contained unit shared among all the disciplines; and the Materials Science Research Facility (MSRF), a three-rack system that will feature modular, swappable components to increase the facility's versatility.

One of the experiments that will make use of the MSG is Pore Formations and Mobility (PFM), for which Richard Grugel, of MSFC, is the PI. PFM will look at the formation of materials that are directionally solidified (i.e., the melt is "frozen" from one end of the sample to the other) in microgravity. Occasionally this process causes undesirable holes, or pores, in the solid. The experiment will be 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. With a better understanding of this phenomenon, researchers may be able to eliminate the formation of pores in the future. PFM hardware to be used in the glovebox was assessed for readiness in the experiment's design review preboard and then successfully passed functional and procedural validation tests in the MSG ground unit, a duplicate facility that allows reviewers to determine, as much as is possible in a 1-g environment, that the experiment will work once it is in orbit.

Investigators are working to identify the best materials for radiation shielding during long-term space travel and a stay on a planetary base.

Another experiment that will be conducted in the Microgravity Science Glovebox, Solidification Using a Baffle in Sealed Ampoules (SUBSA), also completed its design review preboard this year, and the ground unit to test the experiment was assembled. SUBSA tests the performance of an automatically moving baffle (a plate in the sample container that moves as a result of the expansion and contraction of the sample material melting and freezing) in microgravity to determine the behavior of encapsulated liquids in microgravity and the possible advantages to studying liquids enclosed in such an apparatus. It is hoped that adding the baffle to the directional solidification process will significantly reduce convection that naturally occurs in the melt and result in better-mixed, less-segregated alloy materials at no greater cost than current solidification methods. Aleksander Ostrogorsky, of Rensselaer Polytechnic Institute, is the PI for SUBSA.

The Materials Science Research Facility, a facility that will house microgravity materials science experiments in Destiny, the U.S. laboratory module of the ISS, participated in an ISS facility re-plan review, a process for reassessing the MSRF program to assure that procedures are being implemented appropriately. The MSRF comprises three modular payload racks, called Materials Science Research Racks (MSRRs). The first MSRR (MSRR-1) was granted authority to proceed through its critical design review, as was the Quench Module Insert, an MSFC-developed furnace insert for the MSRR-1. (For more information about the MSRF, see p. 55.)

Two experiments destined eventually for the ISS were flight-tested this year aboard NASA's KC-135 aircraft, an airplane that flies in parabolic trajectories to produce limited periods of microgravity conditions. One experiment tested was Identification and Control of Gravity-Related Defect Formation During Melt Growth of Electro-Optic Single Crystals: Sillenites, headed by August Witt, of the Massachusetts Institute of Technology. Witt took advantage of the microgravity conditions (which lasted less than 20 seconds at a time) to better prepare for long-duration microgravity investigations. The materials Witt is studying have properties that suit them for a wide range of opto-electronic substances and devices, but the inability to control defects in the materials as they solidify impedes the realization of their full potential. The microgravity experiment is intended to help develop processing methods that will enhance the ability to manipulate the structure and properties of the materials.

Designed by students at Auburn University, the Payload Equipment Restraint System holds tools in place for ISS crews.

The other experiment tested aboard the KC-135 was Transient Interfacial Phenomena in Miscible Polymer Systems (TIPMPS), headed by John Pojman, of the University of Southern Mississippi. TIPMPS tested a theoretical model that is almost 100 years old which has yet to be verified. The theory predicts that convection can be induced at the transient interface between miscible fluids, fluids that combine thoroughly when mixed together, through variations in temperature and concentration, causing the miscible fluids to act like immiscible fluids, or fluids that maintain separate phases when combined with each other. If this theory is proven through experiments in microgravity, it may have an effect on how researchers process materials in space.

A modular system of components designed to assist the ISS crew in restraining and transferring payload equipment passed both a safety and a design review. The Payload Equipment Restraint System (PERS) combines straps, mesh pockets, Kevlar, Velcro, and various connecting devices into a system that attaches to the ISS's rack seat track system, preventing tools from "floating" away while astronauts are at work in the microgravity environment of orbit. Although PERS was originally intended to assist crewmembers working at the MSRF, the system, which was designed by students at Auburn University, will now be used throughout the ISS. PERS is currently awaiting deployment on STS-102 (Utility Flight 5A.1).

Science concept reviews were completed for a number of materials science experiments during FY 2000. These experiments, listed below, are now awaiting the panel's formal notice of authority to proceed:

- **Properties of Undercooled Glass-Forming Metallic Alloys**, by William Johnson, of the California Institute of Technology, examines various thermophysical properties of undercooled glass-forming metallic alloys.
- **Transitions in Undercooled Liquid Phases**, by Richard Weber, of Containerless Research, Inc., seeks to expand the knowledge base related to liquid-phase processing of technologically important oxide materials.
- **Gravitational Effects on Distortion in Sintering**, by Randall German, of Pennsylvania State University, examines the role of porosity in liquid phase sintering (the formation of a coherent mass by heating a material without melting it).
- **Transient Dendritic Solidification Experiment***, by Matthew Koss, of Rensselaer Polytechnic Institute, investigates time-dependent dendritic growth.
- **Crystallization of Oxide Melts in Space***, by Delbert Day, of the University of Missouri, Rolla, examines the fundamental issues of why melts in microgravity form glass more easily and why the chemical homogeneity of these glasses is better than that of the glasses made on Earth.
- **Spaceflight Holography Investigation in a Virtual Apparatus***, by James Trolinger, of Metrolaser, Inc., seeks to understand the physics of particle interactions with fluids and other particles in low–Reynolds number flows in microgravity.

**These projects have been recommended to proceed toward requirements definition reviews.*

Highlights

Student Inventor Has It All Sealed Up

While a freshman working on a NASA-funded grant, Andrew Neice, center, received the BF Goodrich Collegiate Inventor of the Year award. Neice is pictured here with James Hillier, left, who served on the selection committee, and William Krantz, co-investigator for the NASA project.

Holes in membranes or films meant to separate different types of materials can cause big problems, allowing substances to penetrate the barrier and get to places they don't belong. Andrew Neice, an undergraduate student working with PI Alan Greenberg on a NASA-funded project at the University of Colorado, Boulder, has found a way to solve those problems, and for his effort, he was chosen as a BF Goodrich Collegiate Inventor of the Year. Neice, one of only three undergraduate students in the country to receive the prestigious award, earned a cash prize and induction into the National Inventors Hall of Fame in Akron, Ohio.

The device and method developed by Neice use a nonuniform electric field to control the pore structure of porous membranes and films. Initial studies indicated that this device could be used to reduce or eliminate macrovoid defects — pinholes — in the material that can undermine the effectiveness of the films for such uses as desalinization of seawater, water treatment, and delivery of pharmaceuticals. A patent for Neice's device was filed by the University of Colorado in June 2000. Negotiations are now taking place with a membrane manufacturer for licensing rights to the invention.

Getting a Charge out of Levitating Materials

Although clinging clothes are the things that most often come to mind when one thinks of static electricity, the phenomenon can be, in fact, an extremely useful tool for the microgravity research program. The Electrostatic Levitator (ESL), a ground-based facility used in the program, makes use of static electricity to suspend samples of material in a vacuum chamber for study. The ESL is a crucial facility for the ground-based microgravity research program, as it allows researchers to examine molten material samples without possible interference by a container.

This technique, also known as containerless processing, has several major advantages for materials scientists. One is that a container may contaminate a pure sample, so being able to process the sample in a containerless environment can be a real boon for researchers. Another advantage is that the processing temperatures necessary for some materials may be so high that only expensive and exotic container materials will suffice; therefore, containerless processing is cheaper and more practical. Finally, with containerless processing, undercooling experiments become possible in which the material is coerced into falling well below its equilibrium freezing point before nucleation can occur. New and exciting structures can be obtained by this means.

Samples of molten materials are studied without the contaminating effects of a container in the Electrostatic Levitator Facility at Marshall Space Flight Center.

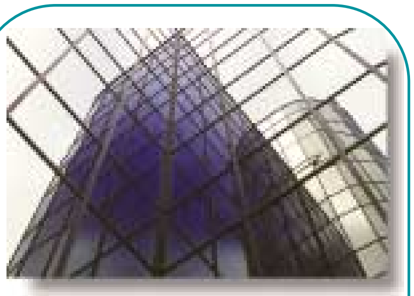
Levitation of sample materials is much easier to accomplish in microgravity, as the amount of energy required is considerably reduced. Nevertheless, the ESL is able to perform many of the experiments previously requiring the containerless environment of the space shuttle. While the problems of gravity-induced convection and sedimentation remain, the ESL can enable many useful measurements of a levitated sample.

In FY 2000, the ESL was upgraded to allow processing of multiple types of material samples by different PIs. One of the experiments performed in the ESL, A Study of the Undercooling Behavior of Immiscible Metal Alloys in the Absence of Crucible-Induced Nucleation, led by PI Michael Robinson, of MSFC, resulted in the publication of a paper titled "High Undercooling of $Ni_{59}Nb_{41}$ Alloy in a Containerless Electrostatic Levitation Facility", by Robinson et al., in the November 13, 2000, issue of *Applied Physics Letters*. Through his work, Robinson has decisively proved that there is no miscibility gap for this composition and that much greater undercooling of this particular alloy is possible.

Taking a New Approach and Reaping the Rewards

Sometimes approaching a tried-and-true technology from an unusual angle can result in undreamed-of improvements to the technology — and benefit the innovative researcher besides. That's exactly what happened as a result of research performed by Reid Cooper, of the University of Wisconsin, Madison, and a former graduate student, Glen Cook, now of Corning, Inc. Cooper and Cook were recently awarded a patent for work done partly under the auspices of a NASA grant. Their invention is a binary alloy liquid metal bath that can be used for the float processing of high–melting temperature glasses.

Float processing is the term used to describe the technique by which almost all glass used in architectural and automotive applications is produced. In float processing, molten silicate glass is poured out onto a large pool of molten tin. The two melts are kept separate as a result of gravity — the tin is much more dense than the glass — and the effects of gravity and interfacial energies result in extremely flat glass. But this technology is nearly a half-century old, and there is room for improvement, as Cooper and Cook found out.



While conducting experiments with a molten material that had a metal and silicate component, researchers hit on an idea for improving the standard method for producing flat sheets of glass used in buildings and automobiles.

The researchers were primarily working on using microgravity to produce very fine-grained ceramics with extremely uniform grain size and structure through the solidification of an inviscid oxide liquid. However, they began their work with a silicate model melt, with the goal of applying the knowledge obtained from the model to the oxide ceramic materials they were ultimately pursuing. An additional benefit to working with the silicate is that the material could illustrate thermodynamic and kinetic processes that were at work in the early stages of the formation of the Sun and the Solar System — a genuine instance of microgravity processing!

In the process of performing reduction experiments on iron oxide–bearing, multicomponent silicate melts, where the equilibrium between the metal and ceramic components is a primary concern, Cooper and Cook surmised that they could articulate a new float processing technique, one in which the float bath used to process the silicate glass is a heavily alloyed metal, rather than the high-purity tin bath typically used by the industry, for better results. One advantage to the alloyed bath is that the process can be performed effectively at much higher temperatures than is currently possible; another is that, with appropriate alloying of the float bath, the glass can be doped with other elements, which may infuse the glass with new electrical or electro-optical properties. Such glasses could be used for the manufacture of flat-panel displays for computer and video markets.

Cooper's present NASA-funded project, Dynamic Reduction and the Creation of Fine-Grained Ceramics From Inviscid Oxide/Silicate Melts, is designed to chemically produce a fine-grained (nanometer-scale), broadly dispersed, metal second phase within low-viscosity ionic melts. The dynamic reduction requires containerless processing to control surface chemistry of the melts and microgravity to avoid segregation of the metal and oxide phases. The structures produced within the suspended silicate droplets in the laboratory are similar to those found in the silicate components of primitive chondritic meteorites.

Here the iron, or metal component, of the molten experiment sample forms crystals on the surface of the silicate component (magnesium aluminosilicate). These results led the science team to explore solidifying glass on top of a heavily alloyed metal.

"Lasing" a New Trail

The Crystal Growth of ZnSe (zinc selenide) experiment, headed by PI Ching-Hua Su, of MSFC, has led to an offshoot of the original project that may prove very useful in medical applications. The discovery by a group at Lawrence Livermore Laboratory that zinc selenide crystals doped with chromium after they are grown make a good mid-infrared (IR) laser material resulted in that group approaching Su and his co-investigators, who include Arnold Burger, of Fisk University, and asking them to grow the chromium-doped zinc selenide from scratch by adding chromium to the crystal growth preparation materials.

New laser capabilities may be provided by this crystal of zinc selenide doped with chromium.

Since infrared light has less energy than visible light, IR lasers could be used for more subtle applications, such as delicate medical surgery, than typical lasers, which emit visible red light. At the moment, however, there is no good IR laser available. If a laser can be developed using chromium-doped zinc selenide that is small, portable, and energy-controllable, the potential for the instrument would be great.

The advantages to pre-doping the zinc selenide with chromium are that there is more control over the structure of the material and that the structure is more uniform, without undesirable defects. The collaboration resulted in Burger presenting a talk titled "The Preparation Conditions of Chromium-Doped ZnSe and Their Effect on the Infrared Luminescence Properties" at the 12th American Conference on Crystal Growth and Epitaxy, held August 13–18, 2000, in Vail, Colorado.

Untangling Undiscovered Complexities in Liquid Phase Sintering

Results from a microgravity experiment in sintering have led a researcher to discover that gas plays more of a role in the process than was believed. Here large pores or holes formed by gases are shown unexpectedly coalescing in the experiment sample.

Items too small and precise for machining are produced by sintering. Microgravity research is contributing to a better understanding of this process on the ground and may lead to improved manufacturing of sintered products.

The manufacture of small, high-precision products, such as precision gears, for example, can pose a number of difficult challenges. The size of the products, the detailed structure, and the required hardness of the items can make simply machining the item impractical. When that is the case, a process called liquid phase sintering is often used to produce the desired material.

In liquid phase sintering, particles of different materials are combined, compacted, heated to high temperatures, and then solidified. The particles generally have two components to them: one component has a very high melting point, like tungsten carbide, and one has a lower melting point. As the material is heated, the particles with the lower melting point turn liquid and seep around the still-solid grains of the other material, acting as a sort of glue to hold the whole thing together. Or at least, that's what was surmised to happen during the sintering process, until PI Randall German, of Pennsylvania State University, began delving into the physical mysteries of this technique.

German heads the experiment Gravitational Effects on Distortion in Sintering. Initially, German was examining the kinetics of liquid phase sintering in order to understand problems that sometimes occurred while using the technique, such as "slumping," a result of gravity causing heavy matter to sink to the bottom of the agglomerated material and distort the shape of the finished product. German used microgravity to suppress gravitational effects that can obscure the physics of sintering, thereby helping to reveal the processes at work in the technique. However, on a closer look, it was discovered that the whole sintering process was much more complex than had been assumed. To the surprise of researchers, when sintering was performed in microgravity, a large number of pores — some very peculiarly shaped — manifested themselves in the solidified material.

The presence of these pores meant that sintering was not just the fairly simple, two-phase (liquid and solid) technique it had been thought; instead, the pores meant that there was also gas present in the material. And that gas had its own effects that were as yet unaccounted for. German is still exploring the physics involved in liquid phase sintering and rewriting the theory behind the process, which has multiple stages. His work will be applied to refining sintering techniques used by the multi-million-dollar powder metallurgy industry. German has published many papers based on his research, including articles in such notable journals as *Metallurgical and Materials Transactions*, *Acta Materialia*, and the *International Journal of Powder Metallurgy*.

A BUNDLE of Science

"Bigger isn't always better" is an adage that scientists and engineers at Marshall Space Flight Center have found to be true when it comes to furnaces used to melt, solidify, and quench materials. The MSFC team has developed an unusually small furnace for conducting spaceflight research. The furnace can be flown singly, if research space on a carrier is limited, or can be bundled in packs of two to eight furnaces, or more, if more space is available. For example, four furnaces can be accommodated in an EXpedite PRocessing of Experiments to Space Station (EXPRESS) rack, a type of rack that is currently being used on the ISS, and an eight-pack can be used in a double rack on a space shuttle SPACEHAB research mission. Volume flexibility, however, is just one advantage the furnace offers.

Called the Bridgman Unidirectional Dendrites in Liquids Experiment, or BUNDLE, the small furnace — only 3.5 inches in diameter — and ancillary equipment melt sample materials, directionally solidify them by moving the samples along a temperature gradient, and quench them with a helium gas. The furnace can reach temperatures of 1,200 ˚C and requires only 250 watts at 1,000 ˚C. The furnace accommodates samples up to 10 millimeters in diameter, which means that four furnaces can be packaged side-by-side in order to process four samples simultaneously. When eight furnaces are bundled together, as many as 80 samples can be processed per 16-day research mission, which is an increased throughput capability over previous spaceflight furnaces. A complete BUNDLE facility includes one or more furnaces, a translation system, a quench system, water cooling, vacuum control, crucibles, an experiment apparatus container, and avionics for system control and data collection.

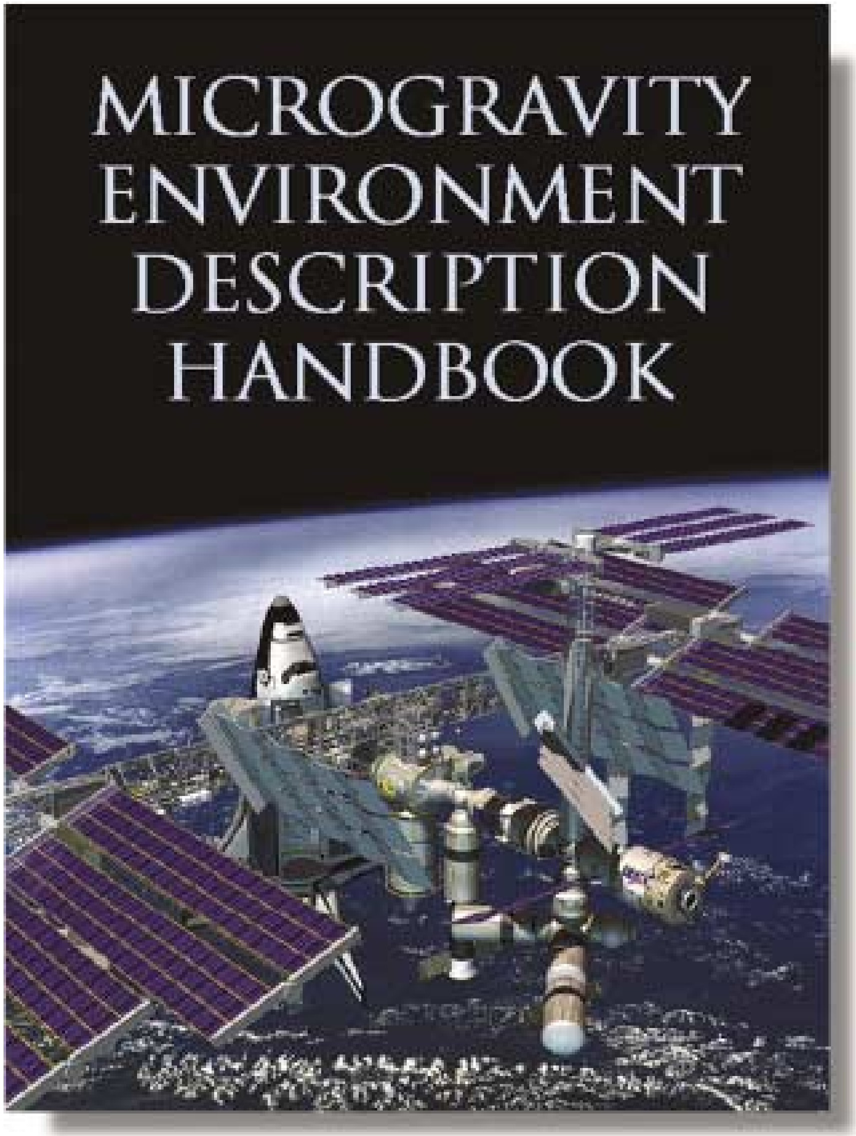
The MSFC team has worked to reduce the cost of the BUNDLE facility by using commercial off-the-shelf parts for its avionics systems and by investigating novel uses of existing technologies for the containers, or crucibles, that hold the samples during processing. This technology has enabled a crucible to withstand the extreme temperature differences in the furnace, in addition to containing a molten sample, thereby providing a safe system that is relatively inexpensive. Low mass, low power consumption, high temperature capability, low cost, and unprecedented flexibility will make the BUNDLE furnace an excellent candidate for many material science investigators. The furnace prototype unit is currently being used and further developed for the research projects of two investigators.

Both experiments are concerned with studying the microstructural development of solidifying metal alloys. Depending on a number of factors, like the temperature of the sample and the speed at which it is cooled, a molten metal alloy will solidify with different microstructures, such as a flat, or planar, structure; a cellular, or finger-like, structure; or a dendritic, or branching, structure. The type of structure dictates the properties of the resulting alloy, so scientists are very concerned with knowing the conditions under which these structures occur and how they make the transition from one structure to another.

Theories predicting how conditions during solidification will affect microstructure generally assume no flow in the melt. In practice on Earth, however, the picture is much more complicated because gravity usually promotes fluid flow in the liquid due to the development of unstable density gradients. This in turn causes segregation and poor material properties. In microgravity, flow due to gravity, or buoyancy-induced convection, is greatly reduced, providing researchers with an opportunity to test theories that predict structure. Refinement of such theories could lead to improved processing techniques for alloys that are commonly cast and used on Earth in products such as turbine blades.

Rohit Trivedi, of Iowa State University, and David Poirier, of the University of Arizona, are the two NASA investigators for whom the BUNDLE furnace was originally designed. They will be the first researchers to use the furnace when the flight version is ready and manifested on a spaceflight mission. Trivedi is interested in accurately defining the conditions for a cellular structure in aluminum-copper alloys, which are commonly used in industry. Poirier is working to understand the relationship between processing parameters and the morphology of dendritic microstructures in lead-tin alloys, materials that are easy to work with and have been used to model solidification processes in the past. Both researchers have had success processing samples of their research alloys in the ground unit of the BUNDLE furnace at MSFC and will use these results to further refine their spaceflight goals and for future comparison to their future spaceflight results.

A four-pack BUNDLE facility will be online for the processing of multiple samples in fall 2001.



Helping researchers understand the microgravity environment and the impact of accelerations on microgravity science experiments is the goal of the acceleration measurement program.

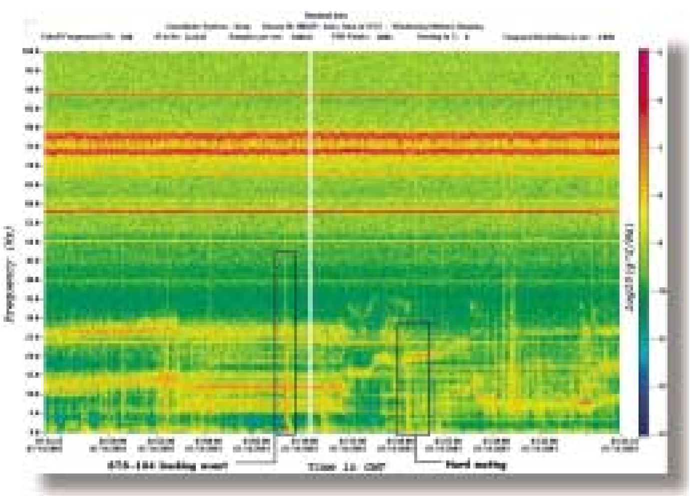
Variations in the quality of a microgravity environment can have an adverse effect on experiment results. Sometimes the very tools that enable an experiment to be conducted in microgravity can be responsible for these variations. Experiment hardware, crewmembers, and even the flight vehicle itself can 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. The Orbital Acceleration Research Experiment (OARE) and its second-generation unit, the Microgravity Acceleration Measurement System (MAMS), measure the microgravity environment for low-frequency accelerations. The Space Acceleration Measurement System (SAMS) measures higher-frequency accelerations (up to 300 hertz). Second-generation SAMS units, (originally called SAMS-II, but now known simply as SAMS units) were developed to improve upon the original SAMS technology, making it more compact and more easily adaptable to a variety of experiment needs; to that end, these second-generation units will support experiments and facilities on the ISS. SAMS for Free-Flyers (SAMS-FF) was developed to measure the microgravity environment aboard sounding rockets. In fiscal year (FY) 2000, the management of all of the acceleration measurement devices was consolidated into one project.



A sample color spectrogram of acceleration data obtained during a shuttle docking with the space station.

With an emphasis on providing critical support to PIs and other Microgravity Research Program (MRP) participants, such as vibration isolation programs, the Principal Investigator Microgravity Services (PIMS) project processes, interprets, and analyzes accelerometer data. The information collected and produced by the acceleration measurement program is made available through the PIMS project in mission summary reports, data files on CD-ROM and on Internet file servers, and specialized analysis reports for PIs, scientists, and the ISS program.

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 third consecutive year, the acceleration measurement program offered its tutorial to PIs and project scientists in the MRP during a three-day session in Cleveland, Ohio, December 7–9, 1999. The tutorial 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 on microgravity experiments. A 500-page reference book provided participants with a guide to maximizing the success of their microgravity research.

In addition to the tutorial, the acceleration measurement program also held its 19th International Microgravity Measurements Group meeting July 11–13, 2000, in Cleveland. 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 microgravity science disciplines and to other ISS program participants. Proceedings from the meeting were made available on CD-ROM.

Flight Support

SAMS-FF

SAMS-FF is a compact system consisting of a small triaxial sensor head connected to a portable computer. The flexible modular design and the integration of commercial, off-the-shelf parts have dramatically reduced the cost and size of the unit and have increased the performance of the system. The hardware can be easily adapted to the requirements of an individual experiment. Presently, the system is manifested for flights on the KC-135 parabolic aircraft, on sounding rockets, on the space shuttle, and on the ISS. The system is also capable of performing ground characterizations of a wide range of environments.

In FY 2000, the SAMS-FF team developed the Parabolic Aircraft Rating System for use by researchers and flight crew on the KC-135. The system uses the SAMS-FF sensor head and control computer. Custom-designed software produces a real-time display of the relative g-level of each low-gravity trajectory. The raw data is displayed on a laptop computer and compared to a database to rate each parabola on a scale of 1 to 10. After each parabola, the rating is immediately made available to investigators as an indication of the duration and level of low gravity. The SAMS-FF team will be working with Johnson Space Center to make the system a permanent part of the KC-135.

SAMS-FF also supported two experiments conducted on sounding rockets. SAMS-FF measured the microgravity environment during the low-gravity portion of the flight of the Pool Boiling Experiment on a Terrior-Orion sounding rocket in December 1999. SAMS-FF provided data on vibrations and vehicle dynamics using the fiber-optic gyroscope roll-rate sensor system and was instrumental in testing the sounding rocket due to the sensors' ability to provide high resolution and low noise. The SAMS-FF team also delivered an acceleration measurement system for the Spread Across Liquids-6 experiment, which is scheduled to fly on a sounding rocket in February 2001. During development of the hardware for the sounding rocket flight, SAMS-FF also supported the experiment in a free-floating rig, which was flown on the KC-135 aircraft.

Space shuttle mission STS-107, which is scheduled for launch in late 2001, will include a SAMS-FF system to support the Combustion Module-2 (CM-2) and the Mechanics of Granular Materials experiments. The unit will feature three sensor heads and a fiber-optic gyroscope roll-rate sensor system. In FY 2000, SAMS-FF was modified to allow data to be downlinked and viewed by the CM-2 team during the mission. An OARE system, which is designed to measure very low–frequency accelerations, will also be flown in support of the STS-107 flight.

SAMS and MAMS

The acceleration measurement program prepared SAMS and MAMS units to support ISS payloads beginning in the spring of 2001, when access to microgravity conditions for science experiments is expected to be available. SAMS for the ISS is a redesign of the original SAMS unit (built for the space shuttle), featuring an enhanced design that utilizes ISS capabilities and optimizes the size of the unit and the use of off-the-shelf, readily available components. MAMS, which was designed to verify that the ISS produces a microgravity environment in accordance with ISS program requirements, comprises independent high-frequency and quasisteady (low-frequency) sensor subsystems.

Preparations for launch of the SAMS unit aboard ISS assembly flight 6A included building training and flight versions of the Interim Control Unit and sensor head rack drawers, completion of verification testing, and training of the SAMS operation team. SAMS flight equipment was also delivered to Kennedy Space Center (KSC), where it was successfully tested. The PIMS team verified that acceleration data flowed from the SAMS unit as planned. Subsystems necessary for the integration of science experiments with acceleration measurement hardware were provided to investigators whose research will be part of the flight 6A payload.

In FY 2000, MAMS was delivered to KSC, where testing was completed in preparation for its launch, along with the SAMS unit, on assembly flight 6A. In September 2000, MAMS participated in the U.S. laboratory module's

MAMS installation into an Expedite Processing of Experiments to Space Station rack for launch to the International Space Station.

(Destiny's) Integrated Compatibility Test and was one of the first systems to send data through the laboratory during the test. MAMS testing was completed in December 2000, and the unit was turned over for integration into the Multi-Purpose Logistics Module built by the Italian space agency.

PIMS also continued its preparations for measuring accelerations on the ISS. Under development in FY 2000 were specialized software tools to allow for both real-time and offline analysis of acceleration data received from SAMS and MAMS. The software enables the generation of real-time acceleration data plots that will be distributed to the microgravity science community via the Internet. The software also generates SAMS and MAMS acceleration data archives. Offline processing tools will enable the creation of data plots and acceleration data files for time periods specified by the researcher.

Highlights

New Insights on the Growth of Bacteria in Space

Accelerations that change the quality of the microgravity environment may be having an effect on how bacteria grow and on the effectiveness of antibiotics in space. Emily Nelson, of the Computational Microgravity Laboratory at Glenn Research Center (GRC); Margaret Juergensmeyer, of the University of Montana; and Elizabeth Juergensmeyer, of Judson College, presented new information about the response of bacteria to the microgravity environment at the 19th International Microgravity Measurements Group Meeting. The notions that bacteria in space show a higher rate of proliferation and become more resistant to antibiotics than bacteria on Earth are widely accepted. However, a careful and comprehensive reading of literature published on the subject reveals that bacterial proliferation and antibiotic resistance may increase, decrease, or remain the same in space as on Earth. The response of the bacteria is a function of a multitude of environmental factors, including temperature, the presence of nutrients, the duration of the experiment, and the type of microbe examined. The researchers expect that residual acceleration is also a factor in some experiments. Although this theory has never been directly tested, it suggests new avenues for research.

A Unique Laboratory Helps Ensure Experiment Success

The driver of a well-engineered car knows that even the most finely tuned devices can produce subtle vibrations during use that can spoil a perfect ride. But what if your car is a space station and the passenger is a science experiment that requires an environment as free from vibrations as possible in order to return useful results? Helping researchers and engineers assess the vibrations produced by mechanized experiment components is the job of the new Microgravity Emissions Laboratory (MEL), developed by GRC.

The 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. If too large, these emissions could adversely affect science performed on the ISS by disrupting the microgravity environment. The MEL became fully operational in November 1999, and since then, approximately two tests per month have been conducted in the laboratory. In FY 2000, the MEL lent its support to the Fluids and Combustion Facility for the ISS and to other project offices at GRC.

The Microgravity Emissions Laboratory (MEL) aids researchers in assessing the vibrations produced by mechanized equipment. Pictured here is the MEL accelerometer platform.

Conducting research aboard the ISS will enable world-class scientists from a variety of discreet 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 International Space Station (ISS) provides researchers with a permanent orbiting laboratory in space in which to conduct experiments 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 discreet 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 microgravity program will contribute enormously to these discoveries through the development of science experiments that can benefit from the unique environment that the ISS provides and through the application of knowledge gained about the microgravity environment to exploration initiatives planned by NASA. To that end, the Microgravity Research Program has designed five 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 Fluids and Combustion Facility (FCF), the Low-Temperature Microgravity Physics Facility (LTMPF), the Materials Science Research Facility (MSRF), and the Microgravity Science Glovebox (MSG). Their descriptions appear below.

Space Station Facilities for Microgravity Research

BTF

The BTF, which is in the planning stages at Johnson Space Center, is designed to meet the requirements of the science community for conducting low-gravity, long-duration biotechnology experiments. The facility is intended to serve the community of 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 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. Capable of processing 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 *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.

Biotechnology research during the early phases of the ISS will be conducted using a modular accommodations rack system know as the Expedite Processing of Experiments to Space Station (EXPRESS) rack. The EXPRESS rack requires individual payloads to develop additional capabilities and involves science implementation trade-offs. The EXPRESS rack will hold currently existing 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. The BTF is targeted to be operational in 2005.

FCF

The FCF is a modular, multiuser facility that will be located in the U.S. Laboratory Module of the ISS to accommodate sustained, systematic microgravity experimentation in both the fluid physics and combustion science disciplines. The FCF flight segment consists of three powered racks called the Combustion Integrated Rack (CIR), the Fluids Integrated Rack (FIR), and the Shared Accommodations Rack (SAR). These FCF racks will be incrementally deployed to the ISS, and then fully integrated into the FCF system upon the arrival of the SAR. The three racks will operate together with payload experiment equipment, ground-based operations facilities, and the FCF ground segment to perform fluid physics and combustion science experiments. The facility will also support experiments from other science disciplines and commercial and international investigations.

The FCF is being developed at Glenn Research Center (GRC) in Cleveland, Ohio. A contract called the Microgravity Research Development and Operations Contract was initiated by GRC in FY 2000 for primary development of the FCF by Logicon Northrup Grumman, who will also develop, integrate, and support the operation of the initial FCF combustion science and fluid physics payloads, including the Multiuser Droplet Combustion Apparatus and the Light Microscopy Module. Preparations for a system-level preliminary design review of the FCF were made in FY 2000, including completion of performance and environmental testing of key FCF common subsystem hardware. The NASA Continuous Improvement Award was conferred on the FCF project team for continuous improvements to the design of the FCF and excellence in the team's efforts to develop a premier facility for the ISS.

LTMPF

The LTMPF project completed a successful year in which the Mission 1 instrument preliminary design review and Mission 2 science concept review were successfully held and two of the three Mission 2 instruments were granted authority to proceed. The facility peer design review (PDR) was held in July 2000 to support the system PDR in December. Because the proposed facility budget was above the guidelines, the project was given direction to evaluate alternative methods of implementation and report back with a new plan early in calendar year 2001.

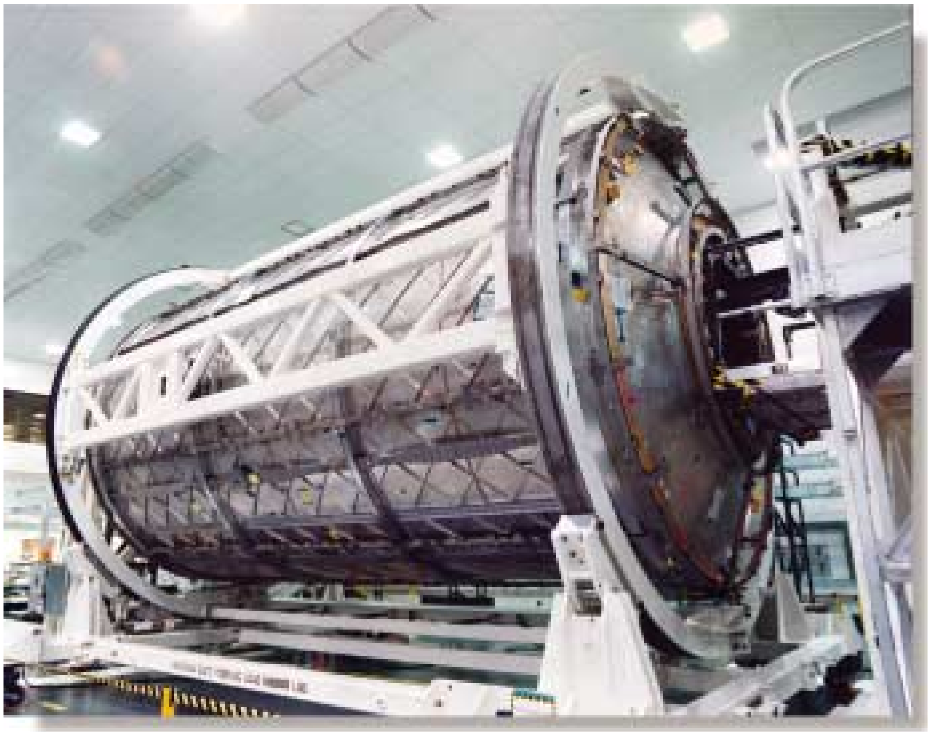
Trade studies continued in 2000 and have resulted in the selection of a facility that supports two instruments, one in each end of the facility in separate vacuum spaces. The configuration of the LTMPF remains a single dewar with two instruments per mission. The design work this year resulted in the design and fabrication of a protoflight truss probe that has been successfully qualified to meet protoflight launch loads and thermal isolation requirements for the instruments. Flight-like components were also qualified for instruments that will be used by three of the selected principal investigators who will conduct their experiments in the LTMPF. A single-board computer and Ethernet controllers were radiation tested to levels derived from ISS specifications. LTMPF software was coded and tested with an ISS-provided portable tester. Prototype measurement and control electronics for Germanium Resistance Thermometers were tested and shown to meet LTMPF requirements. A leading circuit design for a Superconducting Quantum Interference Device was also tested with flight-like high-resolution thermometers provided by the investigators.

Manifest changes have moved the LTMPF proposed launch from June 2004 to April 2005.

MSRF

The MSRF is being developed to provide a flexible, permanent platform in the U.S. Laboratory for conducting experiments in materials science. The modularity of the MSRF will satisfy the requirements of the majority of materials science investigations and will enable the development of experiment modules specifically suited for individual classes of materials, thereby avoiding the development and deployment of redundant supporting systems. The MSRF will also incorporate technology improvements through phased rack and hardware deployment and will employ common designs in the follow-on racks and experiment modules in order to optimize flexibility and accommodation of the various multidiscipline and materials science themes, along with new initiatives in development in the NASA microgravity program. The MSRF is being developed to promote international cooperation and provide the most cost-effective and productive near-term and long-range approaches to performing science investigations in the microgravity environment on the ISS.

The modular facility comprises autonomous Materials Science Research Racks (MSRRs). The initial MSRF concept consists of three MSRRs (MSRR-1, MSRR-2, and MSRR-3), which will be developed for phased deployment beginning on the third Utilization Flight (UF-3). Each MSRR will be composed of either on-orbit replaceable experiment modules; module inserts; investigation-unique apparatus; and/or multiuser, generic processing apparatus. The ISS Active Rack Isolation System will be employed in the MSRRs to reduce the detrimental effects of vibrations on the station. The MSRRs will support a wide range of materials science themes, allowing the MSRF to support investigations in basic and applied research in the fields of solidification of metals and alloys, thermophysical properties, polymers, crystal growth of semiconductor materials, and ceramics and glasses, as well as new multidiscipline initiatives planned by NASA.



Experiments funded by the Microgravity Research Program will be conducted in five specialized facilities in the U.S. Laboratory Module of the space station. Shown here under construction, the U.S. Laboratory module is 28 feet long and 14 feet in diameter. The lab consists of three cylindrical sections and two endcones with hatches to allow it to be mated to other space station components.

The first experiment module planned for MSRR-1 is currently being developed by NASA and European Space Agency (ESA). This module, called the Materials Science Laboratory (MSL), will incorporate several processing devices, or module inserts. This first materials science payload will be integrated into an International Standard Payload Rack, which will initially be shared with a NASA Commercial Payload, the Space Experiment Facility (SEF) experiment module. Following completion of its on-orbit research activities, the SEF will be replaced with a follow-on materials science experiment module.

NASA is currently developing the Quench Module Insert (QMI) and the Diffusion Module Insert (DMI) for the MSL. The QMI is a high-temperature Bridgman-type furnace with an actively cooled cold zone. The QMI is being designed to accommodate a rapid quenching capability. The DMI is a Bridgman-type furnace insert designed to accommodate processing temperatures up to 1,600 °C. The requirements for this insert include precise control and the ability to operate in a mode with high isothermality. ESA is currently developing the Low Gradient Furnace (LGF) and Solidification Quench Furnace (SQF) module inserts. The LGF is a Bridgman-Stockbarger furnace and is primarily intended for crystal growth experiments, providing for directional solidification processing with precise temperature and translational control. The SQF is being optimized for metallurgical experiments requiring large thermal gradients and rapid quenching of samples. Both of the ESA module inserts can accommodate processing temperatures up to 1,600 °C. Additional module inserts can be developed and utilized over the lifetime of the MSL.

MSRR-2 and MSRR-3 rack configurations will be consistent with ongoing reference experiment studies and rack architectural studies currently being conducted at Marshall Space Flight Center. These racks will have optimum flexibility for on-orbit maintenance and change-out of key components. They will be designed to accommodate the cadre of current materials science investigations and future NASA Research Announcement selections through the use of a variety of on-orbit, replaceable, investigation-unique experiment modules. The racks will also be capable of accommodating experiment modules developed by space station international partners in addition to apparatus supporting multidisciplinary research. MSRR-2 will support the first of the follow-on experiment modules and will incorporate new technology and enable automated operations. Its anticipated launch readiness date is mid-2005. MSRR-3's anticipated launch readiness date is in late 2007. Several experiment modules to accommodate science investigations on MSRR-2 and MSRR-3 are currently in concept definition.

In FY 2000, the MSRF participated in an ISS facility replan review, a process for reassessing the MSRF program and assuring that procedures are being implemented appropriately. The Program Management Council granted authority for the first MSRR to proceed through its critical design review. The QMI underwent its critical design review.

MSG

The MSG is a multidisciplinary facility for small, low-cost, rapid-response scientific and technological investigations in the areas of biotechnology, combustion science, fluid physics, fundamental physics, and materials science. It allows preliminary data to be collected and analyzed prior to any major investment in sophisticated scientific and technological instrumentation. Additionally, its enclosed working volume offers a safe interface between investigations of potentially hazardous materials and space station crewmembers and the environment of the space station. NASA's previous successes with gloveboxes flown on the space shuttle and on *Mir* provided valuable experience in determining the requirements for the MSG.

The MSG is being developed through an international agreement between NASA and ESA. In exchange for developing the MSG, the agreement provides ESA with early utilization opportunities in the facility without any exchange of funds between the two agencies. ESA's prime contractor for the MSG is Astrium.

Schedule of Flights

Approximately 18 flight opportunities have been planned to date for the delivery of the U.S. Laboratory and its components (including the microgravity facilities described above), the utilization of the space station for microgravity experiments, the delivery of modules and racks developed by NASA and its international partners, and the delivery of the crew habitation module that will provide living quarters for the ISS crew. A list of milestones, flights, and dates significant to the microgravity program are listed below. Descriptions of flight hardware to support microgravity experiments are listed in Appendix B.

Table 9 — ISS Flights Significant to the Microgravity Program

Milestone	Flight	Launch Date*
U.S. Laboratory Delivery	STS-98	February 2001
U.S. Laboratory Outfitting	STS-102	March 2001
First two EXPRESS Racks, Microgravity Capability	STS-100	April 2001
Phase Two Complete	STS-104	June 2001
U.S. Laboratory Outfitting, Two Additional Express Racks	STS-105	June 2001
Utilization Flight	STS-109	October 2001
Utilization Flight, Fifth EXPRESS Rack, and MSG Rack	STS-111	February 2002
First Utilization Logistics Flight	STS-114	June 2002
Spacehab Flight, Continued U.S. Laboratory Outfitting	STS-119	January 2003
Spacehab Flight, Continued U.S. Laboratory Outfitting	STS-122	June 2003
Utilization Flight, External AMS Facility	STS-123	October 2003
Japanese Experiment Module (JEM) Laboratory Delivery	STS-127	May 2004
Utilization Flight, Combustion Integrated Rack (CIR), and First Materials Science Research Rack (MSRR-1)	STS-130	September 2004
European Space Agency (ESA) Laboratory Delivery	STS-131	October 2004
Delivery of External Facility of the JEM	STS-133	January 2005
Delivery of Fluids Integrated Rack (FIR), Sixth and Seventh EXPRESS Racks, and First External Pallet	STS-134	February 2005
Delivery of Fluids and Combustion Shared Accommodations Rack, Eighth and last EXPRESS Rack and Third External Pallet	STS-136	June 2005
Delivery of Crew Habitation Module	STS-138	September 2005
Biotechnology Facility, MSRR-2, MSRR-3, and X-Ray Crystallography Facility		Post 2005

* Launch dates subject to change

In fiscal year (FY) 2000, NASA continued to maintain very productive ground facilities for reduced-gravity research. These facilities included KC-135 parabolic flight aircraft, a 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.

JSC's KC-135 is NASA's primary aircraft for ground-based reduced-gravity research. 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 approximately 6,000 feet is experienced. More than 50 parabolas can be performed in a single flight. In FY 2000, 38 experiments were performed during 1,828 trajectories during 94 flight hours.

Each parabolic maneuver performed by the KC-135 aircraft gives researchers 18–25 seconds of low-gravity conditions. Here, researchers carefully release their experiment rig in the freefall environment.

Table 10 — Use of Ground-Based Low-Gravity Facilities in FY 2000			
	KC-135	2.2-Second Drop Tower	Zero Gravity Research Facility
Number of investigations supported	38	33	6
Number of drops or trajectories	1,828	1,023	106
Number of flight hours	94	N/A	N/A

The GRC 2.2-Second Drop Tower offers a shorter test time than the KC-135, but its simple mode of operation and a throughput capacity of several 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 20,000 tests have been performed in the drop tower to date. In FY 2000, 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 in an enclosure known as a drag shield to isolate the test hardware from aerodynamic drag during a 24-meter freefall in an open environment. Thirty-three experiments were supported during the 1,023 drops performed in FY 2000. 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.

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 underground.

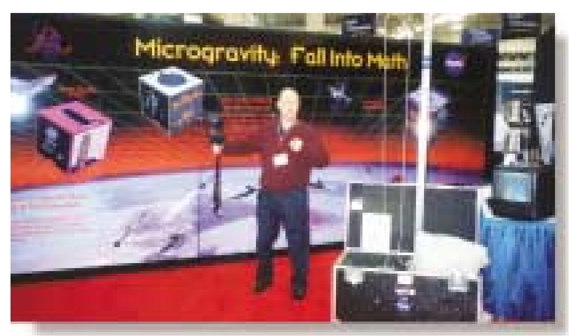
Aerodynamic drag on the freely falling experiment is nearly eliminated by dropping in a vacuum. This procedure restricts drop tests to two per day, resulting in fewer projects supported in this facility than in the 2.2-Second Drop Tower. However, the relatively long test time and excellent low-gravity conditions more than compensate for the lower test throughput rate. In FY 2000, six major projects were supported as 106 test drops were executed.

These photos show an experiment being decelerated after falling 132 meters during 5.18 seconds of low gravity.

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 Microgravity Research Program's (MRP's) 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.

Methods for communicating the substance of the program are as varied as the audience 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 MRP to reach a worldwide audience.

Entranced youngsters watch a demonstration showing how undercooled metal alloys are more resilient than conventional metal alloys. The demonstration was part of an exhibit on the benefits of space research at AirVenture 2000 in Oshkosh, Wisconsin.



More than 400 employees of Marshall Space Flight Center have participated in Project LASER (Learning About Science, Engineering, and Research), which provides mentors, education tours, classroom presentations, and curriculum development to teachers and students in and around Huntsville, Alabama.

Program Summary

At the April 2000 conference of the National Council of Teachers of Mathematics, held in Chicago, Illinois, Jimmy Grisham of Marshall Space Flight Center demonstrates to a teacher the classroom-size Microgravity Drop Tower Demonstrator.

In fiscal year (FY) 2000, more than 50,000 elementary and secondary school teachers and administrators attended annual national and regional meetings of the National Science Teachers Association, the National Council of Teachers of Mathematics, the International Technology Education Association, and the National Association of Biology Education, all of which featured booths staffed by MRP personnel. These major national educator conferences give NASA the opportunity to demonstrate new ways to teach students about the importance of microgravity research. 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.

Several new microgravity education products were developed and made available to educators in FY 2000. Two NASA educational guides were developed — *Microgravity: Earth and Space* and *NASA's Student Glovebox: An Inquiry-Based Educator's Guide*. Efforts were increased in FY 2000 to make educators aware of all the microgravity research education products that are available online through MRP WWW pages, NASA Spacelink, and the NASA CORE (Central Operation of Resources for Educators) education distribution system.

Cover of *Microgravity News* Winter 1999 issue.

The MRP's quarterly newsletter, *Microgravity News*, continues to reach thousands of K–12 teachers, curriculum supervisors, science writers, university faculty, graduate students, scientists, principal investigators, and technology developers. *Microgravity News* features articles on experiment results, flight missions, science and technology developments, research funding opportunities, meetings, collaborations, and profiles of microgravity science researchers. The distribution for each issue is about 11,000 copies. A rise has been seen in the number of individuals requesting to be added to the mailing list via e-mail submission to the address *microgravitynews@msfc.nasa.gov.* The newsletter is available on the WWW at *http://mgnews.msfc. nasa.gov*.

The Microgravity Research Program Office's (MRPO's) web page at *http://microgravity.nasa.gov* provides news highlights, information about upcoming conferences, microgravity-related research announcements, enhanced links to microgravity research centers and projects, educational links, and links to the microgravity image archive. The Microgravity Research Results web site at *http://mgnews/msfc.nasa.gov/site/resindex.html* features reviews of several benchmark microgravity flight experiments. A list of important microgravity WWW sites is presented on p.65.

The World Wide Web continues to be an important distribution method for the MRP's outreach and education products. Table 11 lists several K–12 microgravity education products and the number of separate "downloads" for each of these products in FY 2000. This number is considered a more accurate accounting of actual product use than the frequently used "hits," because it indicates those users who downloaded the printer description files (PDFs) to their computers.

Table 11 - Microgravity Outreach Education Products downloaded in FY 2000

Month	Microgravity Teacher's Guide	The Mathematics of Microgravity	Microgravity Video Resource Guide	Microgravity Demonstrator	Microgravity — Fall Into Mathematics
10/99	24,344	345	45	153	273
11/99	1,976	288	50	148	241
12/99	6,821	227	32	100	215
1/00	5,728	322	58	109	276
2/00	11,284	352	65	196	335
3/00	10,857	324	34	165	281
4/00	4,492	383	46	121	280
5/00	10,396	334	70	160	284
6/00	1,355	269	61	131	230
7/00	5,527	324	25	135	278
8/00	3,302	276	63	122	435
9/00	11,443	219	43	138	531
Total	97,525	3,663	592	1,678	3,659

Highlights

Students Get Their Hands on Science

This year students had several opportunities to get hands-on microgravity science experience. Students from middle and high schools across the nation helped with preparations for the Enhanced Gaseous Nitrogen Dewar, the first long-duration experiment conducted onboard the International Space Station (ISS). The experiment is designed to allow many protein samples to crystallize in orbit with very few demands on power or crew time. Proteins often form well-ordered crystals in microgravity, allowing scientists a better view of an individual protein's structure. Such information may be used by pharmaceutical companies to design more effective drugs and by scientists who are studying the physics of crystallization.

Student participation in the program began with kits that guided teachers and students through growing protein crystals in their classrooms. This activity was supported with 22 workshops for training teachers in the use of the kits. The workshops were sponsored by the MRPO at Marshall Space Flight Center (MSFC). Following the classroom activity, students entered a competition to be selected to attend another workshop, which included tours of structural biology laboratories and companies where they were introduced to the uses of the information protein crystals can yield. The students then spent a day preparing and loading samples for the space station experiment.

The process of preparing samples for the experiment is fairly simple. Set amounts of protein and precipitant (solution that draws the water from the liquid protein sample) are flash-frozen in a narrow piece of tubing and then placed in the dewar, or Thermos-like container. When the dewar reaches the station, the samples thaw, allowing mixing and thus crystallization to begin.

Thirteen sample preparation workshops were sponsored by the MRPO. Students and teachers from Alabama, California, Florida, and Tennessee helped ready the biological samples for flight. The students prepared 150 samples of 500 different proteins, which were all loaded into a dewar that was carried by the STS-106 space shuttle flight to the ISS in September 2000.

This year high school students also had the opportunity to compete for experiment time in a NASA drop tower. Glenn Research Center (GRC) sponsored the competition, which was called Dropping in a Microgravity Environment. Students were invited to develop concepts for a microgravity experiment and prepare and submit an experiment proposal for review and selection for conduct in Glenn's drop tower. A team of NASA scientists and engineers will evaluate the proposals, and the top five proposals will be selected. The five teams will complete the design of their experiment, fabricate the experimental apparatus, and visit GRC to operate their experiments in the 2.2-Second Drop Tower.

Web Outreach

In FY 2000, students, teachers, and the general public connected with researchers in the microgravity program in two new ways. Craig Kundrot, a biophysicist at MSFC, chatted online with students from more than 20 schools across the nation as part of MSFC's "Ask a Scientist" program. "Ask a Scientist" and its sister program "Ask an Astronaut," linked MSFC and more than two dozen middle and high school classrooms nationwide via live Internet voice feeds for interviews with NASA astronauts, scientists, and engineers.

These high school students are screening crystals of various proteins that are part of the ground-based work that supports the Enhanced Nitrogen Dewar experiment, conducted on the International Space Station.

Students and other visitors to a new web site called “Profiles of Women in Microgravity” also gained insight into the careers and accomplishments of successful researchers and engineers in the microgravity program. The web page features eight profiles in which female scientists and engineers share their inspirations, paths to achievement, and advice to young women.

The women profiled have made remarkable progress in fields long occupied mostly by men, but their successes stand on their own. For instance, research conducted by Sandra Olsen, of Glenn Research Center, led NASA to re-evaluate and revise the response procedures to fires on spacecraft, improving safety aboard the space shuttles and the International Space Station for both the crew and equipment. Chiaki Mukai, of NASDA, the national space agency of Japan, is also featured on the site. Mukai is a highly published and honored medical doctor who flew on two space shuttle missions as a payload specialist.

The researchers’ areas of expertise include biochemistry, biotechnology, combustion science, engineering, fluid physics, fundamental physics, materials science, and medical research.

Teaching the Teachers

A new microgravity education product is making a hit with teachers. With an old copier paper box and *NASA Student Glovebox*, an inquiry-based technology educator’s guide, teachers are introducing students to an important tool for conducting science experiments in space. The guide gives instructions for assembling a glovebox out of a paper box, provides information about glovebox parts and their functions, and contains an inquiry-based activity. At the annual Science Educators Council of Ohio conference in February 2000, a science facilitator for the Columbus, Ohio, public schools participated in a session on creating a glovebox using the educator’s guide. The facilitator then requested 50 copies of the guide from the National Center for Microgravity Research on Fluids and Combustion (NCMRFC), the developer of the product, so that the activity could be incorporated in the science curriculum for eighth-graders in the district.

NASA Student Glovebox was one of three NASA guides featured at the annual Microgravity Training Day held on April 25, 2000, in Cleveland, Ohio. This year’s training included workshops in the use of the glovebox guide, the *Microgravity* Teacher’s Guide, and *How High Is It?*, a new math education guide related to the space program that was also developed by NCMRFC. One hundred fifty directors from the Educator Resource Center Network and the Technology Program at various NASA centers participated. The directors will train hundreds of educators in their regions through summer workshops. The training day was part of a week-long conference sponsored by both NASA headquarters and Glenn Research Center’s Office of Education. The location of the conference rotates among NASA field centers. The three guides may be downloaded from the World Wide Web at *http://spacelink.nasa.gov/ Instructional.Materials/NASA.Educational.Products/.index.html*.

Thomas Turk, an engineer at Glenn Research Center, waits for more visitors at a mockup of the Destiny laboratory module that was exhibited at AirVenture 2000 in Oshkosh, Wisconsin. Visible behind Turk are three racks that will make up the Fluids and Combustion Facility.

Teachers also learned about the benefits of the microgravity environment during NASA Educational Workshops held in the summer of 2000 at GRC and MSFC. The sessions, designed for kindergarten through sixth-grade teachers, provided a three-hour introduction to gravity, the effects of gravity, and microgravity. The sessions were sponsored by NCMRFC and the MRPO.

At Experience 2000, a partnership project of NASA held at Johnson Space Center, four research scientists from the microgravity cellular biotechnology program gave a talk titled “Life in Microgravity: View From the Units of Life — Cells.” Space biology and the use of NASA’s bioreactors in both ground- and space-based research were discussed with members of the Life Sciences Educator Network and the Life Sciences Museum Network. This event provided an opportunity to translate NASA science into classroom activities and museum projects and programs.

Going Public

The microgravity program strives to share with the public the goals, progress, and results of microgravity research. To this end, the program sponsors and supports numerous exhibits at national events and at NASA center open houses.

Richard DeLombard of Glenn Research Center hands to an AirVenture 2000 visitor the release line of a microgravity combustion experiment demonstrator, which shows the effects of microgravity on candle flames.

Glenn Research Center's Microgravity Science Division organized and hosted the Microgravity Science, Space Product Development, and International Space Station exhibit at AirVenture 2000 in Oshkosh, Wisconsin. More than 700,000 attendees and more than 10,000 aircraft participated in this 48th annual event. Personnel from GRC and MSFC exhibited the ISS U.S. laboratory mockup with the Fluids and Combustion Facility racks; the ISS Microgravity Science Glovebox; an ISS scale model; a microgravity materials science display; several Space Product Development exhibits, including two from the University of Wisconsin; a large model of the space shuttle; and a three-dimensional video booth featuring the Fluids and Combustion Facility. About 50 volunteers from GRC, MSFC, and the Wisconsin Commercial Space Center participated to make this activity a huge success.

The 2000 Houston Livestock Show and Rodeo, which features the world's largest and highest-paying regular season rodeo, the world's largest livestock show, and a world-class horse show and educational exhibits, also included an exhibit sponsored by the microgravity cellular biotechnology program as part of the Johnson Space Center displays. Nearly two million visitors attended the event held February 18–March 5, 2000, where they had the opportunity to view and learn about the program's space bioreactor, a device for growing cells in microgravity. A video featuring bioreactor experiments during the space shuttle mission STS-70 and posters explaining other program hardware and cell science and tissue engineering projects were also on display. The Houston Livestock Show and Rodeo is a charitable event, committed to benefiting youth and supporting education throughout Texas.

The demonstrations at the booths for Fundamental Physics in Space were again a popular venue with the thousands of visitors to Jet Propulsion Laboratory's 2000 Open House in Pasadena, California. Visitors gathered to see the effects of reduced gravity at the drop tower, and they were shown the extraordinary sensitivity of superconducting instruments.

Demonstrators explained why investigators in the microgravity program can improve their measurement results enormously by performing their experiments in orbit. The research topics studied by the investigators in the fundamental physics program were illustrated, and models of the facilities used to support the experiments on the ISS were shown. More than 20 volunteers supported this outreach effort over the two days of the open house.

On May 20, 2000, MSFC held a public open house with 18,000 visitors in attendance. Displays of the effects of freefall were presented to the visitors, and the Microgravity Development Laboratory was open for tours.

Important Microgravity WWW Sites

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

NASA Biological and Physical Research
http://spaceresearch.nasa.gov/
Goals and organization of this research enterprise, as well as links to current research opportunities.

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

Microgravity News
http://mgnews.msfc.nasa.gov/
Online issues of *Microgravity News*, a quarterly newsletter about research in microgravity.

Microgravity Research Results
http://mgnews.msfc.nasa.gov/site/resindex.html
Site with links to the history and results of select flight experiments.

Microgravity Research Task Book and Bibliography
http://microgravity.nasa.gov/tb.html
Brief descriptions of all research projects currently 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 (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/home.html
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 information and search capabilities for NASA microgravity flight experiments.

Reduced-Gravity Program
http://jsc-aircraft-ops.jsc.nasa.gov/rgpindex.htm
Overview of the reduced-gravity program, which uses the KC-135 aircraft.

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

NASA Human Spaceflight
http://spaceflight.nasa.gov/
A comprehensive source for information about NASA's spaceflight programs.

Shuttle Flights
http://spaceflight.nasa.gov/shuttle/
http://www.ksc.nasa.gov/
Information on the most recent space shuttle mission with links to all missions to date.

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

Funding for the Microgravity Research Program in fiscal year (FY) 2000 totaled $220.9 million. This figure includes the Microgravity Research Program budget of $108.7 million and $112.2 million of the Office of Space Flight's budget, which is allocated for International Space Station (ISS) utilization and facilities. These funds supported a variety of activities across the microgravity science disciplines of biotechnology, combustion science, fluid physics, fundamental physics, and materials science, including an extensive ground-based research and analysis program; development and flight of microgravity space shuttle and sounding rocket missions; planning, technology, and hardware development for the ISS; and outreach and education. The funding distribution for combined flight and ground efforts in the various microgravity research disciplines is illustrated in Figure 1.

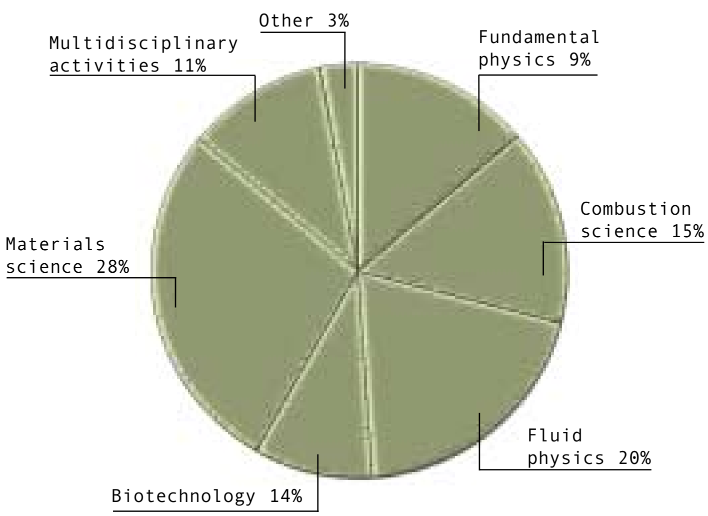


Figure 1 — FY 2000 Microgravity Funding Distribution by Science Discipline

Figure 2 presents the allocation of funding in support of ISS mission planning, development of ISS technology and hardware, development of flight- and ground-based research projects, execution of flight and ground investigations, and development of technology to support those investigations.

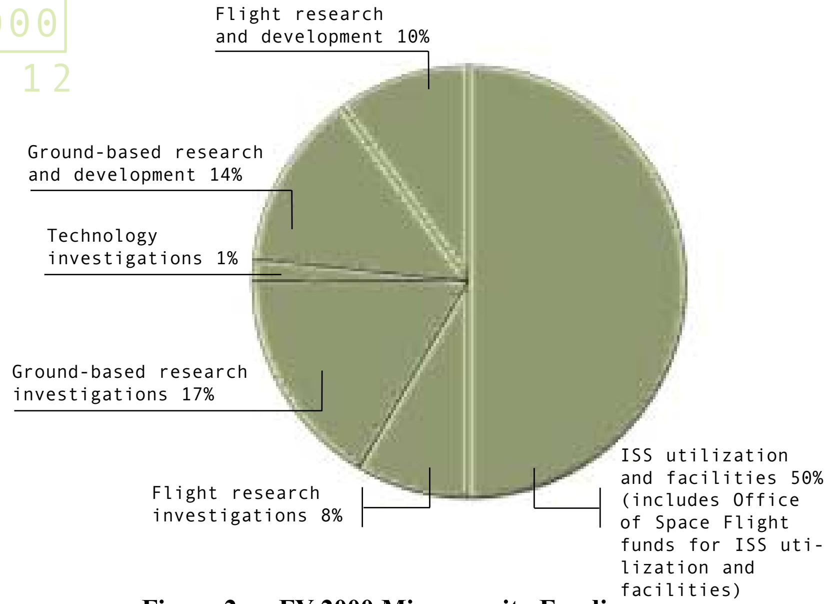


Figure 2 — FY 2000 Microgravity Funding by Mission Function

The Microgravity Research Program operates primarily through four NASA field centers. Figure 3 illustrates the funding distribution among these centers and includes NASA headquarters funding. The Microgravity Research Program science discipline authority and major responsibilities are as follows:

- **Glenn Research Center** — combustion science, fluid physics, and microgravity measurement and analysis.
- **Jet Propulsion Laboratory** — fundamental physics.
- **Johnson Space Center** — cell and tissue culture portion of the biotechnology discipline.
- **Marshall Space Flight Center** — materials science, molecular science portion of the biotechnology discipline, and the glovebox program.

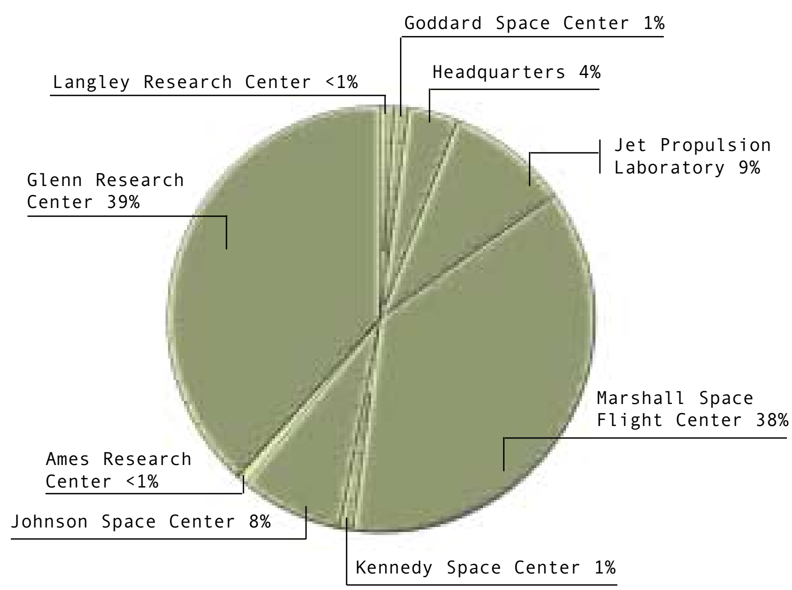


Figure 3 — FY 2000 Microgravity Funding Distribution by NASA Field Centers

Appendix A: Fiscal Year 2000 Grant Recipients, by State

(Includes some continuing projects at no additional cost)
\

Alabama

J. B. Andrews
University of Alabama, Birmingham; Birmingham, AL
Coupled Growth in Hypermonotectics
Materials Science

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

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

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

Daniel C. Carter
New Century Pharmaceuticals, Inc.; Huntsville, AL
Protein Crystal Growth Facility–Based Microgravity Hardware: Science and Applications
Biotechnology

Alexander A. Chernov
Universities Space Research Association; Huntsville, AL
Marshall Space Flight Center; Huntsville, AL
Morphological Stability of Stepped Interfaces Growing From Solution
Materials Science

Alexander A. Chernov
Universities Space Research Association; Huntsville, AL
Marshall Space Flight Center; AL
Origin of Imperfections in Growing Protein Crystals by In-Situ *Rocking Curve Analysis*
Materials Science

Krishnan K. Chittur
University of Alabama, Huntsville; Huntsville, AL
Infrared Signatures for Mammalian Cells in Culture
Biotechnology

Peter A. Curreri
Marshall Space Flight Center, Huntsville; Huntsville, AL
Fundamental Studies of Solidification in Microgravity Using Real-Time X-Ray Microscopy
Materials Science

Lawrence J. DeLucas
University of Alabama, Huntsville; Huntsville, AL
A Comprehensive Investigation of Macromolecular Transport During Protein Crystallization
Biotechnology

Lawrence J. DeLucas
University of Alabama, Huntsville; Huntsville, AL
Development of Robotic Techniques for Microgravity Protein Crystal Growth
Biotechnology

Lawrence J. DeLucas
University of Alabama, Huntsville; Huntsville, AL
Microgravity Studies of Medically Relevant Macromolecules
Biotechnology

Lawrence J. DeLucas
University of Alabama, Huntsville; Huntsville, AL
Protein Crystal Growth in Microgravity
Biotechnology

Edwin C. Ethridge
Marshall Space Flight Center; Huntsville, AL
Mechanism for the Crystallization Studies of ZBLAN
Materials Science

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

Donald C. Gillies
Marshall Space Flight Center; Huntsville, AL
Solidification of II—VI Compounds in a Rotating Magnetic Field
Materials Science

Donald C. Gillies
Marshall Space Flight Center; Huntsville, AL
Use of Computed Tomography for Characterizing Materials Grown Terrestrially and in Microgravity
Materials Science

Richard N. Grugel
Marshall Space Flight Center; Huntsville, AL
Novel Directional Solidification Processing of Hypermonotectic Alloys
Materials Science

Richard N. Grugel
Marshall Space Flight Center; Huntsville, AL
Utilizing Controlled Vibrations in a Microgravity Environment to Understand and Promote Microstructural Homogeneity During Floating-Zone Crystal Growth
Materials Science

Russell Judge
Marshall Space Flight Center; Huntsville, AL
Macromolecule Nucleation and Growth Rate Dispersion Studies: A Predictive Technique for Crystal Quality Improvement in Microgravity
Biotechnology

Craig E. Kundrot
Marshall Space Flight Center; Huntsville, AL
Optimizing the Use of Microgravity to Improve the Diffraction Quality of Problematic Biomacromolecular Crystals
Biotechnology

Sandor L. Lehoczky
Marshall Space Flight Center; Huntsville, AL
Crystal Growth of II—VI Semiconducting Alloys by Directional Solidification
Materials Science

Sandor L. Lehoczky
Marshall Space Flight Center; Huntsville, AL
Growth of Solid-Solution Single Crystals
Materials Science

Samuel A. Lowry
CFD Research Corporation; Huntsville, AL
Influence of Natural Convection and Thermal Radiation on Multi-Component Transport and Chemistry in MOCVD Reactors
Materials Science

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

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

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

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

Witold Palosz
Universities Space Research Association; Huntsville, AL
Marshall Space Flight Center; Huntsville, AL
Investigation of Convective Effects in Crystal Growth by Physical Vapor Transport
Materials Science

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

Marc L. Pusey
Marshall Space Flight Center; Huntsville, AL
Fluorescence Studies of Protein Aggregation in Under- and Over-Saturated Solutions
Biotechnology

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

Marc L. Pusey
Marshall Space Flight Center; Huntsville, AL
The Study and Optimization of Flow in Solution Biological Crystal Growth
Fluid Physics

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

Michael B. Robinson
Marshall Space Flight Center; Huntsville, AL
A Study of the Undercooling Behavior of Immiscible Metal Alloys in the Absence of Crucible-Induced Nucleation
Materials Science

Robert S. Snyder
New Century Pharmaceuticals; Huntsville, AL
Electrophoretic Focusing
Biotechnology

Doru M. Stefanescu
University of Alabama, Tuscaloosa; Tuscaloosa, AL
Particle Engulfment and Pushing by Solidifying Interfaces (PEP)
Materials Science

Ching-Hua Su
Marshall Space Flight Center; Huntsville, AL
Crystal Growth of ZnSe and Related Ternary Compound Semiconductors by Vapor Transport
Materials Science

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

Frank R. Szofran
Marshall Space Flight Center; Huntsville, AL
Reduction of Defects in Germanium-Silicon (RDGS)
Materials Science

Peter G. Vekilov
University of Alabama, Huntsville; Huntsville, AL
Effects of Convective Transport of Solute and Impurities on Defect-Causing Kinetics Instabilities in Protein Crystallization
Biotechnology

Peter G. Vekilov
University of Alabama, Huntsville; Huntsville, AL
Protein-Precipitant-Specific Criteria for the Impact of Reduced Gravity on Crystal Perfection
Biotechnology

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

Arizona

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

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

Kenneth A. Jackson
University of Arizona; Tucson, AZ
Growth of Rod Eutectics
Materials Science

Kenneth A. Jackson
University of Arizona; Tucson, AZ
Non-Equilibrium Phase Transformations
Materials Science

Jeffrey W. Jacobs
University of Arizona; Tucson, AZ
An Experimental Study of Richtmyer-Meshkov Instability in Low Gravity
Fluid Physics

David R. Poirier
University of Arizona; Tucson, AZ
Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments
Materials Science

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

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

Bruce C. Towe
Arizona State University; Tempe, AZ
Development of Microflow Biochemical Sensors for Space Biotechnology
Biotechnology

California

Davood Abdollahian
Scientech, Inc.; Campbell, CA
Experimental and Analytical Study of Two-Phase Flow Parameters in Microgravity
Fluid Physics

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
Fluid Physics

Guenter Ahlers
University of California, Santa Barbara; Santa Barbara, CA
The Superfluid Transition of ^{4}He Under Unusual Conditions
Fundamental Physics

M. Y. Bahadori
Science and Technology Development Corporation; Los Angeles, CA
Gravitational Effects on Laminar, Transitional, and Turbulent Gas-Jet Diffusion Flames (TDGF)
Combustion Science

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

Sanjoy Banerjee
University of California, Santa Barbara; Santa Barbara, CA
Numerical Simulation of Electrochemical Transport Processes in Microgravity Environments
Fluid Physics

Martin B. Barmatz
Jet Propulsion Laboratory; Pasadena, CA
California Institute of Technology; Pasadena, CA
Microgravity Test of Universality and Scaling Predictions Near the Liquid-Gas Critical Point of ^{3}He
Fundamental Physics

Rajendra S. Bhatnagar
University of California, San Francisco; San Francisco, CA
Expansion and Differentiation of Cells in Three-Dimensional Matrices Mimicking Physiological Environments
Biotechnology

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

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

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

Van P. Carey
University of California, Berkeley; Berkeley, CA
Marangoni Effects on Near-Bubble Microscale Transport During Boiling of Binary Fluid Mixtures
Fluid Physics

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

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

Talso C. Chui
California Institute of Technology; Pasadena, CA
The Lambda Transition Under Superfluid Flow Conditions
Fundamental Physics

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

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

Ellen R. Dirksen
University of California, Los Angeles; Los Angeles, CA
Use of Microgravity-Based Bioreactors to Study Intercellular Communication in Airway Cells
Biotechnology

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

Douglas J. Durian
University of California, Los Angeles; Los Angeles, CA
The Melting of Aqueous Foams/FOAM (Foam Optics And Mechanics)
Fluid Physics

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

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

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

Said E. Elghobashi
University of California, Irvine; Irvine, CA
Effects of Gravity on Sheared Turbulence Laden With Bubbles or Droplets
Fluid Physics

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

C. W. F. Everitt
Stanford University; Stanford, CA
Satellite Test of the Equivalence Principle (STEP)
Fundamental Physics

Robert S. Feigelson
Stanford University; Stanford, CA
Investigation of the Crystal Growth of Dielectric Materials by the Bridgman Technique Using Vibrational Control
Materials Science

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

A. C. Fernandez-Pello
University of California, Berkeley; Berkeley, CA
Flammability Diagrams of Combustible Materials in Microgravity
Combustion Science

A. C. Fernandez-Pello
University of California, Berkeley; Berkeley, CA
Fundamental Study of Smoldering Combustion in Microgravity
Combustion Science

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

John A. Frangos
University of California, San Diego; San Diego, CA
Role of Fluid Shear on Three-Dimensional Bone Tissue Culture
Biotechnology

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

Alice P. Gast
Stanford University; Stanford, CA
The Influence of Gravity on Colloidal Crystallization and Field-Induced Aggregation
Fluid Physics

Joe D. Goddard
University of California, San Diego; San Diego, CA
Material Instabilities in Particulate Systems
Fluid Physics

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

Lawrence H. Heilbronn
Lawrence Berkeley National Laboratory; Berkeley, CA
Radiation Transmission Properties of In-Situ Materials
Materials Science

Douglas E. Holmes
Telcom Devices; Camarillo, CA
Dimensional Stability of Supermatrix Semiconductors
Materials Science

George M. Homsy
University of California, Santa Barbara; Santa Barbara, CA
Microgravity Fluid Mechanics: G-Jitter Convection and the Mechanics of Fluidized Beds
Fluid Physics

George M. Homsy
University of California, Santa Barbara; Santa Barbara, CA
Problems in Microgravity Fluid Mechanics: Thermocapillary Instabilities and G-Jitter Convection
Fluid Physics

George M. Homsy
University of California, Santa Barbara; Santa Barbara, CA
Solid-State Electrochemical Oxygen Conversion for Martian and Lunar Environments: Materials Development, Reactor Concepts, and Chemical Conversion Cycles
Materials Science

Arlon J. Hunt
Lawrence Berkeley National Laboratory; Berkeley, CA
Porosity and Variations in Microgravity Aerogel Nanostructures
Materials Science

Melany L. Hunt
California Institute of Technology; Pasadena, CA
Granular Materials Flows With Interstitial Fluid and Electrostatic Charging Effects
Fluid Physics

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

Farrokh Issacci
Honeywell International; Torrance, CA
Two-Phase Flow in Multi-Channels — Liquid Holdup and Capillary Flow
Fluid Physics

William L. Johnson
California Institute of Technology; Pasadena, CA
Physical Properties and Processing of Undercooled, Metallic, Glass-Forming Melts
Materials Science

William L. Johnson
California Institute of Technology; Pasadena, CA
Thermophysical Properties of Metallic Glasses and Undercooled Liquids
Materials Science

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

Robert E. Kelly
University of California, Los Angeles; Los Angeles, CA
Studies in Thermocapillary Convection of the Marangoni-Benard Type
Fluid Physics

Ian M. Kennedy
University of California, Davis; Davis, CA
The Impact of Buoyancy and Flame Structure on Soot, Radiation, and NOx Emissions From a Turbulent Diffusion Flame
Combustion Science

Edgar Knobloch
University of California, Berkeley; Berkeley, CA
Weakly Nonlinear Description of Parametric Instabilities in Vibrating Flows
Fluid Physics

James L. Lambert
Jet Propulsion Laboratory; Pasadena, CA
Development of a Noninvasive Glucose Monitor
Biotechnology

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

Melora E. Larson
Jet Propulsion Laboratory; Pasadena, CA
Second Sound Measurements Near the Tricritical Point in ^{3}He-^{4}He Mixtures
Fundamental Physics

Melora E. Larson
Jet Propulsion Laboratory; Pasadena, CA
Static Properties of ^{4}He in the Presence of a Heat Current in a Low-Gravity Simulator
Fundamental Physics

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

John A. Lipa
Stanford University; Stanford, CA
Confined Helium Experiment (CHeX)
Fundamental Physics

John A. Lipa
Stanford University; Stanford, CA
Fundamental Physics Experiments With Superconducting Cavity — Stabilized Oscillators on Space Station
Fundamental Physics

John A. Lipa
Stanford University; Stanford, CA
High-Resolution Study of the Critical Region of Oxygen Using Magnetic Levitation
Fundamental Physics

John A. Lipa
Stanford University; Stanford, CA
A New Test of Critical Point Universality by Measuring the Superfluid Density Near the Lambda Line of Helium

Fundamental Physics
John A. Lipa
Stanford University; Stanford, CA
A Renewal Proposal to Study the Effect of Confinement on Transport Properties by Making Use of Helium along the Lambda Line
Fundamental Physics

John A. Lipa
Stanford University; Stanford, CA
A Test of Supersymmetry Theory by Searching for Anomalous Short Range Forces
Fundamental Physics

Jing Liu
California State University, Long Beach; Long Beach, CA
Magnetorheological Fluids: Rheology and Nonequilibrium Pattern Formation
Fluid Physics

Alexander J. Malkin
University of California, Irvine; Irvine, CA
Growth Processes and Defect Structure of Macromolecular Crystals
Biotechnology

Stephen B. Margolis
Sandia National Laboratories; Livermore, CA
Dynamics of Liquid Propellant Combustion at Reduced Gravity
Combustion Science

John R. Marshall
Ames Research Center; Moffett Field, CA
Microgravity Experiments to Evaluate Electrostatic Forces in Controlling Cohesion and Adhesion of Granular Materials
Fluid Physics

Alexander McPherson Jr.
University of California, Irvine; Irvine, CA
Enhanced Dewar Program
Biotechnology

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

Eckart H. Meiburg
University of California, Santa Barbara; Santa Barbara, CA
The Dynamics of Particulate Deposition and Resuspension Processes at Moderate to High Reynolds Numbers
Fluid Physics

Jack Miller
Lawrence Berkeley National Laboratory; Berkeley, CA
Radiation Transport Properties of Potential In Situ–Developed Regolith-Epoxy Materials for Martian Habitats
Materials Science

Kenichi Ohsaka
University of Southern California, Los Angeles; Los Angeles, CA
Dynamically Induced Nucleation of Deeply Supercooled Melts and Measurement of Surface Tension and Viscosity
Materials Science

Richard E. Packard
University of California, Berkeley; Berkeley, CA
Superfluid Gyroscopes for Space
Fundamental Physics

David Pearson
California Institute of Technology; Pasadena, CA

Superfluid Density of Confined ^{4}He Near Tl
Fundamental Physics

Robert L. Powell
University of California, Davis; Davis, CA
Experimental Studies of Multiphase Materials Using Nuclear Magnetic Resonance (NMR) and NMR Imaging
Fluid Physics

Constantine Pozrikidis
University of California, San Diego; San Diego, CA
Dynamics of Accelerated Interfaces: Parametric Excitation and Fluid Sloshing in Closed Containers and Open Tanks
Fluid Physics

Seth J. Putterman
University of California, Los Angeles; Los Angeles, CA
Diffusing Light Photography of Containerless Ripple Turbulence
Fluid Physics

Won-Kyu Rhim
Jet Propulsion Laboratory; Pasadena, CA
Measurements of Thermophysical Properties of Molten Silicon and Germanium
Materials Science

Pat R. Roach
Ames Research Center; Moffett Field, CA
A Microgravity Helium Dilution Cooler
Fundamental Physics

Paul D. Ronney
University of Southern California, Los Angeles; Los Angeles, CA
Extinction and Instability Mechanisms of Polymerization Fronts
Materials Science

Paul D. Ronney
University of Southern California, Los Angeles; Los Angeles CA
Studies of Premixed Laminar and Turbulent Flames at Microgravity
Combustion Science

Paul D. Ronney
University of Southern California, Los Angeles; Los Angeles, CA
Transport and Chemical Effects on Concurrent and Opposed-Flow Flame Spread at Microgravity
Combustion Science

Joseph Rudnick
University of California, Los Angeles; Los Angeles, CA
Finite Size Effects near the Liquid-Gas Critical Point of ^{3}*He*
Fundamental Physics

Satwindar S. Sadhal
University of Southern California, Los Angeles; Los Angeles, CA
Ground-Based Studies of Internal Flows in Levitated Laser-Heated Drops
Fluid Physics

Satwindar S. Sadhal
University of Southern California, Los Angeles; Los Angeles, CA
Nonintrusive Measurement of Thermophysical Properties of Liquids by Electrostatic-Acoustic Hybrid Levitation
Materials Science

Robert L. Sah
University of California, San Diego; San Diego, CA
Cartilage Tissue Engineering: Circumferential Seeding of Chondrocytes Using Rotating Reactors
Biotechnology

Benjamin D. Shaw
University of California, Davis; Davis, CA
Combustion Experiments in Reduced Gravity With Two-Component Miscible Droplets
Combustion Science

Benjamin D. Shaw
University of California, Davis; Davis, CA
Combustion of Han-Based Monopropellant Droplets in Reduced Gravity
Combustion Science

Greg P. Smith
SRI International; Menlo Park, CA
Quantitative Interpretation of Optical Emission Sensors for Microgravity Experiments
Combustion Science

Owen I. Smith
University of California, Los Angeles; Los Angeles, CA
Acoustically Forced, Condensed-Phase Fuel Combustion Under Microgravity Conditions
Combustion Science

Donald M. Strayer
California Institute of Technology; Pasadena, CA
Precise Measurements of the Density and Critical Phenomena of Helium Near Phase Transitions
Fundamental Physics

Peter Taborek
University of California, Irvine; Irvine, CA
Superfluid Contact Line Dynamics
Fluid Physics

Theofanis G. Theofanous
University of California, Santa Barbara; Santa Barbara, CA
The Pool Boiling Crisis From Flat Plates: Mechanism(s) and Enhancement
Fluid Physics

James D. Trolinger
MetroLaser, Inc.; Irvine, CA
Investigate the Influence of Microgravity on Transport Mechanisms in a Virtual Spaceflight Chamber
Materials Science

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

Forman A. Williams
University of California, San Diego; San Diego, CA
Droplet Combustion Experiment (DCE/DCE-2)
Combustion Science

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

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

Colorado

John M. Alford
TDA Research, Inc.; Wheat Ridge, CO

Formation of Carbon Nanotubes in a Microgravity Environment
Combustion Science

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

Noel A. Clark
University of Colorado, Boulder; Boulder, CO
Structure, Hydrodynamics, and Phase Transitions of Freely Suspended Liquid Crystals
Fluid Physics

Joshua E. Colwell
University of Colorado, Boulder; Boulder, CO
Collisions Into Dust Experiment-2
Fluid Physics

Joshua E. Colwell
University of Colorado, Boulder; Boulder, CO
Dusty Plasma Dynamics Near Surfaces in Space
Fluid Physics

Joshua E. Colwell
University of Colorado, Boulder; Boulder, CO
Physics of Regolith Impacts in Microgravity Experiment (PRIME)
Fluid Physics

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

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

Alan R. Greenberg
University of Colorado, Boulder; Boulder, CO
Influence of Solutocapillary Convection on Macrovoid Defect Formation in Polymeric Membranes
Materials Science

John L. Hall
University of Colorado, Boulder; Boulder, CO
Fundamental Physics Using Frequency-Stabilized Lasers as Optical "Atomic Clocks"
Fundamental Physics

John E. Hart
University of Colorado, Boulder; Boulder, CO
Stratified Taylor-Couette Flow With Radial Buoyancy
Fluid Physics

Larry W. Mason
Lockheed Martin Astronautics; Denver, CO

CO^2 Acquisition Membrane (CAM)
Materials Science

John J. Moore
Colorado School of Mines; Golden, CO
A Fundamental Study of the Combustion Synthesis of Ceramic-Metal Composite Materials Under Microgravity Conditions — Phase III: Effect of Gravity on the Combustion Synthesis of Advanced, Engineered, Porous Materials
Combustion Science

Daniel R. Ohlsen
University of Colorado, Boulder; Boulder, CO
Waves in Radial Gravity Using Magnetic Fluid
Fluid Physics

Jacques I. Pankove
Astralux, Inc.; Boulder, CO
Optoelectric Neural System
Biotechnology

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

Donald Sullivan
National Institute of Standards and Technology; Boulder, CO
Primary Atomic Reference Clock in Space (PARCS)
Fundamental Physics

Paul Todd
University of Colorado, Boulder; Boulder, CO
Preparation and Analysis of RNA Crystals
Biotechnology

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

Connecticut

Robert E. Apfel
Yale University; New Haven, CT
Novel Concepts in Acoustophoresis for Biotechnology Applications
Biotechnology

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

Amir Faghri
University of Connecticut; Storrs, CT
Evaporation, Boiling, and Condensation on/in Capillary Structures of High Heat Flux Two-Phase Devices
Fluid Physics

Amir Faghri
University of Connecticut; Storrs, CT
Heat Transfer in Rotating Thin Liquid Films Including Nucleate Boiling
Fluid Physics

Kurt Gibble
Yale University; New Haven, CT
Investigation of Future Microgravity Atomic Clocks
Fundamental Physics

Marshall L. Grant
Yale University; New Haven, CT
Effect of Structure-Dependent Interactions on the Formation of Colloidal Aggregates and Nuclei
Fluid Physics

Juha Javanainen
University of Connecticut; Storrs, CT
Bose-Einstein Condensate and Atom Laser: Coherence and Optical Properties
Fundamental Physics

Mark A. Kasevich
Yale University; New Haven, CT
Atom Interferometry in a Microgravity Environment
Fundamental Physics

Michael Loewenberg
Yale University; New Haven, CT
Flows of Wet Foams and Concentrated Emulsions
Fluid Physics

Michael Loewenberg
Yale University; New Haven, CT
Rheology of Concentrated Emulsions
Fluid Physics

Marshall B. Long
Yale University; New Haven, CT
Computational and Experimental Study of Laminar Diffusion Flames in a Microgravity Environment
Combustion Science

Daniel E. Rosner
Yale University; New Haven, CT
Combustion of Individual Bubbles and Submerged Gas Jets in Liquid Fuels
Combustion Science

Daniel E. Rosner
Yale University; New Haven, CT
Design/Interpretation of Microgravity Experiments to Obtain Fluid/Solid Boundary Conditions in Non-Isothermal Systems
Fluid Physics

Mitchell D. Smooke
Yale University; New Haven, CT
Computational and Experimental Study of Energetic Materials in a Counterflow Microgravity Environment
Combustion Science

Delaware

Siu-Tat Chui
University of Delaware; Newark, DE

Droplets of ^{3}He-^{4}He Mixtures
Fundamental Physics

Eric W. Kaler
University of Delaware; Newark, DE
Protein Crystallization in Complex Fluids
Biotechnology

Eric W. Kaler
University of Delaware; Newark, DE
Surfactant-Based Critical Phenomena in Microgravity
Fluid Physics

Leonard W. Schwartz
University of Delaware; Newark, DE
Free-Surface and Contact-Line Motion of Liquids in a Microgravity Environment
Fluid Physics

Florida

Reza Abbaschian
University of Florida; Gainesville, FL
In-Situ Monitoring of Crystal Growth Using MEPHISTO
Materials Science

Reza Abbaschian
University of Florida; Gainesville, FL
Morphological Stability of Faceted Interfaces
Materials Science

Timothy J. Anderson
University of Florida; Gainesville, FL
An Electrochemical Method to Visualize Flow and Measure Diffusivity in Liquid Metals
Materials Science

Timothy J. Anderson
University of Florida; Gainesville, FL
An Electrochemical Method to Visualize Flow in Liquid Metals
Materials Science

Donald F. Cameron
University of South Florida; Tampa, FL
Development of an Insulin-Secreting, Immunoprivileged Cell-Cell Aggregate Utilizing the NASA Rotating Wall Vessel
Biotechnology

Ravindran Chella
Florida State University; Tallahassee, FL
Lattice-Boltzmann Techniques for Multiphase Flow and Transport in Microgravity Environment
Fluid Physics

Charles E. HelmMarshallter
Florida Institute of Technology; Melbourne, FL
New Cell Culture Technology
Biotechnology

Anthony J. Ladd
University of Florida; Gainesville, FL
Microgravity-Driven Instabilities in Gas-Fluidized Beds
Fluid Physics

Bruce R. Locke
Florida State University; Tallahassee, FL
Analysis of Electrophoretic Transport of Macromolecules Using Pulsed Field Gradient NMR
Biotechnology

Efstratios Manousakis
Florida State University; Tallahassee, FL
Theoretical Studies of Liquid ^{4}He Near the Superfluid Transition
Fundamental Physics

Ranga Narayanan
University of Florida; Gainesville, FL
Separation of Species by Oscillatory Flow
Fluid Physics

Daniel R. Talham
University of Florida; Gainesville, FL
The Features of Self-Assembling Organic Bilayers Important to the Formation of Anisotropic Inorganic Materials in Low-Gravity Conditions
Materials Science

Daniel R. Talham
University of Florida; Gainesville, FL
The Features of Self-Assembling Organic Bilayers Important to the Formation of Anisotropic Inorganic Materials in Microgravity Conditions
Materials Science

Georgia

Vincent P. Conticello
Emory University; Atlanta, GA
Design, Synthesis, and Characterization of Well-Defined, Biomimetic Polypeptide Networks
Biotechnology

Nikolaus Dietz
Georgia State University; Atlanta, GA
Optical Characterization of Gas Phase, Gas Phase Chemistry, and Surface Chemistry During High-Pressure, Vapor-Phase Deposition Processes Under Laminar and Turbulent Flow Conditions
Materials Science

Arun M. Gokhale
Georgia Institute of Technology; Atlanta, GA
Effect of Gravity on the Evolution of Spatial Arrangement of Features in Microstructure: A Quantitative Approach
Materials Science

G. P. Neitzel
Georgia Institute of Technology; Atlanta, GA
Noncoalescence in Microgravity: Science and Technology
Fluid Physics

Minami Yoda
Georgia Institute of Technology; Atlanta, GA
Novel Optical Diagnostic Techniques for Studying Particle Contact and Deposition Upon a Large Cylinder in a Sheared Suspension
Fluid Physics

Illinois

Jens Alkemper
Northwestern University; Evanston, IL
The Evolution of Dendrite Morphology During Isothermal Coarsening
Materials Science

Hassan Aref
University of Illinois, Urbana-Champaign; Urbana, IL

Fluid Physics of Foam Evolution and Flow
Fluid Physics

S. G. Bankoff
Northwestern University; Evanston, IL
Control of Flowing Liquid Films by Electrostatic Fields in Space
Fluid Physics

Kenneth Brezinsky
University of Illinois, Chicago; Chicago, IL
Combustion Synthesis of Materials in Microgravity
Materials Science

David M. Ceperley
University of Illinois, Urbana-Champaign; Urbana, IL
Prediction of Macroscopic Properties of Liquid Helium From Computer Simulation
Fundamental Physics

Soyoung S. Cha
University of Illinois, Chicago; Chicago, IL
Three-Dimensional Velocity Field Characterization in a Bridgman Apparatus: Technique Development and Effect Analysis
Materials Science

Jonathan A. Dantzig
University of Illinois, Urbana-Champaign; Urbana, IL
Adaptive-Grid Methods for Phase-Field Models of Microstructure Development
Materials Science

Jonathan A. Dantzig
University of Illinois, Urbana-Champaign; Urbana, IL
Phase-Field Modeling of Microstructure Development in Microgravity
Materials Science

Stephen H. Davis
Northwestern University; Evanston, IL
Interfacial Dynamics
Fluid Physics

Shankar Krishnan
Containerless Research, Inc.; Evanston, IL
Structure-Property Correlations of Phase Transitions in Group IV and III-V Liquids
Materials Science

Jennifer A. Lewis
University of Illinois, Urbana-Champaign; Urbana, IL
Colloidal Stability in Complex Fluids
Materials Science

Seth Lichter
Northwestern University; Evanston, IL
The Micromechanics of the Moving Contact Line
Fluid Physics

Chang Liu
University of Illinois, Urbana-Champaign; Urbana, IL
Integrated Biomimetic Sensors Using Artificial Hair Cells
Biotechnology

Bernard J. Matkowsky
Northwestern University; Evanston, IL
Filtration Combustion for Microgravity Applications: (1) Smoldering, (2) Combustion Synthesis of Advanced Materials — PHASE 2
Combustion Science

Constantine M. Megaridis
University of Illinois, Chicago; Chicago, IL
Fluid Dynamics and Solidification of Molten Solder Droplets Impacting on a Substrate in Microgravity
Fluid Physics

Constantine M. Megaridis
University of Illinois, Chicago; Chicago, IL
Microgravity Investigation on the Formation of Oxides and Adsorbed Oxygen Films in Solder Jetting Applications Pertinent to the Electronics Manufacturing Industry
Materials Science

Constantine M. Megaridis
University of Illinois, Chicago; Chicago, IL
Molten-Metal Droplet Deposition on a Moving Substrate in Microgravity: Aiding the Development of Novel Technologies for Microelectric Assembly
Fluid Physics

Allan S. Myerson
Illinois Institute of Technology; Chicago, IL
Diffusion, Viscosity, and Crystal Growth of Proteins in Microgravity
Biotechnology

Allan S. Myerson
Illinois Institute of Technology; Chicago, IL
Thermodynamic and Spectroscopic Studies of Secondary Nucleation in Microgravity
Materials Science

Alexander Z. Patashinski
Northwestern University; Evanston, IL
Nonlinear Relaxation and Fluctuations in a Nonequilibrium, Near-Critical Liquid With a Temperature Gradient
Fundamental Physics

Ishwar K. Puri
University of Illinois, Chicago; Chicago, IL
Gravitational Effects on Partially Premixed Flames
Combustion Science

Hermann Riecke
Northwestern University; Evanston, IL
Complex Dynamics in Marangoni Convection With Rotation
Fluid Physics

Mary Silber
Northwestern University; Evanston, IL
Competing Instabilities and the Spatio-Temporal Dynamics of Interfacial Wave Patterns
Fluid Physics

Siavash H. Sohrab
Northwestern University; Evanston, IL
Combustion of Rotating Spherical Premixed and Diffusion Flames in Microgravity
Combustion Science

David M. Tiede
Argonne National Laboratory; Argonne, IL
Mechanisms for Membrane Protein Crystallization: Analysis by Small-Angle Neutron Scattering
Biotechnology

Peter W. Voorhees
Northwestern University; Evanston, IL
Coarsening in Solid-Liquid Mixtures (CSLM)-2
Materials Science

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

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

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

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

Charles F. Zukoski
University of Illinois, Urbana-Champaign; Urbana, IL
Particle Interaction Potentials and Protein Crystal Quality
Biotechnology

Indiana

Osman A. Basaran
Purdue University; West Lafayette, IN
Forced Oscillation of Pendant and Sessile Drops
Fluid Physics

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

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

Mark J. McCready
University of Notre Dame; Notre Dame, IN
Fundamental Processes of Atomization in Fluid-Fluid Flows
Fluid Physics

D. J. Morr
Purdue University; West Lafayette, IN
Biological Particle Separation in Low Gravity
Biotechnology

Issam Mudawar
Purdue University; West Lafayette, IN
Investigation of Critical Heat Flux in Reduced Gravity Using Photomicrographic Techniques
Fluid Physics

Christie M. Traycoff
Indiana Cancer Research Institute; Indianapolis, IN
Self-Renewal Replication of Hematopoietic Stem Cells in Microgravity
Biotechnology

Arvind Varma
University of Notre Dame; Notre Dame, IN
Mechanistic Studies of Combustion and Structure Formation During Synthesis of Advanced Materials
Combustion Science

Iowa

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

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

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

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

L.- D. Chen
University of Iowa; Iowa City, IA
Reflight of ELF (Enclosed Laminar Flames) Investigation
Combustion Science

John A. Goree
University of Iowa; Iowa City, IA
Plasma Dust Crystallization
Fluid Physics

Carole A. Heath
Iowa State University; Ames, IA
Determining the Conditions Necessary for the Development of Functional Replacement Cartilage Using a Microgravity Reactor
Biotechnology

Jeffrey S. Marshall
Iowa Institute of Hydraulic Research; Iowa City, IA
Rivulet Dynamics With Variable Gravity and Wind Shear
Fluid Physics

David W. Murhammer
University of Iowa; Iowa City, IA
Continuous, Noninvasive Monitoring of Rotating Wall Vessels and Application to the Study of Prostate Cancer
Biotechnology

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

Tonya L. Peeples
University of Iowa; Iowa City, IA
Extremophilic Interfacial Systems for Waste Processing in Space
Biotechnology

Victor G. Rodgers
University of Iowa; Iowa City, IA
Evaluating Oxidative Stress in Virally Infected Cells in Simulated Microgravity
Biotechnology

Rohit K. Trivedi
Iowa State University; Ames, IA
Dynamical Selection of Three-Dimensional Interfacial Patterns in Directional Solidification
Materials Science

Rohit K. Trivedi
Iowa State University; Ames, IA
Interface Pattern Selection Criterion for Cellular Structures in Direction Solidification
Materials Science

John M. Wiencek
University of Iowa; Iowa City, IA
Rejuvenation of Spent Media Via Supported Emulsion Liquid Membranes
Biotechnology

John M. Wiencek
University of Iowa; Iowa City, IA
Thermodynamics of Protein Crystallization and Links to Crystal Quality
Biotechnology

Kansas

Mark D. Hollingsworth
Kansas State University; Manhattan, KS
Crystal Growth of New Families of Ferroelastic Materials
Materials Science

Kenneth J. Klabunde
Kansas State University; Manhattan, KS
Nanocrystal Superlattices: Synthesis and Properties
Materials Science

Christopher Sorensen
Kansas State University; Manhattan, KS
Gelation in Aerosols: Non-Meanfield Aggregation Kinetics
Fluid Physics

Kentucky

Lori J. Wilson
Eastern Kentucky University; Richmond, KY
Metastable Solution Structure and Optimization Strategies in Protein Crystal Growth

Biotechnology

Louisiana

Timothy G. Hammond
Tulane University Medical Center; New Orleans, LA
Differentiation of Cultured Normal Human Renal Epithelial Cells in Microgravity
Biotechnology

Timothy G. Hammond
Tulane University Medical Center; New Orleans, LA
Production of 1-25- diOH D3 by Renal Epithelial Cells in Simulated Microgravity Culture
Biotechnology

John J. Hegseth
University of New Orleans; Lakefront, LA
A Geophysical Flow Experiment in a Compressible Critical Fluid
Fluid Physics

John J. Hegseth
University of New Orleans; Lakefront, LA
Geophysical Flow Experiment in a Rotating Spherical Capacitor
Fluid Physics

John J. Hegseth
University of New Orleans; Lakefront, LA
Growth and Morphology, Boiling, and Critical Fluctuations in Phase-Separating Supercritical Fluids
Fluid Physics

Kim C. O'Connor
Tulane University, New Orleans; LA
Insect-Cell Cultivation in Simulated Microgravity
Biotechnology

Maryland

Robert F. Berg
National Institute of Standards and Technology; Gaithersburg, MD
Critical Viscosity of Xenon-2 (CVX-2)
Fundamental Physics

Linda G. Blevins
National Institute of Standards and Technology; Gaithersburg, MD
Carbon Monoxide and Soot Formation in Inverse Diffusion Flames
Combustion Science

Kim D. Collins
University of Maryland Medical School; Baltimore, MD
Ions and Protein Association: aw and Protein Crystals
Biotechnology

Sam R. Coriell
National Institute of Standards and Technology; Gaithersburg, MD
Interface Morphology During Crystal Growth: Effects of Anisotropy and Fluid Flow
Fluid Physics

Jocelyne Diruggiero
University of Maryland, College Park; College Park, MD
Microbial Resistance to Solar Radiation: DNA Damage and Application of Repair Enzymes in Biotechnology
Biotechnology

Richard A. Ferrell
University of Maryland, College Park; College Park, MD
Critical Dynamics of Ambient-Temperature and Low-Temperature Phase Transitions
Fundamental Physics

D. T. Gallagher
Center of Advanced Research in Biotechnology; Rockville, MD
Protein and DNA Crystal Lattice Engineering
Biotechnology

Ashwani K. Gupta
University of Maryland, College Park; College Park, MD
Studies on the Behavior of Highly Preheated Air Flames in Microgravity
Combustion Science

Anthony Hamins
National Institute of Standards and Technology; Gaithersburg, MD
The Extinction of Low Strain–Rate Diffusion Flames by an Agent in Microgravity
Combustion Science

Cila Herman
Johns Hopkins University; Baltimore, MD
Experimental Investigation of Pool Boiling Heat Transfer Enhancement in Microgravity in the Presence of Electric Fields
Fluid Physics

Takashi Kashiwagi
National Institute of Standards and Technology; Gaithersburg, MD
Ignition and the Subsequent Transition to Flame Spread in Microgravity
Combustion Science

Joseph L. Katz
Johns Hopkins University; Baltimore, MD
Measurement of Liquid-to-Solid Nucleation Rates in Undercooled Metallic Melts

Materials Science

Jungho Kim
University of Maryland, College Park; College Park, MD
Investigation of Pool Boiling Heat Transfer Mechanisms in Microgravity Using an Array of Surface-Mounted Heat Flux Sensors
Fluid Physics

Jungho Kim
University of Maryland, College Park; College Park, MD
Pooling Boiling Transfer Mechanisms in Microgravity and Partial Gravity
Fluid Physics

Henryk Malak
Microcosm, Inc.; Columbia, MD
Cellular Oxygen and Nutrient Sensing in Microgravity Using Time-Resolved Fluorescence Microscopy
Biotechnology

Richard H. Maurer
Johns Hopkins University; Laurel, MD
Development of a Neutron Spectrometer to Assess Biological Radiation Damage Behind Spacecraft Materials
Biotechnology

Geoffrey B. McFadden
National Institute of Standards and Technology; Gaithersburg, MD
Convective and Morphological Instabilities During Crystal Growth
Materials Science

Geoffrey B. McFadden
National Institute of Standards and Technology; Gaithersburg, MD
A Phase-Field/Fluid Motion Model of Solidification: Investigation of Flow Effects During Directional Solidification and Dendritic Growth
Materials Science

Michael R. Moldover
National Institute of Standards and Technology; Gaithersburg, MD
Acoustic Study of Critical Phenomena in Microgravity
Fluid Physics

George Mulholland
National Institute of Standards and Technology; Gaithersburg, MD
Kinetics and Structure of Superagglomerates Produced by Silane and Acetylene
Combustion Science

Hasan N. Oguz
Johns Hopkins University, Baltimore; MD
Production and Removal of Gas Bubbles in Microgravity
Fluid Physics

Ho J. Paik
University of Maryland, College Park; College Park, MD
Search for Spin-Mass Interaction With A Superconducting Differential Angular Accelerometer
Fundamental Physics

William D. Phillips
National Institute of Standards and Technology; Gaithersburg, MD
Evaporative Cooling and Bose Condensates in Microgravity: Picokelvin Atoms in Space
Fundamental Physics

Andrea Prosperetti
Johns Hopkins University; Baltimore, MD
Acoustic Bubble Removal From Boiling Surfaces
Fluid Physics

Andrea Prosperetti
Johns Hopkins University; Baltimore, MD
Acoustic Bubble Removal From Boiling Surfaces and its Optimization
Fluid Physics

Robert J. Schaefer
National Institute of Standards and Technology; Gaithersburg, MD
Thermophysical Properties of High-Temperature Liquid Metals and Alloys
Materials Science

N. B. Singh
Northop-Grumman Corporation; Linthicum, MD
Flight Experiment to Study Double Diffusive Instabilities in Silver-Doped Lead Bromide Crystals
Materials Science

Kathleen J. Stebe
Johns Hopkins University; Baltimore, MD
Marangoni Effects on Drop Deformation and Breakup in an Extensional Flow: The Role of Surfactant Physical Chemistry
Fluid Physics

Kathleen J. Stebe
Johns Hopkins University; Baltimore, MD
Using Surfactants to Control Bubble Growth Coalescence in Nucleate Pool Boiling
Fluid Physics

Jose L. Torero
University of Maryland, College Park; College Park, MD
Diffusion Flame Structure, Shape, and Extinction: Geometrical Considerations
Combustion Science

Denis Wirtz
Johns Hopkins University; Baltimore, MD
Novel Microgravity Optical Technique for Molecularly Engineering Electrophoretic Media

Biotechnology

Massachusetts

George Benedek
Massachusetts Institute of Technology; Cambridge, MA
Kinetic Evolution of Stable and Metastable States in Protein Solutions
Materials Science

Peggy Cebe
Tufts University; Medford, MA
Study of Development of Polymer Structure in Microgravity Using Ellipsometry
Materials Science

Michael J. Cima
Massachusetts Institute of Technology; Cambridge, MA
Forces During Manufacture and Assembly of Microscale Discrete Electronic Components
Materials Science

Merton C. Flemings
Massachusetts Institute of Technology; Cambridge, MA
Measurement of the Viscosity and Surface Tension of Undercooled Melts Under Microgravity Conditions and Supporting Magnetohydrodynamic Calculations
Materials Science

Merton C. Flemings
Massachusetts Institute of Technology; Cambridge, MA
The Role of Convection and Growth Competition on Phase Selection in Microgravity
Materials Science

Seth Fraden
Brandeis University; Waltham, MA
Nucleation of Colloidal and Protein Crystals in the Vicinity of a Metastable Critical Point
Fluid Physics

Lisa E. Freed
Massachusetts Institute of Technology; Cambridge, MA
Microgravity Tissue Engineering
Biotechnology

James C. Hermanson
Worcester Polytechnic Institute; Worcester, MA
Combustion Characteristics of Fully Modulated, Turbulent Diffusion Flames in Reduced Gravity
Combustion Science

James C. Hermanson
Worcester Polytechnic Institute; Worcester, MA
Stability and Heat Transfer Characteristics of Condensing Films in Reduced Gravity
Fluid Physics

R. G. Holt
Boston University; Boston, MA
Rheology of Foam Near the Order-Disorder Transition
Fluid Physics

R. G. Holt
Boston University; Boston, MA
Sonoluminescence in Space: the Critical Role of Buoyancy in Stability and Emission Mechanisms
Fluid Physics

Jack B. Howard
Massachusetts Institute of Technology; Cambridge, MA
Combustion Synthesis of Fullerenes and Fullerenic Nanostructures in Microgravity
Combustion Science

David L. Kaplan
Tufts University; Medford, MA
Hierarchical Assembly of Collagen
Materials Science

Alain S. Karma
Northeastern University; Boston, MA
Phase-field Simulations of Dendritic Growth at Low Undercooling: Confronting Theory and Experiment
Materials Science

Alain S. Karma
Northeastern University; Boston, MA
The Role of Dynamic Nucleation at Moving Boundaries in Phase and Microstructure Selection
Materials Science

Wolfgang Ketterle
Massachusetts Institute of Technology; Cambridge, MA
Towards Precision Experiments With Bose-Einstein Condensates
Fundamental Physics

Matthew B. Koss
College of the Holy Cross; Worcester, MA
Transient Dendritic Solidification Experiment (TDSE)
Materials Science

Gareth H. McKinley
Massachusetts Institute of Technology; Cambridge, MA
Extensional Rheology Experiment (ERE)
Fluid Physics

Gareth H. McKinley
Massachusetts Institute of Technology; Cambridge, MA
An Interferometric Investigation of Contact Line Dynamics in Spreading Polymer Melts and Solutions
Fluid Physics

Gareth H. McKinley
Massachusetts Institute of Technology; Cambridge, MA
Resin-Spinning of Synthetic Polymer Fibers With Silk-Like Properties
Biotechnology

Ali Nadim
Boston University; Boston, MA
Determination of Interfacial Rheological Properties Through Microgravity Oscillations of Bubbles and Drops
Fluid Physics

Keith E. Oslakovic
Molecular Geodesics, Inc.; Boston, MA
Functionally Adapted Biomimetic Materials for Space Exploration
Biotechnology

Peter J. Quesenberry
University of Massachusetts Medical Center; Worcester, MA
Stem Cell Expansion in Rotating Bioreactors
Biotechnology

W. T. Rawlins
Physical Science, Inc.; Andover, MA
Hyperspectral Imaging of Flame Spread Over Solid Fuel Surfaces Using Adaptive Fabry-Perot Filters
Combustion Science

Thomas P. Russell
University of Massachusetts, Amherst; Amherst, MA
Capillary Wavelengths at Interfaces: The Role of Gravity and Electric Field Enhancement
Materials Science

Albert Sacco Jr.
Northeastern University; Boston, MA
Modeling of Macroscopic/Microscopic Transport and Growth Phenomena in Zeolite Crystal Solutions Under Microgravity
Materials Science

Donald R. Sadoway
Massachusetts Institute of Technology; Cambridge, MA
From Oxygen Generation to Metal Production: In-Situ Resource Utilization by Molten OxideElectrolysis
Materials Science

William J. Schwartz
University of Massachusetts Medical School; Worcester, MA
Microgravity and the Biology of Neural Stem Cells
Biotechnology

Frans A. Spaepen
Harvard University; Cambridge, MA
Glass Formation, Nucleation, and Diffusion in Metallic Melts
Materials Science

Frans A. Spaepen
Harvard University; Cambridge, MA
Kinetics of Nucleation and Growth From Undercooled Melts
Materials Science

F. M. Stewart
University of Massachusetts Medical School; Worcester, MA
Influence of Microgravity Conditions on Gene Transfer Into Expanded Populations of Human_Hematopoietic Stem Cells
Biotechnology

Arthur J. Sytkowski
Beth Israel Deaconess Medical Center; Boston, MA
Production of Recombinant Human Erythropoietin by Mammalian Cells Cultured in Simulated Microgravity
Biotechnology

Gretar Tryggvason
Worcester Polytechnic Institute; Worcester, MA
Computational Modeling of the Effect of Secondary Forces on the Phase Distribution in Dispersed Multiphase Channel Flows
Fluid Physics

Gretar Tryggvason
Worcester Polytechnic Institute; Worcester, MA
Computations of Boiling in Microgravity
Fluid Physics

Michael Tsapatsis
University of Massachusetts, Amherst; Amherst, MA
Thin-Film Molecular Sieve Synthesis: Processing-Microstructure Relationships and the Effect of Gravity on Microstructure
Materials Science

Ronald L. Walsworth
Smithsonian Institution; Cambridge, MA
Ground-Based Investigations With the Cryogenic Hydrogen Maser
Fundamental Physics

David A. Weitz
Harvard University; Cambridge, MA
Fabrication of Photonic Structure With Colloid Engineering
Fluid Physics

David A. Weitz
Harvard University; Cambridge, MA
Physics of Colloids in Space (PCS)
Fluid Physics

August F. 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

Michigan

V. S. Arpaci
University of Michigan, Ann Arbor; Ann Arbor, MI
Marangoni Instability-Induced Convection in Evaporating Liquid Droplets
Fluid Physics

Arvind Atreya
University of Michigan, Ann Arbor; Ann Arbor, MI
Radiant Extinction of Gaseous Diffusion Flames
Combustion Sciencer

Andre Benard
Michigan State University; East Lansing, MI
Investigation of Solidification Processes With Convection Using Meshless Methods and Quantitative Experimental Verification
Materials Science

Thomas H. Courtney
Michigan Technological University; Houghton, MI
Gravity-Induced Settling in Interconnected Liquid-Solid Systems
Materials Science

Werner J. Dahm
University of Michigan, Ann Arbor; Ann Arbor, MI
Turbulent Flame Processes Via Vortex Ring–Diffusion Flame Interaction
Combustion Science

James F. Driscoll
University of Michigan, Ann Arbor; Ann Arbor, MI
Flame Vortex Interactions in Microgravity to Assess the Theory of Flame Stretch
Combustion Science

Gerard M. Faeth
University of Michigan, Ann Arbor; Ann Arbor, MI
Flow/Soot Formation in Nonbuoyant Laminar Diffusion Flames
Combustion Science

Gerard M. Faeth
University of Michigan, Ann Arbor; Ann Arbor, MI
Investigation of Laminar Jet Diffusion Flames in Microgravity: A Paradigm for Soot Processes in Turbulent Flames
Combustion Science

Gerard M. Faeth
University of Michigan, Ann Arbor; Ann Arbor, MI
Soot Processes in Freely Propagating Laminar Premixed Flames
Combustion Science

James B. Grotberg
University of Michigan, Ann Arbor; Ann Arbor, MI
Capillary-Elastic Instabilities in Microgravity
Fluid Physics

Ronald Larson
University of Michigan, Ann Arbor; Ann Arbor, MI
Microscopic Visualization of Fluid Flow in Evaporating Droplets and Electro-Osmotic Flows
Fluid Physics

Laura R. McCabe
Michigan State University; East Lansing, MI
Microgravity Regulation of Oncogene Expression and Osteoblast Differentiation
Biotechnology
Marc Perlin
University of Michigan, Ann Arbor; Ann Arbor, MI
On the Boundary Conditions at an Oscillating Contact Line: A Physical/Numerical Experimental Program
Fluid Physics

Marc Perlin
University of Michigan, Ann Arbor; Ann Arbor, MI
Using Nonlinearity and Contact Lines to Control Fluid Flow in Microgravity
Fluid Physics

Michael J. Solomon
University of Michigan, Ann Arbor; Ann Arbor, MI
Aggregation and Gelation in Suspensions of Anisometric Particles: Studies of Colloidal Platelets and Rods
Fluid Physics

Indrek S. Wichman
Michigan State University; East Lansing, MI
Investigation of Diffusion–Flame Tip Instability in Microgravity
Combustion Science

Minnesota

Jeffrey J. Derby
University of Minnesota, Twin Cities; Minneapolis, MN
Atomistic Simulations of Cadmium Telluride: Toward Understanding the Benefits of Microgravity Crystal Growth
Materials Science

Jeffrey J. Derby
University of Minnesota, Twin Cities; Minneapolis, MN
First Principles Calculations of Molten II-IV Compounds and Their Solidification Behavior
Materials Science

Jeffrey J. Derby
University of Minnesota, Twin Cities; Minneapolis, MN
Theoretical Analysis of Three-Dimensional, Transient Convection and Segregation in Microgravity Bridgman Crystal Growth
Materials Science

Mississippi

John A. Pojman
University of Southern Mississippi; Hattiesburg, MS
Transient Interfacial Phenomena in Miscible Polymer Systems
Materials Science

Joe B. Whitehead Jr.
University of Southern Mississippi; Hattiesburg, MS
Phase Separation and Self-Assembly of Liquid Crystals and Polymer Dispersions: A Ground-Based Feasibility Study for Microgravity
Materials Science

W. W. Wilson
Mississippi State University; Mississippi State, MS
Novel Approaches Regarding Protein Solubility
Biotechnology

Missouri

Richard L. Axelbaum
Washington University, St. Louis; St. Louis, MO
Flame Design — A Novel Approach to Clean, Efficient Diffusion Flames
Combustion Science

Richard L. Axelbaum
Washington University, St. Louis; St. Louis, MO
Gas-Phase Combustion Synthesis of Metal and Ceramic Nanoparticles
Combustion Science

Delbert E. Day
University of Missouri, Rolla; Rolla, MO
Kinetics of Nucleation and Crystal Growth in Glass-Forming Melts in Microgravity
Materials Science

Kenneth F. Kelton
Washington University, St. Louis; St. Louis, MO
Phase Formation and Stability: Sample Size Effects
Materials Science

Kenneth F. Kelton
Washington University, St. Louis; St. Louis, MO
Studies of Nucleation and Growth, Specific Heat and Viscosity of Undercooled Melts of Quasicrystals and Polytetrehedral Phase–Forming Alloys
Materials Science

New Hampshire

Christopher J. Crowley
Creare, Inc.; Hanover, NH
Scaling of Multiphase Flow Regimes and Interfacial Behavior at Microgravity
Fluid Physics

Ursula Gibson
Dartmouth College; Hanover, NH
In-Situ Optical Waveguides for Promoting and Monitoring Protein Crystal Growth
Biotechnology

New Jersey

Paul M. Chaikin
Princeton University; Princeton, NJ
The Control and Dynamics of Hard-Sphere Colloidal Dispersions
Fluid Physics

Edward L. Dreizin
New Jersey Institute of Technology; Newark, NJ
In Reactive Molten Metal–Based Systems
Materials Science

Edward L. Dreizin
New Jersey Institute of Technology; Newark, NJ
Interaction of Burning Metal Particles
Combustion Science

Benjamin J. Glasser
Rutgers University; Piscataway, NJ
Effects of Gravity on the Mechanics of Fluidized Beds
Fluid Physics

Chung K. Law
Princeton University; Princeton NJ
Structure and Response of Spherical Diffusion Flames
Combustion Science

Chung K. Law
Princeton University; Princeton, NJ
Aerodynamics and Chemical Kinetics of Premixed Flames at High Pressures
Combustion Science

Dudley A. Saville
Princeton University; Princeton, NJ
Electrohydrodynamic Flows in Electrochemical Systems
Fluid Physics

Dudley A. Saville
Princeton University; Princeton, NJ
Electrohydrodynamics of Suspensions
Biotechnology

Dudley A. Saville
Princeton University; Princeton, NJ
Studies in Electrohydrodynamics
Fluid Physics

New Mexico

Stephen T. Boyd
University of New Mexico; Albuquerque, NM
New Phenomena in Strongly Counterflowing He-II Near Tl
Fundamental Physics

Jeremiah U. Brackbill
Los Alamos National Laboratory; Los Alamos, NM
Dynamic Modeling of the Microgravity Flow
Fluid Physics

Robert V. Duncan
University of New Mexico; Albuquerque, NM
Critical Dynamics in Microgravity
Fundamental Physics

Eiichi Fukushima
New Mexico Resonance; Albuquerque, NM
A Robust Magnetic Resonance Imager for Ground- and Flight-Based Measurements of Fluid Physics Phenomena
Fluid Physics

Daniel J. Kane
Southwest Sciences, Inc.; Santa Fe, NM
Real-Time, Quantitative, Three-Dimensional Imaging of Diffusion-Flame Species
Combustion Science

Joel A. Silver
Southwest Sciences, Inc.; Santa Fe, NM
Quantitative Species Measurements in Microgravity Combustion Flames
Combustion Science

New York

Andreas Acrivos
City College of the City University of New York; New York City, NY
The Synergism of Electrorheological Response, Dielectrophoresis, and Shear-Induced Diffusion in Flowing Suspensions
Fluid Physics

C. T. Avedisian
Cornell University; Ithaca, NY
High-Pressure Combustion of an Unsupported Sooting Fuel Droplet in Microgravity
Combustion Science

Jeffrey A. Bell
NYS Department of Health; Albany, NY
Protein Crystal–Based Nanomaterials
Biotechnology

George T. DeTitta
Hauptman-Woodward Medical Research Institute; Buffalo, NY
Macromolecular Crystallization: Physical Principles, Passive Devices, and Optimal Protocols
Biotechnology

Michael Dudley
State University of New York, Stony Brook; Stony Brook, NY
White Beam X-Ray Topography and High-Resolution, Triple Axis, X-Ray Diffraction Characterization
Materials Science

Peyman Givi
State University of New York, Buffalo; Buffalo, NY
Large Eddy Simulation of Gravitational Effects on Transitional and Turbulent Gas-Jet Diffusion Flames
Combustion Science

Martin E. Glicksman
Rensselaer Polytechnic Institute; Troy, NY
Evolution of Local Microstructures (ELMS): Spatial Instabilities of Coarsening Clusters
Materials Science

Martin E. Glicksman
Rensselaer Polytechnic Institute; Troy, NY
Follow-On Research Activities for the Rensselaer Isothermal Dendritic Growth Experiment
Materials Science

James T. Jenkins
Cornell University; Ithaca, NY
Particle Segregation in Collisional Shearing Flows
Fluid Physics

James T. Jenkins
Cornell University; Ithaca, NY
Sheet Flows, Avalanches, and Dune Evolution on Earth and Mars
Fluid Physics

Donald L. Koch
Cornell University; Ithaca, NY
Turbulence-Induced Coalescence of Aerosol Particles
Fluid Physics

Joel Koplik
City College of the City University of New York; New York, NY
Molecular Dynamics of Fluid-Solid Systems
Fluid Physics

David J. Larson Jr.
State University of New York, Stony Brook; Stony Brook, NY
Defects Numerically Decreased (DENUDE)
Materials Science

David J. Larson Jr.
State University of New York, Stony Brook; Stony Brook, NY
Orbital Processing of Eutectic Rod-Like Arrays (OPERA)
Materials Science

David M. Lee
Cornell University; Ithaca, NY
Studies of Atomic Free Radicals Stored in a Cryogenic Environment
Fundamental Physics

Sung P. Lin
Clarkson University; Potsdam, NY
Absolute and Convective Instability and Splitting of a Liquid Jet at Microgravity
Fluid Physics

Michel Y. Louge
Cornell University; Ithaca, NY
Studies of Gas-Particle Interactions in a Microgravity Flow Cell
Fluid Physics

Charles Maldarelli
City College of the City University of New York; New York, NY
Using Surfactants to Enhance Thermocapillary Migration Bubbles and Drops and Facilitate Drop Spreading on Hydrophobic Surfaces
Fluid Physics

Andreas Martin
Mount Sinai Medical Center; New York, NY
Thyroid Follicle Formation in Microgravity: Three-Dimensional Organoid Construction in a Low-Shear Environment
Biotechnology

Carlo D. Montemagno
Cornell University; Ithaca, NY
Engineering Control of a Biomolecular, Motor-Powered, Nanochemical Device
Biotechnology

Aleksandar G. Ostrogorsky
Rensselaer Polytechnic Institute; Troy, NY
Space- and Ground-Based Crystal Growth Using a Baffle (CGB)
Materials Science

Jeevak M. Parpia
Cornell University; Ithaca, NY
The Effect of Thermal History, Temperature Gradients, and Gravity on Capillary Condensation of Phase Separated Liquid

^{3}He-^{4}He Mixtures in Aerogel
Fundamental Physics

Miriam H. Rafailovich
State University of New York, Stony Brook; Stony Brook, NY
Microgravity Processing of Polymer Thin Films
Materials Science

Liya L. Regel
Clarkson University; Potsdam, NY
Improved Crystal Quality by Detached Solidification in Microgravity
Materials Science

W. M. Saltzman
Cornell University; Ithaca, NY
Enhancement of Cell Function in Culture by Controlled Aggregation Under Microgravity Conditions
Biotechnology

Ashok S. Sangani
Syracuse University; Syracuse, NY
Rapidly Sheared Bubbly Suspensions
Fluid Physics

Albert J. Sievers
Cornell University; Ithaca, NY
Influence of Homogeneity and Fragility on the Dynamical Properties of Glassy Networks
Materials Science

Paul H. Steen
Cornell University; Ithaca, NY
Stability of Shapes Held by Surface Tension and Subjected to Flow
Fluid Physics

Robert E. Thorne
Cornell University; Ithaca, NY
Defects, Growth, and Elastic Properties of Protein Crystals
Biotechnology

Robert E. Thorne
Cornell University; Ithaca, NY
Impurity Effects in Macromolecular Crystal Growth
Biotechnology

Peter C. Wayner Jr.
Rensselaer Polytechnic Institute; Troy, NY
A Study of the Constrained Vapor Bubble Heat Exchanger
Fluid Physics

Peter C. Wayner Jr.
Rensselaer Polytechnic Institute; Troy, NY
Theoretical and Experimental Investigation of the Stability of a Evaporating Constrained-Vapor Bubble
Fluid Physics

William R. Wilcox
Clarkson University; Potsdam, NY
Residual Gas Effects on Detached Solidification in Microgravity
Materials Science

William R. Wilcox
Clarkson University; Potsdam, NY
Use of Microgravity to Control the Microstructure of Eutectics
Materials Science

H. A. Wood
Cornell University; Ithaca, NY
The Effects of Microgravity/Low Shear on Glycosylation and Eukaryotic DNA Virus Replication
Biotechnology

J. H. D. Wu
University of Rochester; Rochester, NY
Ex-Vivo Hemopoieses in a Three-Dimensional Human Bone Marrow Culture Under Simulated Microgravity
Biotechnology

Nicholas J. Zabaras
Cornell University; Ithaca, NY
On the Control of the Effects of Gravity on the Solidification Microstructures Using Optimally Designed Thermal Boundary Fluxes and Electromagnetic Fields
Materials Science

North Carolina

Klaus J. Bachmann
North Carolina State University; Raleigh, NC
Fundamental Aspects of Vapor Deposition and Etching Under Diffusion-Controlled Transport Conditions
Materials Science

Robert P. Behringer
Duke University; Durham, NC
Dynamics of Granular Materials
Fluid Physics

Robert P. Behringer
Duke University; Durham, NC
Gravity and Granular Materials
Fluid Physics

Jerry Bernholc
North Carolina State University; Raleigh, NC
Growth and Properties of Carbon Nanotubes
Materials Science

Charles W. Carter
University of North Carolina, Chapel Hill; Chapel Hill, NC
Quantitative Multivariate Methods for Pre-Flight Optimization and Post-Flight Evaluation of Macromolecular Crystal Growth
Biotechnology

William E. Kraus
Duke University Medical Center; Durham, NC
Differentiation and Maintenance of Skeletal and Cardiac Muscle in Simulated Microgravity
Biotechnology

William E. Kraus
Duke University Medical Center; Durham, NC
Regulation of Skeletal Muscle Development and Differentiation In Vitro by Mechanical and Chemical Factors
Biotechnology

Nancy Ma
North Carolina State University; Raleigh, NC
Models of Mass Transport During Microgravity Crystal Growth of Alloyed Semiconductors in a Magnetic Field
Materials Science

Horst Meyer
Duke University; Durham, NC
Density Equilibration in Fluids Near the Liquid-Vapor Critical Point
Fundamental Physics

Ohio

J. Iwan D. Alexander
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Case Western Reserve University; Cleveland, OH
Dynamics and Statics of Nonaxisymmetric Liquid Bridges
Fluid Physics

J. Iwan D. Alexander
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH;
Case Western Reserve University; Cleveland, OH
Vibrations and G-Jitter: Transport Disturbances Due to Residual Acceleration During Low-Gravity Directional Solidification Experiments
Materials Science

C. D. Andereck
Ohio State University; Columbus, OH
Ultrasonic Thermal Field Imaging of Opaque Fluids
Fluid Physics

Ramaswamy Balasubramaniam
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Glenn Research Center; Cleveland, OH
Instability of Miscible Interfaces
Fluid Physics

Joanne M. Belovich
Cleveland State University; Cleveland, OH
An Acoustically Assisted Bioreactor for Terrestrial and Microgravity Applications
Biotechnology

Gloria Borgstahl
University of Toledo; Toledo, OH
Searching for the Best Protein Crystals: Synchrotron-Based Mosaicity Measurements of Crystal Quality and Theoretical Modeling
Biotechnology

Daniel L. Dietrich
Glenn Research Center; Cleveland, OH
Candle Flames in Microgravity (CFM)
Combustion Science

Daniel L. Dietrich
Glenn Research Center; Cleveland, OH
Combustion of Interacting Droplet Arrays in a Microgravity Environment
Combustion Science

Prabir K. Dutta
Ohio State University; Columbus, OH
Fundamental Studies of Crystal Growth of Microporous Materials
Materials Science

Prabir K. Dutta
Ohio State University; Columbus, OH
Reverse Micelle–Based Synthesis of Microporous Materials in Microgravity
Materials Science

Walter M. Duval
Glenn Research Center; Cleveland, OH
Stereo-Imaging Velocimetry of Mixing Driven by Buoyancy-Induced Flow Fields
Fluid Physics

Paul Ferkul
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Thickness Effects on Fuel Flammability
Combustion Science

Bing Gong
University of Toledo; Toledo, OH
A New Class of Unnatural Folding Oligomers: Helices With Nano-Sized Cavities
Biotechnology

DeVon W. Griffin
Glenn Research Center; Cleveland, OH
Phase-Shifting Point Diffraction Interferometer for Microgravity Fluid Physics
Fluid Physics

Prabhat K. Gupta
Ohio State University; Columbus, OH
Interdiffusion in the Presence of Free Convection
Materials Science

Uday Hegde
Glenn Research Center; Cleveland, OH
Characteristics of Non-Premixed Turbulent Flames in Microgravity
Combustion Science

Tin-Lun Ho
Ohio State University; Columbus, OH
Gravitational Effects in Bose-Einstein Condensate of Atomic Gases
Fundamental Physics

John H. Hughes
Ohio State University; Columbus, OH
The Effects of Microgravity on Viral Replication
Biotechnology

Donald T. Jacobs
The College of Wooster; Wooster, OH
Turbidity and Universality Around a Liquid-Liquid Critical Point
Fundamental Physics

Yasuhiro Kamotani
Case Western Reserve University; Cleveland, OH
Bubble Generation in a Flowing Liquid Medium and Resulting Two-Phase Flow in Microgravity
Fluid Physics

Yasuhiro Kamotani
Case Western Reserve University; Cleveland, OH
Gas-Evolution Effect on Mass Transfer in Rotating Electrochemical Cells Under Microgravity Conditions
Fluid Physics

Mohammad Kassemi
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Bubble Dynamics on a Heated Surface
Fluid Physics

Mohammad Kassemi
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Determination of Gravity-Related Effects in Crystal Growth From Melts With an Immiscibility Gap
Materials Science

Mohammad Kassemi
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Effect of Marangoni Convection Generated by Voids on Segregation During Low-g and 1-g Solidification
Materials Science

William B. Krantz
University of Cincinnati; Cincinnati, OH
Microscopic Flow Visualization in Demixing Fluids During Polymeric Membrane Formation in Low-G
Fluid Physics

David H. Matthiesen
Case Western Reserve University; Cleveland, OH
Diffusion Processes in Molten Semiconductors (DPIMS)
Materials Science

John McQuillen
Glenn Research Center; Cleveland, OH
A Study of Bubble and Slug Gas-Liquid Flow in a Microgravity Environment
Fluid Physics

John McQuillen
Glenn Research Center; Cleveland, OH
Study of Two Phase Gas-Liquid Flow Behavior at Reduced-Gravity Conditions
Fluid Physics

Fletcher J. Miller
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Gravitational Influences on Flame Propagation Through Nonuniform Premixed Gas Systems (Layers)
Combustion Science

Vedha Nayagam
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Dynamics of Droplet Combustion and Extinction in a Slow Convective Flow (DDCE)
Combustion Science

Vedha Nayagam
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Stretched Diffusion Flames in Von Karman Swirling Flows
Combustion Science

Sandra L. Olson
Glenn Research Center; Cleveland, OH
Low-Stretch Diffusion Flames Over a Solid Fuel
Combustion Science

Simon Ostrach
Case Western Reserve University; Cleveland, OH
Industrial Processes Influenced by Gravity
Fluid Physics

Howard G. Pearlman
Glenn Research Center; Cleveland, OH
The High-Lewis Number Diffusive-Thermal Instability in Premixed Gas Combustion and Low-Temperature Hydrocarbon Oxidation and Cool Flames
Combustion Science

Charles S. Rosenblatt
Case Western Reserve University; Cleveland, OH
Determination of the Surface Energy of Liquid Crystals From the Shape Anisotropy of Freely Suspended Droplets
Materials Science

Howard D. Ross
Glenn Research Center; Cleveland, OH
Ignition and Flame Spread of Liquid Fuel Pools
Combustion Science

Kurt R. Sacksteder
Glenn Research Center; Cleveland, OH
Flame Spreading and Extinction in Partial-Gravity Environments
Combustion Science

Constance A. Schall
University of Toledo; Toledo, OH
Influence of Impurities on Protein Crystal Growth

Biotechnology

Peter B. Sunderland
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Glenn Research Center; Cleveland, OH
Investigation of Velocity and Temperature in Microgravity Laminar Jet-Diffusion Flames
Combustion Science

James S. T'ien
Case Western Reserve University; Cleveland, OH
Combustion of Solid Fuel in Very Low-Speed Oxygen Streams
Combustion Science

Fumiaki Takahashi
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Reaction Kernel Structure and Diffusion-Flame Stabilization
Combustion Science

Padetha Tin
Glenn Research Center; Cleveland, OH
Interfacial Energy Determination of Succinonitrile and Succinonitrile-Acetone Alloy Using Surface Light–Scattering Spectrometer
Materials Science

Randall L. Vander Wal
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
Splashing Droplets
Fluid Physics

Randall L. Vander Wal
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH
The Synthesis of Graphite-Encapsulated Metal Nanoparticles and Metal Catalytic Nanotubes
Combustion Science

Nengli Zhang
Ohio Aerospace Institute; Cleveland, OH
Glenn Research Center; Cleveland, OH
Enhanced Boiling on Micro-Configured Composite Surfaces Under Microgravity Conditions
Fluid Physics

Oklahoma

Ajay K. Agrawal
University of Oklahoma; Norman, OK
Gravitational Effects on Flow Instability and Transition in Low-Density Jets
Fluid Physics

M. C. Altan
University of Oklahoma; Norman, OK
Microgravity Impregnation of Fiber Preforms
Materials Science

Feng C. Lai
University of Oklahoma; Norman, OK
Enhancement of Microgravity Fiber Impregnation Using Electrohydrodynamic Induction Pumping
Fluid Physics

Ramkumar Parthasarathy
University of Oklahoma; Norman, OK
Instability and Breakup of Gas Jets Injected in Coflowing Liquids
Fluid Physics

Penger Tong
Oklahoma State University; Stillwater, OK
Studies of Particle Sedimentation by Novel Scattering Techniques
Fluid Physics

Pennsylvania

Portonovo S. Ayyaswamy
University of Pennsylvania; Philadelphia, PA
The Use of Bioactive Glass Particles as Microcarriers in Microgravity Environment
Biotechnology

Mun Y. Choi
Drexel University; Philadelphia, PA
Experiments and Model Development for Investigation of Sooting and Radiation Effects in Microgravity Droplet Combustion (SEDC)
Combustion Science

Lance R. Collins
Pennsylvania State University; University Park, PA
Dynamics of Aerosol Particles in Stationary, Isotropic Turbulence
Fluid Physics

Paul Ducheyne
University of Pennsylvania; Philadelphia, PA
Surface Transformation of Reactive Glass in a Microgravity Environment
Materials Science

Stephen Garoff
Carnegie Mellon University; Pittsburgh, PA
Microscale Hydrodynamics Near Moving Contact Lines
Fluid Physics

Randall M. German
Pennsylvania State University; University Park, PA
Gravitational Effects on Distortion in Sintering
Materials Science

Daniel A. Hammer
University of Pennsylvania; Philadelphia, PA
Engineering of Novel Biocolloidal Suspensions
Fluid Physics

Daniel A. Hammer
University of Pennsylvania; Philadelphia, PA
Polymosomes: Tough Giant Vesicles From Block Copolymers
Materials Science

Peter I. Lelkes
Drexel University; Philadelphia, PA
PC12 Pheochromocytoma Cells: A Proven Model System for Optimizing Three-Dimensional Cell Culture Biotechnology in Space
Biotechnology

Elliot M. Levine
The Wistar Institute; Philadelphia, PA
Multidisciplinary Studies of Cells, Tissues, and Mammalian Development in Simulated Microgravity
Biotechnology

Patrick J. Loll
University of Pennsylvania School of Medicine; Philadelphia, PA
Quantitative Analysis of Surfactant Interactions During Membrane Protein Crystallization
Biotechnology

Gregory S. Rohrer
Carnegie Mellon University; Pittsburgh, PA
Shape Evolution of Small Ceramic Materials
Materials Science

Gary A. Ruff
Drexel University; Philadelphia, PA
Combustion of Unconfined Droplet Clusters in Microgravity
Combustion Science

Peter Schiffer
Pennsylvania State University; University Park, PA
Experimental and Theoretical Studies of Wet Granular Media
Fluid Physics

Robert F. Sekerka
Carnegie Mellon University; Pittsburgh, PA
Lattice Boltzmann Computations of Binary Diffusion in Liquids Under Stochastic Microgravity
Materials Science

Paul J. Sides
Carnegie Mellon University; Pittsburgh, PA
Lateral Motion of Particles and Bubbles Caused by Phoretic Flows Near a Solid Interface
Fluid Physics

Jogender Singh
Pennsylvania State University; University Park, PA
Gravitational Effect on the Development of Laser Weld–Pool and Solidification Microstructure
Materials Science

John M. Tarbell
Pennsylvania State University; University Park, PA
Microgravity Effects on Transendothelial Transport
Fluid Physics

Xiao-lun Wu
University of Pittsburgh; Pittsburgh, PA
Forced Two-Dimensional Turbulence in Freely Suspended Films
Fluid Physics

Xiao-lun Wu
University of Pittsburgh; Pittsburgh, PA
Freely Suspended Liquid Films and Their Applications in Biological Research
Biotechnology

Arjun G. Yodh
University of Pennsylvania; Philadelphia, PA
Colloidal Assembly in Entropically Driven, Low Volume–Fraction Binary Particle Suspensions
Fluid Physics

Rhode Island

Charles Elbaum
Brown University; Providence, RI
Kinetic and Thermodynamic Studies of Melting-Freezing of Helium in Microgravity
Fundamental Physics

Mohammad Faghri
University of Rhode Island; Kingston, RI
Phase Change in Low- and Jittering-Gravity Environment Simulated via Electromagnetic Field
Fluid Physics

George M. Seidel
Brown University; Providence, RI
Dynamics and Morphology of Superfluid Helium Drops in a Microgravity Environment
Fundamental Physics

South Carolina

Adam J. Smolka
Medical University of South Carolina; Charleston, SC
Gastric Mucosal Cell Culture in Simulated Microgravity
Biotechnology

Tennessee

Robert J. Bayuzick
Vanderbilt University; Nashville, TN
Investigation of the Relationship Between Undercooling and Solidification Velocity
Materials Science

Gerard J. Bunick
University of Tennessee, Oak Ridge; Oak Ridge, TN
Reversible Cryogenic Storage of Macromolecular Crystals Grown in Microgravity
Biotechnology

Kenneth Debelak
Vanderbilt University; Nashville, TN
Recovery of Minerals in Martian Soils via Supercritical Fluid Extraction
Materials Science

Andrienne C. Friedli
Middle Tennessee University; Murfreesboro, TN
Development of Anionic Polyelectrolytes for Solid State Battery Applications
Materials Science

William H. Hofmeister
Vanderbilt University; Nashville, TN
Microgravity Processing of Oxide Superconductors
Materials Science

M. Douglas LeVan
Vanderbilt University; Nashville, TN
Separation of Carbon Monoxide From Carbon Dioxide for Mars ISRU
Fluid Physics

Alvin J. Sanders
University of Tennessee, Knoxville; Knoxville, TN
Research and Analysis in Support of Project SEE (Satellite Energy Exchange): Test of the Equivalence Principle and Measurement of Gravitational Interaction Parameters in an Ultra-Precise Microgravity Environment
Fundamental Physics

Lawrence W. Townsend
University of Tennessee, Knoxville; Knoxville, TN
Development of a Monte Carlo Radiation Transport Code System for HEDS
Materials Science

Texas

John G. Albright
Texas Christian University; Fort Worth, TX
Experimental Assessment of Multicomponent Effects in Diffusion-Dominated Transport in Protein Crystal Growth and Electrophoresis and Chiral Separations
Biotechnology

Vemuri Balakotaiah
University of Houston; Houston, TX
Two-Phase Gas-Liquid Flows in Microgravity: Experimental and Theoretical Investigation of the Annular Flow
Fluid Physics

Vimlarani Chopra
University of Texas Medical Branch, Galveston; Galveston, TX
Differentiation of Three-Dimensional Cocultures of Myofibroblasts, Preneoplastic Epithelial, and Mononuclear Cells
Biotechnology

Noel T. Clemens
University of Texas, Austin; Austin, TX
Investigation of Strain/Vorticity and Large-Scale Flow Structure in Turbulent Nonpremixed Jet Flames
Combustion Science

Gerard L. Cote
Texas A&M University; College Station, TX
Investigation of Neuronal Physiology in Simulated Microgravity Using Smart Fluorescent Microcarriers and Bulk Near-Infrared Sensors
Biotechnology

Gerard L. Cote
Texas A&M University; College Station, TX
Noninvasive Near-Infrared Sensor for Continual Cell Glucose Measurement
Biotechnology

Jonathan M. Friedman
University of Houston; Houston, TX
Epitaxial Growth of Protein Crystals on Self-Assembled Monolayers
Biotechnology

Steve R. Gonda
Johnson Space Center; Houston, TX
A Microgravity-Based, Three-Dimensional Transgenic Cell Model to Quantify Genotoxic Effects in Space

Biotechnology

Steve R. Gonda
Johnson Space Center; Houston, TX
Microgravity-Based Three-Dimensional Transgenic Cell Models
Biotechnology

Thomas J. Goodwin
Johnson Space Center; Houston, TX
Lymphocyte Invasion Into Tumor Models Emulated Under Microgravity Conditions In Vitro
Biotechnology

Elizabeth A. Grimm
University of Texas M. D. Anderson Cancer Center; Houston, TX
Application of Bioreactor Technology for Analysis and Counter Measure Development of Microgravity-Induced Suppression of Innate Immunity
Biotechnology

Elizabeth A. Grimm
University of Texas M. D. Anderson Cancer Center; Houston, TX
Application of Bioreactor Technology for a Preclinical Human Model of Melanoma
Biotechnology

Naomi J. Halas
Rice University; Houston, TX
Metal Nanoshell Functionalization and Materials Assembly: Effects of Microgravity Conditions
Materials Science

Daniel J. Heinzen
University of Texas, Austin; Austin, TX
Precision Measurements With Trapped, Laser-Cooled Atoms in a Microgravity Environment
Fundamental Physics

Randall G. Hulet
Rice University; Houston, TX

A Quantum Degenerate Fermi Gas of ^{6}*Li Atoms*
Fundamental Physics

J. M. Jessup
University of Texas Health Science Center, San Antonio; San Antonio, TX
Growth, Metabolism, and Differentiation of MIP-101 Carcinoma Cells
Biotechnology

J. M. Jessup
University of Texas Health Science Center, San Antonio; San Antonio, TX
Use of NASA Bioreactor to Study Cell Cycle Regulation
Biotechnology

Philip C. Johnson
University of Texas Medical School, Houston; Houston, TX
Use of Rotating Wall Vessel (RWV) to Facilitate Culture of Norwalk Virus
Biotechnology

Anil D. Kulkarni
University of Texas Health Science Center, Houston; Houston, TX
Nutritional Immunomodulation in Microgravity: Application of Ground-Based In-Vivo and In-Vitro Bioreactor Models to Study Role and Mechanisms of Supplemental Nucleotides
Biotechnology

Neal R. Pellis
Johnson Space Center; Houston, TX
Microgravity and Immunosuppression: A Ground-Based Model in the Slow-Turning Lateral Vessel Bioreactor
Biotechnology

Lawrence S. Pinsky
University of Houston; Houston, TX
Development of a Space Radiation Monte Carlo Simulation Based Upon The FLUKA and ROOT Codes
Materials Science

Arun S. Rajan
Baylor College of Medicine; Houston, TX
Islet Cell Assembly and Function in a NASA Microgravity Bioreactor
Biotechnology

Lynne P. Rutzky
University of Texas Health Science Center, Houston; Houston, TX
Impact of Microgravity on Immunogenicity Associated With Biostructural Changes in Pancreatic Islets
Biotechnology

Cherylyn A. Savary
University of Texas M. D. Anderson Cancer Center; Houston, TX
Use of NASA Bioreactors in a Novel Scheme for Immunization Against Cancer
Biotechnology

Jamal Seyed-Yagoobi
Texas A&M University; College Station, TX
Thermal Control and Enhancement of Heat Transport Capacity of Cryogenic Capillary-Pumped Loops and Heat Pipes With Electrohydrodynamics
Fluid Physics

Glenn F. Spaulding
Clear Lake Medical Foundation, Inc.; Houston, TX
Application of pH, Glucose, and Oxygen Biosensors to NASA Rotating Culture Vessels
Biotechnology

Harry L. Swinney
University of Texas, Austin; Austin, TX
Instabilities in Surface Tension–Driven Convection
Fluid Physics

Philip Varghese
University of Texas, Austin; Austin, TX
Laser Velocimeter for Studies of Microgravity Combustion Flowfields
Combustion Science

Theodore G. Wensel
Baylor College of Medicine; Houston, TX
Two-Dimensional Crystal Growth in Microgravity
Biotechnology

Boris Yoffe
Baylor College of Medicine; Houston, TX
Liver Tissue Engineering in Microgravity Environment
Biotechnology

Utah

Jules J. Magda
University of Utah; Salt Lake City, UT
Novel Microstructures for Polymer-Liquid Crystal Composite Materials
Materials Science

William E. Mell
University of Utah; Salt Lake City, UT
Simulation of Combustion Systems With Realistic G-Jitter
Combustion Science

Virginia

Harsha K. Chelliah
University of Virginia; Charlottesville, VA
Heterogeneous Combustion of Porous Solid-Fuel Particles Under Microgravity: A Comprehensive Theoretical and Experimental Study
Combustion Science

Leland W. Chung
University of Virginia; Charlottesville, VA
Microgravity-Simulated Prostate Cell Culture
Biotechnology

Leland W. Chung
University of Virginia; Charlottesville, VA
Modeling Prostate Cancer Skeletal Metastasis and Gene Therapy
Biotechnology

M. S. El-Shall
Virginia Commonwealth University; Richmond, VA
Gas-Phase Polymerization and Nucleation Experiments in Microgravity
Materials Science

M. S. El-Shall
Virginia Commonwealth University; Richmond, VA
Studies on Nucleation, Polymerization, and Nanoparticle Composites in Supersaturated Vapors Under Microgravity Conditions
Materials Science

Michael C. Wiener
Health Sciences Center; Charlottesville, VA
Membrane Protein Crystallization Screens Based Upon Fundamental Phenomenology of Detergent and Protein-Detergent Solutions
Biotechnology

John Wilson
Langley Research Center; Hampton, VA
Improved Spacecraft Materials for Radiation Shielding
Materials Science

Washington

E. J. Davis
University of Washington; Seattle, WA
Phoretic and Radiometric Force Measurements on Microparticles Under Microgravity Conditions
Fluid Physics

Ben Q. Li
Washington State University; Pullman, WA
A Comparative Modeling Study of Magnetic and Electrostatic Levitation in Microgravity
Materials Science

Ben Q. Li
Washington State University; Pullman, WA
Study of Magnetic Damping Effect on Convection and Solidification Under G-Jitter Conditions
Materials Science

Ben Q. Li
Washington State University; Pullman, WA
Study of Magnetic Field Effects on Convection and Solidification in Normal- and Microgravity
Materials Science

Philip L. Marston
Washington State University; Pullman, WA
Passive and Active Stabilization of Liquid Bridges in Low Gravity

Fluid Physics

Philip L. Marston
Washington State University; Pullman, WA
Passive or Active Radiation Stress Stabilization of (and Coupling to) Liquid Bridges and Bridge Networks
Fluid Physics

Philip L. Marston
Washington State University; Pullman, WA
Single-Bubble Sonoluminescence in Low Gravity and Optical Radiation Pressure Positioning of the Bubble
Fluid Physics

Thomas J. Matula
University of Washington; Seattle, WA
Buoyancy-Driven Instabilities in Single-Bubble Sonoluminescence
Fluid Physics

Warren Nagourney
University of Washington; Seattle, WA
Indium Mono-Ion Oscillator II
Fundamental Physics

Viola Vogel
University of Washington; Seattle, WA
Motor Proteins as Shuttles for Directed Transport in Synthetic Matrices
Biotechnology

Wisconsin

Reid F. Cooper
University of Wisconsin, Madison; Madison, WI
Dynamic Reduction and the Creation of Fine-Grained Ceramics From Inviscid Oxide/Silicate Melts
Materials Science

Sindo Kou
University of Wisconsin, Madison; Madison, WI
Physical Simulation of Marangoni Convection in Weld Pools
Materials Science

Sindo Kou
University of Wisconsin, Madison; Madison, WI
Thermocapillary Convection in Low Pr Materials Under Simulated Reduced-Gravity Conditions
Fluid Physics

John H. Perepezko
University of Wisconsin, Madison; Madison, WI
Analysis of Containerless Processing and Undercooled Solidification Microstructures
Material Science

John H. Perepezko
University of Wisconsin, Madison; Madison, WI
Analysis of Containerless Solidification Microstructures in Undercooled Melts and Composite Systems
Materials Science

Eric E. Rice
Orbital Technologies Corporation; Madison, WI
Carbon-Based Reduction of Lunar Regolith (CRLR)
Materials Science

Eric E. Rice
Orbital Technologies Corporation; Madison, WI
Development of Methods for Producing and Utilizing Alternate Fuel/Oxidizer Combinations Associated With Mars to Support ISRU-Based Propulsion and Power Systems
Combustion Science

District of Columbia

Glenn R. Joyce
Naval Research Laboratory; Washington, DC
Modeling Dusty Plasmas in Microgravity
Fluid Physics

John H. Konnert
Naval Research Laboratory; Washington, DC
Applications of Atomic Force Microscopy (AFM) to Investigate Mechanisms of Protein Crystal Growth
Biotechnology

Keith B. Ward
Naval Research Laboratory; Washington, DC
Investigation of the Particle Dynamics in the Vicinity of Crystal Surfaces: Depletion Zone Dynamics
Biotechnology

APPENDIX B:

Microgravity Experiment Hardware Flights to the International Space Station

Below are two lists of selected payloads for the International Space Station (ISS) and the associated EXPRESS (Expedite Processing of Experiments to Space Station) racks and microgravity facilities in the order of their flight to the station. Early on, microgravity research is limited to EXPRESS payloads and Microgravity Science Glovebox investigations, 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: This apparatus is a GN_2 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. (Next flight: 5A)

Microgravity Acceleration Measurement System (MAMS): MAMS provides quasi–steady state microgravity acceleration levels at low frequencies (0.01 to 2 Hz) with extreme accuracy. It is an enhanced version of the Orbital Acceleration Research Experiment space shuttle system. 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 will be an early addition to the ISS and will most likely remain onboard for the life of the station. SAMS-II will measure vibratory accelerations (transients) in support of a variety of microgravity science experiments. It will also characterize 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 VDA-2, DCAM, and PCAM. (First flight: 6A)

Protein Crystal Growth — Biotechnology Ambient Generic (PCG-BAG): This apparatus flies PCAM, DCAM, or VDA-2 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 trays, the PCG-BAG holds six trays. (First flight: 6A, as part of the PCG-STES)

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: To be determined)

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, to provide 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 command and data management 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)

Lab Support Equipment — Digital Thermometer: This instrument is an off-the-shelf digital thermometer that will be used by ISS payloads to measure temperatures by utilizing a variety of thermocouple probes. (First flight: 7A.1)

Biotechnology Specimen Temperature Controller (BSTC): This apparatus will provide 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. BSTC will operate primarily in the incubation mode. The Biotechnology Refrigerator (BTR), Biotechnology Cell Science Stowage (BCSS), and the Gas Supply Module (GSM) support BSTC research. (First flight: 7A.1)

Pore Formation and Mobility: This investigation promotes understanding of detrimental pore formation and mobility during controlled directional solidification processing in a microgravity environment. This Microgravity Science Glovebox (MSG) investigation will utilize a transparent material, succinonitrile, so that direct observation and recording of pore generation and mobility during controlled solidification can be made. (First flight: Second Utilization Flight (UF-2))

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: UF-2)

Solidification Using a Baffle in Sealed Ampoules: 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)

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 this investigation will be used to verify the theory that growth rate dispersion plays a role in crystal quality improvement in microgravity. (First flight: First Utilization Logistics Flight (ULF-1)

Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions (InSPACE): InSPACE hardware is being designed to be accommodated by the MSG. Observations of three-dimensional microscopic structures of magnetorheological fluids in a pulsed magnetic field will be made. (First flight: Candidate for 9A)

Coarsening of Solid-Liquid Mixtures-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: Candidate for ULF-1)

Payloads that are planned and/or in development that have not yet been manifested are listed below in alphabetical order.

Colloidal Disorder-Order Transition-2 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 USML–2 and STS-95.

Dynamic Studies of Cellular and Dendritic Interface Pattern Formation: This investigation is designed to provide a fundamental scientific understanding of cellular and dendritic microstructure formation under directional solidification conditions.

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.

Particle Engulfment and Pushing (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.

Wetting Characteristics of Immiscibles (WCI): The WCI investigation, which flew previously in the Middeck Glovebox, will study the effects when two nonmixing alloys are stirred and frozen in normal gravity and then melted and resolidified in microgravity. WCI will be conducted in the MSG.

The Microgravity Research Program Office currently has two candidate unpressurized payloads 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 (the fundamental unit of time, which is tied to the energy difference between two atomic levels in cesium) at an order of magnitude better than that achievable on Earth.

Rubidium Atomic Clock Experiment (RACE): The RACE investigation will interrogate rubidium (^{87}Rb) 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 payload is planned to be flown on the ISS.

Facility for the Study of Crystal Growth and of Fluids Near the Critical Point (DECLIC): The DECLIC facility is being developed by the French space agency (CNES) in cooperation with Glenn Research Center to provide an autonomous or teleoperated capability at middeck locker–scale to accommodate research on high-pressure samples of fluids near the critical point, transparent materials systems during solidification, and other fluids experiments that are compatible with available diagnostics. Through cooperative interagency agreements (negotiated but unsigned at the end of 1999), NASA will provide launch, integration, and resources for DECLIC and will share in the utilization of the facility.