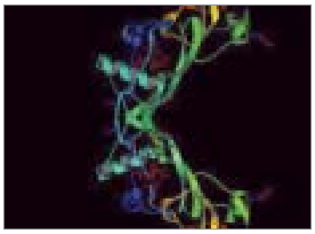
National Aeronautics and
Space Administration

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

ANNUAL REPORT
2003

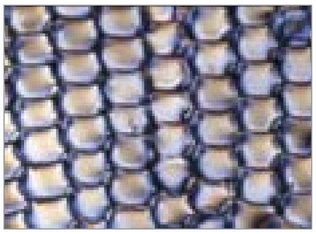
NASA PHYSICAL SCIENCES RESEARCH DIVISION

By integrating bioscience and engineering disciplines, NASA can ensure the safety of humans in space.
See page 4



Biotechnology research helps explain how microgravity and radiation affect humans on a molecular level.
See page 16

Freed of buoyancy, flames in microgravity take on a spherical shape that is easier for scientists to study.
See page 40

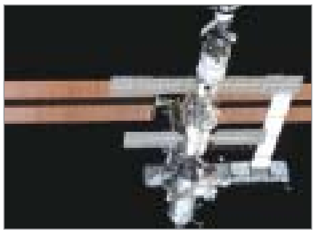


Scientists are learning how to control the passage of light through liquid crystals, shown here as dried droplets.
See page 50

One quest of fundamental physicists is a more precise understanding of the physical laws that govern time.
See page 64

Electrostatic levitation enables scientists to study new alloys without the risk of contamination from containers.
See page 74

Vibrations from spacecraft docking with the International Space Station can disrupt the microgravity research environment.
See page 88



The International Space Station is a gold mine for researchers seeking to conduct experiments in microgravity.
See page 96

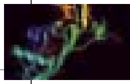
NASA's KC-135 is one of several ground-based facilities that provide researchers with microgravity conditions.
See page 104

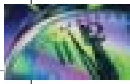
NASA astronauts help inspire the next generation to be scientists and explorers.
See page 106

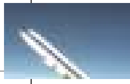
Editor's Note:

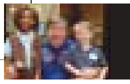
This report covers activity of the Physical Sciences Research Division October 1, 2002–September 30, 2003.

1 Cover Images pg ii
1 Table of Contents pg iii
1 For More Information pg iv
2 Introduction pg 1
3 Bioscience and Engineering pg 4
4 Biotechnology pg 16
5 Combustion Science pg 40
6 Fluid Physics pg 50
7 Fundamental Physics pg 64
8 Materials Science pg 74
9 Acceleration Measurement pg 88
10 International Space Station pg 96
11 Ground-Based Microgravity Facilities pg 104
12 Outreach and Education pg 106
13 Program Resources for FY 2003 pg 120
14 Appendix Microgravity Experiment Hardware pg 121









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

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

Under the direction of the Office of Biological and Physical Research (OBPR), PSR will continue to advance cutting-edge research led by the best scientists in the nation. For more information about OBPR and ongoing microgravity research, contact NASA's Physical Sciences Research Division:

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The heightened anticipation of principal investigators and their NASA collaborators at the launch of the long-awaited STS-107 mission was followed by tremendous excitement when the entire complement of flight experiments was successfully carried out and the return of Space Shuttle *Columbia* promised to bring back a wealth of research data. This did not come to pass, however, as NASA's oldest shuttle perished together with its entire gallant crew in the sky over Texas on February 1, 2003. This single sad event has cast a vast shadow over the entire year as the NASA family and the Physical Sciences Research (PSR) Division community grieved and began to reassess its International Space Station (ISS) research plans.

As the nation awaits the potential redirection of the space program, PSR research activities aboard the ISS have slowed to a minimal pace dictated by the temporary suspension of the space shuttle program. On the other hand, plans for completing the ISS pressurized research facilities for combustion science, materials science, and fluid physics are currently still on track.

In contrast to the temporarily down-scoped ISS flight research activities, ground-based investigators have been prodigiously productive. The grant awards for all the PSR disciplines involved in the 2001 NASA Research Announcement were issued, and resulted in the funding of 53 new investigations in fiscal year (FY) 2003. The work of PSR-funded researchers was featured on the covers of three issues of *Science* magazine and a host of discipline-specific archival publications and received other prestigious recognition in 2003. Among numerous highlights are two notable examples: The July issue of *Physics Today* featured the NASA-developed electrostatic levitation technology that has enabled PSR investigator Kenneth Kelton to experimentally verify a 50-year-old theory describing the process of nucleation of the solid phase in a liquid metal melt, and PSR investigator Wolfgang Ketterle observed the lowest temperature ever reached in any physical system — an astonishing half a nanokelvin — achieved in a cloud of sodium atoms.

The first NASA Research Update sponsored by the Office of Biological and Physical Research took place in 2003 and featured the achievement of PSR investigator Richard Weber, the inventor of a patented glassy material composition enabled by the joint sponsorship of NASA and the National Science Foundation. This feat was noticed by the mainstream press and was the subject of a technology development feature in *Business Week*.

PSR flight research investigators have managed to retrieve 50 to 95 percent of the experimental results from STS-107 through downlinked digital data and video images. The publication of these findings in such diverse disciplines as combustion science, fundamental condensed-matter physics, granular-materials physics, and cellular biotechnology serves as a permanent tribute to the hard work and dedication of the lost *Columbia* crew.

credit: NASA

The PSR program was also an integral part of the *Office of Biological and Physical Research Enterprise Strategy* published in 2003. Road maps guiding PSR activities — both in fundamental research to benefit people on Earth and in strategic research bent on devising unique new technologies essential to the NASA mission of space exploration — have been created to define the program between 2003 and 2016.

As part of an innovative approach, a cross-disciplinary research program has been created to better position PSR for breakthroughs in human space exploration technology and new discoveries from space research. This new NASA Bioscience and Engineering Program teams researchers in chemistry, biology, physics, materials science, and engineering to focus on understanding and controlling biological processes relevant to space-based technologies ensuring the health and safety of spaceflight. In addition, the program is applying newly discovered molecular-scale methods and the theoretical understanding of complex systems to target the molecular processes involved in living systems and relevant to human spaceflight. Active areas of research include transport phenomena in biological systems and devices, tissue bioscience, molecular bioengineering, biomicroelectromechanical systems (bioMEMS), and cellular biomechanics. The NASA Bioscience and Engineering Institute at the University of Michigan, Ann Arbor, was recently selected to be the academic anchor of the program and will team with the existing John Glenn Biomedical Engineering Consortium (Cleveland, Ohio), the intramural NASA biomedical technology arm.

All in all, 2003 was a year of multiple challenges and will be forever marked by the loss of *Columbia*. At the same time, it was a year of scientific achievements as well as programmatic innovation and redefinition. The PSR Division has emerged stronger and more flexible to accomplish the NASA mission to "improve life here, extend life to there, and find life beyond."

Eugene Trinh

— Eugene Trinh
Director, Physical Sciences Research Division

A Tribute to the *Columbia* Crew

credit: NASA

The crew of Columbia*, STS-107 (left to right): David Brown, Rick Husband, Laurel Clark, Kalpana Chawla, Michael Anderson, William McCool, and Ilan Ramon.*
credit: NASA

The crew of Space Shuttle *Columbia* that flew in January 2003 knew, as everyone at NASA knows, that space research offers something never before achievable in the history of humankind: a glimpse of what life — and nature itself — is like in a world without the effects of gravity. They also knew that people like themselves must be directly involved in space research, because all research is rooted in the ability to observe, recognize something new and valuable, and then step out in a new direction, one that often cannot be anticipated or preprogrammed into a machine.

The crewmembers were thrilled with what they were doing. They put in extra time and effort to make sure that the research would be successful. Working with NASA scientists on Earth, they overcame just about every hurdle that could have upset the payloads' operations during the mission. And because of that dedication, valuable scientific information has been gathered from their work.

For example, video that the *Columbia* crew downlinked for the Bioreactor Demonstration System, led by Leland Chung of Emory University, Atlanta, Georgia, showed the growth of extraordinarily large tumor tissues. These tissues are remarkable because they were the first of such size, and although they were not recovered, the metabolic data indicate the tumor tissues achieved such great size and structure without using any more nutrients than the control experiments on the ground did. This finding gives the research team great hope that there was a major difference in the orbital culture.

The Laminar Soot Processes experiment, led by Gerard Faeth, University of Michigan, Ann Arbor, seeks the mechanism that is responsible for the formation of soot in flames so that methods for controlling pollutant emissions can be devised. Observations of these flames during the flight of STS-107 were very successful and have suggested new ways to reduce, and possibly even eliminate, sooty emissions from flames. These new ideas will be evaluated, once again taking advantage of the microgravity environment of space, during upcoming experiments planned for the International Space Station. The reason for studying soot formation in flames is the concern for the significant public health problems it causes.

The objective of the Structure of Flame Balls at Low Lewis-Number (SOFBALL) experiment, led by Paul Ronney, University of Southern California, Los Angeles, was to study the weakly-burning-in-hydrogen-and-methane flames in oxygen-inert mixtures that results in what are called flame balls. According to Ronney, the data obtained during the STS-107 mission will keep combustion scientists busy for many years to come and will help lead to the development of cleaner, more fuel-efficient engines as well as improved methods for ensuring spacecraft fire safety. Among the achievements of the STS-107 experiment were observing the weakest flames ever burned on Earth or in space; the leanest flames ever burned on Earth or in space; and the longest-lived flame ever burned in space (81 minutes). Several totally new results were found, for example, oscillating flame balls and flame balls drifting in a spiral pattern.

The Mechanics of Granular Materials (MGM) III experiment, directed by Stein Sture of the University of Colorado at Boulder, was designed to help scientists understand how granular materials — such as loose sand in an earthquake or grain in a silo — behave under low effective stresses. A better understanding could help improve analytical modeling, which could be used to improve foundations for buildings; increase the understanding of soil liquefaction; manage undeveloped land; and handle powdered and granular materials in chemical, agricultural, and other industries. Because a fair amount of high-quality data from most of the flight experiments was downlinked and stored on Earth during the mission, MGM-III scientists consider the data gained (50 to 60 percent of the data collected during the STS-107 mission) to include very important, publishable results. For example, earthquake liquefaction was successfully simulated through two separate sets of experiments.

The renowned physicist Freeman Dyson once said, "The American space program is at its most creative when it is a human adventure." In this context, he went on to say, science is much more than just space, and space is much more than just science. Human spaceflight is also technology, education, human health, and industrial entrepreneurship, and it deepens the world in so many ways.

Like the crews before and those to come, the people of STS-107 did more than just science. They had and continue to have a higher calling: They inspire our lives.

Table 1 — Physical Sciences Research Overview	2001	2002	2003
Research Tasks	553	533	553
Principal Investigators	451	449	472
Co-Investigators	719	514	583
FY Budget ($ in millions)	130.4	120.0	79.2

Table 2 — Glenn Research Center Task Summary	2001	2002	2003
Ground-Based	158	176	193
Flight Program	54	46	47
Total	212	222	240

Table 3 — Jet Propulsion Laboratory Task Summary	2001	2002	2003
Ground-Based	64	55	61
Flight Program	12	11	10
Total	76	66	71

Table 4 — Johnson Space Center Task Summary	2001	2002	2003
Ground-Based	49	48	42
Flight Program	0	0	1
Total	49	48	43

Table 5 — Marshall Space Flight Center Task Summary	2001	2002	2003
Ground-Based	173	144	168
Flight Program	38	34	31
Total	211	178	199

NASA Physical Science Investigations by State
FY 2003

581 Investigations funded in 41 States and the District of Columbia
**Includes the District of Columbia*

BIOSCIENCE AND ENGINEERING

The bioscience and engineering discipline was formed in 2003 to develop new technologies to ensure astronaut health and safety during long-duration spaceflight, as would be necessary for a mission to Mars or while working on a permanent Moon-based station. By integrating biology, physical sciences, engineering, and medical research, NASA can ensure the safe and effective presence of humans in space while significantly enhancing basic knowledge and technology.

Every biological process involves physicochemical processes. In microgravity, though, these processes often differ significantly from the same systems on Earth. The need to understand the mechanisms underlying these differences is critical, and only close collaboration between biologists and physical scientists can lead to such understanding. NASA's unique facilities and extensive expertise in the behavior of physical systems in microgravity can play a key role by facilitating research at the molecular, cellular, and physiological system levels. Knowledge gained from this research can then be applied to space- and Earth-based biological and medical technology.

Both strategic and fundamental areas are addressed by the bioscience and engineering programmatic thrust. Strategic research includes improvement of systems for monitoring crew health and life support. An important goal of this research is the development of countermeasures to the effects of spaceflight on astronauts, using NASA's state-of-the-art knowledge and expertise in microgravity physical sciences research and associated technologies. Fundamental aspects include research on the effects of low gravity on the fluid-to-cell environment, such as force transduction and flow effects on transport and signaling. Also, cell culturing in space will be improved through the application of discipline-specific traditional microgravity research and expertise in developing flight experiment hardware.

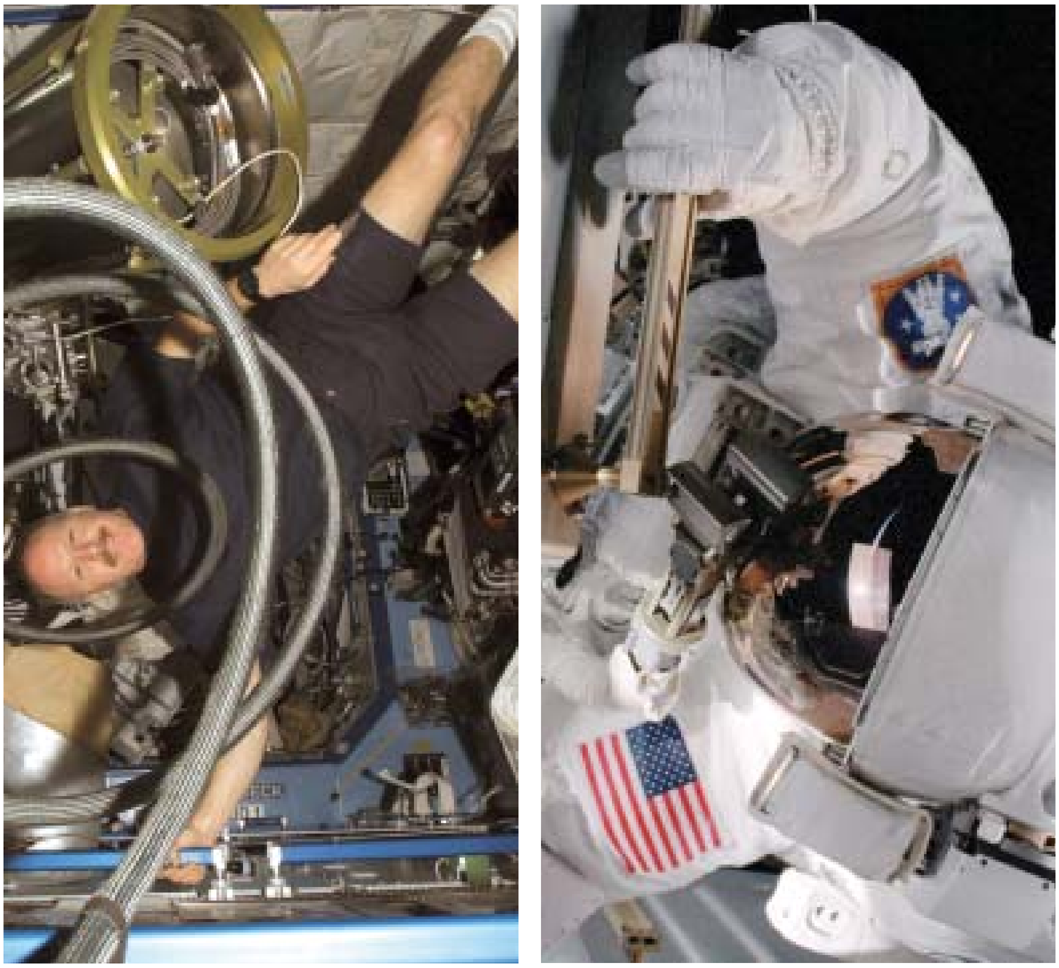
3

OVERVIEW

The Bioscience and Engineering Program brings the basic sciences of physics, biology, and chemistry together with a wide range of engineering disciplines to address two goals:

- to conduct research that will enable the safe and productive human habitation of space and
- to use the space environment as a science laboratory.

This unique cross-disciplinary program applies and leverages knowledge gained from microgravity research to enable the development of new physical-, chemical-, and biological-based systems that are critical to advanced space missions while improving products, practices, and processes on Earth.



credit: NASA

Expedition 6 Mission Commander Kenneth Bowersox is shown in the Destiny laboratory, where many of the experiments on the International Space Station (ISS) are conducted (left). Bowersox lived and worked on the ISS for more than 5 months. In a spacewalk (right), astronaut Patrick Forrester works on the Materials International Space Station Experiment, in which materials that could be used for spacecraft construction were exposed to the microgravity environment for about 18 months. The goals of the Bioscience and Engineering Program are to conduct research that will enable the safe and productive human habitation of space and to use the space environment as a science laboratory.

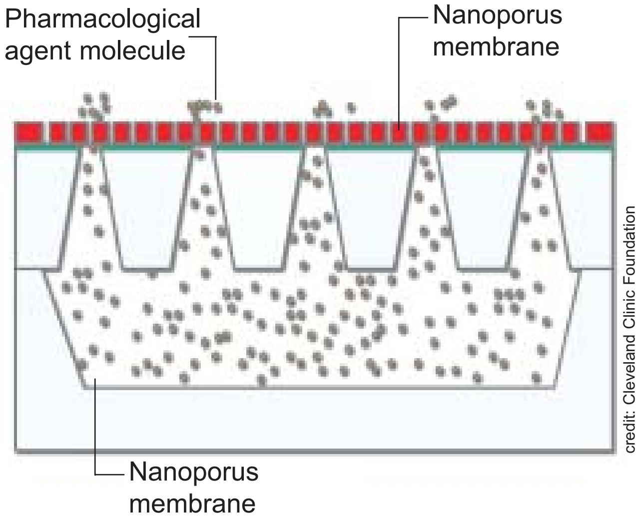
Program Summary

Today, astronauts are spending more time in microgravity than ever before, living and working on the orbiting International Space Station (ISS). They must perform their work and return to Earth without compromising their health. Astronauts who will someday leave the relatively protected atmosphere of low Earth orbit to travel to the Moon or Mars must be safeguarded from the increased cosmic radiation and the usual hazards of space exploration.

Such protection will be made possible only by successfully performing interdisciplinary research in the areas of biology and the physical sciences to develop therapeutics, procedures, techniques, and equipment to address astronaut health and safety issues from a distance. To facilitate this interdisciplinary research, NASA's Office of Biological and Physical Research (OBPR) has established the John Glenn Biomedical Engineering Consortium (GBEC) to be managed by Glenn Research Center (GRC) in Cleveland, Ohio. OBPR has directed the consortium to concentrate on fluid physics and sensor technology that address the risks to crew health, safety, and performance identified in a NASA document known as the *Critical Path Roadmap* (CPR). The CPR serves as a guide for an evolving program of research to prevent or reduce the most critical spaceflight risks that astronauts face.

Members of the consortium are GRC, the National Center for Microgravity Research (NCMR), Case Western Reserve University (CWRU), University Hospitals of Cleveland (UHC), and the Cleveland Clinic Foundation (CCF), all in Cleveland, Ohio. The consortium also works closely with NASA Johnson Space Center (JSC) in Houston, Texas, which is responsible for CPR and ensures that new knowledge and technology are fully applied in space.

Scientists and engineers from NCMR have already assisted NASA in solving fluids-related problems in space applications and in various biomedical and biotechnology areas. By participating in this consortium, the center expands its role through involvement with several consortium research projects. CWRU's biomedical engineering department is one of the five best in the United States. UHC and its research institute, UHRI, are ranked first in Ohio in terms of research support from the National Institutes of Health (NIH), Bethesda, Maryland. Overall, UHRI investigators attract more than $100 million in extramural research funds from federal, nonfederal, and industry sources. UHC's recognized strengths are in the areas of pediatric research, cancer, orthopedics, infectious diseases, dermatology, radiology, radiation oncology, and genetics. CCF obtains approximately $100 million for sponsored medical research and employs more than 400 research scientists, associates, and fellows. It is ranked first in the United States in cardiac expertise. GRC's previous partnerships with the CCF, CWRU, and UHC have yielded patented devices such as heart valves, heart-assist pumps, and bone stress sensors.



The goal of one John Glenn Biomedical Engineering Consortium (GBEC) project is nonstop drug delivery through a slow infusion, which maintains the correct drug concentration in the patient's body while improving control over drug delivery. An implantable microsystem such as the one presented here stores the drug in a micromachined reservoir for delivery through a membrane with nanometer-size pores. This alternative is surely preferable to the pain and discomfort of daily injections.

A targeted solicitation was issued in November 2001 to consortium members for collaborative proposals. Of the 32 proposals that were received, 10 projects were selected for 3-year funding, beginning in fiscal year (FY) 2003 and ending in FY 2005.

Continuous drug delivery through a slow infusion, which maintains the correct therapeutic concentration of a drug in the patient's body while improving control over drug delivery and eliminating the pain of daily injections, is the goal of one of these projects. Continuous drug delivery to the body through an implantable microsystem can be of benefit to all patients, especially those with diabetes. At present, those who take drugs by injection have to cope with a "burst effect," the sudden and sometimes excessive surge of a drug's effects immediately after administration.

For diabetics, a surge of insulin often leads to dangerously low blood sugar levels. Eliminating such surges would enable better glucose level stability in diabetics, thus reducing the likelihood of diabetic complications later in life for some patients. In space, better drug delivery methods would spare astronauts the pain of injections and allow for constant, controlled delivery of antinausea or other medications.

Another consortium project aims to develop a new sensor that will continuously and painlessly monitor the health of the human body. The body is constantly transmitting clues about its state of health that scientists are not yet able to read. Having a more sophisticated ability to interpret the body's messages would greatly refine therapeutic approaches to disease.

Research being conducted by Principal Investigator (PI) Miklos Gratzel and Co-Investigator Koji Tohda, both of the Department of Biomedical Engineering at CWRU, should produce a new monitor for very accurate, continuous monitoring of critical ions and glucose in the interstitial fluid (ISF) between cells and tissues within the skin. The monitor is adaptable, self-checking, and uses very little power.

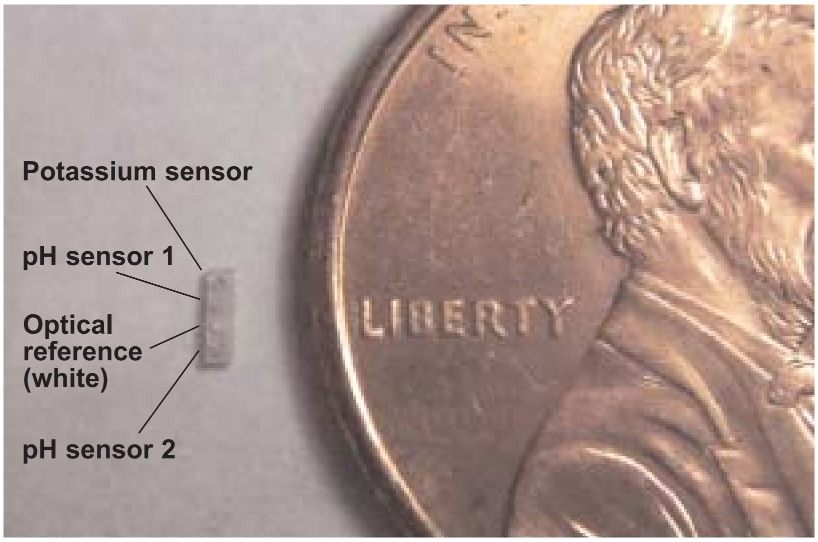
The researchers are working to develop several unique concepts, including a "sliver sensor" that is implanted within human skin for the continuous, in vivo monitoring of critical ions and metabolites in ISF. The sliver sensor is a tiny plastic bar — only 100 to 300 microns (0.004 to 0.011 inches) wide and 1 to 1.5 millimeters (0.04 to 0.06 inches) long — with optical spots or stripes for each ion (sodium, for example) or metabolite (glucose, for example) to be analyzed as well as blanks for calibration. The colors are monitored and interpreted by a watchlike device worn on the skin over the sensor.

The microminiature sliver penetrates the skin easily and painlessly; users can insert it themselves — a not-unimportant feature for astronauts on lengthy missions without direct access to medical professionals. Feasibility testing of the concepts of the sliver sensor indicates that in vivo glucose monitoring with sufficient sensitivity and dynamic range is possible. Continuous monitoring of ISF would be a great improvement over taking repeated blood samples for external analyses.

On Earth, the sliver sensor could help doctors closely monitor levels of electrolytes and other blood plasma components in very ill patients. Many diabetics would also greatly benefit from this technology, which would free them from taking blood samples several times a day to monitor blood sugar levels.

An article by Gratzel and Tohda describing their work on the sliver sensor appeared as an invited feature and cover article in the February 2003 issue of the prestigious *ChemPhysChem*, a European journal of chemical physics and physical chemistry (A Microscopic, Continuous, Optical Monitor for Interstitial Electrolytes and Glucose, *ChemPhysChem,* 4(*2*), 2003, 155–160). This article is the first publication of research results from the GBEC grant.

The eye also warrants special attention. For every tissue type in the body, there is a corresponding tissue type in the eye. A special helmet and goggles proposed by the consortium for use in space will implement several diagnostic procedures simultaneously, using the eye almost as a window on the body for the noninvasive detection of various disorders. One of the technologies in the proposed device, the dynamic light-scattering (DLS) fiber-optic probe, is already being used for the early detection of cataracts in clinical studies jointly sponsored by NASA and



credit: Case Western Reserve University

Principal Investigator Miklos Gratzel and Co-Investigator Koji Tohda are developing several unique concepts to monitor the interstitial fluid that bathes cells within human skin. To achieve accurate, continuous, in vivo monitoring, they use a "sliver sensor" with integrated sensors that change color depending on the fluid's critical ionic and metabolite levels. The sliver sensor, shown here, is a tiny plastic bar — 100 to 300 microns (0.004 to 0.011 inches) wide and 1 to 1.5 millimeters (0.04 to 0.06 inches) long — that can be placed within the skin; sensors include optical spots or stripes for each analyte and pH (a measure of acidity or alkalinity), as well as blanks for calibration.

NIH. Some day, it may enable the very early screening of diseases like diabetes and Alzheimer's during a routine eye exam.

Other noninvasive optical diagnostic technologies are also being considered for integration into the goggle instrument for several purposes: to monitor blood glucose through measurements of optical activity; to monitor blood flow for age-related macular degeneration; to detect cataracts, diabetic retinopathy, and glaucoma; to detect corneal abnormalities after laser keratomileusis (LASIK) surgery; and to evaluate the effects of prolonged weightlessness on circulation in the eye and the central nervous system. This device may ultimately prove useful for several medical applications on Earth, especially for telemedicine.

Other GBEC projects concentrate on *how* research is being done in space. Smaller and faster space experiments will enable more and better science, and biochips are a promising enabling technology to accomplish this goal. A biochip is a collection of miniaturized test sites called microarrays on a surface area usually smaller than a fingernail. The microarrays can perform many biological tests simultaneously. Like a computer chip that can perform millions of mathematical operations in a second, a biochip can quickly perform thousands of biological reactions. As a result, biochips and microarray technologies are rapidly becoming critical for genetic, toxicological, protein, and biochemical research. Biochips could provide miniaturized devices for onboard diagnostic and treatment systems for lengthy NASA missions that no current technology can. In this GBEC-funded research, a biochip simulation capability will be developed that will be suitable to both space and Earth-based biomedical applications.

In support of NASA's Physical Sciences Research (PSR) Division, GRC has developed several unique laser light–scattering fiber-optic probe technologies that may offer diagnostic capabilities and utilities in biomedical applications. Preliminary interactions, including pilot test programs with NIH's National Eye Institute (NEI) and other biomedical communities, have indicated that this technology can provide humans with previously unavailable capabilities for quantitative measurement of several parameters or conditions related to the lens as well as the anterior and posterior chambers of the eye. Results of these preliminary pilot activities indicate that the laser light–scattering eye diagnostic device developed at NASA could benefit a broad segment of the eye research and treatment community. An Interagency Agreement has been signed by NASA and NEI/NIH to support the transfer to NEI and the external research community of ground-based NASA laser light–scattering technology for the early detection and diagnosis of eye diseases. NASA and NIH will split $5 million for this effort, with the funding continuing over 5 years and ending in 2006.

Under a 1996 Interagency Agreement, NEI/NIH and NASA have already been collaborating on the use and clinical evaluation of a novel fiber-optic probe, developed by PI Rafat Ansari at GRC, for the early detection and diagnosis of cataracts. A cataract is a clouding of all or part of the normally clear lens of the eye. It most often occurs in people who are 55 or older and results in blurred or distorted vision. Ansari discovered that cataracts are caused by the agglomeration of protein crystallines in the lens of the eye. Many factors can increase a person's risk of developing cataracts, including exposure to ultraviolet radiation and cigarette smoking. However, cataracts may also develop simply as a result of aging, heredity, disease, or injury. Cataracts interest NASA because studies have shown that exposure to space radiation increases astronauts' risk of developing cataracts.

This collaboration on cataract detection technology between NASA and NEI/NIH has been fruitful and mutually beneficial. Given that cold also causes cataracts, NEI researcher Manuel Datiles conducted basic studies in the NEI clinic lab using the cold cataract model and demonstrated that the DLS fiber-optic probe could detect the earliest changes at 17 ^{o}C (63 ^{o}F), whereas current state-of-the-art devices like the Zeiss Scheimpflug cataract imaging system detected the earliest cataract changes later, at 10 ^{o}C (50 ^{o}F). These results demonstrate the usefulness and sensitivity of the DLS probe to detect and study the earliest changes in cataracts.

Other studies in the NEI Laboratory of Mechanisms of Ocular Diseases (LMOD) by NEI researcher Sam Zigler have demonstrated the utility of the instrument in monitoring changes in the lenses of transgenic mice in vivo and in studying protein–protein aggregation and association phenomena in vitro, again proving the utility of Ansari's device for characterizing the onset of cataracts much earlier than conventional methods.

A clinically useful DLS device was then developed at GRC under Ansari as PI and used at NEI on a small group of human subjects. The initial tests showed excellent results. A three-dimensional (3-D) aiming system enables this clinical instrument to return to the same location within the lens of a patient for repeat analysis at any time after the initial DLS measurements. A simple method of displaying the results — mainly in the form of protein distribution and average particle size — was formulated that further simplifies the analysis and interpretation of data obtained from human subjects.

Through these studies and NIH contacts in the medical and research communities, the technology has been made available to a wide segment of the ophthalmic community. For example, Frank Giblin of Oakland University, Rochester, Michigan, is collaborating with Ansari in the use of the DLS device to study the effect on the lens of radiation and higher-than-normal (hyperbaric) oxygen pressure. Their findings could help researchers understand radiation and oxygen exposure effects on the eyes of astronauts during prolonged stays in space (say, on a mission to Mars) and extravehicular activities (such as ISS construction). The work so far bodes well for advances in ocular health and safety. The 5-year agreement allows scientists to follow up on new and promising directions, building on prior accomplishments to refine and enhance the DLS device and use the device for studies to understand the cause of cataracts.

A new NASA BioScience and Engineering Institute (NBEI) was also established in FY 2003. The University of Michigan, Ann Arbor, responded to a NASA Cooperative Agreement Notice and was selected for this initiative after an independent peer review of several proposals from several institutions. The main purpose of the NBEI is to enable world-class research, development, technology transfer, and education in bioscience and engineering related to NASA's overall missions, with emphasis on biology, physical research, human exploration of space, and space development. The initial funding for this cooperative agreement is planned for 5 years, with a renewal option for 5 additional years.

Although one of the main thrusts of the NBEI is to perform high-quality, state-of-the-art research in bioscience and engineering, it is also charged with additional tasks:

- disseminating advances in knowledge to the science and research community,
- facilitating scientific interchange among NBEI-sponsored research groups,
- cross-training undergraduate and graduate students to create a new generation of interdisciplinary scientists,
- organizing seminars and workshops,
- offering courses in bioscience and engineering,
- establishing needs and priorities for national facilities in bioscience and engineering research, and
- coordinating programs in education (kindergarten through grade 12) and public outreach.

Because formalization of the cooperative agreement occurred very late in FY 2003, there are no significant accomplishments to report. The planned research, though, can be summarized.

The four themes are composed of individual projects, which cover biomicroelectromechanical systems (bioMEMS) and biomaterials, transport phenomena in biology and devices, molecular biophysics and bioengineering, and tissue bioscience and engineering. The components of the theme areas are aligned with the priorities of OBPR.

The bioMEMS and biomaterials theme will center on the design and evaluation of a novel type of minimally invasive medical device for integrated physiological and environmental sensing. The long-term goal is to develop a "skin patch" type of polymer-integrated microsystem that has an interface to the body for physiological sensing and an interface to the external environment for monitoring the environment (for example, air quality). This interdisciplinary and multifaceted project will leverage extensive ongoing research in wireless integrated microsystems, biological sensors, environmental sensors, materials science, and chemistry.

Transport phenomena in biology and devices will have three research components. The first area will examine neural and neurovascular changes in simulated microgravity, including changes in performance arising from simulated microgravity at the systems and cellular level. The second project will develop an Earth-based model of lung physiology in microgravity; the goal will be a model of respiration in microgravity that will facilitate the in-depth investigation of previously unstudied indicators of pulmonary function. The third research project in this area will be directed at lab-on-a-chip (LOC) devices for biomedicine in microgravity with a focus on saliva analysis. This project will concentrate on developing miniaturized fluidic devices and tools for detecting biomarkers in saliva, manipulating deoxyribonucleic acid (DNA) for health monitoring, and detecting radiation damage to DNA.

Research into molecular nanosystems to monitor astronaut radiation sickness and single-molecule biosensors will be included under the molecular biophysics and bioengineering theme. It will center on the design and evaluation of a novel type of minimally invasive medical device for integrated physiological and environmental sensing, with particular application to radiation monitoring. The aim will be a prototype polymer capable of binding to individual cells for monitoring environmental and physiological states, including radiation exposure. The single-molecule biosensor project focuses on the development of an ultra-sensitive, specific, versatile, and rugged biosensor based on catalytic ribonucleic acid (RNA) molecules to detect molecules indicative of life on planetary systems.

In the theme area of tissue bioscience and engineering, one investigation will focus on the effects on muscle function of what is called hindlimb "unweighting" (suspending the hindlimbs of rats so that they are not bearing weight). The changes in skeletal muscle satellite cell function resulting from short- and long-term exposure to simulated microgravity will be examined. A second component of this theme will be to investigate the influence of physical forces on bone adaptation. This project will use a novel hydraulically activated implantable bone chamber that promotes new bone formation in Sprague–Dawley rats; the goal is to identify the short- and long-term cellular and molecular events associated with mechanical stimulation in ground-based experiments. The final component of this theme area will involve parathyroid hormone (PTH) and its local delivery as a counterbalance to microgravity-associated bone loss. Along with cortisol, PTH helps control the amount of calcium available in the body. A polymeric system will be developed to locally deliver PTH at regular intervals. The project will ultimately test this local delivery system in an animal model to verify the delivery and effectiveness of the goal of decreasing bone loss due to microgravity exposure.

GRC and Ames Research Center (ARC), Moffett Field, California, are also working together on ARC's cell culture unit (CCU), with GRC providing fluid physics expertise to analyze flow and concentration patterns in the Cell Specimen Chamber (CSC). The objective is to optimize fluid homogeneity and minimize cell shear stress for various CSC designs and mixing protocols through the use of computational fluid dynamics modeling and analysis to study and understand the response of the cellular process to the space environment in both single- and multicelled organisms. Results from past analyses performed on various design options for the CSC of the CCU, along with recommendations for the preferred suspension culture CSC design, have been provided to managers of the ARC Space Station Biological Research Project (SSBRP) in support of the interim and critical design reviews.

Bioscience and Engineering Program PI Rafat Ansari had several publications during FY 2003. In "Optoelectronics Apparatus Measures Glucose Noninvasively," he describes glucose concentration obtained through a combination of interferometry and polarimetry (*NASA Tech Brief*, **27**(*3*), March 2003, 12A). His article "Ocular Static and Dynamic Light Scattering: A Non-Invasive Diagnostic Tool for Eye Research and Clinical Practice" will be published in 2004 (*Journal of Biomedical Optics*, **9**(*1*), 22–37). A second article, "New Optical Scheme for Polarimetric-Based Glucose Sensor," co-authored with Stefan Böckle and Luigi Rovati, will also be published in the same journal (*Journal of Biomedical Optics*, **9**(*1*), 103–115).

Ansari also published two book chapters. Along with Manuel Datiles, he wrote "Clinical evaluation of cataracts" in *Duane's Clinical Ophthalmology*, 2003 edition (W. Tasman and E. Jaeger, Eds., Lippincott Publishing, Philadelphia, Pennsylvania). He authored "Quasi-elastic light scattering in ophthalmology" in *Coherent-Domain Optical Methods for Biomedical Diagnostics, Environmental and Material Science* (Valery Tuchin, Ed., Kluwer Publishers, Dordrecht, The Netherlands, in press).

Bioscience and Engineering Program PIs received several awards in FY 2003. GBEC PI Shuvo Roy, a 34-year-old biomedical engineer and researcher in the Cleveland Clinic Foundation's Lerner Research Institute, was named one of the world's top 100 young innovators by *Technology Review*, the Massachusetts Institute of Technology's magazine of innovation. The *Technology Review's* top 100 (TR100) features the world's 100 top innovators under age 35. The prestigious list, which showcases some of the most promising technological advancements on the horizon, is compiled by the editors of the magazine and an elite panel of judges. Roy is the only person from Ohio to be included in this year's TR100. Roy's research focuses on microelectromechanical systems (MEMS), an area of science and technology that adapts the techniques for production of computer chips to create microscopic mechanical features and components such as channels, gears, motors, and sensors. These components, in turn, are used to develop miniature medical devices in an emerging field called bioMEMS. Roy's GBEC project, "Controlled-Release Microsystems for Pharmacological Agent Delivery," focuses on the development of a MEMS-based drug delivery system that will enable researchers in space biology and medicine to dispense pharmacological agents locally over a sustained period.

On August 8, 2003, NASA Deputy Administrator Frederick Gregory presented the Abe Silverstein Medal to Rafat Ansari for his innovative research work in light scattering that resulted in practical biomedical and clinical applications. The Abe Silverstein Medal is awarded to a GRC employee for outstanding research contributions that have led to widely recognized practical applications. The award was established to commemorate the long and fruitful career of Abe Silverstein, former director of NASA Lewis Research Center from 1961 to 1969.

Ansari was also asked to serve on Montana Congressman Denny Rehberg's Aerospace, Aviation and

Defense Panel. (For more information about this panel, visit *http://www.house.gov/apps/list/press/mt00_rehberg/052303_EDSumittPanel.html*.)

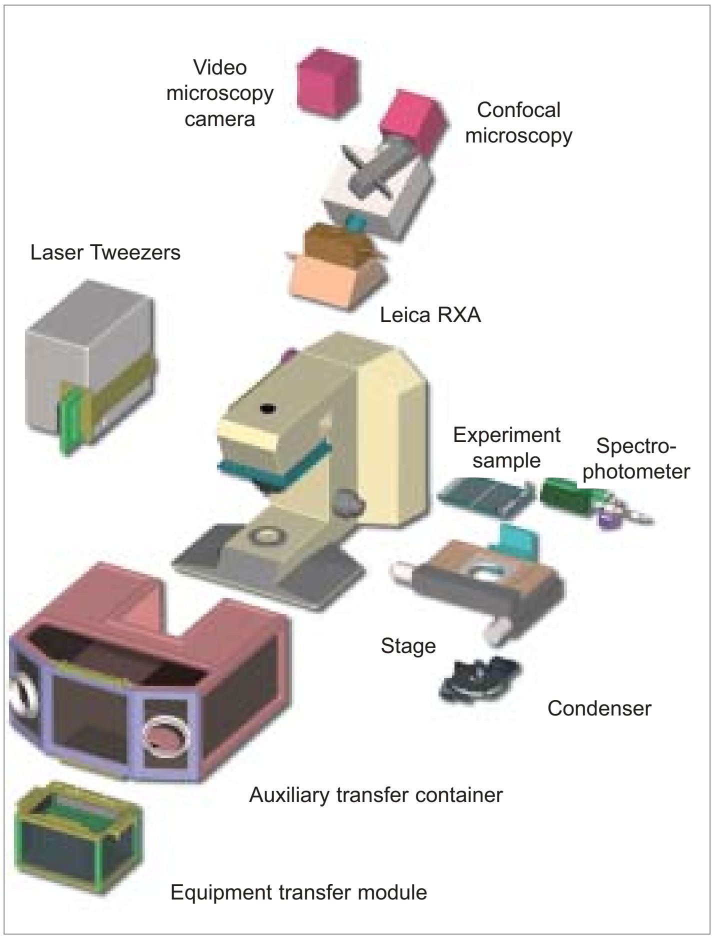
Flight Experiments

The Bioscience and Engineering Program is developing flight hardware to support its research mission and is currently involved with two projects: the Hydrodynamic Focusing Bioreactor-Space (HFB-S) and the Light Microscopy Module (LMM).

NASA researchers at Glenn Research Center (GRC), Cleveland, Ohio, and Johnson Space Center (JSC), Houston, Texas, are collaborating on fluid dynamics investigations for a future cell science bioreactor to fly on the International Space Station (ISS). Project Manager Steven Gonda from the Cellular Biotechnology Program at JSC is leading the development of the HFB-S for use on the space station to study tissue growth in microgravity. The rotating-wall perfused vessel (RWPV) bioreactor has been used with great success on space shuttle flights and on the Russian Space Station *Mir* but has occasionally run into problems with gas bubbles entering the fluid-filled vessel. These bubbles are harmful to the cell science, and bubble removal in the RWPV is problematic. As things stand, the HFB-S has a central access port that has been designed to allow for bubble removal under specific operating conditions.

Principal Investigator (PI) Stanley Kleis, at the University of Houston, Texas, is conducting computational studies of the internal fluid flow of the HFB-S to predict bubble motion as well as other operational parameters. Charles Niederhaus and Henry Nahra from the Microgravity Fluid Physics branch and John Kizito at the National Center for Microgravity Research (NCMR), both at GRC, have been assisting with fluid analysis and experimental verification. Experiments with the HFB-S were conducted in a microgravity environment on the KC-135 parabolic flight aircraft, which is operated by JSC and flies out of Cleveland's Hopkins Airport and Houston's Ellington Field. The KC-135 can provide low-gravity conditions for approximately 18 to 25 seconds as the aircraft traces a parabolic trajectory. During each parabola flown, the KC-135 undergoes an altitude change of about 1,800 meters (approximately 6,000 feet), and during a single flight it can perform more than 50 parabolas.

The first set of flights in July 2002 provided data on bubble trajectories that show the validity of the computational predictions. The latest flights (January 2003) free-floated the apparatus and tested the most recent configuration of the bioreactor, focusing on the bubble removal process itself. These experiments showed that the bubble could successfully be driven to the removal port and purged in microgravity. The last day's experiments were conducted under an excellent microgravity environment due to calm



credit: NASA

NASA's Fluids Program is building a Light Microscopy Module (LMM), a remotely controlled microscope, at Glenn Research Center (GRC), Cleveland, Ohio, for use on the International Space Station primarily to support fluid physics research. The capabilities of the LMM also make it useful for fundamental space biology and cellular biotechnology research. Memoranda of agreement have been developed among the fluid physics, fundamental space biology, and cellular biotechnology disciplines to study and communicate potential use of the LMM and other GRC flight hardware in support of the respective research programs.

air, and the experience gained in previous flights allowed successful bubble removal in 18 of 35 attempts — a remarkable result given the microgravity time constraints and *g*-jitter (random accelerations or vibrations aboard the craft that are superimposed on the reduced gravity environment) on the KC-135.

NASA's Fluids Program is building an LMM, a remotely controlled microscope, at GRC for use on the ISS primarily to support fluid physics research. The LMM allows researchers to choose from six objective lenses of different magnifications and numerical apertures to obtain data. In addition to video microscopy techniques used to record sample features, modifications and enhancements to the microscope include interferometry to measure vapor bubble thin-film thickness, laser tweezers for manipulating and patterning sample particles, confocal microscopy to visualize sample structures in three dimensions, and spectrophotometry to measure photonic properties. This suite of capabilities allows a very broad characterization of fluids, colloids, and two-phase media, including biological samples. They make the LMM useful for fundamental space biology and cellular biotechnology research in addition to fluids research. Memoranda of agreement have been developed by GRC with Ames Research Center (ARC), Moffett Field, California, on fundamental space biology and with JSC on cellular biotechnology to study and communicate potential use of the LMM and other GRC flight hardware in support of those respective research programs.

Astronauts have reported loss of visual acuity as a result of exposure to microgravity, and researchers believe that changes in blood flow in the eye may be responsible. PI Rafat Ansari of GRC has developed a laser Doppler flowmeter to test the theory that changes in blood flow, coupled with changes in pressure within the eye, could alter the shape of the eye enough to result in the vision effects reported by astronauts. Ansari tested his flowmeter on volunteers on a KC-135 flight, but vibrations from the aircraft affected the quality of the data, so the research team is working to make the apparatus less sensitive to such outside interference.

Highlights

Running around the World

Take a walk through the park and notice what your body is doing. Step on an incline and your lower brain orders leg muscles to contract and relax, thus tilting the ankle just right and changing the grip of toes inside the shoe, all so your spine stays vertical. The average person is rarely aware of these subtle movements unless recovering from an injury — or just returning to Earth after months in space. As well as losing muscle and bone mass in microgravity, astronauts also gradually lose the ability to perform this neuromuscular ballet in Earth's gravity.

Because a walk in the park is impossible in the confines of any existing spacecraft, researchers are developing a unique treadmill that could provide much of the missing stimulus for astronauts in orbit and perhaps also for physical therapy patients on Earth. Principal Investigator Susan D'Andrea of the Cleveland Clinic Foundation and co-investigator Jay Horowitz of Glenn Research Center, both in Cleveland, Ohio, are developing a new type of treadmill that will combine elements of virtual reality and motion control systems to give the user the impression that he or she is walking over hill and dale. Their work is sponsored by the John Glenn Biomedical Engineering Consortium.

Traditionally exercise regimens have involved gym equipment — treadmills, stationary bikes, and such — transported from Earth to orbit. The principal concession to low gravitational force has been the addition of restraints to hold the astronaut in place or pull him or her "down." As a result, space workouts have concentrated on aerobic conditioning and have had only partial success in addressing bone loss and other physiological adaptations, such as vestibular disorientation (i.e., balance problems and space adaptation syndrome).

Making a treadmill workout more effective means providing two sets of virtual reality (VR) stimuli: tactile and visual. The VR treadmill being designed by D'Andrea and Horowitz will have two separate, moveable tracks that can be raised or lowered and run at different speeds. The positioning mechanisms for each track and their drives will be controlled through a computer that also generates VR scenery that the astronaut watches while walking or running.

Treadmill design has just begun, but results are promising. Currently, the team is developing the system to simulate walking around a corner. This seemingly basic action requires orchestrating the computer's VR simulation and track drives to provide the correct inputs so users really believe they are walking around a corner instead of simply pacing on a stationary treadmill. This portion of the work is being conducted in the Glenn Reconfigurable User-interface and Virtual-reality Exploration (GRUVE) Laboratory. The prototype unit is being built from two conventional treadmills, with leveling actuators added. Their belt drives will be independent, so the tracks can run at slightly different speeds (like a military tank's treads when it turns) because the foot on the outside of a curve has to move faster to keep pace with the pivot foot on the inside of the curve.

credit: NASA/Cleveland Clinic Foundation

A test subject walks on the virtual reality (VR) treadmill "around the corner," as indicated by the curved walkway on the screen. Her helmet includes cameras to watch eye movements and reflectors so digital cameras can capture subtle head shifts.

At the same time, test subjects in the biomechanical lab are walking under the watchful eyes of digital cameras and computers that are building models of how people walk on flat surfaces, inclines, and stairs. Like actors in a special effects studio, the test subjects wear markers on key body points so the computer can easily follow limb motions. As the experiments evolve, the research team will add sensors to measure muscle response, pressure at key points under the foot, and even eye movements to closely track the response of the vestibular system.

From the data those exercises provide, programmers will develop software to control the VR treadmill and deliver appropriate images on screen so that using the treadmill meets a user's subconscious expectations and the user walks normally without tripping (test subjects wear body harnesses for safety).

D'Andrea expects that the two-track treadmill prototype will be operating by June 2004 and the full VR system will be added by September. After learning how to walk around curves, the system will evolve into more complex movements, such as running. Astronauts and NASA exercise physiologists will test the prototype and suggest improvements. Finally, the system will be ready to be adapted for use in microgravity.

The new VR treadmill could reduce the time required for astronauts to exercise in microgravity by focusing on multiple physiological systems simultaneously. It may also solve a key problem with space exercise: compliance. Many astronauts find exercise boring and sometimes skip workouts. For the same reason, it also could be an ideal tool for the rehabilitation of patients with balance disorders on Earth; it is already being used to rehabilitate patients with gait abnormalities. In addition, a portable, adaptable virtual reality system could be a boon for applications ranging from job training to recreation.

Healthy Bones Mean Normal, Earthlike Stresses

Using acoustic energy (ultrasound) to mimic the normal rebuilding cycle of healthy bones may be a prescription for astronauts on long-duration space missions. It's an intriguing concept that medical researchers are starting to investigate as a therapy for bedridden people on Earth as well. With the support of the John Glenn Biomedical Engineering Consortium (GBEC) to be managed by Glenn Research Center (GRC) in Cleveland, Ohio, Principal Investigator Ulf Knothe (Cleveland Clinic Foundation [CCF], Cleveland, Ohio) and Co-Investigators Dwight Davy (Case Western Reserve University [CWRU]; Cleveland, Ohio), Melissa Knothe Tate (CCF and CWRU), Jerry Myers (GRC), and Stevan Streem (CCF) are investigating the use of acoustic energy both to maintain and restore bone density and health in space.

Bone loss is one of the more serious health issues that astronauts face in microgravity. The loss rate is rapid, ranging from 6 to 24 percent per year — up to six times faster than women with Type I (hormone-related) osteoporosis (which literally means "holes in bones"). Even people with Type II (age-related) osteoporosis have lower bone loss rates than astronauts in microgravity. The danger to astronauts is that on return to Earth's gravitational force (1*g*), they are at greater risk of breaking bones when they resume normal activities, including exercise to rebuild muscle mass and cardiovascular conditioning.

The two big questions facing researchers are

- Why does human bone stop rebuilding itself in microgravity? and

- How can the process be restimulated?

On Earth, human bone continually reweaves itself, without scarring, in response to any activity. Any force that loads a bone causes tiny breaks (microdamage) in the bone's structure. These breaks actually stimulate the bone to rebuild itself. Heavier exercise causes more microdamage and ultimately, stronger bones. In microgravity (or during extended bed rest), this cycle is interrupted because bones don't get the normal loading and unloading they experience on Earth during normal movement and exercise. Bone growth is a living embodiment of the maxim "use it or lose it."

Until recently, scientists thought that bones behaved somewhat like the mechanical equivalent of a thermostat. In that "mechanostat" model, the bone was believed to be programmed to accept a certain load. Heavier loads would cause the body to add new cells until the loads returned to normal. However, the model did not fully explain the build–destroy–rebuild cycle.

Recently, Knothe and colleagues revisited a theory first offered in the 1960s and 1970s called load-induced fluid flow. In this model, bone is considered to be a stiff, fluid-filled sponge. Somewhat like squeezing a sponge, compressing a bone causes fluids to move through the matrix of the collagen and minerals that give the bone strength. The fluid movement enhances molecular transport from the blood supply into bone cells. The response to such a stimulus is increased bone growth.

To Knothe, the sponge model seems to point to a way of stimulating the growth process. Knothe's team is investigating the application of acoustic energy similar to those used to pulverize kidney stones without surgery. Extremely fast, brief pulses of sound are transmitted through the body. Soft tissues yield easily enough. But hard structures — kidney stones or bone — are more resistant and thus fracture. Knothe and his team are investigating what kind of pulse has to be delivered to cause just enough microdamage to simulate normal wear and tear on a bone, without pulverizing the bone completely, like in kidney stone therapy. Experiments with sheep bones, which are structurally similar to human bones, and later experiments with rats will help determine the reactions of bone to different pulse strengths and times.

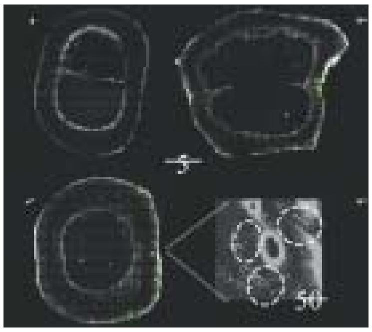
Even if Knothe's technique works, it would not stimulate normal bone regrowth along the entire body but be applied only to areas that need it most, especially the feet, legs, pelvis, and spine, which carry most of the body's mass. Knothe hopes to determine how often the treatment must be applied and how to tailor the pulses so the therapy is painless. Finally, a simple application method must be developed.

Ultrasound techniques for stimulating bone growth may benefit a range of health issues on Earth as well. Other clinical researchers are testing ultrasound techniques to treat non-unions (bone breaks that just won't heal properly on their own), bone spurs, and tendonitis. It could strengthen bone in elderly and other mobility-limited people who are at extreme risk of breaking bones from simple falls or even normal movement. It would be especially beneficial to bedridden people who suffer severe bone loss that can make recovery difficult.

Keeping a Beat on the Heart

Working in space, where astronauts push quarter-ton experiment racks with the greatest of ease, would appear to be an easy job. But it carries hidden risks of sudden cardiac death (SCD), which kills more than 300,000 Americans on Earth each year. No astronaut has been felled in space, but flight surgeons have observed several cases of dysrhythmia (abnormal rhythm), incidents where the pulses driving the heart seem to be out of phase.

Ironically, many of the SCD victims on Earth had had electrocardiogram (EKG) exams and received clean bills of health. In the 1990s, researchers including David Rosenbaum, a heart researcher with MetroHealth Systems at Case Western Reserve University, Cleveland, Ohio, discovered that a tiny bump at the end of a heartbeat — the T-wave — indicated that a patient had a high chance of SCD within the next year.



credit: NASA/Cleveland Clinic Foundation

Application of acoustic energy to blocks of sheep bone resulted in identifiable microdamage (green spots), including diffuse damage and microscopic cracks throughout the cortex of the bone cross section. Damage was clustered along the cortical site, corresponding to the focal zone of the ultrasound unit. In general, microdamage increased with increasing acoustic energy intensity (that is, energy density, number of waves, or both). The bottom right image enlarges a region of overt microdamage.

A T-wave is emitted when the left ventricle, the heart's largest pumping chamber, electrically depolarizes in preparation for the next beat. In hearts in which the nerves don't fire in the right sequence, the T-wave will make subtle changes from beat to beat in an effect called T-wave alternans. A heart will go into fibrillation as the muscle starts quivering rather than pumping, and the patient quickly dies.

Although the causes of SCD remain unknown, flight surgeons have observed similar incidents in astronauts on space missions, during which microgravity causes the human heart to decondition at a steady rate. Indeed, there appears to be a direct relationship between increased heart difficulty and length of time in space. Among other possibilities, space researchers suspect the culprit may be the vasovagus nerve, which regulates heart rate.

For example, during the Apollo 15 mission in 1971, astronauts Dave Scott and James Irwin worked hard enough during their three lunar walks to dehydrate and suffer a type of dysrythmia called bigeminy, in which the heart beats twice in rapid succession, followed by a pause after every two beats. Scott and Irwin also took longer to recover from their flight than members of any other Apollo crew. Since then, astronauts have loaded themselves with potassium-laced drinks to enhance electrolyte levels before spacewalks, but dysrhythmias have still occurred. Two cosmonauts on a spacewalk suffered tachycardia, a rapid heartbeat that can cause a blackout. In either case, a nonfatal cardiac incident in space could quickly become fatal because of the work environment.

As with any disease or disorder, advance warning is crucial. But biomedical instruments available to date are less than ideal. Currently, a patient on Earth who might have heart trouble is given one of two types of monitors to wear. A Holter monitor records 24 to 48 hours of data on tape for later analysis by a physician. Alternatively, an event monitor transmits similar information, and when the patient feels heart stress, he or she can mark the data by pushing an event button. With either system, however, a patient could die before a physician knows there is trouble.

To provide better warning systems both on Earth and in space, Principal Investigator David York of Glenn Research Center (GRC) in Cleveland, Ohio, along with Rosenbaum at MetroHealth, plus their colleagues at the John Glenn Biomedical Engineering Consortium (GBEC) in Cleveland, Ohio, are exploring several available communications technologies, including GRC's own Embedded Web Technology (EWT), to extract information about heart irregularities from the T-wave alternans.

In earlier research, Rosenbaum and MetroHealth colleagues analyzed a series of T-waves and applied a mathematical filter called a fast Fourier transform that can reveal irregularities in seemingly regular signals. They found that if the transform value goes too high at specific frequencies, it's an almost certain predictor of SCD within 8 to 12 months.

credit: NASA

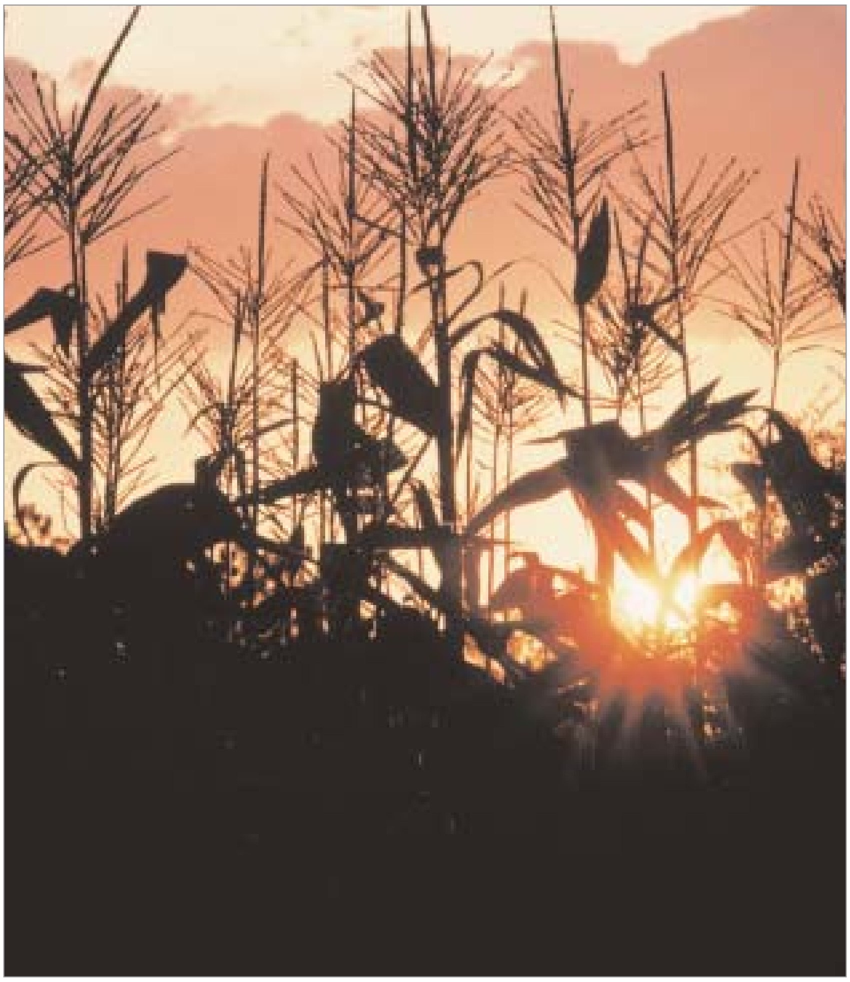
Principal components of the T-wave monitoring system are a personal digital assistant (PDA) controller connected to a Bluetooth adapter to relay signals from the portable monitor (white box) and a Global Positioning System (GPS) monitor. An operational system would have smaller electronics optimized for the task.

GBEC's early warning system uses off-the-shelf cardiac sensors and monitoring gear that apply recent advances in low-power, high-bandwidth cellular phone and other electronics technologies. Volunteers at GRC are wearing prototypes equipped with synthetic heart beats (a standard practice in training) and Global Positioning System sensors. Periodically the volunteers have an "attack" and their monitors call to test the system. The information is displayed on a computer monitor in a Web browser via the EWT.

The next phase in testing will involve developing protocols to conform to federal health information and other rules and to conceal a patient's information and location from anyone other than the physician at the EWT terminal. A space version would work in a similar fashion, with data going from a unit worn by astronauts during health checks, exercise, and spacewalks. Astronauts aboard a spacecraft could use laptop computers to monitor their shipmates' health at the same time. York hopes to have a demonstration version aboard the International Space Station in a few years.

GBEC's work has stimulated interest from NASA's own technology commercialization program and in the health industry, because warning a physician immediately of a patient's impending heart attack could save lives. Even a 1 percent success rate would mean avoiding 3,000 or more premature deaths per year.

BIOTECHNOLOGY



Biotechnology has enabled farmers to increase production with fewer acres and to grow crops that withstand disease, herbicides, and pesticides. Today's vast variety of fruits and vegetables is in part a result of the biotechnological advances that have improved their shelf life, so produce can be shipped over great distances and remain fresh.

The near-absence of gravity in orbit and in space has very real advantages for the study of cell growth and biological molecules. Accordingly, the two main areas of NASA's Microgravity Biotechnology Program are cellular biotechnology, overseen by Johnson Space Center in Houston, Texas, and macromolecular biotechnology, overseen by Marshall Space Flight Center in Huntsville, Alabama. Eventually, by enlarging our collective understanding of life at its most fundamental levels, the program may encourage the development of new drugs and other therapies for disease and dysfunction as well as measures to safely send humans into space for extended periods.

Did you ever stop to consider that some of the foods in your refrigerator are products of biotechnology? This science applies existing knowledge of biological systems and biological processes to the production of consumer goods and services. For example, makers of cheese, yogurt, and beer all harness biological processes, such as the process of bacterial fermentation.

Biotechnology research focuses on how organisms and their component parts function and, in turn, uses that information for various purposes, from gaining a basic understanding of life processes to developing novel technologies to improve life on Earth. Already thanks to biotechnology,

farmers can plant crops that resist certain herbicides or diseases, and researchers can develop bacteria that produce human insulin for the treatment of diabetes and drugs to dissolve blood clots that might otherwise lead to heart attacks and strokes.

Not only end users benefit. Biotechnology also supports a broad range of manufacturing industries. Processes that use biological components or mimic biological systems can serve such purposes as creating new materials, removing contaminants, and improving the efficiency of chemical reactions. For instance, microbes are used to process sewage at city wastewater treatment plants and to produce alcohol-based fuels for motorized vehicles.

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 form of life is the solitary cell, which propagates 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. On the scale of biological complexity, these specialized cells occupy a halfway point, and the scientist’s job is to try to understand their molecular makeup and how they cooperate to enable a complex organism to function.

More than 200 types of cells make up the human body. They are assembled into different tissues, such as skin, bone, and muscle, most of which contain a mixture of cell types. Cells are small and complex — a typical animal cell is about one-fifth the size of the smallest visible particle,

In its most basic form, biotechnology has been used to produce foods such as breads, cheese, and wine for human consumption. For example, yeast fermentation produces the carbon dioxide that causes bread to rise.

BIOTECHNOLOGY

Biotechnology has enabled scientists to use natural sources for pollution control. Bacteria have been genetically altered to perform several environmental cleanup tasks, including ingesting oil spills and treating wastewater.

and collectively the body's cells contain 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, discover its molecular composition, and especially find out how its various components function.

What can be learned about cells depends on the available tools. Culturing (growing) cells outside the body is one of the most basic techniques used by medical researchers. It 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 under the influence of gravity. The result is a thin sheet of cells, a single cell deep, called a monolayer. Cells in human tissues, however, are arranged in complex, three-dimensional structures, and cells grown in a monolayer do not perform all the functions that the original tissue does.

In effect, although much valuable information can be gained from monolayer cell cultures, the unnatural arrangement limits further understanding of the processes that govern cellular functions. A partial remedy is to decrease the influence of gravity, allowing the cells to grow in more tissuelike, three-dimensional aggregates, or clusters. But until the Cellular Biotechnology Program, overseen by Johnson Space Center (JSC) in Houston, Texas, developed a unique technology called the NASA Bioreactor, experiments attempting to generate three-dimensional cell formations were confined to the microgravity environment of space.

The NASA-designed device allows cells to be cultured in a continuous freefall

Some plants have been genetically altered to survive in less-than-ideal environments that might not support food and other resource production without the help of biotechnology.

state, modeling microgravity and providing a unique cell culture environment on Earth. 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 in the Cellular Biotechnology Program are investigating the prospect of developing tissues for transplantation in failed organs and tissues. Other investigators are striving to produce models of human disease to be used in developing novel drugs and vaccines, devising strategies to reengineer defective tissues, and developing new hypotheses for the progression of diseases such as cancer. Finally, when exposed to simulated and true microgravity, cells adapt to it. Examination of the adaptive response will yield new insights into cellular processes, establish the cellular bases 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.

What's more, cells are composed of, produce, and use biological macromolecules. Tens of thousands of these macromolecules are hard at work in the human body. Mostly proteins and nucleic acids, they perform or regulate all functions that maintain life. Proteins transport oxygen and chemicals in the blood, form major components of muscle and skin, and (in the form

of antibodies) aid in fighting infection. The nucleic acids deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) control cellular function and heredity.

Biological molecules act in concert with other systems. Hormones, as regulatory molecules, coordinate operations in the body. A commonly known protein hormone is insulin, which is secreted by the pancreas. Along with the hormone glucagon, insulin regulates blood sugar levels to a nearly constant level despite large fluctuations in dietary sugar intake. If blood sugar rises above normal, for example, the pancreas secretes insulin, which stimulates the liver and muscles to convert blood sugar into glycogen, a storage carbohydrate.

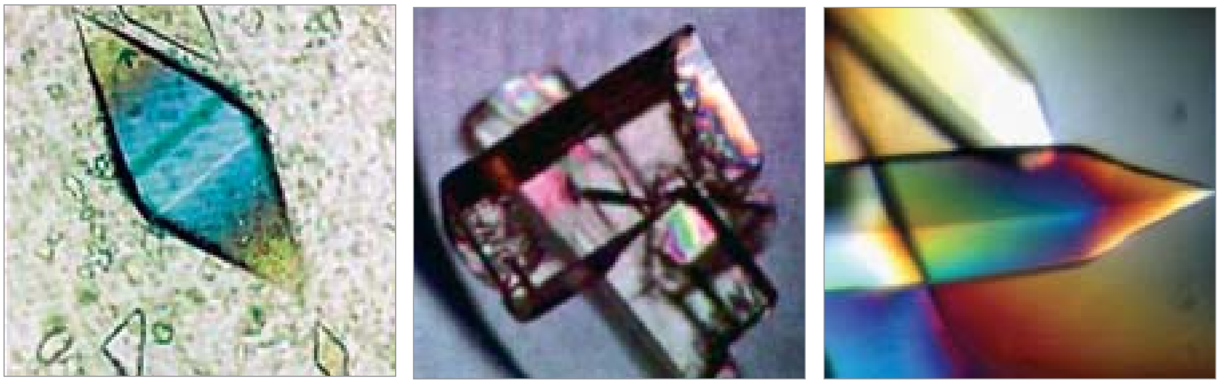
More than 200 types of cells are needed by the human body. They are assembled into several tissues, including skin, bone, and muscle, and nerve fibers (shown here).

The Macromolecular Biotechnology Program, overseen by Marshall Space Flight Center in Huntsville, Alabama, investigates what underlies the other processes that maintain stability in the body, much like insulin manages its balancing act. To recognize how these processes work, it is necessary to study them at the basic, molecular level. For instance, like other proteins and nucleic acids, insulin's shape and chemical components determine the types of molecules with which it can interact — interactions that are the chemical basis of how insulin does its job. In the case of blood sugar regulation, insulin binds to and reshapes a specific receptor molecule on the membrane of muscle cells. The reshaped receptor molecule modifies the structure of messenger molecules inside the cell. This action is the first step of a chain reaction in which Protein *X* activates Protein *Y*, which in turn activates Protein *Z*, and so forth. Eventually the proteins needed to make glycogen are turned on — all because insulin has bound to the outside of the cell.

OVERVIEW

Scientists must be able to picture the complex spatial relationships of organic molecules, which fit together like three-dimensional jigsaw puzzles. Understanding how these proteins fit together, change shape, and “switch on” requires knowing their three-dimensional atomic structure.

X-ray crystallography is the most common method by which scientists study the structure of biological molecules. Crystals of the molecule of interest are formed, and X-rays are passed through a single crystal at various angles. But crystals suitable for X-ray diffraction are difficult to produce, and some molecules such as membrane proteins are notoriously hard to crystallize. Researchers hope that the low-gravity environment, which reduces the fluid flows and sedimentation within the crystallization solution, will permit the successful crystallization of membrane proteins just as NASA’s Macromolecular Biotechnology flight experiments have produced many other crystals that yield more information about the structure of important molecules. Among these are medically important molecules, such as insulin; manganese superoxide dismutase, a vital antioxidant; and the nucleosome, a fundamental unit of DNA packing in cells.



credit: NASA

Proteins are the building blocks of the body. Biological molecules, including proteins, work with other systems to carry out the body’s many functions. Understanding the molecules’ structures improves understanding of how they function (which in turn will help researchers develop therapies for disease). To study their structures, the molecules must be turned into large, well-ordered crystals. Crystals of thaumatin (left), nucleosome core particle (middle), and serum albumin (right) grown in microgravity are larger and better structured than similar crystals grown on Earth and thus can reveal more about their nature to scientists.

Cellular Biotechnology Program Summary

During fiscal year (FY) 2003, the Cellular Biotechnology Program funded nearly two dozen grants under the NASA Research Announcement (NRA) NRA-00-HEDS-03. The 23 grants had been selected and their funding started in FY 2001. Another 16 investigations were funded as no-cost extensions under NRA-97-HEDS-02.

No new investigations were funded during FY 2003, but in July, 11 projects were selected from 99 proposals submitted in response to NRA-01-OBPR-08-B for funding in FY 2004. This NRA was originally released in June 2002, with a proposal deadline of September 6, 2002. Currently, these projects are classified as ground-based research, but the grants specify that if a flight opportunity arises and ground results warrant the upgrade, they could be elevated to flight status.

The NASA Cell Science Conference and Annual Investigators Working Group Meeting fosters collaboration between NASA programs using cell systems in basic and applied research. The 2003 meeting was held February 20–22, in Houston, Texas. Both flight- and ground-based research projects were presented at the 3-day conference, which drew about 170 scientists from universities; NASA centers; the National Institutes of Health (NIH) Bethesda, Maryland; the National Space Biomedical Research Institute (NSBRI), Houston, Texas; and commercial cell culture enterprises.

This annual conference is the joint affair of the Cellular Biotechnology Program, based at Johnson Space Center (JSC) in Houston, Texas, and the Fundamental Space Biology Program, based at Ames Research Center (ARC), Moffett Field, California. The meeting itself, coordinated and hosted by the Cellular Biotechnology Education and Outreach Group, featured a dinner lecture, formal oral presentations, and an exhibit area of products and flight equipment in addition to the Cellular Biotechnology Exhibit, which the outreach group also manned. At a business meeting, Neal Pellis, chief of the Biological Systems Office and manager of the Cellular Biotechnology Program at JSC, and ARC Senior Staff Scientist Ken Souza briefly described the status of the sponsoring programs and the upcoming ground and flight research opportunities. Pellis reminded conference attendees of the September 6, 2002, deadline for submitting proposals under NRA-01-OBPR-08, which solicited biotechnology research in tissue engineering, bioreactor and biosensor design, and gene expression; attendees were further informed that selections were expected to be made around March 2003. As for NRA-02-OBPR-03, which was issued on December 20, 2002, submittals had been scheduled to start on April 30, 2003, with proposals due July 31; however, because of restructuring within the biotechnology program, this NRA was cancelled 2 months later, in April 2003.

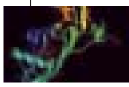
Besides the regular presentations, a plenary dinner lecture titled "Cell Biology in Space: From Basic Science to Biotechnology" was given by someone Pellis described as a "true pioneer" in space cell biology: Augusto Cogoli of the European Space Agency (ESA). Cogoli described the trials and tribulations of his career in that field and traced his work from its meager beginnings to its current state of development. The 2-hour event drew 110 participants. To request a 2003 Cell Science Conference report, visit *http://slsd.jsc.nasa.gov/bso/iwg/assistanceForm.asp?sendTo=Robert*.

The 2003 meeting of the American Society of Clinical Oncology (ASCO) was held May 25 in Chicago, Illinois, and drew 23,000 conferees. ASCO is the world's leading professional organization of physicians who treat cancer patients. Its members set the standard for the care of cancer patients worldwide and lead the fight for more effective cancer treatments, increased funding for clinical and translational research (the process of translating the fundamental understanding of the mechanisms of disease to a clinical setting) on cancer, and, ultimately, cures for the many kinds of cancers that affect millions of people around the world every year.

Also on display at ASCO was an exhibit by the Cellular Biotechnology Program's Education and Outreach Group. Consisting of the biotechnology exhibit backdrop, two bioreactors, an STS-107 video clip run on a laptop computer, and supporting literature, it was part of a larger NASA exhibit with representatives from NASA Headquarters, Washington, D.C.; JSC; Marshall Space Flight Center (MSFC), Huntsville, Alabama; and Kennedy Space Center (KSC), Cape Canaveral, Florida. The new biotechnology education and outreach bookmark and research brochure were well received during the event.

For more detail, visit *http://www.asco.org*. To obtain a conference report, go to *http://www.asco.org/ac/1,1003,_12–002462,00.asp*.

Neal Pellis and Principal Investigators (PIs) John Milburn Jessup of Georgetown University, Washington, D.C., and Timothy Hammond of Tulane University, New Orleans, Louisiana, were invited plenary speakers at the 2003 Experimental Biology Conference, held April 11–15, 2003, in San Diego, California. Their subject was NASA-sponsored research in cell biology. Such research has revealed that microgravity significantly affects many



processes within the cell, including cell shape, movement, growth, and production of biomolecules. These discoveries have potential applications to biomedicine in the areas of tissue engineering, models for studies of human disease, and pharmaceuticals.

The Experimental Biology Conference brings together several scientific societies and disciplines in a diverse biomedical meeting. It featured an abundance of plenary and award lectures, symposia, and oral and poster sessions, not to mention a placement center and an exhibit of scientific equipment, supplies, and publications. More than 12,000 independent scientists attended, representing the American Association of Anatomists, the American Association of Immunologists, the American Physiological Society, the American Society for Investigative Pathology, the American Society for Nutritional Sciences, and the American Society for Pharmacology and Experimental Therapeutics as well as guest societies.

Exhibitors represented government, academia, various societies, and commercial organizations. Jessup and Hammond conducted an exhibitor workshop titled Space Cellular Biology. Visitors to the exhibit booth interested in NASA research funding opportunities and the Cellular Biotechnology Program received a program brochure, a bookmark with useful NASA JSC Web sites, and a handout pertaining to the exhibitor workshop session abstract.

Jackie Jordan, with the Department of Natural Sciences, Clayton College and State University, Morrow, Georgia, presented a poster titled “Three-Dimensional Transgenic Model for Mutational Analysis: Vimentin and Cytokeratin Protein Expression” at the 2002 American Society for Cell Biology Annual Meeting held December 8–12, 2002, in Washington, D.C. Nearly 10,000 cell scientists attended the event. Jordan’s presentation demonstrated that several state-of-the-art areas of biotechnology — namely, genetic cell engineering, tissue engineering, and unique NASA-designed bioreactor systems — have been used to create new test systems that are models of three-dimensional tissues. Jordan participated in a poster competition for graduate students, postdoctoral students, and junior faculty. The posters were presented to three judges, and Jordan, a NASA visiting scientist, placed second in the postdoctoral category.

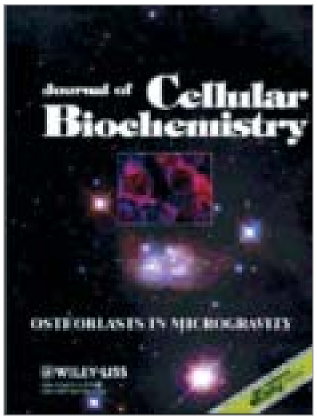
Neal Pellis, who in addition to his duties at JSC was ISS Program Scientist from May 2002 until August 2003, was invited to speak at several major conferences during FY 2003, including the World Space Congress (held once every decade), held October 10–19, 2002, in Houston, Texas, and the ISS Utilization Research Panel, held October 17, 2002, in Houston, Texas. Pellis also presented “Gravitation and Mechanosensory Biology: Spaceflight from the Cellular Perspective” on December 17, 2002, at the 42nd Annual Society for Cell Biology Meeting in San Francisco, California.

John Love, technical monitor for flight definition for the Cellular Biotechnology Program, was invited to speak at the 40th Space Congress held in May at KSC. He presented “The Third Dimension: Growing 3-D Cultures in Space” on May 1, 2003.

Cellular Biotechnology Program PIs published several notable papers in peer-reviewed journals and received one patent (on fibroblast research) during FY 2003. Perhaps most prestigious and certainly of great general interest was the acceptance of “Microarray Analysis Identifies *Salmonella* Genes Belonging to the Low-Shear Modeled Microgravity Regulon” (James W. Wilson, Rajee Ramamurthy, Steffen Porwollik, Michael McClelland, Timothy Hammond, Pat Allen, C. Mark Ott, Duane L. Pierson, and Cheryl A. Nickerson, *Proceedings of the National Academy of Sciences of the United States of America*, **99**(*21*), October 15, 2002, 13,807–13,812). Its nine authors include PI Cheryl A. Nickerson, whose team is investigating how *Salmonella typhimurium* senses and responds to microgravity in hopes of developing remedies for *Salmonella*-caused illness.

PI Laura McCabe’s research was featured on the cover of the *Journal of Cellular Biochemistry* (Simulated Microgravity Suppresses Osteoblast Phenotype, Runx2 Levels and AP-1 Transactivation, *Journal of Cellular Biochemistry*, **88**(*3*), 2003, 427–437). She discusses her initial studies of using a rotating-wall vessel to suppress the differentiation of bone-forming cells (osteoblasts).

PI Joshua Zimmerberg and his research team at the NASA/NIH Center for Three-Dimensional Tissue Culture in Bethesda, Maryland, published a paper on three-dimensional culture systems (Silvia S. Chen, Roberto P.



credit: Journal of Cellular Biochemistry

Cellular Biotechnology Program Principal Investigator Laura McCabe’s article describing her research on osteoblast formation using rotating-wall vessel (RWV) bioreactors was featured on the cover of the Journal of Cellular Biochemistry*.*

Revoltella, Sandra Papini, Monica Michelini, Wendy Fitzgerald, Joshua Zimmerberg, and Leonid Margolis, Multilineage Differentiation of Rhesus Monkey Embryonic Stem Cells in Three-Dimensional Culture Systems, *Stem Cells*, **21**(*3*), 2003, 281–295). The team is studying how the immune system — especially lymph tissues and lymphocytes — changes in microgravity. A grasp of why the human immune response is blunted in space is a first step toward developing countermeasures to protect astronauts. On Earth, such research can help scientists to study and treat autoimmune diseases and immunodeficiencies such as acquired immune deficiency syndrome (AIDS).

PI Jeanne Becker and coauthor Janet G. Drake published a paper on ovarian cancer research (Aspirin-Induced Inhibition of Ovarian Tumor Cell Growth, *Obstetrics and Gynecology*, **100**(*4*), October 2002, 677–682). Human ovarian tumor cells, like breast tumor cells, are extremely hard to grow outside the body, but Becker and her team of researchers at the University of South Florida in Tampa have successfully cultured three-dimensional constructs of such cells using the NASA-developed high–aspect ratio rotating-wall vessel. Becker is using the three-dimensional constructs to study the resistance of ovarian cancer cells to chemotherapeutic drugs.

PIs Lisa Freed and Gordana Vunjak-Novakovic, both of the Massachusetts Institute of Technology (MIT) in Cambridge, published additional results on their tissue engineering studies (with Ming Pei, Luis A. Solchaga, Joachim Seidel, Li Zeng, and Arnold I. Caplan, Bioreactors Mediate the Effectiveness of Tissue Engineering Scaffolds, *FASEB Journal*, **16**(*12)*, October 2002, 1691–1694). The research team is investigating methods of engineering heart muscle by growing cells on polymer scaffolds.

MIT received U.S. Patent No. 6,582,960 on June 24, 2003, for “Use of fibroblast growth factor-2 for expansion of chondrocytes and tissue engineering,” which was developed by Freed and Vunjak-Novakovic, along with their MIT colleagues Ivan Martin and Robert Langer. Patents are also pending in Canada, Europe, and Japan.

Cellular Biotechnology Flight Experiments

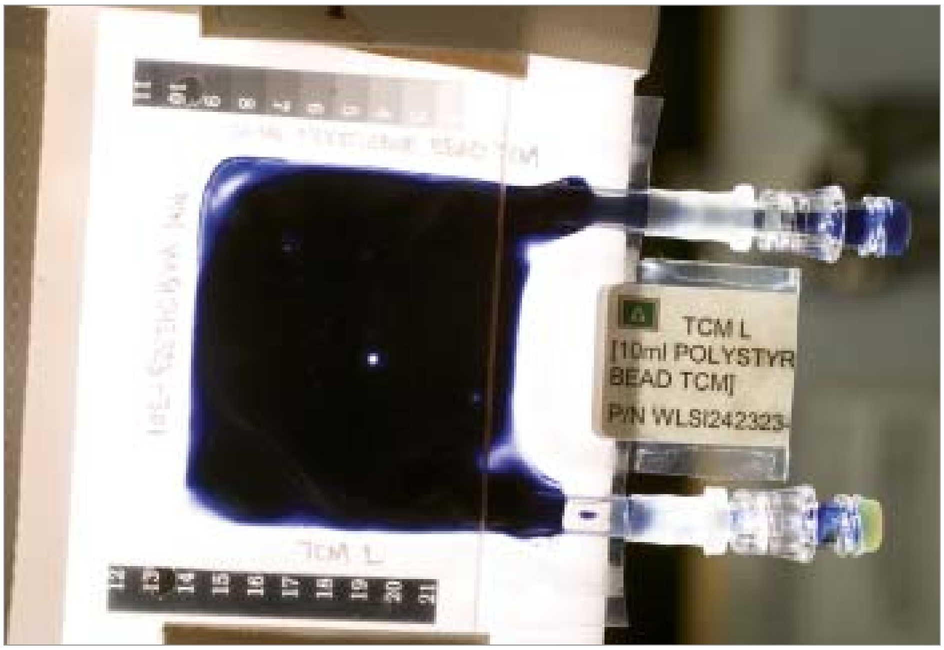
The Cellular Biotechnology Program made headway in several areas in its flight program during fiscal year (FY) 2003. Flight experiments included the Cellular Biotechnology Operations Support System–Fluid Dynamics Investigation (CBOSS-FDI) and the Bioreactor Demonstration System (BDS-05).

CBOSS-FDI is designed to provide researchers with a controlled environment in low Earth orbit for growing three-dimensional tissue cultures, which can mimic living body tissue more closely than tissue grown on Earth. The support system is to be used on the International Space Station (ISS) until the Biotechnology Facility (BTF) is installed.

Growing healthy three-dimensional tissues in microgravity requires a thorough mixing of cells and fluids during the various tissue culture procedures. Accordingly, CBOSS-FDI involves a series of experiments aimed at optimizing fluid-mixing operations while helping characterize the support system’s stationary bioreactor vessel, the Tissue Culture Module (TCM), in terms of fluid dynamics in microgravity. Determining which fluid-mixing techniques are most efficient in orbit is essential to conducting cellular research in that environment and will enhance the probability of success for future investigations on board the ISS. The principal investigators (PIs) responsible for the CBOSS-FDI experiment are Joshua Zimmerberg of the NASA/NIH Center for Three-Dimensional Tissue Culture in Bethesda, Maryland, and John Milburn Jessup of Georgetown University, Washington, D.C.

Aboard the ISS, cell cultures are grown in the TCM. With its two syringe ports, it resembles the bags used to administer intravenous fluids. Frozen cells are flown to the ISS, where they are thawed and introduced by inoculation into a TCM, which already contains culture medium to feed the growing cells. Periodically, some culture medium is replaced with fresh medium (to remove waste products), and the new contents must be completely mixed. If not, some cells will not receive nutrients and will die, causing a “leaching” of waste products that can be toxic to the other cells in the culture, thus jeopardizing the outcome of the experiment.

Several mixing procedures are being assessed to determine which produces the most uniform results. The studies use colored polystyrene beads to mimic cells. By substituting beads for the cells, the researchers can more easily visualize each procedure. Some of the mixing methods include repeated injections of medium into a TCM, mixing its contents by drawing circles on the culture bag (that is, pressing on the bag in a circular motion), and squeezing the TCM. Pictures are taken after each procedure for the PIs to analyze on the ground. This they do by using an optical-density software program that, in essence, measures the concentration of the beads at various locations in the TCM. A well-mixed TCM should exhibit little difference in optical density, and hence bead concentration, throughout the bag. A comparison of the optical densities obtained will reveal which method is best for growing cell cultures.



credit: NASA

Aboard the International Space Station (ISS), the Tissue Culture Module (TCM) is the bioreactor vessel in which cell cultures are grown. With its two syringe ports, it is much like a bag used to administer intravenous fluid. The TCM contains cell culture medium, and when frozen cells are flown to the ISS, they are thawed and introduced into the TCM through the syringe ports. In the Cellular Biotechnology Operations Support System–Fluid Dynamics Investigation (CBOSS-FDI) experiment, several mixing procedures are being assessed to determine which method achieves the most uniform mixing of growing cells and culture medium.

This experiment was developed and implemented on an extremely fast-track schedule and then was flown to the ISS on a Russian Progress vehicle because the space shuttle fleet was grounded after the loss of *Columbia*. However, because astronauts were already on board during the development of FDI, virtual "onboard training" was used with success to train the crew in how to implement the procedures.

In a change from standard ISS protocols, the PIs addressed experimental setup issues by communicating directly with the astronaut performing the experiment instead of using the flight director as an intermediary. In effect, the PIs could apply their unique insights to troubleshooting, which was an efficient way of overcoming difficulties as well as optimizing camera placement and lighting to obtain good imaging. The researchers have continued the diagnosis in their laboratory and will have revised setup procedures for future ISS experiments.

The CBOSS-FDI experiment flew to the ISS on August 29, 2003. Expedition 7 ISS Science Officer Ed Lu underwent onboard training on September 22, 2003, and the CBOSS-FDI procedures began on September 24. The experiment is scheduled to continue through Expedition 8 and return to Earth in April 2004.

CBOSS-04, for which Zimmerberg and Jessup also are the PIs, is scheduled to fly to the ISS with Expedition 9 in July 2005. Zimmerberg hopes to determine whether microgravity is detrimental to immune responses of human lymphoid cell suspensions. In addition, this experiment will study the ability of human tonsil cells to proliferate and secrete antibodies in response to activators. Jessup will study cellular adhesion of MIP-101 cells (human colorectal carcinoma) using microcarrier beads.

BDS-05 launched on *Columbia* (STS-107) on January 16, 2003, and was scheduled to return to Earth on February 1, 2003. The PI for the experiment was Leland Chung of Emory University, Atlanta, Georgia. The BDS-05 payload for the STS-107 research mission included one flight experiment (experiment 14) and two ground experiments (experiments 13 and 15). In the experiments, human prostate cancer (LNCaP) and human bone stromal (MG-63) cells were co-cultured with microcarrier beads in an Experiment Development Unit Re-flight (EDU-1R) bioreactor.

The EDU-1R is a bioreactor system for nurturing cell cultures. It links a rotating 125-milliliter (approximately 4-ounce) cell culture vessel to equipment for temperature control, automated infusion and perfusion of cell growth medium, gas exchange, and independent wall rotation. Support equipment for the system included the Experiment Control Computer (ECC), which automated control of the experiment while allowing the crew to monitor the experiment and change its parameters when necessary. Another part of the EDU-1R was a media tray — a storage system consisting of six bags that hold a total of 9 liters (2.4 gallons)

credit: NASA

Principal Investigator Leland Chung grew prostate cancer and bone stromal cells aboard Space Shuttle Columbia *(STS-107), and although the experiment samples were lost along with the ill-fated spacecraft and crew, he did obtain downlinked video images of the experiment that indicate the enormous potential of growing large tissues in microgravity. Cells grown aboard* Columbia *had grown far larger tissue aggregates at day 14 (left) than cells grown in a NASA Bioreactor on the ground (right). As the latter grow, the bioreactor must rotate faster to keep the cells suspended in the culture medium, and this rotation creates shear, which inhibits large tissue formation.*

of sterile cell growth medium plus other bags that receive and store the waste produced after infusions of medium into the cell culture vessel.

Prostate cancer, the second leading cause of cancer death, is detected in approximately 200,000 men every year in North America. Although it tends to metastasize (spread) to the bones and so become fatal, it is easily treated if diagnosed early. Unfortunately, because of the possibly unpleasant side effects of early treatment, many men put off being tested. In the United States, prostate cancer kills 40,000 men each year, at a public health cost of more than $2 billion per year. Prostate and bone stromal cells (which form bone's supporting framework) play a key role in prostate cancer. In the bioreactor, these cells organize into three-dimensional tissues that are similar to those in the prostate gland itself. The study of the tissues grown in the EDU-1R can help scientists understand the spreading and growth of prostate cancer and allow them to test and assess potential therapies.

Chung had planned to compare the tissue generated during a space shuttle flight with tissue generated in simulated microgravity on Earth to gain insight into the effects of microgravity on cell physiology and gene expression. However, as a result of the *Columbia* disaster, the cell culture samples were lost. Only downlinked metabolic data and video images are available for comparison.

Nonetheless, the video images downlinked from the mission are startling — the tissue aggregates grown in the space shuttle were orders of magnitude larger than those formed in ground-based bioreactors. (Because of gravity, ground-based bioreactors can keep the cells suspended only by rotating faster; the extra shear this rotation creates inhibits the formation of large tissues.) The images vividly illustrate the huge potential of growing large tissues in microgravity, where the absence of gravity and shear forces permit cell–cell interactions to occur more naturally, as in the body. In future studies, when samples returned from orbit can be analyzed, Chung expects that the study of the interactions between the prostate cancer cells and bone stromal cells will advance the understanding of the prostate cancer pathology, which in turn can lead to more effective and selective clinical treatments.

Significant progress was made on the BTF project in FY 2003. This state-of-the-art facility will perform cellular biotechnology research aboard the ISS. It will operate continuously, so that lengthy experiments can be performed and in-orbit scientific throughput boosted. The project staff team was put in place early in FY 2003. The science requirements, system specifications, and specifications for all subrack components were baselined. The BTF preliminary design review (PDR) in April 2003 was successful. The task order and initiation were developed for the new Bioastronautics contract on May 1, 2003. All subrack PDRs were successfully completed in the summer of 2003. The BTF Project Plan, Risk Management Plan, and Configuration Management Plan were baselined between May and July 2003. A detailed design has been initiated and the facility critical design review is scheduled for early 2005.

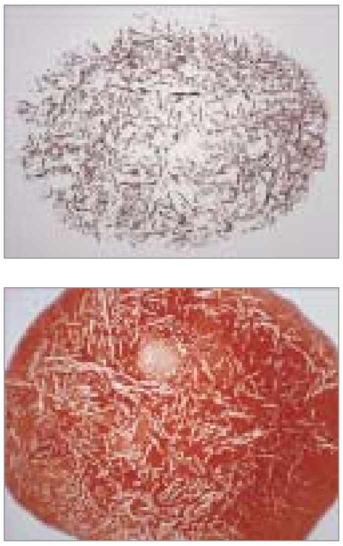
Cellular Biotechnology Highlights

Engineering Tissues for Joints and Heart

Ten years ago, the idea of growing implantable "patches" that can encourage the body to grow and repair damaged tissues and organs was the stuff of science fiction. Ten years ago also marked the start of investigations that led to microgravity tissue engineering studies that now are helping to develop cures for injuries. In essence, these new cures demonstrate that what was once fiction is now fact.

Principal Investigator Lisa E. Freed of the Massachusetts Institute of Technology (MIT), Cambridge, and Co-Investigators Gordana Vunjak-Novakovic of MIT and Maria A. Rupnick of the Harvard Medical School, Boston, Massachusetts, are seeking to understand how cells form healthy tissues, with an aim toward understanding how cells could be used as potential treatments for injuries.

The research is focused on two types of tissue: cartilage and cardiac muscle. Both are of interest to NASA



credit: E. Tognana, F. Chen, R. Paderra, and L. E. Freed

These two images show engineered cartilage shortly after cells were seeded on polymer fibers (top) and after 8 weeks of culture in a rotating-wall vessel (bottom); cartilaginous tissue is stained red; the diameter of the entire sample is approximately 5 millimeters (approximately 0.2 inches).

and to health professionals worldwide. NASA's interest comes from changes experienced by the body in microgravity, which can have a profound impact on astronauts' musculoskeletal and cardiovascular systems. Clinicians' interest comes from the high incidences of osteoarthritis and heart failure and the associated need for new, definitive treatments for both conditions.

On Earth, injuries to cartilage — such as to the knee joint — are quite common, yet are difficult to treat and heal. Instead of surgery to insert an artificial knee joint, the ideal solution would be for the body itself to regenerate an articulating cartilaginous surface capable of bearing normal loads. Similarly, in the case of damage from cardiac disease, the goal would be for the body itself to regenerate heart muscle with normal contractile function. Researchers would like to use living cells to grow "patches" of a particular tissue that could be placed in a damaged area to promote healing and growth.

The approach developed by Freed's group involves the integrated use of biomaterial scaffolds (biocompatible materials that provide a structural template for tissue development and then ultimately biodegrade) and bioreactor vessels (which provide environmental control and supply nutrients and regulatory signals) to create such patches. Scaffold design and bioreactor operating conditions largely determine the development and functionality of the engineered tissue. Challenges have been many. One big problem is the inhomogeneity of patches caused by the gravitational settling of cells "seeded" onto the three-dimensional scaffolds; another is that cardiac cells do not multiply in culture and are extremely sensitive to oxygen concentration.

The answer to these and other difficulties is the development of advanced rotating-wall vessel bioreactors that can provide tissue culture conditions that imitate nature as closely as possible but also simulate microgravity. The microgravity not only prevents gravitational settling but also allows a three-dimensional structure to grow that is much more similar to that found in the body. This device has allowed the research team to advance these studies in several ways.

Cartilage studies conducted in 2003 by Enrico Tognana, Fen Chen, and Robert Padera of MIT focused on the question of how engineered cartilage can mature and integrate with native cartilage and bone. Because it is avascular (no blood or lymphatic vessels), cartilage does not heal well, and integration has traditionally been very difficult to achieve. The use of the rotating-wall vessel to provide a controllable environment makes such studies and clinically relevant developments possible. The result is a very good model system that, while not as complex as that within a body, still allows the systematic variation of numerous factors of interest and measurement of their effects on the cartilage integration.

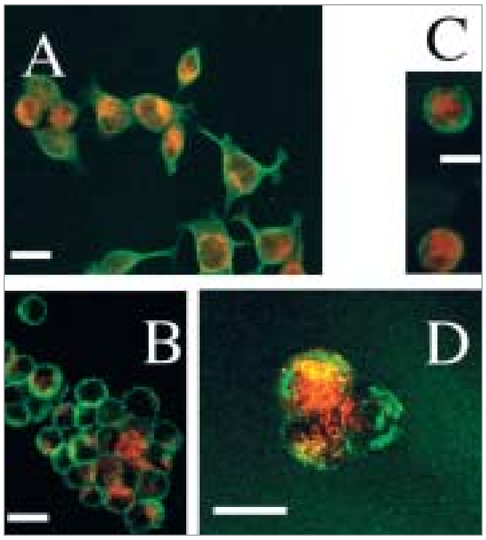
Cardiac studies conducted in 2003 by Milica Radisic, Jan Boublik, and Hyoungshin Park of MIT have led to the development of technologies to establish and maintain viable cultures and cell densities similar to those present in the body. Researchers also have identified some of the regulatory signals that can induce cells to form into functional units, just as they would in real life. In particular, applying key physical and electrical signals that mimic those in the body resulted in markedly better cultures.

The long-term goal of the research is to engineer tissues by culturing cells on biomaterial scaffolds and then use them to replace damaged tissues. Although the ultimate vision is still in the future, current research in understanding cell function and assembly has made great strides by showing the feasibility of turning tissue engineering from fiction to fact.

More complete information on the successes obtained in the past year by this investigation was presented at the NASA Cell Science Conference in Palo Alto, California, February 26–28, 2004. More information about the conference can be found at *http://slsd.jsc.nasa.gov/bso/IWG/*.

A Key to Cell Death

It's been known for decades that in microgravity, astronauts' bones lose density and muscles lose conditioning. Research now indicates that microgravity induces key changes in the individual cells that make up the body, specifically, within the cytoskeleton (the network of



credit: courtesy of John Milburn Jessup

These illustrations show the difference in clumping of microtubules, stained red, grown under normal laboratory conditions on Earth (A and B) and in rotating-wall vessels to simulate microgravity (C and D).

proteins and tubules that give a cell its shape and determine much of its function). That newly documented key change concerns why and how cells die.

Traditionally, scientists use human colorectal carcinoma cells for such studies. Although they are abnormal cells within the human body, they are excellent models for the effects of microgravity, in part because they are resistant to many of the stresses that could kill ordinary cells. Yet, it has been observed that human colorectal carcinoma cells die under simulated and actual microgravity conditions. Understanding why and how they die is important to understanding the effects that take place within normal organisms in microgravity. It also offers insight into potential countermeasures to conditions on Earth, such as heart attack and stroke. John Milburn Jessup, a professor of oncology and surgery at Georgetown University Medical Center, Washington, D.C., is pursuing research into the role of gene expression in such cell death.

Jessup's work suggests that nitrogen- and oxygen-related stress is the cause of the early cell death. According to his hypothesis, nitric oxide and negatively charged oxygen ions combine to form the chemical peroxynitrite, which then nitrates (converts to a salt or ester of nitric acid) and causes the cytoskeleton of the cell to fall apart. Without the tubules and structure, cells are unable to divide and reproduce and therefore die. Jessup and colleagues have shown that as the colorectal cells change shape during culturing, the amount of nitric oxide and reactive oxygen within the cells increases. In the rotating-wall vessel, the amount of nitric oxide increases even more. Normally, genes within the cells act to eliminate such chemical stress, but it appears that the expression of these genes is altered in microgravity. Therefore, understanding that gene expression is a key to understanding early cell death and the effects of gravity (or of its absence) on several tissues. Lastly, Jessup and his colleagues have found that inhibiting a gene that produces nitric oxide prevents the majority of cells from dying.

Jessup's work may prove helpful on Earth, where so-called ischemic reperfusion injuries can trigger heart attacks and strokes. Ischemic reperfusion injuries interfere with the normal blood flow within the body, triggering oxygen- and nitrogen-related stress similar to that seen in the colorectal studies. Jessup's work may also advance other areas of research, such as knowledge about metastasis (the spread of cancer through the body). Jessup, using the NASA-designed rotating-wall vessels, has found that as cancer cells enter the blood, they encounter a simulated microgravity condition because of the flow of the fluid that causes them to increase their nitric oxide and reactive oxygen content. This finding suggests that a small additional increase in nitric oxide, negatively charged oxygen, or both may increase the death rate of these cells. If Jessup's hypothesis is true, then it may be possible to arrest the spread of cancer within the body by providing that increase. Thus, an improved understanding of cell shape change and response to weightlessness may allow doctors on Earth to command cancer cells to die.

To expand the expertise available to NASA researchers, Leonard H. Augenlicht, an expert in the analysis of gene expression at the Albert Einstein Cancer Center, Bronx, New York, has been brought into the project. With Augenlicht, this year Jessup has improved the design of a microchip developed at the Albert Einstein Cancer Center such that it now can assess some 30,000 genes on one chip (as opposed to the approximately 8,000 that it could handle before). Other studies are ongoing to determine the best method for conducting studies on the International Space Station, whose months-long missions make it impossible to return samples for testing with traditional methodologies on the ground.

Meanwhile, on the ground, studies are under way using rotating-wall vessels to simulate microgravity and provide a comparison to control samples grown using traditional methods. Using these results as a basis, researchers will be able to better understand the signal pathways and gene expression involved in cell death.

Taking a Load Off of Bone Research

Loss of bone mass is a problem, on Earth or in space. On Earth, it causes osteoporosis, susceptibility to

bone fractures, and other problems, especially for older people. For astronauts, it seriously limits how long they can stay in space or in orbit. Although short-term exposure (days or weeks) to microgravity does not produce significant problems, long-term spaceflight (months or years) can cause potentially irreversible bone loss for crewmembers.

The cause of bone loss in orbit has been studied and debated for years, but recent research by Laura R. McCabe, an associate professor at Michigan State University, East Lansing, focusing on the nuclei of bone-forming cells called osteoblasts, provides new insights. Conducted in microgravity, McCabe's work is offering valuable new insights into the causes of osteoblast dysfunction, which can lead to osteoporosis.

Bone is a highly dynamic structure. It is constantly being rebuilt and restored as it ages and cracks. In fact, it is thought that the mineral in the bones of a human skeleton is entirely replaced every 10 years. Cells called osteoclasts, on the surface of and inside bones, break down bone; osteoblasts, on the surface, create new bone — in part, by promoting bone mineralization (the deposition and growth of minerals and crystals containing calcium). When osteoblasts become dysfunctional and no longer work as hard as needed, less mineral is deposited because the osteoblasts can no longer keep pace with the breakdown of bone by osteoclasts. As a result, bone density and strength can decrease to levels associated with osteoporosis.

Force associated with skeletal loading is well known to increase bone mineral density and strength. For example, a tennis player may have up to 40 percent more bone density in his or her racket-holding arm than in the "free" arm. Clearly, force causes osteoblasts to work harder and put more mineral into bones to make them stronger.

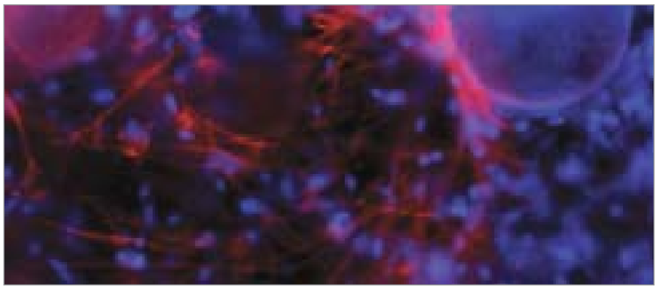
In contrast, lack of exercise reduces the loading force on the skeleton, and bone formation is not encouraged. For people who are inactive or immobilized for a long time, the body perceives that strong bone is no longer required, so the osteoblasts form less new bone, resulting in lower mineral density.

Why osteoblasts don't make as much bone under such conditions is not known. Within any cell, genes regulate growth, maturity, and even cell death. Special proteins known as transcription factors act as switches to turn genes on and off. The activation and deactivation of different genes is what causes cells to multiply, mature, and function. When the transcription factors are modified through signals caused by changes in the environment outside the cell, the proper switches are not thrown at the proper time, and cells fail to mature. Because they can't "grow up," they cannot perform their intended functions. McCabe wondered whether such a mechanism might explain why osteoblasts don't function well under decreased load.

In 2003, McCabe and graduate student Christopher Ontiveros cultured osteoblasts in the NASA-designed rotating-wall vessel to mimic microgravity to find out. They observed that in the vessel, osteoblast function was decreased (consistent with decreased bone mass in astronauts) and that levels of a key transcription factor, Runx-2, were reduced. Without Runx-2, the genes in the cell are not activated to make new bone. This observation suggests that the decrease in Runx2 could be the major "off" signal that decreases bone formation and bone mineral density in microgravity.

Recently, studies by T. S. Gross at the University of Cincinnati, Ohio, have suggested that in addition to the lack of mechanical forces, unloading may also reduce the oxygen supply to bone cells, creating a condition known as hypoxia. Determining which factor — mechanical load or oxygen supply — is more important in causing osteoblast dysfunction cannot be done in animal studies, because the effects cannot be separated. However, by modifying the rotating-wall vessel, McCabe's lab was able to uncouple the effects of hypoxia from the effects of mechanical unloading on the osteoblasts. Her team's approach indicates that hypoxia is indeed a factor in suppressing the production of Runx-2 and preventing the osteoblasts from maturing under conditions of decreased skeletal loading.

Additional research that determines how transcription factor "switches" are influenced by unloading and microgravity may help researchers devise a means to stop the suppression of bone formation in astronauts. Moreover, such information may contribute to the development of treatments for bone loss stemming from osteoporosis or prolonged bed rest.



credit: Laura McCabe

This photograph shows the nuclei of cells in a culture (blue) and stretched actin fibers in the cytoskeleton of osteoblasts. The actin cytoskeleton helps the osteoblasts obtain and maintain their shape and also allows the formation of extensions.

Macromolecular Biotechnology Program Summary

credit: *Journal of Molecular Biology*

Geoffrey Chang of Scripps Research Institute, La Jolla, California, is an active NASA investigator whose work in membrane proteins was featured on the cover of an issue of the Journal of Molecular Biology. *Membrane proteins are notoriously difficult to study because their nature inherently complicates their isolation, purification, characterization, and crystallization.*

In fiscal year (FY) 2003, the Macromolecular Biotechnology Program continued its fundamental research with ground and flight studies. The focus was on growing high-quality macromolecular crystals for structural studies, with the emphasis being on molecules of biological importance that are challenging to grow on Earth. Developments were made to in-flight hardware that will enhance the crystallization process, and ground research further improved methods of preserving and studying crystals.

As the program moved to align with Office of Biological and Physical Research (OBPR) research priorities, two groups were formed to establish and implement future strategic research: Strategic Biomolecular Research for Exploration (SBRE) and Lab-on-a-Chip Applications Development (LOCAD).

The SBRE team set about establishing a molecular-based research program that will join with other NASA centers and research institutions to address astronaut health during lengthy exposure to reduced gravity. The group is interested in identifying, at the molecular level, the mechanisms that explain the formation and breakdown of bone and muscle tissue and how they may change on exposure to a reduced-gravity environment. SBRE is also looking into the molecular pathways relevant to radiation damage, repair, and risk assessment.

LOCAD grew out of NASA's Iterative Biological Crystallization (IBC) Program. After developing lab-on-a-chip (LOC) technology for use in high-throughput crystallography (iterative biological crystallization), the IBC group discovered that their capabilities were well matched for LOC technologies that will allow humans traveling in space to maintain good health and a safe environment. LOC technology is appropriate for use in spacecraft systems because it allows labor-intensive processes that require many pieces of laboratory equipment to be done on a tiny chip and a chip-control unit. LOCAD researchers anticipate that future space explorers will use miniature chips and control units in the form of handheld devices that will sense and diagnose an astronaut's medical condition and will monitor and analyze a spacecraft's environmental conditions. (See Highlight "Lab-on-a-Chip: Smaller *Is* Better" on page 37.)

In FY 2003, the Macromolecular Biotechnology Program funded 26 investigators to conduct flight and ground research for another fiscal year. No new researchers were funded in FY 2003 because of the programmatic restructuring that resulted in the April 14 cancellation of the biotechnology NASA Research Announcement (NRA) issued December 20, 2002.

NASA's principal investigators (PIs) in macromolecular biotechnology published approximately 77 peer-reviewed articles in scientific journals during FY 2003. PI Gloria Borgstahl, Eppley Institute, University of Nebraska Medical Center in Omaha (formerly of the University of Toledo, Ohio), published two papers: "Improved Three-Dimensional Growth of Manganese Superoxide Dismutase Crystals on the International Space Station" (A. Vahedi-Faridi, J. Porta, and G. E. O. Borgstahl, *Acta Crystallographica*, **D59**, 2003, 385–388; early results from this research were highlighted in the NASA Physical Sciences Research Division's 2001–2002 Annual Report) and "Physical and Structural Studies on the Cryocooling of Insulin Crystals" (A.Vahedi-Faridi, J. Lovelace, H. D.

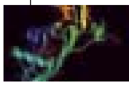
Bellamy, E. H. Snell, and G.E.O. Borgstahl, *Acta Crystallographica*, **D59**, 2003, 2169–2182).

The research of several PIs was portrayed on the covers of the journals in which their articles appeared. Geoffrey Chang of the Scripps Research Institute in La Jolla, California, is an active NASA PI whose work in membrane proteins made the cover of the *Journal of Molecular Biology* (Structure of MsbA from *Vibrio cholera*: A Multidrug Resistance ABC Transporter Homology in a Closed Conformation, **303**(2), 2003, 419–430). Membrane proteins can baffle investigation because their very nature complicates their isolation, purification, characterization, and crystallization. Yet membrane proteins are of tremendous scientific interest as part of the boundary between the cell and its environment and, frequently, transport molecules crucial to the cell's function and survival across the membrane boundary. Chang's research focuses on one family of such molecules, the adenosine triphosphate (ATP)–binding cassette transporters (ABC transporters). The question is whether these molecules can be crystallized more easily in microgravity. Chang expects his research to significantly improve knowledge and understanding of the function of these molecules and the details of how they work through three-dimensional structure determination.

credit: *Journal of Synchrotron Radiation*

The work of NASA Principal Investigator Edward Snell and Co-Investigator Mark van der Woerd, both of Marshall Space Flight Center and BAE Systems in Huntsville, Alabama, was featured on the cover of the Journal of Synchrotron Radiation*. Snell and colleagues developed a method of thermally imaging the process of cryocooling macromolecular crystals.*

The research of PI Edward Snell and Co-Investigator Mark van der Woerd of Marshall Space Flight Center (MSFC) and BAE Systems, both in Huntsville, Alabama, was featured as a cover article of the *Journal of Synchrotron Radiation* (Seeing the Heat: Preliminary Studies of Cryocrystallography Using Infrared Imaging, **9**, 2002, 361–376). Rapid cooling or cryopreservation of macromolecular crystals is a technique that has received much attention in structural biology research. It is routinely used to preserve crystals of biological molecules for structural analysis by X-ray diffraction. Unless the crystals are carefully preserved and stored, they may not remain intact for later analysis or withstand radiation damage from the intense X-rays used (the synchrotron X-ray sources used are 10 orders of magnitude more intense than a typical dentist's X-ray system). Flash cooling of crystals to near 100K (–280 °F) (cryocooling) extends their lifetime and makes them less prone to the secondary radiation damage that occurs during X-ray analysis. Cryocooling also reduces thermal motions of the molecules, which gives more detailed structural information and allows for data collection from very thin or small crystals.



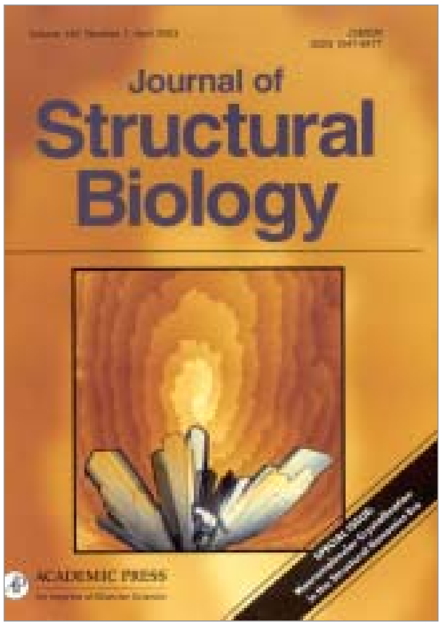
The prolonged life of crystals and the improved X-ray data quality lead to better-defined three-dimensional structures of the molecules under study. These structures are typically used for designing pharmaceuticals, obtaining knowledge about life processes, making new agricultural chemicals, and other such processes.

Because these crystals contain anywhere from 30 to 70 percent water, ice crystals can form during cryocooling and ruin not only the original crystal but also the data obtained from the crystal. Cryoprotectants, though, can replace water in the structure and slow the formation of ice so much that flash cooling the crystal does not freeze it, but rather vitrifies it — turns it into a glassy substance. Snell has studied water and aqueous mixtures of various cryoprotectants in the macromolecular structure to understand how cryoprotectants interact with the crystal at the molecular level. The cryoprotectants do not chemically react with the crystal and are simply present to protect the crystal from the effects of freezing, much as antifreeze protects cooling water in an automobile. Cryocooling of crystals is an empirical process that the two researchers aim to visualize, understand, and optimize.

Snell also attended the 21st European Crystallographic Meeting in Durban, South Africa, August 24–29, 2003. He presented "Hot Views on Cold Crystals: The Application of Thermal Imaging in Cryocrystallography," a collaboration with Mitchell Miller and Ashley Deacon from the Stanford Synchrotron Radiation Laboratory, Stanford, California.

The *Journal of Structural Biology* published a special issue (**142**, 2003) for research articles on macromolecular crystallization and its importance in an era of structural genomics research. PI Alexander McPherson (University of California, Irvine), whose article "Macromolecular Crystallization in the Structural Genomics Era" was featured on the cover, edited the special issue in which 9 of 19 articles featured were written by NASA-funded investigators.

PI Peter Vekilov's research group also published a noteworthy article on crystallization in a journal devoted to statistical, nonlinear, and soft-matter physics (Peter



credit: A. Greenwood and A. McPherson, University of California, Irvine

NASA Principal Investigator Alexander McPherson (University of California, Irvine) edited a special edition of the Journal of Structural Biology, *which included nine articles by NASA-funded researchers. An article by McPherson was featured on the cover. Here, a cluster of bacterial lipase crystals is seen against an atomic force micrograph of a screw dislocation on the surface of a growing trypsin crystal.*

Vekilov, Hong Lin, and S.-T. Yau, Dissipating Step Bunches during Crystallization under Transport Control, *Physical Review E*, **67**, 2003, 0031606). Vekilov, of the University of Houston, Texas, also presented “Hydration Interactions between Apoferritin Molecules and the Phase Behavior of the Solution,” coauthored by D. N. Petsev, S. Brandon, and P. Katsonis. The occasion was the 225th National Meeting of the American Chemical Society, March 22–27, 2003, in New Orleans, Louisiana. Vekilov and his research team study protein solutions as they change from liquids to crystalline solids, specifically, the process of nucleation (the beginning phase of crystallization that sets the stage for crystal growth). Vekilov himself studies apoferritin, a protein precursor to ferritin, the protein that stores iron in the body and then releases it in a controlled fashion.

Molecules must come together before nucleation can occur to form a crystal, and getting them together — especially in the correct orientation — can be a tough job. Vekilov and his research team study how some specific salt ions act to bring molecules of apoferritin together and how some other ions work to keep the molecules apart.

PI George DeTitta of the Hauptman–Woodward Medical Research Institute in Buffalo, New York, was an invited lecturer at the International Conference of Structural Genomics Workshop held in Berlin, Germany, in October 2002. This 2-day workshop provided an overview of the current research activities in the field of automation of structure determination. Advances in automated software development for structure solution and model building were discussed in DeTitta’s lecture, “Automation of X-ray Structure Determination for Structural Genomics.”

NASA organized two types of external sessions (with non-NASA speakers) on biological crystal growth at the American Crystallographic Association’s Annual Meeting in Covington, Kentucky, July 26–31, 2003. The first session, Biological Neutron Diffraction, a transactions symposium, was organized by PIs Gerard Bunick and Leif Hanson, both of Oak Ridge National Laboratory, Tennessee, and covered several topics: neutron crystallography, low-resolution neutron crystallography, and contrast variation in single crystals of biological molecules as well as hydrogen and hydration in protein structural chemistry, D_2O exchange in protein crystals, spallation (a process in which neutrons are ejected from the nucleus of a heavy element target as a result of bombardment with high-energy protons), neutron protein crystallography, and neutron diffraction. The second conference, “Biomacromolecular Solutions, Phase Separation, and Nucleation,” was chaired by PI Alex Chernov of BAE Systems, Huntsville, Alabama. It tackled intermolecular interactions and the thermodynamics and kinetics of phase transitions in protein solutions; modeling the crystal growth rates of tetragonal lysozymes; structure, morphology, and mechanical properties of two-dimensional protein crystals on lipid layers; two- and three-dimensional crystallization of membrane proteins; and the development and application of membrane protein crystallization screens based on detergent phase behavior. Many PIs in the Macromolecular Biotechnology Program attended these sessions, and most of them also gave presentations. A report on the conference is available from *http://www.hwi.buffalo.edu/ACA/*.

In June 2003, LOCAD hosted a workshop for 40 participants to discuss the benefits and challenges of LOC technology as it pertains to NASA’s missions. Attendees represented four research centers — Johnson Space Center (JSC) in Houston, Texas; Glenn Research Center (GRC), Cleveland, Ohio, the Jet Propulsion Laboratory (JPL), Pasadena, California; and MSFC — and the U.S. Army Aviation and Missile Command, Redstone Arsenal, Huntsville, Alabama. Their talks concerned packaging and reliability issues of LOC and microelectromechanical systems (MEMS) devices, microfluidics, and LOC technologies for life detection.

The newly assembled SBRE team hosted several workshops and seminars in which many notable researchers participated. (See Highlight, “Enhancing Strategic Biomolecular Research for Exploration,” page 38.)

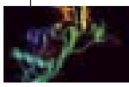
The Radiation Effects Team Workshop, held April 14 and 15, 2003, welcomed 15 PIs as participants or contributors. Contributing PIs included John Dicello, Johns Hopkins University, Baltimore, Maryland; Timothy Hammond, Tulane University, New Orleans, Louisiana; Ann Kennedy, University of Pennsylvania, Philadelphia; and Honglu Wu, Johnson Space Center, Houston, Texas.

The work of Macromolecular Biotechnology Program researchers resulted in four patents in FY 2003. On December 24, 2002, Gloria Borgstahl, Jeffrey Lovelace (Eppley Institute for Cancer Research, University of Nebraska Medical Center, Omaha), and Edward Snell received a patent for “Method of measurement of physical characteristics of crystals” (University of Toledo, U.S. Patent No. 6,498,829). In June 2003, a patent was issued for a “Method for growing protein crystals,” devised by Lawrence Delucas, Robyn Rouleau, Barbara Williams, and Helen Powell (UAB Research Foundation, Birmingham, Alabama, U.S. Patent No. 6,579,358). Patents also were awarded in July and September 2003 for methods of high-density protein crystal growth devised by Delucas and Rouleau, Kenneth Banasiewicz, and Barbara Williams (UAB Research Foundation, Birmingham, Alabama, U.S. Patent Nos. 6,623,708 and 6,592,824).

Macromolecular Biotechnology Flight Experiments

Ultimately, all investigations of protein crystal growth (PCG) depend on the movement of large molecules (macromolecules) through a fluid as the solubility of protein decreases until the protein molecules contact each other and form a crystal, much like piling up bricks in orderly stacks. Crystal growth depends on many variables: temperature, salt (precipitant) concentration, acid–base balance (pH), protein concentration, and sample purity. It may also be controlled by the noncrystalline aggregation of molecules; such aggregates and other impurities also control the growth rate. Differences in density are another factor, affecting how the fluid bends light (by changing the index of refraction). Thus, an optical system that shows variations in density can be a powerful diagnostic technique for distinguishing how differences in temperature, concentration, or pH drive crystal growth.

One of the main objectives of flight experiments in the Macromolecular Biotechnology Program is to grow protein crystals that are more suitable for detailed structural analysis than crystals grown under the influence of gravity on Earth. On Earth, differences in density produce convective disturbances that can reduce overall crystal quality. In space or microgravity, crystal growth becomes diffusion-limited because of an absence of density-driven convection. Flight experiments that studied PCG were meant to accomplish three goals:



- to establish a PCG facility with improved sample capacity, thus boosting the odds of obtaining suitable crystals and, hence, the overall science return from each mission;
- to produce larger, more perfect protein crystals to support numerous research programs in structural biology and structure-based drug design; and
- to use the facility to delineate factors contributing to the effect of microgravity on the growth and quality of protein crystals, which can be used to improve both in-flight and ground-based methods.

The biological crystallization payload for STS-111 was launched on June 5, 2002, along with the International Space Station (ISS) Expedition 5 crew. Six Protein Crystallization Apparatus for Microgravity (PCAM) cylinders were housed in a Single-locker Thermal Enclosure System (STES). Developed by Daniel Carter of New Century Pharmaceuticals, Huntsville, Alabama, and colleagues at Marshall Space Flight Center (MSFC), Huntsville, Alabama, PCAM is a self-contained apparatus for crystal growth that uses multiple seven-chamber trays as a disposable interface. It was designed to enable vapor-diffusion crystallization experiments on board the space shuttle and later the ISS. The apparatus accommodates a large number of experiments that are typically stored in a thermal carrier at a temperature of 22 °C (72 °F) during spaceflight. The sample chambers, which each hold a drop of protein solution, are surrounded by an absorbent material that controls crystal growth after activation. The wells are filled on Earth and sealed to prevent crystal formation before launch and activation. Nine plastic trays can be loaded in one PCAM cylinder, and six cylinders can be carried in a temperature-controlled locker.

Ten different macromolecules (378 samples total) were flown to the ISS aboard STS-111 and remained in orbit until October 18, 2002. The principal investigators (PIs) who flew macromolecules on STS-111 included Daniel Carter; Craig Kundrot of MSFC; Barbara Golden of Purdue University, West Lafayette, Indiana; Aniruddha Achari of MSFC and Raytheon, Huntsville, Alabama; and Bill Thomas of MSFC and the Universities Space Research Association, Huntsville, Alabama; other researchers included Jean-Paul Declercq of the University of Louvain, Belgium; Dean Myles of the European Molecular Biology Laboratory, Grenoble, France; and Naomi Chayen of Imperial College, London, U.K. Among the molecules flown were human serum albumin, ß-glucocerebrosidase (the deficiency of which causes Gaucher disease), basic fibroblast growth factor (bFGF), a deoxyribonucleic acid (DNA) that inhibits bFGF activity, cytochrome p450, and thaumatin.

Human serum albumin, the major protein of the human circulatory system, contributes 80 percent to osmotic blood pressure and is chiefly responsible for maintaining blood pH. Additionally, albumin is involved with the binding and transportation of several small molecules throughout the circulatory system, including most currently known pharmaceuticals. Structural details of albumin and albumin–drug complexes can be used to explore the potential for improving the safety and efficacy of therapeutics and for developing novel albumins for various applications.

Decreased levels of the enzyme acid ß-glucocerebrosidase characterize the autosomal recessive (one allele abnormal and one normal) disorder called Gaucher's disease. It is the most common single-enzyme lysosomal storage disorder, and it affects 20,000–30,000 people worldwide. Acid ß-glucocerebrosidase catalyzes the hydrolysis of the glycolipid glucocerebroside to glucose and ceramide, and in the event of a shortfall, leaves the glucocerebroside to accumulate within the lysosomes of the immune cell (monocyte/macrophage) system. Lipid-engorged cells with eccentric nuclei, known as Gaucher cells, displace healthy, normal cells in the liver, spleen, and bone marrow and are associated with enlargement of the liver and spleen, organ dysfunction, and skeletal deterioration. If more were understood about the structure of ß-glucocerebrosidase, researchers might better understand how the enzyme works, which could lead to the design of therapeutics for the management and treatment of Gaucher's disease.

bFGF helps cancerous tumors acquire a blood supply; researchers have found that inhibiting it can prevent tumor growth. By studying how DNA binds to and therefore inhibits bFGF, it may be possible to devise a drug that would act in the same way, which could then be used as an anticancer therapeutic strategy. Cytochrome p450 plays important and diverse roles in a broad range of biological processes, including carcinogenesis and drug metabolism. Thaumatin is a protein from the African Serendipity berry (*Thaumatococcus danielli*) and is valued for its intensely sweet taste. Thaumatin crystals were grown to test the reproducibility of PCG experiments on the ISS.

STS-112, which launched on October 2, 2002, also carried PCAM cylinders housed in an STES. The PIs for this flight included Daniel Carter, Craig Kundrot, Barbara Golden, Geoffrey Chang (The Scripps Research Institute, La Jolla, California), Gloria Borgstahl (Eppley Institute for Research in Cancer and Allied Diseases at the University of Nebraska Medical Center, Omaha), and Ronald Kaplan (Finch University of Health Sciences, Chicago Medical School, Illinois).

Among the macromolecules sent into orbit were membrane transporters involved in multidrug resistance. (Determining the atomic structure of integral membrane proteins has been extremely difficult in Earth-based laboratories.) Other experiments worth noting involved DNA-binding proteins, blood proteins, plant proteins, and antioxidant enzymes as well as proteins involved in optical properties of the lens of the eye and in diseases such as diabetes. The crystallized macromolecules were returned to Earth on December 7, 2002. Preliminary results indicate that some samples produced good crystals suitable for data collection.

Additional macromolecules for crystallization were flown to the ISS aboard STS-113 on November 23, 2002. This flight represented the first space station experiment for the Diffusion-Controlled Apparatus for Microgravity (DCAM) hardware. Also developed by Daniel Carter and colleagues at MSFC, DCAM enables investigators to use the dialysis or liquid–liquid methods for crystallization. A total of 81 individual experiments are housed inside the STES in three separate tray assemblies. PIs who contributed macromolecules to this flight include Daniel Carter; Gerard Bunick of Oak Ridge National Laboratory, Tennessee; Craig Kundrot; Aniruddha Achari; and Bill Thomas from Universities Space Research Association, Huntsville, Alabama. They flew samples of nine molecules: apoferritin, bFGF, catalase, ferritin, ß-glucocerebrosidase, glucose isomerase, nucleosome core particle, serum albumin, and thaumatin.

Additionally, the Macromolecular Biotechnology Program plans to fly Biological Carrier (BiC) experiments for molecular structure determination. The selection process for these experiments has not yet been completed.

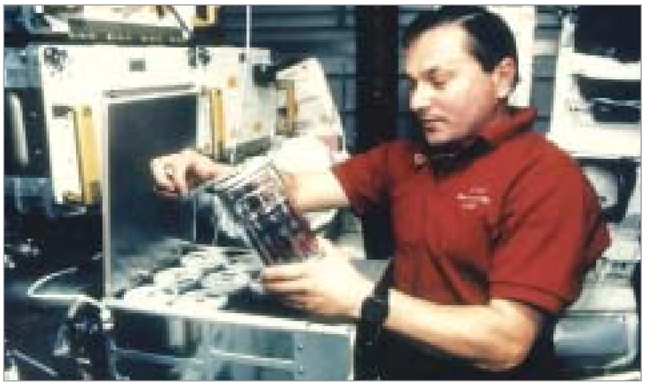
The Macromolecular Biotechnology Program in fiscal year (FY) 2003 made steady strides in the engineering and development of new hardware for use with fundamental crystal growth studies in microgravity. PI Lori Wilson of Eastern Kentucky University, Richmond, is studying the crystallization process to design new methods for crystal growth. Her research may benefit not only drug design techniques but also the fundamental understanding of many biological mechanisms.

Wilson's experiment, Metastable Solution Structure and Optimization Strategies in Protein Crystal Growth, has the eventual goal of furthering the understanding of the fundamental processes of protein nucleation and crystal growth, both on the ground and in microgravity. Specifically, she hopes to determine whether gravity affects the formation, size distribution, and average size of the aggregates in the protein samples and their transport to the crystal surface. She is also investigating whether the aggregates play a different role in the crystal growth process in microgravity than they do on Earth. Her hope is that the research will allow crystallographers to design crystallization methods that control aggregate formation, thereby increasing the quality of crystals obtained on the ground and in microgravity. Better crystal structures can lead to better structural data, which has implications for the fields of drug design, protein engineering, and many areas of biomedical research.

In the first stage of her research, Wilson is studying the presence and distribution of aggregates in supersaturated solutions by using chemical cross-linking, hence her experiment's nickname, XLINK. Ultimately, she intends to use these data to develop so-called simplex optimization techniques for PCG, to be used by investigators experimenting with microgravity crystallization experiments on the ISS. The fact that simplex optimization requires fewer experiments than either the single-factor-at-a-time approach or factorial designs will aid in conserving material on the ISS.

In FY 2003, testing was completed and improvements were made in reagent mixing for the cross-linking experiment, which is tentatively scheduled to fly aboard STS-116 in 2005 (space shuttle flights beyond the two return-to-flight test missions scheduled for 2004 have not been finalized). The stability and safety of the different fluids to be used in the experiment were improved, and the solution conditions to be tested were optimized. A 6-month shelf life test of the proteins was performed along with materials compatibility testing while the temperature sensitivity of storage and reaction timelines was analyzed. The Payload Integration Plan (PIP) was written and submitted.

The XLINK hardware is self-contained and will likely be operated in the space shuttle middeck. It will fly four Group Activation Packs (GAPs), each of which will contain eight microgravity test tubes called the Fluid Processing Apparatus (FPA), in which the crystallization will take place. Each GAP provides three levels of containment and allows for mixing of different reagents; it is activated by a crewmember turning a hand crank. Two program-provided cameras will capture the reaction process, recording the data for later analysis.


credit: NASA

Principal Investigator Lori Wilson's experiment, Metastable Solution Structure and Optimization Strategies in Protein Crystal Growth (XLINK for short), entails studying the crystallization process to design new methods for crystal growth. Results should ultimately further the understanding of the fundamental processes of protein nucleation and crystal growth both on the ground and in microgravity. Here, Russian cosmonaut Vladimir Titov activates one of four Group Activation Packs (GAPs) on orbit. Wilson's crystallization experiments will run in "microgravity test tubes" called Fluid Processing Apparatus (FPA); each GAP contains eight FPAs.

Work on the Delta-Length (Delta-L) flight hardware progressed in FY 2003. Delta-L is a custom-built piece of scientific equipment designed to study the process of PCG itself rather than growing the crystals for structure determination. It is known that at least some crystals show a different growth pattern in microgravity than on the ground, possibly because the physical phenomena of transporting protein molecules from solution to a growing crystal are changed in microgravity. The Delta-L hardware allows for measurement of crystal growth over time. It consists of a fluid assembly, a data-acquisition and -control system, and an imaging system. The assembly allows crystallization fluid in the growth cell to be exchanged, making fresh growth solution available for continued crystal growth; the second component is self-explanatory; and the imaging system allows images of crystals to be collected by a video microscope camera.

The Delta-L imaging system has not gone unappreciated. It won the prestigious 2003 Imaging Solution of the Year award from *Advanced Imaging* magazine in the Microscopy category, announced in the January 2003 special issue. The imaging system was chosen from many design nominations that deserve industry attention for their practical handling of digital-imaging and image-processing challenges. The Delta-L system incorporates a novel illumination technique in the imaging lens that maintains the illumination constant regardless of the position of the lens or the sample, meaning that each image is identically illuminated.

Delta-L data are expected to provide crystal growth rates and, from those, a measure of the growth rate dispersion. With these data in hand, scientists will be able to test the hypothesis, based on several observations, that crystal quality is correlated with growth rate dispersion in microgravity. In growth rate dispersion, individual crystals grow at slightly different rates under the same solution conditions. MSFC scientists taking part in the study believe that growth rate dispersion may be a simple experiment conducted on the ground to predict whether crystal quality could be improved in microgravity. The hypothesis must first be tested by determining whether growth rate dispersion is truly reduced in microgravity before a simple test on the ground could become available.

Thermal testing to determine the STES system performance using the Delta-L hardware was completed in FY 2003. Several programmatic issues related to the science aspects of the Delta-L flight experiment, including the Experiment Data Management Plan, initial toxicology and materials compatibility lists, and the Delta-L/Glovebox Integrated Microgravity Isolation Technology (g-LIMIT) memorandum of understanding were completed, and new criteria for mission success have been defined. Each of these issues represents a major milestone involved in integrating the science payload for flight to the ISS.

The Delta-L imaging and control unit assemblies are scheduled to be flown on STS-118 in late 2005, and the fluid assembly is scheduled for flight on STS-119 in early 2006 (space shuttle flights beyond the two return-to-flight test missions scheduled for 2004 have not been finalized).

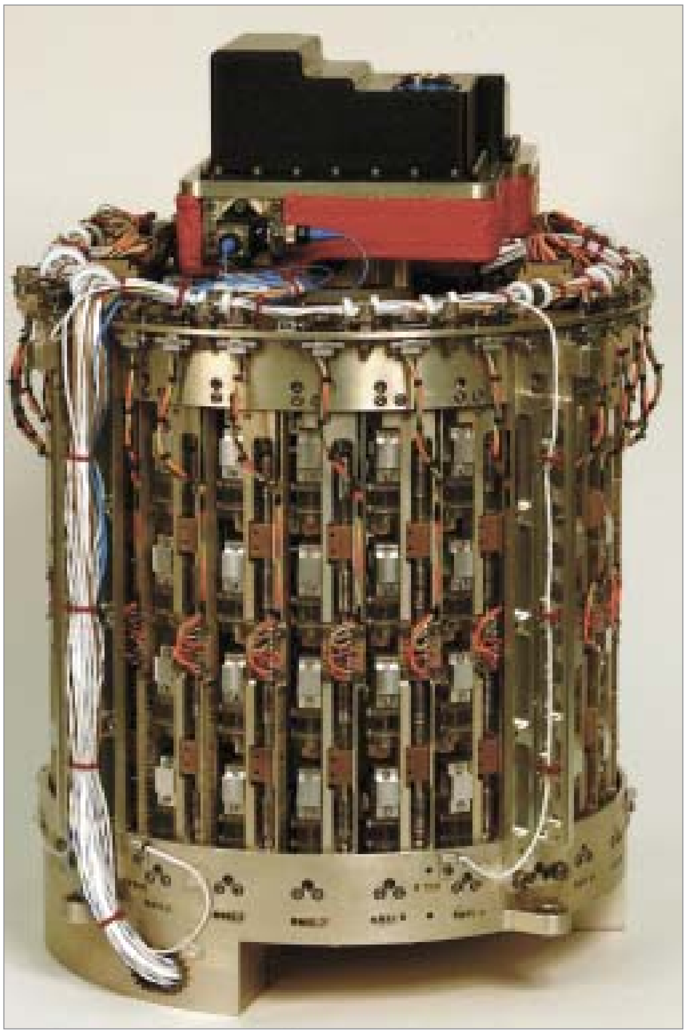
Observable Protein Crystal Growth Apparatus (OPCGA) hardware, designed to provide a road map leading to optimal crystal diffraction and structural information in microgravity, was developed by PI Alexander McPherson of the University of California, Irvine. The purpose of the OPCGA flight investigation is to conduct liquid–liquid diffusion (LLD) PCG in space, better distinguish the process in microgravity from that on Earth, and optimize the LLD method of PCG in microgravity. The most immediate objective is to test the theory of the depletion zone. The idea is that Earth- and microgravity-grown crystals differ in size and structural perfection in the presence or absence of density-driven convection and sedimentation. It has been hypothesized that in the absence of gravity, a protein depletion zone forms in the solution near the growing crystal. Depletion zones form when proteins attach to the crystal surface faster than replacements move in from the solution, so that the neighborhood is nearly devoid of proteins. As a result, the solution properties local to the crystal–liquid interface can be quite different from those of the bulk solution. Supposedly, the stability of the depletion zone in the absence of convection provides time for more orderly addition of macromolecules from solution to the most energetically favorable sites on the crystal lattice.

The OPCGA flight experiment apparatus will allow unintrusive in situ observations of the fundamental fluid phenomena around growing macromolecular crystals in laboratories on Earth as well as in microgravity. The researchers will be able to define the size and location of crystals, growth rates, and macromolecule concentration in the surrounding fluid. Initially, these data will be collected from a set of well-characterized macromolecules covering a range of molecular sizes and growth conditions. A phase-shift Mach Zehnder interferometer will map the refractive index of the crystal growth solution. Images from the interferometer and a video microscopy system set up at right angles to it will be recorded for the measurement of crystal size and gross growth rates. From these images and ground-based data correlating the refractive index with concentration, two-dimensional concentration maps of the growing crystals can be developed. Finally, these flight measurements will be compared with computer-simulated models of the depletion zone developed in collaboration with the University of Alabama in Huntsville.

The planned OPCGA experiments will also test two secondary hypotheses: crystals nucleate at positions within the fluid that allow optimized growth, and that electrostatic effects produce a crystal distribution more closely approximating a colloidal dispersion. If these hypotheses are observed, then additional experiments can be conducted to alter the electrolyte properties of the mother liquor and correlate these changes with distribution patterns.

OPCGA hardware includes 96 individual experiment cells and can collect optical data on 72 of those cells. It is designed to fit in the EXPRESS (EXpedite the PRocessing of Experiments to the Space Station) Rack aboard the ISS. Thus far, hardware for the OPCGA experiment has been designed and fabricated, and the component-level testing has been completed. The system is in the final stages of verification testing — the last steps before flight–ground integration testing at Kennedy Space Center, Cape Canaveral, Florida, to support turnover and flight.

In FY 2003, McPherson's team completed crew-training procedures, conducted flight testing, and completed



credit: NASA

The Observable Protein Crystal Growth Apparatus (OPCGA) flight experiment apparatus is designed for the unintrusive observation of the fundamental fluid phenomena that surround macromolecular crystals as they grow, in microgravity and on Earth. The OPCGA experiment module shown here has 96 individual experiment cells and can collect optical data on 72 of those cells.

the Phase III Ground Safety Reviews and the Phase III Flight Safety Review. The OPCGA is scheduled for a videocassette recorder and stowage flight on STS-116 and for a test flight on STS-117, both tentatively planned for 2005. The videocassette recorder, cables, videocassettes, and other miscellaneous items will sent on STS-116 to the ISS, where they will be either be set up in an EXPRESS rack or stowed. The science samples will follow on the next shuttle flight; they will be installed in the EXPRESS rack, the system will be connected and activated, and then the collection of science data will begin.

Macromolecular Biotechnology Program Highlights

Lab-on-a-Chip: Smaller *Is* Better

Lab-on-a-chip (LOC) technology is one of the hottest topics in life sciences today, with good reason. Just as the world of commercial electronics was reshaped by miniaturization, biotechnology systems are being transformed by the drive to develop postage stamp–sized biological laboratories with tiny features only microns in size. NASA has a particular interest in LOC technology because compact onboard laboratories would reduce mass, power, volume, and crew time — all important considerations for spacecraft systems. In the future, astronauts could use handheld devices to detect microbes, monitor water, and perform biological and clinical analyses important to maintaining crew health.

LOC technology is more efficient and accurate because it reduces the need for laboratory space, reduces the required amount of reagents, permits the use of portable devices for remote sensing, increases the number of samples tested and product output, and allows analyses that are clearly defined. Microchip-sized biological laboratories are made using techniques that were initially developed by the microelectronics industry. Miniature circuits, channels, and valves direct the flow of chemical reagents (chemicals, proteins, deoxyribonucleic acid (DNA), solutions, and so forth) on a microchip; the reagents can be mixed, diluted, reacted, separated, and controlled automatically in much the same way that they are by technicians using standard equipment in full-sized laboratories.

What makes such dramatic miniaturization possible is the science of microfluidics, which allows the manipulation of fluid volumes measured in nanoliters (10^{-9} L) and picoliters (10^{-12} L). In the life sciences, microfluidic systems may be used for biochemical assays, genetic analysis, drug screening, electrochromatography (separating the components of a substance by applying a voltage), and blood cell separation and analysis (to determine blood cell counts and the presence of disease), thus reducing the time and cost of performing complex biochemical processes. Indeed, microfluidics has the potential to facilitate and automate scientific research across multiple disciplines. LOC technology is a potential springboard for medical diagnostic and therapeutic devices that may help NASA develop tools that will diminish the negative effects of long-term space travel on humans.

credit: NASA and Caliper Technologies Corp.

Several pieces of laboratory equipment and many labor-intensive processes are replaced by a glass chip and a chip control unit. This stamp-sized lab-on-a-chip is being installed for processing by a member of the Lab-on-a-Chip Applications Development (LOCAD) team. The chip is being installed on the Caliper 42 Control Unit, a chip-processing unit developed for NASA by Caliper Technologies.

In fiscal year (FY) 2003, NASA's Iterative Biological Crystallization (IBC) Program extended its capabilities to include the development of technologies that will allow humans traveling in space to maintain good health and a safe environment. IBC became Lab-on-a-Chip Application Development (LOCAD). Helen Cole is the LOCAD project manager, Lisa Monaco is the project scientist, and Scott Spearing is the lead systems engineer.

LOCAD engineers and scientists began building a LOC Control Unit in support of applications development that would advance NASA's critical mission objectives. This one-of-a-kind microfluidics control unit, completed in FY 2003, allows the precise control of fluids on a chip via pressure; it will be configured to include fluid control by electrokinetics (a branch of physics that deals with the motion of electric currents or charged particles) once the first unit completes testing in early FY 2004. The unit is designed to be operated either by a person near the unit or from a remote location via the Internet.

In June 2003, the LOCAD team hosted a workshop to discuss the benefits and challenges of LOC technology as it pertains to NASA's missions. Participants from Johnson Space Center in Houston, Texas; Glenn Research Center (GRC) in Cleveland, Ohio; Jet Propulsion Laboratory, Pasadena, California; Marshall Space Flight Center (MSFC), Huntsville, Alabama; and the U.S. Army Aviation and Missile Command, Redstone Arsenal, Huntsville, Alabama, gave talks on subjects ranging from packaging and reliability issues to microelectromechanical systems (MEMS) devices, microfluidics, and the use of LOC technologies for the detection of organic biomarkers for both extinct and extant life on Mars.

During the year, the LOCAD team formed several collaborations with researchers for feasibility testing, process development, and flight hardware development. Some of these collaborations included a general interagency agreement between LOCAD and the U.S. Army at Redstone Arsenal to develop custom chips for government-funded research and the Modular Assay for Solar System Exploration (MASSE) project. MASSE Principal Investigator Andrew Steele of the Carnegie Institute in Washington, D.C., worked with LOCAD to successfully perform novel investigations on lysing (breaking down) microorganisms. This preliminary work will be valuable as the MASSE team prepares to develop analysis tools to detect biological "signatures" that may be used to find signs of extant life on Mars.

In a joint effort on capillary-driven flow studies with Jeff Allen of the National Center for Microgravity Research at GRC, the LOCAD group helped provide data in support of fundamental fluid physics studies. Fundamental studies of this type will aid developing technologies with capillary flow issues, such as microfluidic devices, biochip systems, LOC systems, microscopic reactors, and microscopic power systems. The LOCAD team also collaborated on developing microfluidic devices for microbial detection with Norman Wainwright of the Marine Biology Laboratory (Woods Hole, Massachusetts). In this work, LOCAD was able to significantly reduce the reaction times for the mixing of cellular components with *Limulus* amebocyte lysate assay for endotoxin detection in serum, water, and other liquids. Detection of endotoxins (poisonous substances present in bacteria) is an important part of microbial detection.

Enhancing Strategic Biomolecular Research for Exploration

The Strategic Biomolecular Research for Exploration (SBRE) team, made up of scientists and managers from the Microgravity Science and Applications Department at Marshall Space Flight Center, Huntsville, Alabama, met in early 2003 to formulate a strategic research plan that would address health risks that affect astronauts during long-term exposure to reduced gravity conditions and ionizing radiation. The team recognized that understanding and mitigating the effects of the long-term absence of gravity on human health would require a vigorous interdisciplinary approach that would draw on the analytical strengths of biochemists, molecular biologists, cell biologists, biophysicists, structural biologists, and medical researchers. In addition, because all biological components of the body work together, this difficult task would require the integration of research on four biological levels: organism, tissue, cell, and molecule.

The SBRE team agreed that molecular-based research could provide important insight into the conditions that threaten space travelers. After examining all these conditions, they elected to focus on three key areas: muscle atrophy, bone loss, and the physiological damage produced by ionizing radiation. Because laboratory facilities and a staff of scientists and technicians with extensive expertise were already in place within the Microgravity Science and Applications Department, the team could easily implement strategic research on specific molecules that underlie the bases of these conditions. Additionally, research in these three areas would integrate well with that of other NASA centers and would align with Office of Biological and Physical Research research priorities by addressing the following three (of five) organizing questions:

- How can we ensure the survival of humans traveling far from Earth?

- What new opportunities can our research bring to expand our understanding of the laws of nature and enrich lives on Earth?

- What technology must we create to enable the next explorers to go beyond where humans have been?

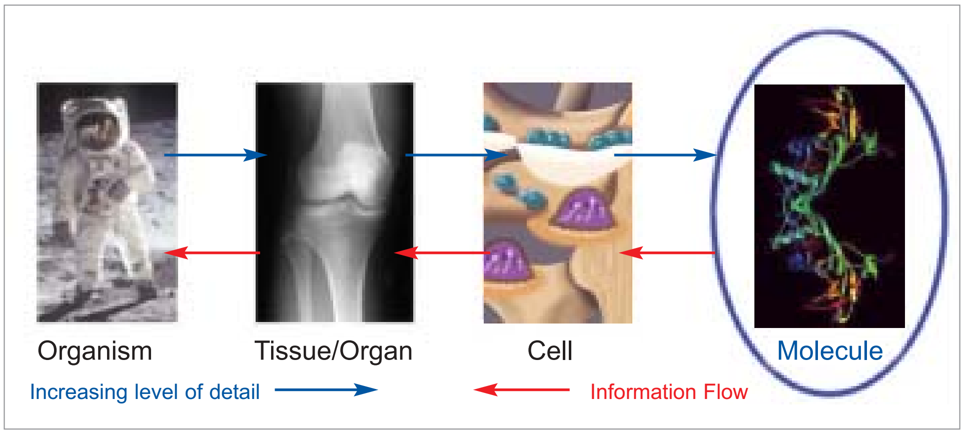
The principal goal established by the SBRE team is to understand at the molecular level the effects of long-term absence of gravity and presence of radiation on human health. This understanding will lead to the development of countermeasures and therapeutics; the development of in-flight instrumentation to monitor health and diagnose disease; and the refinement of risk assessment.

During fiscal year (FY) 2003, subteams were formed to zero in on how best to structure molecular research in each of the focus areas: bone, muscle, and the effects of radiation damage to the human body. Subteams in each research area contacted medical professionals, NASA scientists, and prominent academic researchers nationwide, and in FY 2003, SBRE hosted 11 seminars in which top researchers with expertise in each of the three areas briefed the entire group on their research. SBRE also hosted a radiation workshop at which top researchers met to give advice and provide resources to SBRE scientists. As a result of these activities, four important collaborative relationships were established, and other groups expressed interest in forming research associations.

The SBRE bone research subteam received funding for a joint proposal with Jane Lian and Gary Stein of the University of Massachusetts Medical School, Worcester, to study pivotal molecules for bone formation. The SBRE muscle studies subteam will work with Se-Jin Lee of Johns Hopkins University, Baltimore, Maryland, on the protein myostatin, which functions to regulate and inhibit muscle growth. In addition to myostatin studies, the bone subteam will work with Darryl Groll of the University of Arizona, Tucson, to study calpastatin, an inhibitor of calpain, an enzyme which breaks down muscle. Calpastatin is a very complex molecule, and up to now only small parts of it have been crystallized for structure analysis.

The SBRE radiation effects subteam will collaborate with Principal Investigator Timothy Hammond of Tulane University, New Orleans, Louisiana, to analyze gene expression arrays from cells that have been irradiated both under normal gravity and under conditions that mimic some aspects of microgravity.

Future SBRE plans involve efforts to form collaborations with notable research institutions and other NASA groups as well as continued research on bone- and muscle-specific proteins — research that will advance the understanding of the problems of bone loss and muscle atrophy at the metabolic level.



credit: Protein Data Bank reference: PDB 1LX5 (molecule); NASA

To help scientists to understand how the long-term absence of gravity and the presence of ionizing radiation in space affect the human body, the new Strategic Biomolecular Research for Exploration (SBRE) team will pursue interdisciplinary research on four biological levels: organism, tissue/organ, cell, and molecule.

COMBUSTION SCIENCE

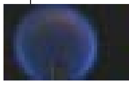
Combustion and other chemically reactive processes provide power for transportation, industry, and many other daily activities. But the soot and the other polluting by-products they emit harm humanity and the environment. The more heavily the world relies on these processes, the greater the need to control and understand them.

Combustion and its by-products affect every one of us every day, for good and ill. Although combustion fuels most of the world's electric power production, home heating, and ground and air transportation, its by-products pollute the air and contribute to global warming. In addition, unintended fires claim thousands of lives and do billions of dollars' worth of damage to property every year. Society would greatly benefit from improved control of combustion but is hindered by how egregiously little is known about combustion fundamentals.

Earth's gravitational forces are to blame for this state of affairs. Under the influence of gravity, the hot, lightweight gases produced during combustion move upward, generating airflows that make for often unsteady and asymmetrical flames — witness any campfire. Because this gravity-induced flow renders the flames very difficult to model mathematically, combustion theories tend to be based on steady, symmetrical flames and are difficult to test in the real world. Because it effectively eliminates the cause of these airflows, microgravity resolves this dilemma. It offers unprecedented opportunities for the exact measurement of large, steady, slow-moving, symmetrical flames.

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. For example, such research has revealed information about the thermal and chemical processes that play roles in flame propagation and extinction — processes that exist on Earth but are often hidden by more dominant reactions attributable to the forces of gravity.

The Office of Biological and Physical Research (OBPR) continues to focus on the five organizing questions that make up the backbone of its recently updated research plan for the future. (For more information about the research plan, see *http://spaceresearch.nasa.gov/general_info/strat.html*.) The questions focus on the technology and scientific knowledge that NASA will need to further enable space exploration. But as the search for understanding and knowledge continued, it became apparent that within the combustion science discipline of the Physical Sciences Research Division, a class of phenomena called chemically reacting systems (CRS) was at risk of falling through the cracks.



CRS tie into exploration research because of the anticipation they arouse. They could generate the capability to convert waste materials into useful energy (incineration), reclaim oxygen from waste products (regenerative life support), and produce fuels and materials from in-situ resources (such as soil from Mars). But combustion also is a form of chemical reaction and, as such, is scientifically similar to CRS. Accordingly, the combustion science discipline has been expanded to include combustion science and chemically reacting systems.

Program Summary

In fiscal year (FY) 2003, Office of Biological and Physical Research (OBPR) research in microgravity combustion sought primarily to understand fundamental combustion processes and flame structures. At the same time, the program strengthened its applications-based focus to aid NASA in resolving crew health and safety issues. A list of all ongoing combustion science research projects, along with the names of the 46 investigators conducting the research, is provided in Appendix B.

FY 2002's NASA Research Announcement (NRA) for combustion (NRA-01-OBPR-08-C) was announced on December 21, 2001. Ninety proposals were received by March 22, 2002, and by October 22, 2002, ground-based proposals had been selected for funding. Actual funding starts in FY 2004. Topics for which the NRA solicited proposals included gaseous flames; droplets, sprays, particles, and dust clouds; and surface combustion and fire safety as well as chemical vapor deposition and vapor infiltration processing, supercritical water oxidation, in-situ resource utilization and chemical processing, and thermal plasmas.

Topic selections were made for the FY 2003 combustion NRA. Released in December 2002, NRA-02-OBPR-03-B attracted 79 proposals. Twenty-one researchers were selected to receive grants totaling some $9.4 million to conduct ground-based microgravity combustion research over the next 4 years. Seven of the topics are fundamental science investigations, specifically, gas-diffusion flames, droplet combustion, and diagnostics, as well as a new fundamental area, microscale combustors, judged meritorious through the peer review process. Also added to the strategic research portion of the research portfolio were eight investigations associated with spacecraft fire safety and six studies in noncombusting chemically reacting systems. A complete list of funded projects is available from *http://research.hq.nasa.gov/code_u/code_u.cfm*.

During fiscal year 2003, the combustion science discipline became the combustion science and chemically reacting systems discipline on the grounds that many chemically reacting systems are scientifically similar to combustion reacting systems even though they do not technically combust. The study of these systems will add to the scientific knowledge that NASA's Office of Biological and Physical Research needs for strategic research, such as the exploration of space.

The Seventh International Workshop on Microgravity Combustion and Chemically Reacting Systems was held in Cleveland, Ohio, June 3–6, 2003. The event, attended by more than 200 people, served as both a conference for the discipline and a strategic workshop on spacecraft fire safety and space exploration technologies. OBPR's Deputy Associate Administrator (acting) Howard Ross spoke at the workshop about the future research to be conducted and the strong impact fundamental research will have on industrial processes on Earth.

Enterprise Scientist Merrill "Mickey" King briefed the attendees on how the research program was restructured in the light of the findings of the Research Maximization and Prioritization (ReMAP) Task Force, which had been established to examine OBPR's research portfolio and assign priorities. He defined the new strategy for the discipline — and indeed all of OBPR — and introduced the plan for the FY 2004 NRA, scheduled for public release in December 2003.

At the end of the main combustion science and chemically reacting systems (CS & CRS) conference, two more narrowly focused workshops were held: the Second (Biannual) Workshop on Spacecraft Fire Safety and the Space Exploration Technologies Workshop. The former included panel discussions and presentations by researchers and spacecraft development representatives. The latter formally introduced discussions of space exploration technologies, such as those pertaining to in-situ resource production and utilization and to research topics in regenerative life support systems.

Additionally, the CS & CRS discipline was an active participant in many cross-discipline workshops held in FY 2003 to focus and define road maps for the gaps in exploration technology. Consider, for example, the workshop Gravitational Effects in Reacting Systems for Space Exploration, hosted by Glenn Research Center (GRC) and the National Center for Microgravity Research (NCMR) on Fluids and Combustion, both based in Cleveland, Ohio. Its purpose was to draw up research and development road maps for strategic research in closed-loop life support and in-situ resource utilization. Experts in ground-based development of these technologies met with experts in reacting systems in microgravity and partial gravity environments and together produced substantial road map elements, which will be presented to the 7th International Workshop on Microgravity Combustion and Reacting Systems in Cleveland, Ohio, in June 2004.

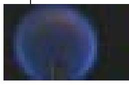
Many principal investigators (PIs) received invitations to speak at non-NASA workshops and conferences. For instance, the French scientific community invited Paul Ronney, a flight PI, to deliver a plenary talk on microgravity combustion at the Congrès Français de Mécanique. Held September 1–5, 2003, in Nice, France, the Congrès is a biannual gathering of scientists and engineers researching fluid and solid mechanics. Ronney's speech, "Effect of Gravity on Combustion Processes," emphasized the ways in which reduced-gravity experiments and modeling have led to a better understanding of combustion processes such as transport mechanisms, which are effectively hidden by the forces of gravity.

Other researchers were published in prominent journals. For example, in *Combustion Modeling and Theory*, PI Ishwar Puri and fellow researcher Chun Choi discussed changes to flame propagation speed that take place when curved and uncurved flames are stretched in "Response of Flame Speed to Positively and Negatively Curved Premixed Flames", (*Combustion Modeling and Theory*, **7**, 2003, 205–220).

Two of the discipline's funded investigators were accorded the highest professional honor that can be awarded to an engineer: Chung (Ed) Law, Robert H. Goddard Professor of aerospace and mechanical engineering at Princeton University, Princeton, New Jersey, and William Sirignano, professor of mechanical and aerospace engineering at the University of California, Irvine, became members of the National Academy of Engineering. Law is actively leading a flight investigation on clean flames and conducting a ground-based investigation of premixed gaseous flames. He also is chair of the Combustion Discipline Working Group, advising NASA on the breadth and depth of the discipline. Sirignano recently completed modeling analysis supporting the Spread Across Liquids flight investigation (for which OBPR's Howard Ross is the PI) and continues to conduct analyses supporting a wide array of flight and ground investigators in the discipline. His expertise covers spray combustion, aerospace propulsion, ignition, and nonequilibrium gas dynamics.

At the other end of a career, a presentation titled "Comparisons of Model Predictions with Measurements of Microgravity Laminar Diffusion Flame Shapes" won Jason M. Abshire the First Place Graduate Presentation Award at the American Institute of Aeronautics and Astronautics (AIAA) 2003 Annual Region III Student Conference held at the University of Kentucky, Lexington, on April 4, 2003. Abshire is a graduate student at (Indiana University-Purdue University at Indianapolis, Indiana,) where his advisor is Microgravity Combustion Science PI Sivakumar Krishnan.

One combustion advance with great practical potential is an external cavity diode laser being developed by PI Jeffrey Pilgrim of Southwest Sciences, Inc., Santa Fe, New Mexico. He wants to make diode lasers tunable over a wider range of wavelengths than is now possible, increasing the types of gases they can identify and the sensitivity of their measurements and reducing gaps in wavelength coverage. Over the 2-year contract, Pilgrim has filed several patent applications. Two of them are now U.S. patents pending, two are Patent Cooperation Treaty filings for intellectual property protection outside the United States. He also filed a U.S. Provisional Patent Application in 2003. The contract with Southwest Sciences, Inc., has produced two Tech Briefs as well: one was also selected as Photonics Tech Brief of the Week, and another has been selected but has not yet been printed. (Tech Briefs are NASA-based publications on discoveries that may lend themselves to commercialization and thus result in a positive impact on the economy or industrial processes.) In fact, Southwest Sciences, Inc., is already offering a commercial external-cavity laser product based on the technology developed under this contract.

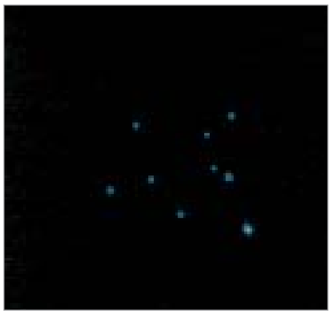


Overall, the ground-based microgravity combustion science program continues to increase the body of knowledge in the combustion science community at large. Activities during FY 2003 have yielded findings of value both to the fundamental science of combustion and in terrestrial and space-based areas of application. The program has also addressed NASA's need to solve fire safety problems in spacecraft and nonterrestrial habitats, where such solutions are vital to long-term space exploration. The safety issues — linked to questions of material flammability phenomena, fire detection, and fire suppression — are of crucial importance to the scientifically challenging missions that NASA plans to pursue. Current areas of ground-based studies include developing an apparatus to assess the flammability of materials in microgravity and researching the chemical and physical aspects of fire suppression elsewhere than on Earth.

Flight Experiments

The familiar teardrop shape of a candle flame is caused by hot, spent air rising and cool, fresh air flowing in behind it. This airflow obscures many of the processes basic to combustion and impedes the understanding and modeling of key combustion controls used for manufacturing, transportation, fire safety, and pollution. But when experiments are conducted on board the space shuttles or the International Space Station (ISS), these impediments vanish, freeing scientists to refine and validate combustion theories and extend their understanding of newly evident combustion phenomena. The longer-lasting (weeks or months) and generally higher-quality microgravity conditions that can be obtained in orbit on the space shuttles and the ISS are invaluable to combustion researchers, because some phenomena (such as slow-burning smoldering reactions) are difficult to observe in the few seconds of microgravity conditions obtainable in ground-based facilities.

No combustion experiments were conducted on the ISS during FY 2003, but it still was a big year for microgravity research. Dedicated entirely to scientific research, STS-107 carried more than a hundred experiments in physical science, life science, and other fields, as well as commercial research. Although Space Shuttle *Columbia* and its crew of seven were tragically lost during reentry on February 1, 2003, much of the experiment data had already been downloaded and was retrievable for investigation.



credit: NASA

The Structure of Flame Balls at Low Lewis-number experiment, run on Space Shuttle Columbia *in 2003, tested various fuel mixtures in microgravity to produce flame balls, which are symmetric and steady flames that reveal combustion processes hidden by the volatile effects of gravity on Earth. Here, the burning of a hydrogen–oxygen–sulfurhexafluoride fuel mixture produced nine flame balls (false colored to enhance visibility) — the most ever created at once —one of which was the longest-lasting flame ever in space or in orbit (81 minutes).*

FY 2003 saw the long-awaited flight of Combustion Module-2 (CM-2) dual-rack system and its three investigations aboard STS-107. The Combustion Module-1 (CM-1) system, an earlier version, had flown aboard STS-83 and STS-94 in 1997 and supported the initial portion of test matrices for two investigations: Laminar Soot Processes (LSP), and Structure of Flame Balls at Low Lewis-number (SOFBALL). LSP was headed by Principal Investigator (PI) Gerard Faeth, University of Michigan, Ann Arbor, and SOFBALL by PI Paul Ronney, University of Southern California, Los Angeles. The investigations of Faeth and Ronney, as well as a third investigation — Water Mist (Mist), led by PI Thomas McKinnon, Colorado School of Mines, Golden — were launched and carried out successfully aboard STS-107. Mist had been added to the CM-2 system more recently than LSP and SOFBALL, proving that a robust multiuser combustion research program could be run on a facility developed prior to the definition of specific investigations. Most of the CM-2 results were downlinked to the ground team during the mission, before reentry. Although the facility and its three experiments provided the answers for many research questions, they also raised new questions.

The largest and most complex pressurized system ever flown by NASA, the CM-2 was encased within the SPACEHAB module. Both CM-1 and CM-2 are precursors to the Fluids and Combustion Facility (FCF) now in development and are intended to fly aboard the ISS.

Soot causes 60,000 premature deaths per year in the United States alone. The LSP experiment studied how soot forms in flames with a view to devising methods for controlling it so as to eliminate or mitigate the serious public health problems caused by its emissions. Observations of LSP flames during the flight of Space Shuttle *Columbia* were highly successful, and the LSP results have already suggested new ways to reduce and possibly even eliminate soot emitted by flames.

The SOFBALL objective was to study the weakly-burning-in-hydrogen-and-methane flames in oxygen-inert mixtures that results in what are called flame balls. Because flame balls are steady and symmetrical and occur in fuels with simple chemistry, they are the simplest possible interaction of chemistry and transport in flames. Among the accomplishments of the experiment were the weakest and leanest flames ever burned (30 joules/minute [0.5 watts] of thermal power and only 8 percent of the fuel usually needed for chemical balance) and the longest-lived flame ever burned in space (81 minutes). Several findings were totally unexpected, including oscillating flame balls and flame balls drifting in a spiral or corkscrew pattern. All in all, the data obtained during the mission will help lead to engines that are cleaner (more fuel-efficient) as well as improved methods of ensuring fire safety aboard spacecraft.

The Mist experiment was motivated by the need to replace halons, widely used as chemical fire suppressants, now that their use has been banned for being harmful to the ozone layer. Water mist, a fine fog of very small droplets, is one alternative; this nontoxic, inexpensive, and efficient technology would also minimize property damage. The Mist findings have gone far to elucidate the physical and chemical mechanisms of how fine water droplets interact with and suppress flames. For example, small droplets are more effective than larger ones for suppressing lean flames. The results will be provided to manufacturers of fire-suppression equipment eager to design the next generation of fire extinguishers for use in enclosed spaces such as airplanes, ships, libraries, museums, and homes. Water mist may also become a viable fire suppression system onboard orbiting spacecraft such as the ISS.

credit: NASA

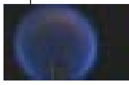
The Laminar Soot Processes experiment ran in Combustion Module-2 on Space Shuttle Columbia *in 2003. The steady flames produced during the flight will help Principal Investigator Gerard Faeth to refine the mathematical models of combustion so as to better understand the less-than-uniform flame shapes that occur on Earth. Filmed during orbit, the flame shown here was produced through a 0.4-millimeter (0.016-inch) nozzle with propane fuel at 1 atmosphere of pressure (equivalent to Earth's atmosphere).*

The data analysis of two 2001 Microgravity Smoldering Combustion Reflight Experiment (MSCRE) space shuttle flights was finalized at the end of FY 2003 by PI Carlos Fernandez-Pello and his research team at the University of California, Berkeley. The team reported the successful operation of the experiment aboard STS-105 (August 2001) and STS-108 (December 2001). Results suggest that the smolder hazard is greater in low gravity than in Earth's gravity, a conclusion that compares favorably with the team's numerical model.

Similarly, data analysis from the Spread Across Liquids (SAL) sounding rocket flight in 2001 is nearing completion. SAL is contributing to the fundamental knowledge of combustion through the study of pools of liquid minus buoyancy effects. In addition, the modeling efforts involved in SAL will lend themselves to generalizations, drawing further benefits from its results for the combustion research community.

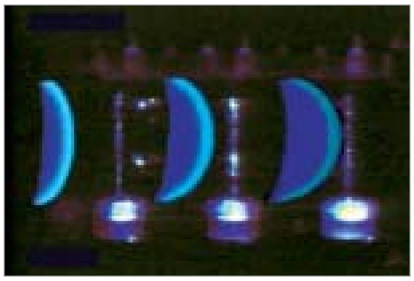
The sixth and final flight of the SAL experiment took place aboard a Black Brandt sounding rocket at the White Sands Test Range (New Mexico) in 2001, rewarding PI Howard Ross of Glenn Research Center (GRC), Cleveland, Ohio, with unique data about how a flame spreads across pools of liquid under varying conditions. The near absence of gravity enabled detailed characterization of the liquid and gaseous flow phenomena that control the flame spread, so the factors that control the instability of flame spread could be (and were) determined and used to validate a numerical model of flame spread.

During FY 2003, only one microgravity experiment was scheduled for a future flight. The Dust and Aerosol measurement Feasibility Test (DAFT) experiment completed its executive pre-ship review at GRC on August 21, 2003, and is scheduled for a trip aboard Russian Progress flight 13P. The purpose of the DAFT risk mitigation experiment is to evaluate how P-Trak (a commercially available condensation nucleus counter [CNC] that counts ultrafine dust particles), from TSI, Inc., in Shoreview, Minnesota, performs in microgravity. P-Trak is a key diagnostic device proposed for use in the Smoke investigation, which is being carried out in a Microgravity Science Glovebox (MSG) in support of research into fire safety on spacecraft. The performance of the P-Trak in microgravity has been flagged as a significant technical risk to Smoke's success because the operation of the instrument depends on the proper internal recirculation and flow of isopropyl alcohol in both the liquid and vapor phases.



Conception of the DAFT experiment began in February 2003, when the Smoke project team was offered the chance to fly a small payload aboard a Russian Progress vehicle. Environmental Controls and Life Support Systems personnel have expressed interest in the subsequent use of the P-Trak on the ISS for measuring particulates in the cabin atmosphere. This application, of course, will depend on acceptable in-orbit hardware performance.

Although space shuttle flights were suspended pending the outcome of the *Columbia* investigation, development of ISS research facilities and experiments continued. Two research facilities, the Combustion Integrated Rack (CIR) and the MSG, are being prepared for upcoming flights. (More details about CIR (page 98) and MSG (page 102) can be found in the ISS section of this report.



credit: NASA

The Water Mist (Mist) experimenters value water as a means of putting out fires that is less toxic and more gentle than chemicals. Run on Space Shuttle Columbia *in 2003, Mist performed 94 percent of its scheduled runs, despite a leak that was repaired by the astronauts. Captured during orbit, these three successive images show a flame weakening as it travels from left to right through the Mist tube, which contains uniformly distributed water mist.*

The CIR, along with the Fluids Integrated Rack, is part of the Fluids and Combustion Facility (FCF). A permanent multiuser facility for the ISS, FCF will support both combustion and fluid physics experiments. With the development of the CIR, the combustion science program is working on several experiments and their associated hardware for upcoming research flights to the ISS. Detailed engineering is under way for the Multi-User Droplet Combustion Apparatus (MDCA) and the apparatus described as the Flow Enclosure Accommodating Novel Investigations in

credit: NASA

A multiuser facility, the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS) will be the main test bed for solid fuel combustion research aboard the International Space Station. Here, the engineering model's flow tunnel has its three-sided fuel carousel attached. Carousels are used to introduce fuel samples, one at a time, into the flow tunnel for combustion testing. The shroud of the carousel to the right of the tunnel has been removed, exposing one of the three fuel trays.

Combustion of Solids (FEANICS). Each apparatus will enable several experiments to be conducted within the CIR.

The MDCA is intended for droplet combustion research and will be the first research payload in the CIR. Diesel engines, industrial turbine engines, and many other practical devices deliver fuel in droplet form to combustors, whose optimization could improve fuel efficiency and reduce pollution, among other things. Microgravity allows researchers to study spherical fuel droplets, which are much easier to model mathematically than the tear-shaped droplets influenced by Earth's gravity.

The initial four research projects using the combined capabilities of the CIR and MDCA systems are the Droplet Combustion Experiment-2, the Bi-Component Droplet Combustion Experiment, the Sooting and Radiation Effects in Droplet Combustion Investigation, and the Dynamic Droplet Combustion Experiment. Each has completed its science definition phase, and the project is now developing the flight system to perform the science. The MDCA will also remain available for use with new droplet investigations that may be proposed in the future (multiuser hardware such as the MDCA allows more effective resource use of the ISS and the CIR).

Six investigations of solid fuels will be conducted in the FEANICS apparatus within the CIR. This research is directly applicable to the Spacecraft Fire Safety initiative in that it contributes to understanding how fire starts, persists, and is extinguished in microgravity. Both thick and thin solid fuels will be studied. The FEANICS hardware contains a flow tunnel for testing fuels at various flow velocities and directions. Within the flow tunnel are several fuel carousels, which are used to introduce fuel samples, one at a time, into the tunnel for combustion testing.

The first six FEANICS investigations are

- Forced Ignition and Spread Test,
- Radiative Enhancement Effects on Flame Spread,
- Analysis of Thermal and Hydrodynamic Instabilities in Near-Limit Atmosphere,
- Transition from Ignition to Flame Growth Under External Radiation in Three Dimensions,
- Solid Inflammability Boundary at Low Speed, and
- Smolder, Transition, and Flaming in Microgravity.

Of these experiments, the first five have completed their flight definition peer reviews, but the sixth, which entered the program more recently, is still only a candidate for review. FEANICS itself is currently in the Engineering Model development phase. A three-sided carousel has been built and tested, and two others are being fabricated. The next stage will be to check out the design and build the flight hardware.

Following the completion of the FEANICS investigations, the combustion program will expand into gaseous combustions, addressing flame design, clean flames, and spherical flames. Presently, 14 combustion investigations are to be conducted within the CIR by 2011, with possibly another four or more sponsored and developed by commercial and international partners.

In readying a balanced research portfolio for deployment to the ISS, four investigations are slated to use the MSG facility. Fiber-Supported Droplet Combustion (FSDC-3), created to study the interaction of two flames, has been shelved while awaiting its third flight aboard the space shuttle. The remaining three experiments are in the last stages of development and will be shelved when complete, also to await the space shuttle's next flight. Candle Flames in Microgravity will study solid-to-liquid and liquid-to-solid fuel transitions. The final two experiments are applications based: The Smoke Point in Coflow Experiment studies soot generation in gaseous flames, whereas Smoke investigates the performance of spacecraft smoke detectors under low-gravity conditions. The Smoke results will provide direct insight into performance differences between Earth-based and in-orbit fire detection.

Highlights

Fighting Fire in Space

Imagine that you're in a closed container, your only protection from a deadly environment, and a fire starts that you can't see. This is precisely the problem that astronauts would face if a fire broke out in an equipment rack.

On Earth, sprinklers might automatically drench the flames, or a technician might pull out a rack to spray it with a portable fire extinguisher. In microgravity, however, neither spraying water nor dismantling racks is practical — so a fire inside a rack must be fought sight unseen. But how?

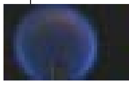
The current plan calls for astronauts to use portable fire extinguishers to flood the interior of the racks with carbon dioxide (CO_2), thereby smothering the fire by depriving it of oxygen. Safety requirements call for reducing the amount of oxygen by 50 percent within 60 seconds.

Yet scientists need to answer several important technical questions about the current system to ensure both adequate fire suppression and proper fire response. Co-Investigators Gary Ruff of Glenn Research Center (GRC) and Ming-shin Wu of the National Center for Microgravity Research at GRC, Cleveland, Ohio, are now investigating such questions. For example, how fast is the concentration of oxygen reduced at any given location? To find out, Ruff and Wu are performing numerical simulations to model the flow of carbon dioxide in and around the equipment and wires in the rack. Their effort uses a computational fluid dynamic model developed by the National Institute of Standards and Technology and also builds on other research performed on NASA's KC-135 "Vomit Comet" aircraft examining the effectiveness of varying concentrations and velocities of carbon dioxide in extinguishing fires in microgravity.

Because carbon dioxide is heavier than air, on Earth, the gas would rapidly settle to the bottom of the rack. That effect limits the usefulness of ground-based testing to determine what actually happens in microgravity, where buoyancy is eliminated and the dispersion of the gas is determined only by the forced convection from the fire extinguisher and the geometry of the rack. Instead of sinking to the bottom of the rack, the carbon dioxide is forced to mix with or displace air within the rack, eventually filling the entire rack and suppressing the fire. Understanding this process — and determining whether the system works as required — is crucial to ensuring the safety of crews in space. That is the task shouldered by Ruff and Wu.

According to results to date, the current fire suppression system actually exceeds the basic requirements. When carbon dioxide is discharged into a rack from a portable fire extinguisher, the oxygen is reduced by 50 percent in the front part of the rack within 20 seconds and in the back portion of the rack within 41 seconds, well ahead of the 60-second requirement. Such fast action should prevent further damage to sensitive equipment. That's the good news.

However, the studies also show that the carbon dioxide does more than simply put out the fire. It forces the air out the research utilization panel at the bottom of the rack, pushing with it smoke and other gases. The air is expelled very quickly, presenting a new set of safety considerations for crews because the resultant smoke and gases fill the crew cabin.



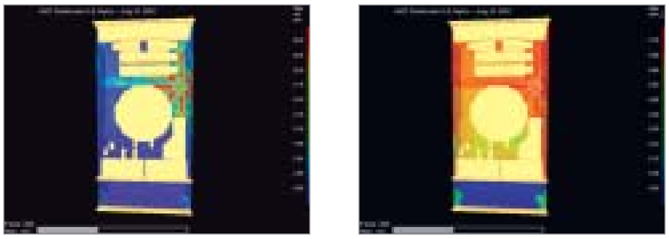
To model what happens in more detail and provide realistic fire training, Ruff and Wu are now exploring what happens to the gases in the open volume of the crew modules. Their studies could lead to the creation of complex interactive computer simulations that would allow crewmembers to experience fighting a fire virtually, thus preparing them for the real thing should it ever be required.

Taking Fire's Temperature

How hot is hot? That question is vital for researchers trying to understand fire in order to harness it for commercial use or prevent the destruction it can cause, but measuring the temperature of flames in microgravity has proven difficult. The key problem is that techniques used to measure flame temperatures on Earth are simply too time-consuming for use in orbit. To overcome this hurdle to advancing flame research, a team headed by Peter Sunderland at Glenn Research Center, Cleveland, Ohio, has developed an innovative technique for the rapid measurement of flame temperatures in microgravity that uses tiny fibers commonly found in boat hulls and tennis rackets.

Under most conditions on Earth, combustion researchers use simple thermocouples to map temperatures at various points in a flame. Thermocouples are inexpensive, versatile tools that combine two different metals to give rise to measurable voltage changes as temperatures change. Completely mapping a flame with a thermocouple, however, involves substantial manipulation and readjustment, as well as up to about 3 hours of time.

Such labor-intensive requirements could not be reasonably met by astronauts working in microgravity. So Sunderland and his team turned to a technique first developed by researchers at Wright-Patterson Air Force Base,



Gary Ruff of Glenn Research Center (GRC) and Ming-shin Wu of the National Center for Microgravity Research at GRC, Cleveland, Ohio, are studying ways to suppress fires in research racks aboard the International Space Station quickly without endangering the crew. The visual model shows the velocity (left) and CO2 concentration (right) of foam within the rack after eight seconds of discharge from a portable fire extinguisher. The foam flow extends to the left from the extinguisher on the right, between the components of the rack (shown in yellow).

credit: NASA

Ohio, for taking temperatures in turbulent flames, where thermocouples are ineffective. Called thin-filament pyrometry, the technique depends on superstrong silicon carbide fibers one-fifth the diameter of a human hair. Such fibers are normally used in manufacturing to add strength to various products.

Just as metals glow orange when sufficiently heated, eventually shifting to white as the temperature increases, the silicon carbide fibers also glow different colors as they are heated to different temperatures. Because the fibers are so thin, they do not, for practical purposes, disturb a flame, and their temperature matches that of the flame. When single fibers are arranged across a given flame at various distances above the flame source, the color of each fiber indicates the flame's temperature at each point. So, by photographing the fibers extended across a flame, the color of their incandescence can be analyzed to give temperature readings. Indeed, the fibers vary sufficiently in color for temperature readings ranging from about 800 to 2400K (980 to 3860 ºF). Higher temperatures damage the fibers, but the range of the fiber's capability is well suited to most flames used in experiments, especially in microgravity.

As a variation on this basic scheme, the group has also conducted experiments using colored camera filters to film flames and fibers at different light wavelengths. Because the ratio of a fiber glow's intensity as measured using one colored filter compared with that measured using another colored filter can be used to calculate temperatures, this technique might be useful in situations where researchers are concerned about the long-term accuracy of an unfiltered camera's calibration. It could be used, for example, if an experimental apparatus was expected to be on the International Space Station (ISS) for a number of years, where dust or other buildup could affect its calibration. Such buildup could be expected to have a uniform effect on measurements taken using various colored filters, possibly eliminating calibration concerns. Sunderland says it is not yet clear whether the filtered or unfiltered technique will prove most useful for future experiments.

To test the thin-filament pyrometry technique, Sunderland's team has run various experiments using a simple methane burner system and comparing temperature measurements from both fibers and thermocouples. Currently, accuracy is within 50K (–370 ºF) of the thermocouple measurements — a small margin of error in measuring flame temperature.

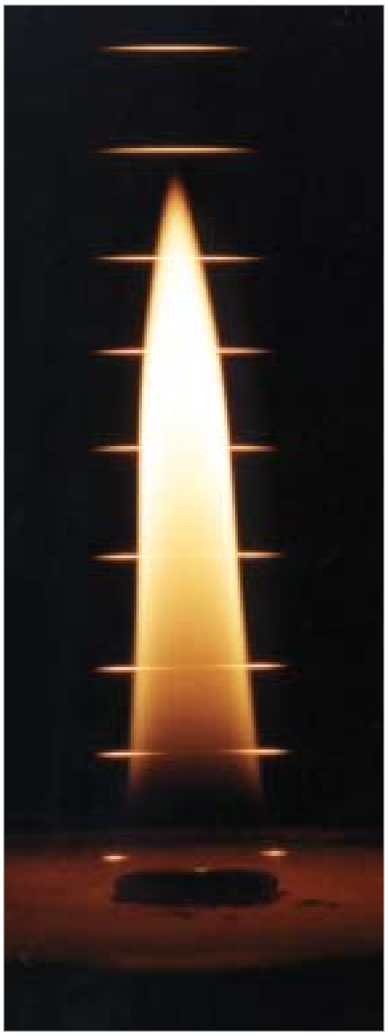
Sunderland's work, which began in 1998, has now advanced to the point that it has been approved for use in an upcoming project called the Flame Design Experiment, which could reach the ISS as soon as 2008. The project is aimed at increasing the understanding of how fire spreads, improving fire suppression techniques, and improving the efficiency of industrial combustion while decreasing the pollution — important on Earth, because combustion is responsible for 85 percent of the United States' energy production.

Peering into the Heart of a Flame

Better understanding how fire behaves is a critical step in both maximizing its usefulness and preventing its destructive spread, but fundamental study remains difficult because fire's true nature is obscured by gravity. By studying flames in a microgravity environment, however, Fumiaki Takahashi, a staff scientist at the National Center for Microgravity Research at Glenn Research Center (GRC), Cleveland, Ohio, has been able to look into the very heart of fire.

Takahashi does not study flames that are premixed, that is, produced downstream of the point where air mixes with the fuel (the blue flames of a typical gas stove burner are one example). His work focuses instead on diffusion flames, which are produced in situations where fuel and air are initially separated but sustain the flame or allow it to spread where they come together (some examples are the multicolored flames of a campfire, a burning house, or an industrial burner in a power plant). In fact, he is principal investigator of the NASA-funded Flame Stability, Spread, and Suppression project at GRC, which has a diffusion flame research component.

Although the solid wood in a campfire may appear to be burning, in reality, the fire heats wood so that combustible gases form; these combustible gases mix with the oxygen in air to feed the fire. In many commercial applications, diffusion flames are preferred because premixed



credit: Peter Sunderland

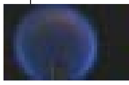
The color of silicon carbide fibers extended through a flame can indicate temperature at each point.

flames, especially in larger systems, are prone to flash back into the system and cause an explosion. In industrial combustors, a burner with supplied fuel is located within a region of airflow, allowing mixing outside (right at the base of the flame, in the mouth of the burner) rather than inside the burner and upstream from the flame. Takahashi's goal for the diffusion flame research is to discover what happens in that critical mixing zone.

In Earth's gravity, flame studies are difficult because the gas buoyancy that elongates a candle's flame also obscures the basic physics of fire and, hence, a diffusion flame's mixing zone. In microgravity, buoyancy is eliminated, leading to spherical flames and allowing clear observation of flame phenomena. To view flames unaltered by buoyancy, Takahashi has used a simple ethane burner system whose fuel jet was a 3-millimeter (0.12-inch) steel tube that did not allow premixing; the entire system encased a combustion chamber with a video camera. He carefully analyzed video of the flames produced as the apparatus fell from the 2.2-Second Drop Tower at GRC. Video of the same burner operating under normal gravity was also analyzed for comparison.

Takahashi's main goal was to analyze the flame's base — its most reactive portion — which also determines a fire's stability and how it spreads. (Fire extinguishers are most effective when aimed at the base of flames.) By analyzing the flame videos, Takahashi determined that in the spherical microgravity flames, molecules of fuel diffused outward uniformly in every direction, instead of only up, and at the same time, oxygen in the air diffused inward.

Although Takahashi's work was built on years of previous microgravity flame research, no previous flame study had ever peered so closely into the internal structure of diffusion flames. Using data from the drop experiments, Takahashi is working to fully calculate this structure. Already he has found a small cool or "quenched" region near the burner formed as a result of the burner's walls conducting heat away from the flame. Such quenching causes the most intense portion of the flame to form close to the burner. Takahashi has determined that in this flame base is a peak reaction zone, which he dubbed a "reaction kernel," that holds the rest of the flame in place.



Proper control of this flame-holding phenomenon is a key element in designing safe and efficient commercial burners. Therefore, new insights from Takahashi's flame research could lead to improvements in commercial combustion systems.

The reaction kernel is also the critical zone in any spreading fire. So, using experiment data, Takahashi ultimately hopes to create the most accurate computer model ever of spreading fire. Creating such a model could allow more accurate computer simulation of fires and ultimately lead to improved fire-suppression techniques for the ISS and other spacecraft as well as better designs for future combustion research experiments in microgravity.

Besides continuing his drop tower experiments, Takahashi is modifying his drop tower experiment for use on NASA's KC-135A plane, nicknamed the "Vomit Comet," which would allow more sustained observation.

credit: Fumiaki Takahashi

Free of the effects of buoyancy that cause flames' characteristic teardrop shape in Earth's gravity, flames in microgravity take on a spherical shape that allows researchers to study the fundamental factors that control them.

FLUID PHYSICS

The behavior of fluids, whether frozen, flowing, or gaseous, is dictated by the laws of physics.

Evidence of gravity's sway over the movement of fluids on Earth is everywhere. In nature, gravity guides the flow of rainwater into streams and rivers and the cascades of water into fountains; it also shakes seemingly solid ground into rippling waves of soil during an earthquake. At home, gravity causes bubbles of carbon dioxide to float to the top of a glass of root beer and brings a pot of water to 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 a mixture. In fact, gravity has such a strong influence over fluids that it can mask evidence of other forces affecting fluid behavior.

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

Fluid physics research in the Physical Sciences Research Division is composed of five main areas: complex fluids, interfacial phenomena, dynamics and instabilities, biological fluid physics, and multiphase flows and phase changes. Experiments in complex fluids involve gases or liquids that contain particles of other substances dispersed within them. One type of complex fluid is a colloid, which is a system of fine particles suspended in a fluid; orange juice and paint are colloids. Another complex fluid is a magnetorheological fluid, a colloid whose viscosity (resistance to flow) can be varied by applying an external magnetic field. Foam, another complex fluid, exhibits features of solids, liquids, and vapors, even though it is not classified as any of these phases.

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 relates to the interaction of surfaces in response to heating, cooling, and chemical influences. A better understanding of these phenomena will help humans learn how duck feathers and waterproof tents repel water, how water spontaneously displaces air in the gaps of a sponge, and more.

The area of dynamics and instability includes research in drop dynamics, capillarity, and magneto/electrohydrodynamics. 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 in microgravity. Research in magneto/electrohydrodynamics involves the study of the effects of magnetic and electric fields on fluid flows.

The subdiscipline of biological fluid physics 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 deoxyribonucleic acid (DNA) in an evaporating droplet of liquid are a few examples.

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

Paint is a household example of a colloid, a system of fine particles suspended in a fluid. Fluid physicists can study other colloids to observe how crystals form from colloidal particles.

credit: Julie Poudrier

Program Summary

The research that the microgravity fluid physics program sponsors supports NASA's overarching goals. In addition to contributing to fundamental knowledge of fluid phenomena, the results of fluid physics investigations conducted in orbit should yield useful applications for lengthy missions, the exploration of other planets, and the enhancement of life on Earth. In fiscal year (FY) 2003, the program funded about 125 principal investigators (PIs). Of these, 106 were working on ground-based research projects and 19 were working on flight projects.

Supporting the exploration of the Moon and planets will require addressing multiphase fluid engineering challenges associated with NASA's technologies. Many of these challenges were discussed at the Two-Phase Flow, Fluid Stability and Dynamics Workshop in Cleveland, Ohio, in May 2003.

Researchers learned about specific areas of research in fluid physics at various workshops and conferences this fiscal year. On March 6, the NASA Glenn Research Center (GRC) in Cleveland, Ohio, sponsored a workshop in Austin, Texas, on soft condensed-matter physics, chaired by Paul Chaikin of Princeton University, Princeton, New Jersey, and co-chaired by Sidney Nagel of the University of Chicago, Illinois. Twenty-three participants represented the United States and five other countries.

The Fourth American Society of Mechanical Engineers (ASME) and Japanese Society of Mechanical Engineers (JSME) Joint Fluids Engineering Conference was held in Honolulu, Hawaii, July 6–10, 2003. A forum titled Multiphase Flows: Work In Progress was organized by fluid physics PI Andrea Prosperetti of Johns Hopkins University, Baltimore, Maryland; two sessions on multiphase flows in microgravity were included. Keynote speakers for the sessions related to microgravity included Bhim Singh of GRC; Tomoji Takamas, Tokyo University, Japan; Masahiro Kawaji, University of Toronto, Canada; and Satwindar Sadhal, University of Southern California (USC), Los Angeles.

The National Center for Microgravity Research (NCMR) and GRC hosted the Two-Phase Flow, Fluid Stability and Dynamics Workshop in Cleveland, Ohio, on May 15, 2003. Fifty-six representatives from industry, academia, and government attended the workshop to define a coherent scientific and technical plan to address the multiphase fluid engineering problems associated with NASA's technologies to support the exploration programs of the future.

The 5th International Bone Fluid Flow Workshop was held on September 17 and 18, 2003, also in Cleveland, Ohio, with the theme "Organ to Cell, Lab to Bedside, on Earth and in Space." The workshop featured seven invited keynote talks, plus presentations and posters. Ian McCarthy, University of Lund, Sweden, presented the keynote paper, "Fluid Shifts due to Microgravity and Their Effects on Bone." The workshop was directed by Melissa Knothe-Tate of the Cleveland Clinic Foundation, Cleveland, Ohio; J. I. D. "Iwan" Alexander, Case Western Reserve University, Cleveland, Ohio; and Bhim Singh of GRC served on the local organizing committee.

Nengli Zhang of GRC presented "Profile Measurement and Flow Visualization of Sessile Drop through Laser Shadowgraphy" at the 7th Triennial International Symposium on Fluid Control, Measurement and Visualization during the week of August 25–29 in Sorrento, Italy. The paper, co-authored by David Chao, also of GRC, describes an evaporating sessile drop (one that is on a surface) and how a far-field image (one taken from a relatively longer distance) of a laser shadowgraph of the drop is used to measure the drop's instantaneous parameters, such as instantaneous contact angle, height, and volume. It is also used to identify the patterns of the test drops' contact line region through the concentrated light they reflect (the caustics and caustic diffraction) in their far-field shadowgraphic images. Four basic shapes are revealed by this method. Additionally, the interference-fringe method based on the caustic diffraction is used to estimate the drop profile near the contact line. (An interference fringe is the pattern of light and dark patches created when two beams of light come together.) Any convective flow inside the drop can be visualized simultaneously. All these findings are important to understand the physics of liquid spreading.

Ramaswamy Balasubramaniam of NCMR presented a keynote address at the Microgravity Transport Processes in Fluid, Thermal, Materials, and Biological Sciences Conference III, organized by Engineering Conferences International and held in Davos, Switzerland, September 14–19, 2003. The talk, "Thermocapillary Convection in Bubbles and Drops," was co-authored by Shankar Subramanian of Clarkson University, Potsdam, New York. Sponsored by NASA and the National Science Foundation (NSF) and chaired by Satwindar Sadhal, the conference was mainly intended as a venue for the exchange of technical information and ideas among scientists and engineers working in microgravity fluid, thermal, biological, and materials sciences. Some 65 papers and keynote lectures were presented in the areas of protein crystal growth, biotransport phenomena, crystal growth, materials technology, drops and bubbles, boiling phenomena, interfacial phenomena and Marangoni flows, and dynamics and instabilities as well as electrostatic and acoustic levitation, electromagnetic phenomena, and space systems.

GRC and Air Force Research Laboratory (AFRL) are collaborating on a two-phase (liquid–vapor) spray cooling system for use in microgravity. AFRL will design and build the hardware, and GRC will provide access to microgravity test equipment, including the KC-135 parabolic flight aircraft, and to a wealth of experience in working with fluids in microgravity. Minimal work has been done on spray cooling in microgravity, particularly in areas such as phase separation and fluid management during evaporation. Both nuclear spacecraft and conventional spacecraft thermal subsystems can benefit from spray cooling technology, especially in improving the efficiency of evaporator designs that involve less mass than other modes of heat transfer such as radiation, conduction, or single-phase convection.

AFRL is investigating spray cooling as a potential method of solving anticipated thermal challenges in future space and aircraft weapons systems. This collaborative approach involves the following investigations:

- defining the fundamentals of spray cooling, including fluid management during the spray cooling process;

- examining evaporation on the microscale, when droplets hit a hot surface; and

- research scaling by extrapolating test data to design multiple-kilowatt space-based systems for heat rejection.

GRC and Advanced Bionics Inc. (ABI) have signed a Space Act Agreement to apply advanced flow diagnostics to the flow field of a novel centrifugal pump. They want to determine fluid stresses, flow losses, and whether the pump can be used as an artificial heart. ABI will provide GRC with a fully functional model of the heart pump made entirely of acrylic. In turn, GRC will endeavor to map the pump's flow field, paying close attention to the inlet region, outlet region, touch-down areas, and inner blade/disk region. Flow visualization will be used to determine losses and fluid stresses, determine any turbulent flows, and register impeller motion as well as observe the pump's surface and determine its movement, if any, and investigate the availability of computational fluid dynamics codes for pump analysis. GRC will provide ABI with all findings, data, test results, and analysis. John Sankovic in the fluid physics discipline at GRC is the key NASA official and the principal point of contact for this agreement.

Awards and Honors

Fluid physics Principal Investigator (PI) Andrea Prosperetti of Johns Hopkins University, Baltimore, Maryland, was presented with the 2002 Otto LaPorte Award for "breakthroughs in the theory of multiphase flows, the dynamics of bubble oscillations, underwater sound, and free-surface flows and for providing elegant explanations of paradoxical phenomena in these fields." The award recognizes outstanding research accomplishments pertaining to the physics of fluid dynamics. Endowed by the friends of Otto LaPorte and the Division of Fluid Dynamics, the annual award was established as an American Physical Society award in 1985 but had existed as a division lectureship prize for the 12 previous years.

Two fluid physics PIs were elected to the National Academy of Engineering (NAE). Dudley Saville of Princeton University, Princeton, New Jersey, was elected for advancing the understanding of electrokinetic and electrohydrodynamic processes and their application to the assembly of colloidal arrays. He is working on ground-based NASA-funded research in the electrohydrodynamics of suspensions and the electrohydrodynamic flows in electrochemical systems. Ronald Larson of the University of Michigan, Ann Arbor, was elected for elucidating the flow properties of complex fluids at the molecular and continuum levels through theory and experimentation. Larson has been a fluid physics PI since 1998. He is conducting ground-based research on the microfluidic and dielectric processing of deoxyribonucleic acid (DNA).

The NAE elected 77 new members and nine foreign associates this year, according to NAE President William Wulf. This brings the total U.S. membership to 2,138 and the number of foreign associates to 165. Election to NAE is among the highest professional distinctions accorded an engineer. Academy membership honors those who have made "important contributions to engineering theory and practice, including significant contributions to the literature of engineering theory and practice" and those who have demonstrated accomplishment in "the pioneering of new fields of engineering, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education."

Paul Chaikin, Henry DeWolf Smyth Professor of Physics at Princeton University, was named fellow of the American Academy of Arts and Sciences in 2003. He was among 216 scholars, scientists, artists, business leaders, educators, and public officials elected in recognition of their contributions to their respective fields. Chaikin is a Fellow of the American Physical Society and a past winner of the prestigious Guggenheim Fellowship and A. P. Sloan Foundation Fellowship. Since receiving his doctorate in physics from the University of Pennsylvania, Philadelphia, he has co-authored *Principles of Condensed Matter Physics*, the definitive book on the subject, and has published more than 300 papers.

William Meyer of GRC and his collaborators were awarded U.S. Patent No. 6,469,787 on October 22, 2002, for an optical probe that determines particle size (from nanometers to microns) in a liquid sample. To determine particle size, scientists aim a laser through a sample, whose light scatters off of the particles as they move around in Brownian motion. The motion causes the scattered light to sum in a way that flickers on and off, depending on how fast the particles are dancing around. The probe incorporates all the advantages discussed in the collaborators' earlier patent (#5,956,139) issued in 1999. In addition, the new patent addresses problems that arise during various situations such as when the sample appears rather opaque, particles are of more than one size, particles are too small to scatter enough light, or the sample size is too small. Meyer's collaborating inventors are David Cannell of Santa Barbara, California, and Anthony Smart of Costa Mesa, California. The assignees are Ohio Aerospace Institute, Cleveland, and the Regents of the University of California, Oakland. U.S. Patent Application No. 825,117 was filed on April 3, 2001.

Several notable papers describing the work of fluid physics PIs were published in *Nature*, *Science*, and other prestigious journals in FY 2003. Four deserve special mention:

- R. B. Hartley and R. P. Behringer. Logarithmic Rate Dependence of Fame Networks in Sheared Granular Materials. *Nature*, **421**, February 2003, 928–31.

- A. D. Dinsmore, Ming F. Hsu, M. G. Nikolaides, Manuel Marquez, A. R. Bausch, and D. A. Weitz. Colloidosomes: Selectively Permeable Capsules Composed of Colloidal Particles. *Science*, **298**, November 1, 2002, 1006–1009.

- Igor Volkov, Jayanth R. Banavar, Stephen P. Hubbell, and Amos Maritan. Neutral Theory and Relative Species Abundance in Ecology. *Nature*, **424**, August 2003, 1035.

- D. A. Coleman, J. Fernsler, N. Chattham, M.Nakata, Y. Takanishi, E. Körblova, D. R. Link, R. F. Shao, W. G. Jang, J. E. Maclennan, O. Mondainn-Monval C. Boyer, W. Weissflog, G. Pelzl, L.-C. Chien, J. Zasadzinski, J. Watanabe, D. M. Walba, H. Takezoe, and N. A. Clark. Polarization-Modulated Smectic Liquid Crystal Phases. *Science*, **301**, August 29, 2003, 1204.

Flight Experiments

Fluid physicists made many advances with flight experiments in fiscal year (FY) 2003. By studying colloids, fluid viscosity, bubble interactions, and the behavior of granular and forced liquid flows, they learned much of value about fluids. Experiments that did not fly this year nonetheless made good progress toward being ready for launch to the International Space Station (ISS).

Physics of Colloids in Space (PCS) experiments, which involve observing how microgravity affects the way crystals and other structures form from colloidal particles (particles suspended in a fluid), took several steps forward in FY 2003. The original experiment, PCS, was conducted on the ISS in FY 2001 and FY 2002 in Rack 2 of EXPRESS (EXpedite the PRocessing of Experiments to Space Station; for more information, see Highlight, "Getting the Big Picture at the Molecular Level", on page 60). Conceived by Principal Investigator (PI) David Weitz of Harvard University, Cambridge, Massachusetts, and Co-Investigator (Co-I) Peter Pusey of the University of Edinburgh, Scotland, United Kingdom, PCS is helping researchers learn how these delicate structures can form without interference from convective flow or sedimentation.

For PCS, eight samples were selected from three types of colloids: binary colloids, which contain particles of two sizes and may help explain the behavior of alloys; colloid and polymer mixtures, in which the polymer makes the colloid particles slightly attractive as they form gels and crystals; and fractal colloids, which form gels with highly disordered networks, like the network that holds gelatin together. The samples were studied using the PCS apparatus, a versatile and sophisticated digital-imaging and light-scattering instrument that allows for the change-out of samples once back on Earth with no need to realign its precision diagnostics.

In FY 2003, Weitz's group made a detailed analysis of data from four samples. The group analyzed all data from the two binary colloidal alloys to determine the growth rates of the crystals and found that there is an induction period when no crystals are formed, then a rather rapid growth period when most of the crystals form, followed by a very slow coarsening period. From the sample data on the critical point of colloid polymers, the group determined the surface tension between the two (liquidlike and gaslike) regimes, which drives the coarsening period; the surface tension was about two orders of magnitude lower than expected, suggesting that the researchers are approaching the critical point of the phase (liquid–gas) separation. For the fractal colloid (gel), the group determined the gel cluster size and found that cluster size continues to increase in microgravity, whereas it saturates on Earth. The saturation occurs at exactly the point predicted by a theory that considers the effects of gravitational drag through the fluid, indicating that there is a limit to the lower volume fraction that can be gelled on Earth. Thus, some of Weitz's models and theories for understanding the behavior of weak gels are being corroborated by the PCS flight data.

The PCS hardware is being refurbished for use in two more colloid experiments: PCS+, run by Paul Chaikin, Princeton University, Princeton, New Jersey, and PCS-3, led by Weitz; Michael Solomon, University of Michigan, Ann Arbor; and Eric Weeks, Emory University, Atlanta, Georgia. PCS+ extends the basic research in colloid physics using light-scattering techniques. The monodisperse (single-sized) colloids of PCS+ that will be flown to the ISS in late 2004 or early 2005 serve as a model for crystal growth, dendrite growth, and glass formation. These simplified model systems are advancing the fundamental knowledge of thermodynamic phase transitions, which in turn could generate novel drugs and materials.


credit: NASA

Engineers assemble the sample carousel of the Physics of Colloids in Space Plus (PCS+) experiment that will be taken to the International Space Station in 2005.

PCS-3 seeks to answer fundamental questions about the formation (or nucleation), growth, and morphology of binary colloidal crystal alloys, colloid polymer gels, fractals, binary glasses, and anisometric colloidal gels (the latter of which are colloids that either have more than one size or constituent or are long and thin rather than round). Knowledge gained from this experiment could enhance such terrestrial processes as the use of environmentally friendly supercritical carbon dioxide for food extractions, pharmaceutical processing, and dry cleaning.

A colloids experiment that provided unique insights into how directional forces such as magnetic fields influence structural transformations was conducted on the ISS in FY 2003. Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (InSPACE), as the magnetorheological experiment is named, was led by Alice Gast of the Massachusetts Institute of Technology (MIT), Cambridge. The hardware was flown to the ISS in June 2002, and the samples were delivered in November 2002. InSPACE was conducted in the Microgravity Science Glovebox (MSG; for more information about the MSG, see page 102).

Astronaut Don Pettit ran nine pulsed-power tests, each 1 to 2 hours long, on three vials, each containing a magnetorheological (MR) fluid with a different particle size. Two cameras recorded columns or two-dimensional sheets of particles that folded and fluctuated, instead of the three-dimensional fishlike structures that Gast had expected. These results gathered before operations ended in July 2003 suggest that amid the competition of interfacial, magnetic, and gravitational forces, the last play a critical role in the formation of ellipsoidal structures in MR fluids.

The study of these colloidal systems should encourage the development of "smart fluids" for use in feedback-controlled devices such as shock absorbers and suspension systems and for use as colloidal modifiers in protein crystallization or colloidal suspensions. Techniques that Gast's team used could possibly be used to induce two-dimensional crystallization of proteins in these suspensions.

A follow-on experiment with new samples, InSPACE-2, will be delivered to the ISS on a Russian Progress flight scheduled to launch in March 2004. (See Highlight "Getting the Right Touch with Magnetic Fluids" on page 59.)

The Binary Colloidal Alloy Test-3 (BCAT-3) is a fast-track experiment. Conceived in March 2003, it was delivered in August 2003 for Russian Progress flight 13P, with operations planned for early 2004. Weitz, Pusey, and Arjun Yodh (University of Pennsylvania, Philadelphia) are the PIs. In BCAT-3, which is a follow-on experiment to BCAT-2 and BCAT (conducted on Russian Space Station *Mir*), the long-term behavior of three classes of colloids will be studied in microgravity, where the effects of sedimentation and convection are greatly reduced, to allow a better fundamental understanding of colloids, their assembly and thermodynamics, and how to engineer their properties.

BCAT-3 is designed to operate as a stand-alone experiment in the ISS maintenance work area. At the start of the experiment, astronaut Michael Foale will mix the 10 colloid samples and then take photographs to document colloid formation. The experiment will help clarify the most basic physical properties of colloids, which may someday form the foundation of new classes of optical switches, displays, and other optical devices for communications and computer applications.

Five of the fluid physics experiments slated to fly on the ISS will be run in the new Light Microscopy Module (LMM), a microscope adapted for conducting in-orbit colloid and other fluid physics experiments. The LMM was

credit: NASA

Astronaut Kalpana Chawla reviews instructions for running the Mechanics of Granular Materials experiment aboard Space Shuttle Columbia *in January 2003. Although* Columbia *and its crew did not return safely to Earth, a significant amount of data was collected and analyzed via real-time downlink telemetry and limited video downlinks.*

designed by a team in the microgravity fluid physics program for use with the Fluids Integrated Rack (FIR), which will be the fluid physics facility in the Destiny laboratory of the ISS. (For more information about the LMM and the FIR, see pages 99 and 100.)

The experiments that will use the new LMM are Constrained Vapor Bubble (CVB), led by Peter Wayner of Rensselaer Polytechnic Institute, Troy, New York; Physics of Hard Spheres Experiment-2 (PHaSE-2), led by Chaikin; PCS-2, an investigation to be conducted by Weitz and Pusey and related to PCS+ and PCS-3; Low Volume Fraction Colloidal Assembly (LFCA), led by Yodh; and Micromechanics of Magnetorheological Fluids (μMRF), conducted by Gast. The first experiment investigates heat conductance in microgravity as a function of liquid volume and heat flow rate to determine, in detail, the transport process characteristics in a curved liquid film. The other four experiments investigate various complementary aspects of the nucleation, growth, structure, and properties of colloidal crystals in microgravity and the effects of micromanipulation on their properties.

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

This characterization of flow (or rheological) data will allow designers of both space- and ground-based material processes to create improved models of complex two- and three-dimensional fluid flows. Non-Newtonian fluids are significant in many industrial processes, such as spinning fibers, spraying, and coating with films. Insight into the extensional viscosity of these fluids also helps in understanding the complex fluid phenomena involved in the stability and breakup of fluid jets; enhanced oil recovery; and reduction in turbulent drag for advanced aircraft, boats, and submarines. In FY 2003, a high-fidelity training unit for SHERE was completed, and the SHERE flight hardware unit was further developed.

The Bulk Viscosity of Xenon (BVX) experiment, led by PI Michael Moldover of the National Institute of Standards and Technology, Gaithersburg, Maryland, is scheduled to fly on Expedition 17 of the ISS in 2007–2008. This experiment will help scientists develop a novel acoustic resonator to measure the element xenon's liquid–vapor critical point and its ability to behave with a dilatational (push–pull) motion in response to any disturbance. The experiment will be conducted over a range of temperatures, and the data will be used to test theories that apply to the liquid–vapor critical points of other fluids. For example, the operating temperature and density of steam used to drive the turbine of an electric generator are near their critical conditions, so understanding the significance of the steam bulk viscosity near its critical condition is important to improving turbine design. In FY 2003, the BVX team designed and tested critical hardware components for the xenon sample cell, critical components of the electronic support system, and components for the environmental control system.

Bubbles take center stage in many fluid physics experiments. For example, the Microgravity Observations of Bubble Interactions (MOBI) experiment, planned for operation on the ISS in the FIR in 2008, studies the behavior of a monodispersed bubble suspension when sheared in a cylindrical couette cell, a device with two concentric shells with the outer shell spinning. A bubble suspension is introduced into the gap between the shells. The motion of the outer shell creates a centrifugal force that pushes the bubbles toward the inner shell while the bubble phase pressure pushes them away from each other due to shearing force. The competition between these forces results in a bubble volume fraction in the couette gap. The outcome of this experiment, led by Ashok Sangani of Syracuse University, New York, and Don Koch of Cornell University, Ithaca, New York, will be a comparison of experimental measurements with theoretical predictions of bubble concentration in the gap, the intent of which is to verify the averaged equations of motion of bubble suspensions under potential flow settings.

MOBI will add to scientists' understanding of multiphase flows and fundamental knowledge valuable in the engineering and design of microgravity materials processing and life support systems for extended spaceflight. Moreover, terrestrial applications for which MOBI's results can be crucial include boiling heat exchangers, bubble columns, and the flow rates of oil and gas wells, which are typically two- and three-phase flows complicated by gravity-induced segregation. Knowledge gained from the MOBI experiment may also apply to bubble segregation in bioreactors, where it may throw more light on the effect of bubble segregation on the efficiency of transporting oxygen to the cells being cultivated within the bioreactor.

In FY 2003, the Johnson Space Center Payload Safety Review Panel conducted an informal review of the MOBI fluid system and provided positive feedback on the safety aspects of the design. The MOBI system design was modified to reduce the amount of water required to run the experiment in orbit by 65 percent. The modified design also has reduced the time to make the required bubbly suspension to less than 1 minute. Moreover, bubble generation experiments were successfully conducted onboard the KC-135 airplane and resulted in bubble size distribution compliant with the science requirements.

Bubbles also figure prominently in boiling, which is an important field of study because they can effectively cool a surface by moving energy away from it through the phase change of liquid to gas. Because boiling is a preferred mode of heat transfer in space, what investigators learn about boiling in microgravity can be applied to thermal management of many spacecraft systems, such as supply systems for life-support fluids and electronic packages powering various instrumentation and control systems. To study these phenomena, scientists and engineers created the Boiling Experiment Facility (BXF), which will accommodate experiments on the ISS beginning in 2006.

Two experiments are planned for the BXF in 2006, the Nucleate Pool Boiling Experiment (NPBX), led by Vijay Dhir of the University of California, Los Angeles (UCLA), and the Microheater Array Boiling Experiment (MABE), led by Jungho Kim of the University of Maryland, College Park. Dhir will study bubble nucleation, growth, and departure during boiling in microgravity and the cooling that results in microgravity. NPBX will increase in complexity from experiments using a single bubble to others using three inline bubbles to yet others with five bubbles placed on a two-dimensional grid.

Bubble growth on a heater surface is complex because the bubble shape changes continuously throughout the process, and superheated liquid is confined to only a thin region, known as the contact line region, around the bubble. Available models do not properly account for all the forces that act on a bubble: inertia of the liquid and vapor, liquid drag on the bubble, buoyancy, and surface tension. In FY 2003, Dhir's team developed wafer heaters with shaped cavities (trapping gas to aid in the nucleation of bubbles) on the fluid side. As before, heating elements and temperature sensors are epoxied to the back side to complete the heater fabrication. Using FC-72, a fluid with compounds of six carbons and a low boiling point, the researchers performed low-gravity experiments to test the algorithms for nucleating (forming) bubbles, growing bubbles, and predicting the departure characteristics of a small number of bubbles. They also used numerical simulations to study the dynamics and heat transfer associated with multiple bubble mergers.

MABE will help scientists know how much cooling can be achieved with fluid in microgravity. It will use two 96-element microheater arrays, 2.7 by 2.7 millimeters (about .11 by .11 inches), and 7.0 by 7.0 millimeters (about .28 by .28 inches), respectively. This arrangement will allow local heat fluxes to be measured as a function of time and space. Boiling heat-transfer mechanisms in reduced gravity are not currently understood, but the MABE team hopes that minimizing the effects of gravity will simplify the problem and so lead to a better appreciation of boiling heat-transfer mechanisms in Earth's gravity. During FY 2003, the MABE team gathered data on the boiling process in microgravity, Earth's gravity, and hypergravity using a heater array on a KC-135 airplane flying in a parabolic pattern. Results this year confirm previous findings that very low heat transfer occurs in low gravity because a large primary bubble covers almost the entire heated area. In high gravity, the bubble shrinks, allowing liquid to wet the outside of the heaters and increase heat transfer.

Scientists also are studying the flow of granular materials, which are substances made up of solid particles distributed in a gas or liquid. Beginning in 2009, the Granular Flow Module (GFM) will be operated in the FIR as a multiuser mini-facility for use in studying granular materials. (For more information about the GFM, see page 99.) The first three investigations to be conducted on the GFM are Microgravity Particle Segregation in Collisional Shearing Flows (μgSEG); Studies of Gas–Particle Interactions in a Microgravity Flow Cell, also known as Solids Interacting with a Gas in a Microgravity Apparatus (SiGMA); and Gravity and Granular Materials (GGM).

The objective of the μgSEG experiment, conducted by PI James Jenkins and his team at Cornell University, is to test mechanisms of granular segregation that are not controlled by gravity. When gravity is absent and the grains flow fast enough that the grain–grain interactions are only elastic (or slightly inelastic) collisions, physics similar to those described by the kinetic theory of gases govern the motions of the grains. This theory predicts that a binary mixture of grains will "unmix" (segregate) itself based on particle size or mass as long as a gradient of velocity fluctuation is present in the flow.

In the experiment, which is scheduled to run in 2009, the grains are contained in the gap between parallel cylindrical walls. The required distribution of granular fluctuation energy will be controlled by fitting the rotating cylindrical walls with "bumps" that have specific shapes and collision properties. Digital video will record the particles' trajectories between the rotating walls, and then, from the trajectories, researchers will extract mean velocities and fluctuation energy across the cell for each grain species. The experiment will quantify the geometric segregation of spheres with different sizes but equal masses and with different masses but equal sizes. Measurements will be compared with theory and with molecular dynamics simulations. In FY 2003, the team adjusted its imaging analysis method to detect metal spheres using a ring light (an array of lights in a doughnut shape) to distinguish between shiny and dull spherical particles and then compared their measurements of mean and fluctuating velocities with predictions of their numerical simulations and theory. The team also further developed its interactive evaluation tool to speed up data evaluation.

SiGMA, conducted by PI Michel Louge and his team at Cornell University, studies the effect of surrounding gas on the dynamics of particles. Two aspects of the gas–particle interaction will be tested: dissipation of granular energy by the action of gas viscosity (also called viscous dissipation) and how the gas drag on the solids affects their distribution of fluctuation energy (viscous drag). Scheduled to run in 2008, the experiments will measure two parameters that appear in new theories predicting viscous dissipation and viscous drag. The dependence of these parameters on solids concentration will be tested against the theoretical predictions. The flow cell is similar to that used in μgSEG. However, the flow regime requires that the grain speeds be slower to bring out the effects of viscous forces exerted by the gas. In FY 2003, the SiGMA team — like the other Cornell team — adjusted its imaging analysis method to detect metal spheres using a ring light technique and then compared their measurements of mean and fluctuating velocities with predictions of their numerical simulations and theory. The team also further developed its interactive evaluation tool to speed up data evaluation.

GGM, conducted by PI Robert Behringer of Duke University, Durham, North Carolina, will explore the fluctuation of forces in low- and high-density granular samples. The effects of the fluctuation range from clustering at low density to jamming particle chains at high density. In the flight hardware, the sample volume is the space between two concentric cylinders of different diameters, with one stationary end plate and one end plate that rotates to drive a shearing motion. The granular particles are 0.8-millimeter (.03-inch) glass beads. The volume of the beads varies from gaslike (relatively long distances between each bead) to liquidlike (average gap between beads is less than the diameter of the bead). Findings from the experiment, which will be run in 2009, may yield a better grasp of the mechanical behavior of granular materials and indicate how to avoid such industrial problems as clogged chutes, silo failures, and poorly mixed medicinal components. In FY 2003, the team conducted breadboard testing to show the capability of the optical stress sensors to record three stresses with one sensor. The team has designed a sapphire window for viewing the spheres in the chamber.

The third Mechanics of Granular Materials (MGM) III experiment flew on Space Shuttle *Columbia* as part of STS-107 in January 2003. MGM-III, led by PI Stein Sture and Co-I Nicholas Costes, both of the University of Colorado, Boulder, used microgravity to test the response of sand columns to compression and relaxation — forces that occur during earthquakes and landslides when compacted soil loosens and flows much like a liquid.

In MGM's two previous flights, the researchers had measured the effect of gravity on friction between grains of dry sand and discovered the strength and stiffness of the sand columns to be many times greater than conventional theory predicted. For MGM's third flight, they studied the behavior of water-saturated sand in drained and undrained conditions using three sand samples in 10 different experiments. Although *Columbia* and its crew did not return any specimens for postflight internal examination with computer tomography, real-time downlink telemetry and limited video downlinks nevertheless allowed 50 to 60 percent of all the data collected for MGM-III to be saved and analyzed. The experiments provided the first-ever measurements of sand strength and stiffness and of induced pore water pressures when pressure is cyclically applied and released, as happens during an earthquake. They also achieved liquefaction and identified a conditional boundary for this condition.

Another accomplishment was a new specimen-reforming technique that will be of great use to future space station research because it enables the reuse and retesting of a sample under controlled initial conditions. Results of the MGM experiments will further the understanding of design models for soil movement under confinement and various stresses. Discoveries from MGM investigations may help engineers design more earthquake-tolerant buildings, increase safety in mining operations, aid coastal and offshore engineering projects, and assist researchers in understanding the geology of various planetary bodies for space exploration initiatives.

To study the flow rate of other fluids, NASA and the German space agency, Deutschen Zentrum für Luft- und Raumfahrt (DLR), are collaborating on Critical Velocities in Open Capillary Channel Flows (CCF). The DLR will design and build the experiment with PI Michael Dreyer from the University of Bremen, Germany. The first set of experiments will be conducted in 2008 in the MSG, which will investigate forced liquid flows through various types of open capillary channels, such as parallel plates and V-shaped corners. The primary goal of this research is to develop a model to predict the maximum flow rate achievable through capillary vanes, which can ultimately lead to significant design improvements for spacecraft fuel tanks and other types of liquid-storage and -handling devices.

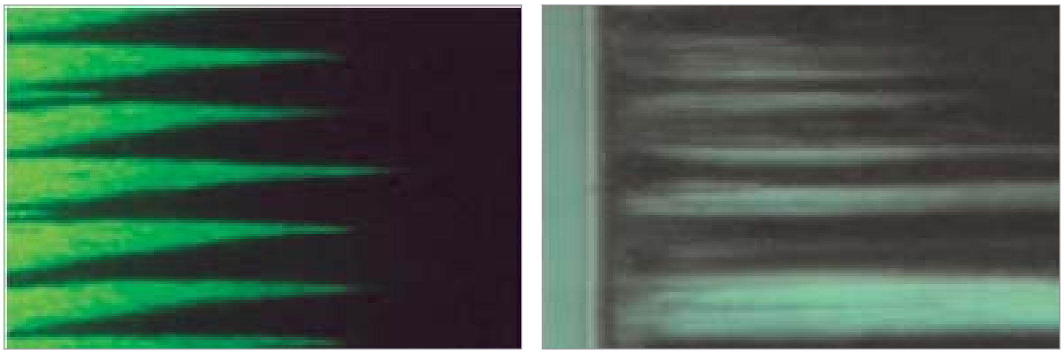
After the DLR experiments, a NASA-selected PI will have access to the experiment to conduct related investigations. The CCF team successfully completed their initial feasibility studies (phase A) during FY 2003 and plans to conduct a sounding rocket experiment in spring 2004.

Highlights

Getting the Right Touch with Magnetic Fluids

The surgeon gently inserts a scalpel into the patient and, using the varying resistance of healthy and cancerous tissue as a guide, deftly excises a tumor. In this scenario, patient and surgeon are several feet away from each other. The scalpel is wielded by a tiny robotic arm snaked down the patient's esophagus. Crucial to the operation is a special type of fluid that helps sense the telltale difference between healthy and malignant tissue under the scalpel, then translate that difference into varying pressures on the surgeon's fingertips.

Such remotely personal touch is one of many potential applications for an emerging class of materials known as magnetorheological (MR) fluids. The term "magnetorheological" means magnetic flow, indicating that the fluids are literally reshaped by magnetic fields. MR fluids are used in a wide range of commercial and research applications, including shock absorbers in trucks and prosthetic limbs, stair-stepper exercise machines tuned to the user's weight, and even a bridge in China (to keep suspension cables from swaying too much in severe winds). Several other applications, including surgery, are in the offing, but scientists first need to understand better how MR fluids work, including why they appear to wear out under certain conditions.



Video microscope images (both illuminated with a green light) of magnetorheological (MR) fluids on Earth show the MR fluid forming columns or spiked structures (left); in microgravity aboard the International Space Station, they form broader columns (right).

credit: Alice Gast

"MR fluids are made up of tiny particles, each carrying magnetic material," explains Principal Investigator Alice Gast, vice president of research and assistant provost at the Massachusetts Institute of Technology in Cambridge. "In the absence of a magnetic field, the particles flow around [aimlessly], much like the microscopic fat globules in homogenized milk. Once you apply a field, the magnetic material [in the particles] becomes magnetized, then, acting as small magnets, the particles form chains with neighboring particles."

Absent a magnetic field, an MR fluid assumes the shape of its container like a normal fluid, because the molecules have no inherent magnetic field. They are paramagnetic, which means that they react only to magnetic fields imposed from without, like nails respond to a magnet. When an external magnetic field is applied, the particles in the MR fluid align themselves along the field lines to form chains. These chains become countless molecule-thin support rods that stiffen the fluid along the field lines, thus giving the fluid the strength of a gel or soft rubber.

The particle chains are denser than the surrounding fluid and settle to the bottom of a container, thus making it difficult for scientists to get a clear view of what happens in the fluids at the molecular level and slowing efforts to manipulate the design of MR fluids for precision control. To eliminate sedimentation, Gast turned to the microgravity environment of space.

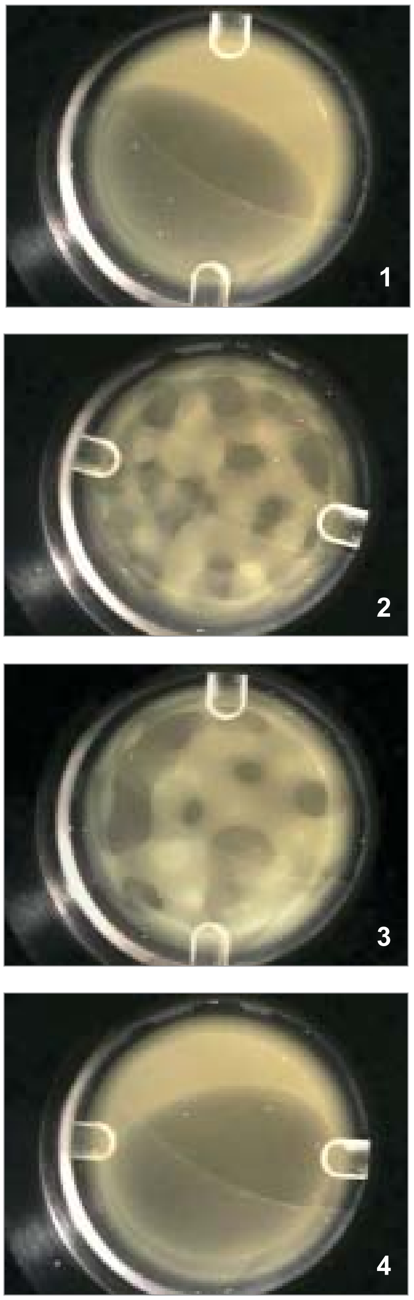
From November 2002 through April 2003, Gast's experiment, Investigating the Structures of Paramagnetic Aggregates from Colloidal Emulsions (InSPACE) was conducted aboard the International Space Station (ISS) with the crew using the Microgravity Science Glovebox. Astronauts set up and operated an apparatus composed of a glass vial — just a millimeter square and 50 millimeters long (0.0015 by 1.97 inches) — filled with MR fluid and encased in a Helmholtz coil, an adjustable electromagnet. Data were collected from video cameras that viewed through microscopes. Each of nine tests lasted 1 to 2 hours. Gast noted that the experiments benefited from the collaboration of science officers Don Pettit, a chemical engineer (like Gast), and Edward Liu. Their observations and suggestions helped Gast and her team improve the experiments.

The results were very different from what Gast expected. In microgravity, MR fluids in a pulsed magnetic field sometimes evolved into what Gast calls a "fluctuating dynamic sheet." She had expected to find the particles forming aggregates that took on ellipsoidal or football shapes because of mutual attraction, or sometimes forming long thin columns. Instead, they formed columns under some conditions and formed two-dimensional sheets under others, and the football-shaped aggregates that formed interacted with the walls of the container. And that is part of the challenge in using MR fluids. Ideally, an MR shock absorber would have electronics to sense the load it is carrying and the input from the road, then calculate how to pulse the magnetic fluid to lessen the impact. But tuning the field can also cause the molecules to clump and then settle out, reducing the shock absorber's effectiveness. The ISS results suggested that when gravity, magnetism, and forces between fluids compete on Earth, gravity often dominates.

Until the ISS experiments, all the studies of MR fluids took place on Earth. Now the absence of gravity has allowed the magnetic and surface tension forces to create more extended and diverse aggregate shapes than can be observed on the ground. In other words, much of what is known today about magnetic suspensions may be influenced by gravity, and current understanding of them needs to be reconsidered. Such knowledge will be crucial to giving surgeons and other experts the confidence that MR fluids will give them just the right touch.

Getting the Big Picture at the Molecular Level

One usually thinks of model as a "small imitation of the real thing." But teams of scientists at Harvard University in Cambridge, Massachusetts, and Princeton University in Princeton, New Jersey are working with large imitations to understand how things work on a much smaller



Images of the first Physics of Colliods in Space (PCS) experiment taken aboard the International Space Station in 2001 show the segregation of a colloid sample — plastic microbeads suspended in a polymer solution to mimic a mixture of gas and liquid. At the start (1), the beads are about to be homogenized after separating while sitting on Earth. In less than 4 hours (2), they separate into colloid-rich (colloidal liquid) and colloid-poor (colloidal gas) phases and continue to coarsen (3) 13 hours, 24 minutes into the experiment. After 35 days (4), phases are completely separated; the colloid-rich phase is the layer that extends around the cell, an effect that often cannot be observed in Earth's gravity.

credit: David Weitz

molecular scale. Even so, their models still qualify as tiny — barely large enough to fill a petri dish.

David Weitz of Harvard and Paul Chaikin of Princeton are principal investigators (PIs) on two separate Physics of Colloids in Space (PCS) experiments that will share some hardware aboard the International Space Station (ISS). The original PCS, for which Weitz was the PI, ran aboard the ISS from May 2001 to February 2002 in EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Rack 2. Its successor, PCS+, will be the original PCS hardware returned to the ISS. An even later experiment, PCS-3, will install a new test section while using the avionics from PCS+.

Colloids are very small particles (about 1/100 the thickness of a human hair) suspended in a liquid or a gas. Paint, ink, mayonnaise, milk, and even smoke are everyday examples of colloids. Colloids (from the Greek word for "glue") differ from many other materials because they do not dissolve in water. Furthermore, the properties of colloidal particle suspensions vary widely and often cannot be realized in other forms of materials.

For both PCS+ and PCS-3, the investigators will use microscopic plastic or glass beads in polymer solutions to simulate the actions of molecules as they self-assemble into crystalline structures. In effect, the beads will provide an enlarged view of what happens at the molecular level in various processes important to industry. The microscopic spheres are small enough that intermolecular forces dominate their behavior — that is, if the effects of gravity are removed by taking the specimens into orbit.

The PCS test section is a hermetically sealed container that houses several cells on a rotating carousel. The cells are filled with colloidal samples, spheres about a micron (about 0.0000394 inch) in diameter. Each cell is rotated into position under a video camera where its sample is photographed under different lighting conditions that reveal how the spheres interact and mimic gels, gas–liquid mixtures, and other materials.

For PCS+, the sample cells will each hold monodisperse or single-size microspheres (with separate cells having different sizes) that serve as models for the formation of crystals, dendrites (treelike branches on materials, such as ice crystals on a car windshield), and glass (where the particles are too densely packed to allow crystallization). Scientists hope that these simplified model systems will advance the fundamental knowledge of thermodynamic phase transitions, that is, actions inside materials as temperature changes produce structural changes. Enhanced understanding from these experiments could lead to novel drugs and materials.

PCS-3 seeks to answer fundamental questions about the nucleation, growth, and morphology of binary colloidal crystal alloys (two sizes of particles); colloid polymer gels (single-size particles in a stabilizing fluid); fractals (particle solutions to which salt is added to cause an irreversible formation of fractals); binary glasses (two particle sizes so closely packed that they behave like glass); and anisometric colloidal gels (colloids that either have more than one size or constituent or are long and thin rather than round). The aim of experiments with these more complex colloids has been to better understand the underlying physics of colloidal self-assembly that could be used to verify or modify theories of complex colloidal structures. Fundamental knowledge gained about critical phenomena in colloidal systems could enhance terrestrial processes such as the use of environmentally friendly supercritical carbon dioxide (generated under high pressure) for applications in extracting contaminants from foods, pharmaceutical processing, and dry cleaning, among others.

Chaikin's PCS+ experiment successfully completed system-level flight acceptance testing in 2003 and will be ready to fly as soon as space shuttle flights to the ISS resume. For PCS-3, the build-up of a second test section and spare avionics section flight drawers began. According to Chaikin, the PI for several space shuttle experiments, "Our aim is both the understanding of very fundamental problems such as the liquid–solid transition, the existence of glasses, [and] the effects of long-range hydrodynamic interactions and the use of these techniques for colloidal architecture to create new and unusual structures." PCS-3 is anticipated to be ready for flight in 2005.

Meanwhile, Weitz and his group at Harvard have been analyzing flight data from PCS. Some of their models and theories for understanding the behavior of polystyrene fractal gels have been corroborated by the PCS flight data. In the gel, the sizes of the bead clusters continued to increase in microgravity, in contrast to observations on Earth, where cluster size saturates. Saturation on Earth occurs where predicted by a theory that considers the effects of gravitational drag through the fluid. This shows that there is a limit to the volume fraction that can be gelled on Earth. In the crystal growth experiment, Weitz and his group found that there was an initial period devoid of crystal formation, then a rather rapid growth period during which most of the crystals formed, followed by a very slow coarsening period during which the beads formed larger particles.

Finally, from the sample data on the critical point of colloid polymers, the Harvard group was able to determine the surface tension between the two regimes (resembling liquid and gas states), which drives the coarsening. Surface tension was about two orders of magnitude lower than expected — and the lowest reported for colloid mixtures — suggesting that the critical point of the phase separation is approaching.

Smart Windows

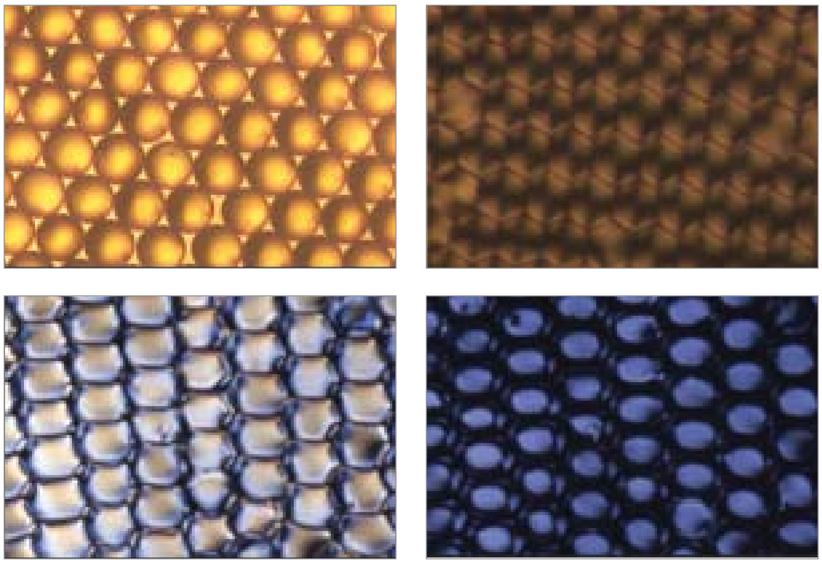
In the popular series of Harry Potter books by J. K. Rowling, Harry and his classmates subscribe to wizard newspapers illustrated not with still photographs but with movies seemingly embedded in the paper. This bit of fantasy may be moving closer to reality in a newspaper (or an annual report) near you, thanks to a recent advance in the design of liquid crystal devices to control the passage of light.

David Weitz of the Division of Engineering and Applied Sciences at Harvard University, Cambridge, Massachusetts, is developing a new class of liquid crystals that one day could become displays painted on seemingly ordinary materials. The liquid crystals are applied as microscopic droplets in highly ordered two-dimensional arrays that respond to voltage changes as small as 0.03 to 0.05 volts per micron (0.03 to 0.05 volts per 0.0000394 inch).

Conventional liquid crystal displays (LCDs) for computers and other devices have been around for decades. Such displays consist of micromachined glass or plastic plates that trap liquid polymers within microscopic pits. Applying an electrical current to the polymers aligns or randomizes the molecules, thus allowing or blocking the passage of light from a source behind the display. Because the polymers possess certain crystalline characteristics, they were dubbed liquid crystals. Manufacturing LCDs has always been difficult, because defects occur at a modest rate, thus raising the cost for large or defect-free specialty units.

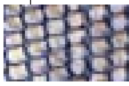
One application of LCDs is the "smart window" in which the nematic liquid is dispersed onto a conductive polymer matrix (where *nematic* refers to the threadlike structure of the molecules). Normally, the molecules have no arrangement and block light. When an electrical potential is applied across the liquid, the molecules align like a crystal, the liquid assumes the same index of refraction as the outer layers of the "sandwich," and light passes through the resulting window. But the smart window application is limited: Precise control of the light is impossible because droplet shape, size, and arrangement are imprecise.

Weitz and his team have developed a new method of applying liquid crystal droplets with enough precision to raise the possibility of "painting" LCDs in a method



These images from David Weitz' liquid-crystal research show ordered, uniform-sized droplets (upper left) before they are dried from their solution. After the droplets are dried (upper right), they are viewed with crossed polarizers that show the deformation caused by drying, a process that orients the bipolar moment of the droplets. When an electric field is applied to the dried droplets (lower left) and then increased (lower right), the droplets switch their alignment, thereby reducing the amount of light that can be scattered by the droplets when a beam is shown through them.

credit: Dana Weitz



similar to inkjet printing. The new technique resembles a pipe gently injecting a fluid into a slow stream of water. When the drop becomes large enough that the viscous drag of the water exceeds the surface tension of the drop, the drop detaches, and the process starts again. (A similar dynamic balance in which gravity replaces viscous flow causes a leaky faucet to release a series of drops of similar size.)

Weitz uses a thin capillary tube, 3 to 10 microns (up to 1/250 of an inch) in diameter to extrude nematic liquid into a stream of water with 1 percent polyvinyl alcohol. A small volume of the resulting emulsion of nematic droplets and water is placed on an electrically conductive glass slide. As the water evaporates, the nematic droplets organize themselves into a hexagonal array of droplets, each about 7 microns (0.0002756 inches) thick and 15 microns (0.0005906 inches) in diameter. More important, the size variation is no more than 3 percent, making the droplets almost uniform. The layer is only one droplet deep and thus is considered to be two-dimensional.

Such a smart window can do more than toggle between opaque and transparent. Molecules within a droplet can be arranged by electric fields to diffract light according to its wavelength, causing constructive or destructive interference. This effect makes most wavelengths cancel each other out, so the window passes just a narrow spectral band that is tuned to the size of the droplet and molecules. The window then becomes a precise color filter that can be used in telescopes, manufacturing, and other applications. The grating effect can also direct the light as it exits the droplets, thus allowing application as a data switch in an optical computer.

The origin of this interference can be traced back to the uniform droplet size, giving each droplet essentially the same effective refractive index during the relaxation process, when the molecules return to their random distribution. This effect, which cannot occur with a wide distribution of droplet size or shape, can be used to study the internal workings of individual droplets. Moreover, very low switching voltages and relatively fast switching speeds (on the order of hundredths of a second) can be achieved by exploiting the interference effects of these phase gratings. Weitz reports that his fabrication method "can be considered as a potential system toward new display-on-anything and paintable display technologies."

Weitz and his team are still conducting fundamental research to characterize the new materials and have built only very small windows, about 5 millimeters (0.1968504 inches) across. At some point, microgravity experiments may be needed to fully characterize the structure and fluid dynamics of the new material. But one day we'll pick up a newspaper with a moving picture and simply say, "Wizard!"

FUNDAMENTAL PHYSICS

One quest of fundamental physicists is a more precise understanding of the physical laws that govern time; another is the development of instruments to improve the measurement of time.

Do you ever wonder what new tools doctors will use to detect cancer 50 years from now? or what new technology might replace compact disc (CD) players? or whether astronauts will have the instruments they need to make deep space exploration possible? The answers ultimately depend on the work of scientists studying fundamental physics, but not directly. These scientists don't tackle the technological end of things; rather, they ask much deeper questions about how the universe works.

Science in general is driven by curiosity about nature. Fundamental physics, though, zeroes in on the principles underlying the behavior of the world. Research in this area lays a foundation for many other branches of science and provides the intellectual underpinning needed to maintain and further develop highly technological society.

Whether in the laboratory or aloft in space, experimentation at this fundamental level has two goals. One is to acquire an ever-fuller grasp of physical laws governing matter, space, and time. In-depth examination of the cosmos' smallest building blocks and the largest structures is called for, and this examination is helped by a space environment that opens up access to different space–time coordinates and by the reduction of disturbing effects caused by gravity on Earth. The other goal is to discover and understand the organizing principles of nature from which structure and

By studying nature unfettered by gravity, fundamental physicists hope to better understand how the universe developed.

complexity emerge. Although the basic laws of nature may be simple, the universe they have given rise to is amazingly complex and diverse. By studying nature apart from the influence of Earth's gravity, scientists can better understand how the universe developed and how best to use these principles in service to humanity.

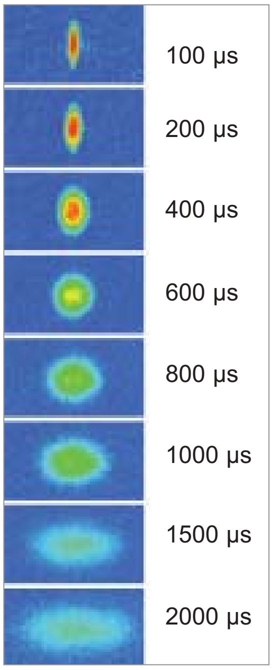
Society will profit in many ways from this kind of research, not immediately but over the long run. For example, if physical laws and natural principles are to be studied with unprecedented precision, the resulting advances in instrumentation will provide the foundation for tomorrow's breakthrough technologies. These advances contribute to the competitiveness of U.S. industry and further support and enhance the presence of humans in space.

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

Fundamental physicists start with basic questions about how the universe works. What they find can help answer myriad other narrower questions, such as "What new tools will doctors use 50 years from now to detect cancer?"

Program Summary

In fiscal year (FY) 2003, several NASA-funded fundamental physicists made notable advances in their research and then shared the good news at workshops, in special invited talks, and in published papers. A few received prestigious awards for their achievements. In addition, 14 scientists received new funding to continue their work for the next few years or to begin new research.



credit: John Thomas

John Thomas of Duke University, Durham, North Carolina, has studied a gas cloud of lithium-6 atoms after it was cooled and subjected to a magnetic field. The topmost figure shows that the cloud resembled a cigar shape just after it was released from the laser trap (at 100 microseconds [μs]). The cloud expanded dramatically over the next 2,000 microseconds in the direction perpendicular to the cigar's axis and has assumed an elliptical shape.

The topics presented to the 75 attendees at the 2003 Fundamental Physics Conference held in Oxnard, California, April 14–16, 2003, were many and varied. Subjects ranged from properties of clouds of degenerate Fermi atoms (a dense, low-temperature gas of atoms with an odd number of total protons, neutrons, and electrons) to forces acting on ribonucleic acid (RNA; proteins associated with the control of a cell's chemical activities) to techniques to probe for added space–time dimensions.

Plenary speaker Randall Hulet, principal investigator (PI) at Rice University, Houston, Texas, talked about lithium-6 atoms cooled to Fermi degeneracy by sympathetic cooling with lithium-7 atoms. The latter readily respond to evaporative cooling and can act as refrigerants for lithium-6 atoms. One goal of this research is to observe lithium-6 atoms in a superfluid state, flowing without resistance or dissipation.

PI Wolfgang Ketterle (Massachusetts Institute of Technology, Cambridge) described another degenerate Fermi system. His group has produced a new macroscopic quantum system in which a degenerate lithium-6 Fermi gas coexists with a large and stable sodium-23 Bose–Einstein condensate (BEC). In a BEC, clouds of atoms all display the same type of wave, locking together like troops marching in formation. This is the first time that a degenerate Fermi sea (a large group of atoms under given circumstances) was produced with a BEC as a "refrigerator." (See Highlight, "Lab Research Yields the Biggest Chill," page 72.)

Along with learning about science updates, attendees heard about how NASA's strategic plan has changed. Mark Lee, the enterprise scientist for fundamental physics at NASA Headquarters, Washington, D.C., described the revised plan's development under NASA Administrator Sean O'Keefe's leadership. Lee explained that the fundamental physics community now needs to align its research program and the fundamental physics road map describing the program's long-term goals with the NASA plan. He described the annual NASA Research Announcement (NRA) process that emphasizes a different focus each year and explained that the focus for the upcoming year is applying fundamental research to NASA's exploration goals.

The writing of the road map was discussed by fundamental physics discipline scientist Ulf Israelsson of the Jet Propulsion Laboratory (JPL), Pasadena, California, who explained that it will be done under the leadership of the Fundamental Physics Discipline Working Group. The chairman of the working group, Nicholas Bigelow of the University of Rochester, New York, outlined how investigators can contribute to writing the road map.

The cosmic microwave background figured prominently at the Tuesday evening banquet in the after-dinner talk given by Andrew Lange of the California Institute of Technology, Pasadena. Lange described how nonuniformities in the cosmic microwave background — a diffuse radiation bath that permeates the entirety of the universe at a temperature of approximately 2.7K (–455 °F) — reflect development of the universe after the Big Bang and that the measured radiation variations constrain the theories of evolution.

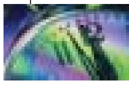
The Quantum Fluids and Solids Conference (QFS-2003) was held in Albuquerque, New Mexico, on August 3–8, 2003. Topics discussed at this conference included liquid and solid helium-4, helium-3, helium-4–helium-3 mixtures as well as hydrogen. JPL was a cosponsor of this international conference, which emphasized recent major scientific advances in any system exhibiting long-range quantum order (as would be true of superfluid lithium-7) and the effects of a phase-coherent matter wave, as in Bose–Einstein condensation. The conference also included a session on quantum-correlated/Bose-condensed atoms in optical traps, which use laser beams to trap and manipulate particles and atoms. Robert Duncan, a fundamental physics investigator at the University of New Mexico, Albuquerque, hosted the conference. Invited papers from fundamental physicists included "Impurity-Helium Solids: Chemistry and Physics at 1.5K," by David M. Lee of Cornell University, Ithaca, New York, and "Dynamics of a Highly-Degenerate, Strongly-Interacting Fermi Gas," by John Thomas of Duke University, Durham, North Carolina.

Lee explained that hydrogen and deuterium atoms are produced by sending a mix of hydrogen (H), deuterium (D), and helium (He) into superfluid helium by means of a radiofrequency discharge. The result is a slushy impurity-helium solid, which forms when helium atoms collect in “snowballs” around impurity atoms like D and H and then the “snowballs” collect. In such solids, the impurity atoms are separated by many He atoms that provide a barrier for recombination of the atoms into molecules. In impurity-helium solids formed in this manner, exchange tunneling reactions occur. These reactions are a quantum effect during which atoms of different elements, separated by a large energy barrier, can move across that barrier. The reactions in this mix increase the concentration of hydrogen atoms in the solid. By varying the initial ratios of H_2 and D_2, the Cornell group has been able to obtain a maximum average hydrogen concentration in impurity-helium solids of 7.8×10^{17} atoms per cubic centimeter (7.8×10^{17} atoms per 0.061 cubic inch). Typically the atoms are contained in solid clusters of D_2, H_2 , and HD, as evidenced by the occurrence of prominent satellite lines associated with spin flips of protons on neighboring hydrogen molecules. These experimenters are using electron spin resonance to measure the populations of the various atoms in the slush — a magnetic field applied to the slush–atom mixture causes the electrons to spin around the magnetic field lines at a specific frequency (resonance). As in nuclear magnetic resonance, the local environment changes the resonance frequency of the individual species. Thus, the resonant signal from a D atom will have slightly shifted lines associated with D atoms that are next to other D atoms, or next to H atoms, rather than next to the predominant He atoms. Also, the spin state of the atoms next to the D atom will also shift the resonant frequency slightly, providing further splitting of the resonance signal. The total strength of the resonance signal (summed over the central and all satellite frequencies) indicates the population of each type of atom. Because the density of hydrogen within these clusters is orders of magnitude higher yet, the group hopes to see evidence for a transition to superfluidity in the hydrogen in these cold solids.

Thomas described how lithium-6 atoms in a cigar-shaped optical trap are cooled by evaporation to a state of degeneracy. Applying a small magnetic field induces strong interactions between the atoms that are attractive or repulsive, depending on the field’s value. At a certain field value, on releasing the cloud from the optical trap, the atoms expand rapidly at a right angle to the trap’s original axis while remaining nearly stationary along the axis. The expansion dynamics are interpreted in terms of collisionless superfluid and collisional hydrodynamics.

Additional invited papers presented by fundamental physics PIs were “Strongly Interacting Fermi Gas,” by Randall Hulet; “Experiments to Study the Effect of Light on Electron Bubbles in Helium,” by Humphrey Maris, Brown University, Providence, Rhode Island; “Non-Axial Equal Spin Pairing Superfluid 3He Found in 99.4% Porosity Aerogel,” by Douglas Osheroff, Stanford University, California; and “Critical Properties of the Two-Dimensional Weakly Interacting Bose Gas,” by Nicolay Prokofiev, University of Massachusetts, Amherst. All told, fundamental physics investigators presented more than 25 papers at the meeting. All of the papers presented at the conference are listed at *http://www.qfs2003.0rg/qfs2003/files/PRGM-ABSTBK-POST-7–28FINAL.pdf*.

Earlier in the year, Hulet presented “Tunable Interactions in Bose and Fermi Gases of Lithium” to the Division of Atomic, Molecular, and Optical Physics, May 20–23, 2003, in Boulder, Colorado. In an ultracold atomic gas, said Hulet, interatomic interactions are mediated by elastic collisions between the atoms. But because of the atoms’ internal electron structure, the collisions can be strongly affected by applying an external magnetic field. Known as a Feshbach resonance, this magnetic field dependence allows scientists a high degree of control over interatomic interaction. In this way, Hulet’s group has made a quantum degenerate Fermi gas of more than 1 million atoms of lithium-6 by first sympathetically cooling them with lithium-7, and then using dual evaporation in the final stages.



Several notable papers describing the work of fundamental physics PIs were published during FY 2003 in prestigious journals, including *Science, Physical Review Letters*, and *Nature*. Of particular note were the following:

- K. M. O’Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, and J. E. Thomas. Observation of a Strongly Interacting Degenerate Fermi Gas of Atoms. *Science*, **298**, 2002, 2179.

- Robert Bluhm, Alan Kostelecky, Charles Lane, and Neil Russell. Clock-Comparison Tests of Lorentz and CPT Symmetry in Space. *Physical Review Letters*, **88**, 2002, 090801.

- K. S. Strecker, G. B. Partridge, A. G. Truscott, and R. G Hulet. Formation and Propagation of Matter Wave Soliton Trains. *Nature*, **417**, 2002, 150.

- A. E. Leanhardt, T. A. Pasquini, M. Saba, A. Schirotzek, Y. Shin, D. Kielpinski, D. E. Pritchard, and W. Ketterle. Adiabatic and Evaporative Cooling of Bose–Einstein Condensates below 500 Picokelvin. *Science*, **301**, 2003, 1513–1515.

- J. A. Lipa, J. A. Nissen, S. Wang, D. A. Stricker, and D. Avaloff. New Limit on Signals of Lorentz Violation in Electrodynamics. *Physical Review Letters*, **90**, 2003, 060403.

The American Physical Society awarded Mark Kasevich of Stanford University, California, the 2003 I. I. Rabi Prize in Atomic, Molecular, and Optical Physics for his work on atom interferometers and on cold-atom phenomena. Specifically, the prize cited "developing atom interferometer inertial sensors with unprecedented precision, and for pioneering studies of BECs, especially the achievement of nonclassical spin states and the demonstration of a mode-locked atom laser." The Rabi Prize recognizes and encourages outstanding research in atomic, molecular, and optical physics by investigators who have held a doctorate for 10 years or fewer. Mark is the third fundamental physics investigator to receive this prize; Randall Hulet won it in 1995 and Wolfgang Ketterle in 1997.

Randall Hulet was elected a Fellow of the American Academy of Arts and Sciences — one of the highest forms of recognition a scholar can receive. Hulet was selected for contributions to his field, such as transforming collections of atoms into BECs (a new state of matter), which could lead to a better understanding of superconductivity. The academy was founded in 1780 by John Adams, James Bowdoin, John Hancock, and other scholar-patriots to cultivate art and science by honoring intellectual achievement, leadership, and creativity in all fields.

Efstratios Manousakis of Florida State University, Tallahassee, was elected as a Fellow of the American Physical Society for "innovative and original computational studies in the many-body problem including development of novel algorithms to tackle the many-fermion problem with very important applications to condensed matter physics." Don Jacobs, a professor of physics at The College of Wooster, Wooster, Ohio, was elected to be a Fellow of the American Physical Society from the Division of Chemical Physics. Jacobs was recognized by his peers for "contributions to the understanding of critical phenomena in liquids, and for sustained mentoring of undergraduate students engaged in research."

Wolfgang Ketterle has been made a member of the European Academy of Sciences. He was also elected to be a member of the Academy of Sciences in Heidelberg, Germany, and has been chosen to be a foreign associate of the National Academy of Sciences in the United States. He was elected a Fellow of the Institute of Physics, an international professional body that promotes the advancement and dissemination of knowledge of and education in the science of physics, pure and applied.

NASA announces opportunities for new research grants at regular intervals to maintain a productive research community at the cutting edge of the science topics in fundamental physics. New ideas for research broaden the topics of the experiments supported and bring their standing up to date.

New awards to 14 winners were announced in January 2003 for applicants to the 2001 NRA in fundamental physics. One was a flight definition award, and the rest were for ground research. The flight definition award is to John Lipa of Stanford University for an experiment to be conducted as a guest investigation on the Critical Dynamics in Microgravity Experiment instrument that is scheduled for the first flight of the Low-Temperature Microgravity Physics Facility, hardware planned for the International Space Station.

Awards for the 2002 NRA in fundamental physics will be announced early in FY 2004.

With the selections made this year, the fundamental physics investigation count stands at 10 flight or flight definition investigations and 68 ground investigations. For a complete listing of awardees of the 2001 NRA, visit *http://spaceresearch.nasa.gov/general_info/OBPR-03–046.html*. Note that management of the fundamental physics grants has been transferred to Glenn Research Center (GRC), Cleveland, Ohio. JPL has been aiding the PIs to prepare new required documents for GRC and has provided technical reviews to GRC for the progress reports and the new plans for research.

Flight Experiments

The fundamental physics experiments intended for the International Space Station (ISS) were delayed 2 years because of delays in deploying the Japanese Experiment Module–Exposed Facility to the ISS. So the experiments selected for the first flight of the Low-Temperature Microgravity Physics Facility (LTMPF), in January 2008, have been adjusted to maximize the scientific breadth of this main facility for fundamental physics research. To this end, the Critical Dynamics in Microgravity Experiment (DYNAMX), which is a low-temperature physics experiment, remains on the first LTMPF flight. However, the Superconducting Microwave Oscillator (SUMO), a space clock involving gravitational physics, will fly on the first LTMPF flight in place of the Microgravity Scaling Theory Experiment (MISTE), which is also a low-temperature physics experiment. MISTE has been moved to the ground program, as has the Coexistence Boundary (COEX) experiment, which was to share the MISTE hardware, and Boundary Effects on the Superfluid Transition (BEST), a candidate for the second flight of the LTMPF. These experiments will have a chance to respond to future NRAs to compete for future LTMPF flights.

DYNAMX, headed by Principal Investigator (PI) Robert Duncan of the University of New Mexico, Albuquerque, will study how liquid helium becomes a superfluid while being driven far from equilibrium by a heat current. When helium is cooled to extremely low temperatures (nearing absolute zero, –273 °C [–460 °F]), 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 its ability to conduct heat is infinite — this state is called superfluid. The critical point for superfluidity (that is, the temperature and pressure at which the transition occurs) has proved an excellent model of the physics of other transitions between states, such as the liquid–gas critical point. By studying the superfluid transition of helium-4 driven away from equilibrium by the application of a highly controlled heat flow, the DYNAMX results will supply a bridge between theoretical models and real systems.

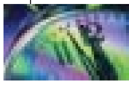
In fiscal year (FY) 2003, the DYNAMX team completed the design of its instrument sensor package, which includes 107 released drawings. This set of drawings forms the baseline for the DYNAMX science instrument. The team also began fabrication of the flight cell sidewall assembly and high-resolution thermometers.

Another superfluid helium investigation, the Enhanced Heat Capacity of Helium-4 near the Superfluid Transition (CQ) experiment, will share the DYNAMX flight instrument. The DYNAMX and CQ experiment teams have collaborated to make the first measurements of a new temperature–entropy wave in liquid helium, which propagates against an applied heat flux when the helium sample is in a self-organized critical (SOC) state. They also made the first measurements of the heat capacity of liquid helium as it transitions to this SOC state.

SOC states exist throughout nature. In this state the system, though subject to external forces that would normally drive it away from equilibrium, manages to exist in a steady state close to its phase transition or "critical line." In the above case, the system is liquid helium, the critical line is the superfluid transition, and the external force is a heat flux applied to the helium sample. If a heat pulse is applied to a normal liquid, it would dissipate diffusively; however, in the SOC state, this same heat pulse is observed to travel like a wave with virtually no dissipation and propagate against the heat flux in an SOC state. The measured wave velocity agrees well with a simple theory for this new diffusive wave.

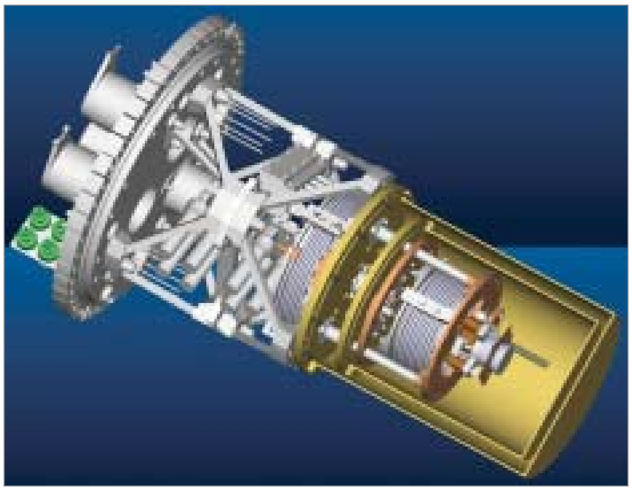
The heat capacity of the SOC state and the superfluid thermal gradient have been measured with the heat coming from above. These measurements confirm earlier SOC state measurements, indicating that the superfluid thermal gradient in the heat-from-above configuration may be substantially larger close to the breakdown in superfluidity than when the sample is heated from below. This disparity may mean that these two experimental configurations lead to fundamentally different helium physics, which would be a surprising finding. Future measurements will attempt to resolve these questions.

The DYNAMX hardware consists of a cell for measuring the thermal conductivity of liquid helium, thermometers with a very high resolution (to below a billionth of a degree), and heaters that can be controlled to a picowatt. These components will be mounted on a JPL-developed thermal platform with several Superconducting Quantum Interference Devices (SQUIDs), which are used to get the phenomenal temperature resolution. The DYNAMX instrument will reside in the vacuum space of the LTMPF liquid helium dewar, and the LTMPF facility electronics will read and control it.



The purpose of the SUMO experiment, run by PI John Lipa (Stanford University, California) is to improve on the classical tests of Einstein's special theory of relativity and to evaluate recently developed extensions to the standard model of physics, which is the general explanation of how matter works on Earth and in the universe at the atomic scale.

This year's efforts have concentrated on raising SUMO's engineering level. In particular, the SUMO team developed and verified flightlike electronic systems in preparation for the requirements definition review, held in September 2003. Also this year, the resonator design met two principal performance requirements for the first time: a large quality factor (Q; a measure of how sharp the resonance frequency of the oscillator is) equal to 1 billion,



credit: NASA

Schematic representation shows the Critical Dynamics in Microgravity Experiment (DYNAMX) instrument for the Low-Temperature Microgravity Physics Facility (LTMPF).

and a reduced acceleration sensitivity of less than 10 parts per trillion per gravity-level of acceleration.

SUMO uses two superconducting resonators mounted at right angles to each other in a liquid helium cryostat that cools them to 1.4 kelvins above absolute zero. While a room-temperature electromagnetic resonator rings with about the same Q as an ordinary bell, low-temperature operation can increase the Q for a superconducting resonator by a million times or more. This large Q makes it possible to test the frequency differences between the two resonators to one part in 10^{17} as the experiment orbits Earth.

NASA urged JPL to test the feasibility of developing an in-orbit link between SUMO and the Primary Atomic Reference Clock in Space (PARCS) was urged on JPL to further strengthen the scientific return of the initial fundamental physics experiments being deployed to the ISS. Such a link would benefit both experiments and would expand the science capabilities of the first flight.

The PARCS experiment, led by Don Sullivan of the National Institute of Standards and Technology (NIST) in Boulder, Colorado, will test aspects of Einstein's special and general theories of relativity by flying a nearly perfect atomic clock on the ISS and comparing the rate at which it ticks with that of the clock on the ground at NIST that defines the second used as the base unit of time for the United States. Both clocks will use laser-cooling techniques, which bring atoms nearly to rest at the intersection of a set of laser beams and so provide the extreme control needed for ultraprecise measurements.

Atomic clocks are the most accurate timekeepers on Earth, but gravity limits their performance. In a laser-cooled atomic clock, laser beams slow down the movement of the atoms to improve the clock's accuracy. Such a clock developed for a microgravity environment might be a hundred times as accurate. In fact, an atomic clock on the ISS could serve as a primary frequency standard, providing laboratories around the world with the premier definition of the second and perhaps enabling hitherto-impossible experiments in fundamental physics. Such a clock also could aid in deep space navigation and navigation on Earth by improving the accuracy of the Global Positioning System (GPS).

The clock's ticking rate will also be compared with that of a mechanical clock, the SUMO device in the LTMPF, to test assumptions about the inherent "sameness" of different points in space. Atomic energy levels are among the most reproducible signatures found in nature, making atoms nearly perfect laboratories for precision measurements of the kind found in atomic clocks.

This year the PARCS ground test bed was used to cool atoms to 2 millionths of a degree above absolute zero and then make the precise spectroscopic measurements that are at the heart of the proposed PARCS clock experiment. Two prototype narrow-frequency tunable diode lasers were manufactured to PARCS specifications by New Focus Inc., of San Jose, California, to be used in these tests. New microwave interrogation methods were also developed for the PARCS flight clock. In an early payoff from this research, some of these methods were adopted at NIST to operate the national standard for time more reliably. The design of the next-generation national standard for time (NIST-F2) draws significantly from the design of the PARCS flight instrument.

The baseline flight payload, which will attach directly to the Japanese Experiment Module–Exposed Facility, involves a laser and optics subsystem, a physics package used for microwave interrogation, command and control electronics, a microwave synthesizer, and a GPS receiver. In addition, a high-performance frequency link to the SUMO clock will be used to compare the tick rates of the PARCS and SUMO clocks.

The second flight of the Critical Viscosity of Xenon Experiment (CVX-2), led by PIs Robert Berg and Michael Moldover, both of NIST in Gaithersburg, Maryland, was flown on the STS-107 mission of Space Shuttle *Columbia* in January 2003. The experiment flew so researchers could measure the viscous behavior of xenon, a gas used in flash lamps and ion rocket engines. They examined xenon at its liquid–vapor critical point, the specific temperature and pressure at which the distinction between liquid and vapor disappears. By studying how xenon behaves in a critical state, researchers can learn how other materials behave under normal conditions.

On Earth, gravity compresses fluids at their critical points. A layer of fluid as thin as a dime collapses under its own weight, increasing the density at the bottom of the sample and distorting the data. Conducting experiments in microgravity eliminates these density differences and allows scientists to make more precise measurements.

CVX-2 used a tiny metal screen vibrating between two electrodes immersed in xenon at the critical point. To measure xenon's viscosity, the electrodes applied an electrical charge to oscillate the screen. As the screen fluctuated, seesawing in the liquid, the electrodes measured how the fluid dampened (decreased) the screen's vibrations. Several sets of measurements were made as the temperature was increased and decreased, bringing xenon into and out of its critical state. The experiment was housed in a special container with a thermostat that ensured the microdegree temperature control required to maintain the xenon fluid at its critical temperature.

During the flight of CVX-2 on *Columbia*, the experiment performed continuous operations from 4 hours after launch until just before preparations for the shuttle to break its orbital flight pattern. Data was collected at six frequencies from 1 to 12 hertz and downloaded to researchers on Earth. The downloaded data, none of which showed dramatic evidence of shear thinning, fulfilled almost all the goals of the experiment. The measured absence of shear thinning is a new constraint on the analogy between polymer fluids and pure fluid near its critical point.

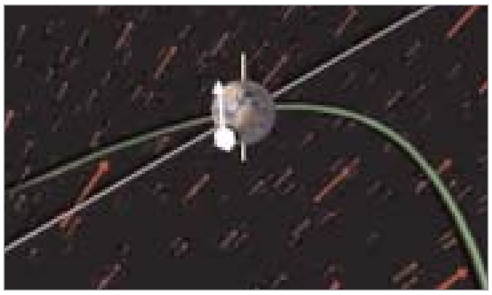
Highlights

Was Einstein Wrong? Space Station Research May Find Out

Ultraprecise clocks on the International Space Station (ISS) and other space missions may determine whether Albert Einstein’s theory of relativity is correct and could dramatically change human understanding of the cosmological structure of the universe. The theory, introduced in 1905, holds that if an observer moves at a uniform speed, no matter how fast or in what direction, the laws of physics and the speed of light are always the same. For example, if you stand still and drop a coin, it will fall straight down. Similarly, if you drop a coin inside a car while you’re driving down the freeway at a steady speed, it will also fall straight down. However, recent theories attempting to combine gravity and particle physics suggest that special relativity might not always apply; changes in space and time may occur that could not be measured easily on Earth.

Whereas the special theory of relativity holds that in space there is no “up” or “down,” recent theories predict that there are, in fact, “preferred” directions. Under this premise, as a spacecraft such as the ISS orbits Earth, the orientation of a clock traveling onboard changes, ultimately leading to changes in its ticking rate.

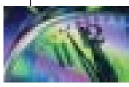
“The International Space Station will have ultrasensitive clocks on board, and it is a good place to test the theory,” said Alan Kostelecky, a professor of physics at Indiana University, Bloomington. “By comparing extremely precise clocks [clocks based on different atomic systems that would be affected differently by directionality in space] that can operate under [microgravity], minuscule changes in the ticking rate might be found as the spacecraft moves around Earth.” This change of rate would violate Einstein’s theory, which says there should be no change if different clocks in the same gravity environment are compared. “Finding such changes would cause an upheaval in the science community and revolutionize our thinking about the fundamental structure of space and time,” he added. “It would lead to new insights about how our universe formed and how nature operates.”



credit: Alan Kostelecky

In this diagram, the rotating Earth orbits the Sun along the green elliptical curve. A spacecraft such as the International Space Station is represented by the white square moving around Earth; the white arrow on it shows the direction traveled by an onboard clock. Whereas Einstein’s special theory of relativity holds that in space there is no “up” or “down,” recent theories predict that there are, in fact, “preferred” directions (red arrows). Under this premise, as the spacecraft orbits Earth, the orientation of the clock changes relative to the red arrows, ultimately leading to changes in its ticking rate.

The ISS or similar satellite in low Earth orbit rotates faster around Earth than Earth rotates on its axis. Thus, measurements in space would be more sensitive to minute changes that would violate Einstein’s theory of relativity. Kostelecky and colleagues Robert Bluhm of Colby College, Waterville, Maine; Charles Lane of Berry College, Mount Berry, Georgia; and Neil Russell of Northern Michigan University, Marquette, describe the use of various types of clocks on the ISS. For example, one type would use a maser, a cousin of the laser. Instead of emitting light, the maser emits microwave energy at a specific frequency, which produces a very specific clock signal. Other types of clocks already planned for flight on the ISS could be used, too. Upcoming missions include the Primary Atomic Reference Clock in Space and the Superconducting Microwave Oscillator. In addition, the European Space Agency will fly the Atomic Clock Ensemble in Space on the ISS.



Kostelecky says clock experiments in space may yield other intriguing results. For example, they might provide evidence for “string theory.” Traditionally, scientists have believed that the smallest units in the universe are particles. However, advocates of string theory believe the smallest units are elongated like tiny pieces of string, and that subnuclear particles are modes on those strings. In some string theories, empty space has an intrinsic direction. The direction can occur when strings are intersections of branes, which are theoretical parallel universes existing on their own membranes less than a millimeter away from our own universe. When a string intersects a brane, the orientation of the local brane gives direction to local space. The direction is fairly steady but may change over long periods. That intrinsic directionality could cause the clocks on the

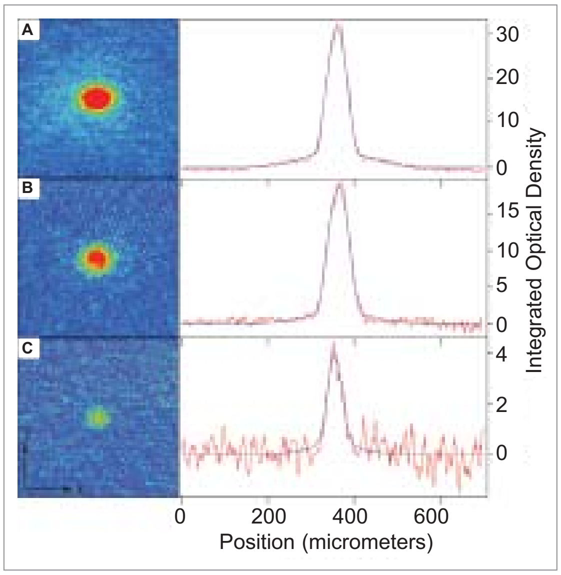
ISS to tick at changing rates as their orbit causes them to change orientation with respect to that intrinsic direction.

A paper by Kostelecky and his colleagues appeared in the March 4, 2002, issue of *Physical Review Letters*; a preprint is available online free of charge at *http://arxiv.org/PS_cache/hep-ph/pdf/0111/0111141.pdf*. Animation of how Kostelecky's theoretical research would be evidenced in proposed ISS experiments is available at *http://www.jpl.nasa.gov/videos/sg/space_physics.html* and *http://physics.indiana.edu/~kostelec/mov.html*.

Lab Research Yields the Biggest Chill

NASA-funded researchers at the Massachusetts Institute of Technology (MIT) in Cambridge have cooled sodium gas to the lowest temperature ever recorded: half a billionth of a degree above absolute zero, which is –273 °C (–460 °F). Absolute zero is the point at which no further cooling is possible; all motion stops except for tiny atomic vibrations, because the cooling process has extracted all energy from the particles. (Neutral sodium atoms can be cooled relatively easily.) This new temperature is six times lower than the previous record and marks the first time that a gas was cooled below 1 nanokelvin (1 billionth of a kelvin) — the closest scientists have succeeded in getting to absolute zero.

"To go below 1 nanokelvin is like running a mile below four minutes for the first time," said Wolfgang Ketterle, a MIT physics professor, Nobel Prize winner, and co-leader of the research team. "Ultralow-temperature gases could lead to vast improvements in precision measurements by allowing better atomic clocks and sensors for gravity and rotation," said David Pritchard, also an MIT physics professor, pioneer in atom optics and atom interferometry, and co-leader of the team.



credit: Wolfgang Ketterle

The temperatures in these picokelvin condensates are 1 nanokelvin (A) , 750 picokelvins (B), and 450 picokelvins (C).

Ketterle has been seeking absolute zero for nearly a decade. In 1995, his MIT team, along with a group led by Eric Cornell and Carl Wieman at the University of Colorado, Boulder, cooled atomic gases to below 1 microkelvin (one-millionth of a degree above absolute zero). In doing so, they discovered a new form of matter, the Bose–Einstein condensate (BEC), in which atoms of the same material are cooled to extremely low temperatures and all display the same type of wave, locking together like troops marching in formation instead of flitting around independently. BECs display unusual "quantum" phenomena, including superfluidity, in which fluid substances show no resistance to flow. The discovery was recognized with the Nobel Prize in Physics 2001, which Ketterle shared with Cornell and Wieman.

Since the 1995 breakthrough, many groups have routinely reached nanokelvin temperatures, with 3 nanokelvins as the lowest temperature previously recorded. The new record set by Ketterle's and Pritchard's group is 500 picokelvins, six times lower. At such low temperatures, atoms cannot be kept in physical containers, because they would stick to the walls. Also, no known container can be cooled to such temperatures. To reach the record-low temperatures, the researchers invented a novel way of confining atoms that they call a gravitomagnetic trap. Before being placed in the trap, the atoms are cooled with laser cooling techniques. Once in the trap, evaporation removes the hotter atoms, leaving the remaining atoms cooler. Active manipulation of the height of the trap can accelerate evaporation cooling. Magnets surround the atoms to confine the gaseous cloud horizontally without touching it, and gravitational forces trap the atoms vertically.

Ketterle and Pritchard describe their achievement of this new low-temperature record and the trapping and cooling techniques in "Cooling Bose–Einstein Condensates Below 500 Picokelvin" (*Science*, **301**, 2003, page 1513).

Frozen Light: Cool NASA Research Holds Promise

NASA-sponsored research at Harvard University that literally stops light in its tracks may someday lead to breakneck-speed computers that shelter enormous amounts of data from hackers. The research, conducted by a team led by Harvard physics professor Lene Hau, is one of 12 research projects featured in a special spring 2003 edition of *Scientific American* titled "The Edge of Physics." In their laboratory, Hau and colleagues have been able to slow a pulse of light and even stop it for several thousandths of a second. They've also created a "roadblock" for light that can shorten a light pulse by a factor of a billion. "This could open up a whole new way to use light, doing things we could only imagine before," Hau said. "Until now, many technologies have been limited by the speed at which light travels."

The speed of light in a vacuum is approximately 300,000 kilometers per second (about 186,000 miles per second) — so fast that light emitted by the Sun races out beyond Jupiter in just 1 hour at this speed. Transparent substances, such as water, glass, and diamonds, slow light to a limited extent. More drastic techniques are needed to dramatically reduce the speed of light as Hau's team did. They accomplished "light magic" by laser cooling a cigar-shaped cloud of sodium atoms to one-billionth of a degree above absolute zero (–273 °C [–460 °F]). Using a magnetic field, the researchers suspended the cloud in an ultrahigh vacuum chamber and cooled it with lasers until it formed a frigid, swamplike goop of atoms.

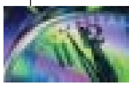
Laser cooling works by bombarding the atoms head-on with photons of light from a laser beam. When the lithium atoms come into contact with the laser light, the light bounces off the atoms and scatters in many directions. Any time that the atoms scatter some of the light photons, they get pushed backward a little bit. Imagine that the atoms are bowling balls and the photons are Ping-Pong balls. If you throw enough Ping-Pong balls at an oncoming bowling ball, the Ping-Pong balls will eventually slow the bowling ball down and stop it. So, Hau's group kept bouncing photons off the atoms, and eventually the atoms stopped moving; that is, they cooled.

When Hau's group shot a light pulse into the cloud, the light bogged down, slowing dramatically, and then eventually stopped and turned off. The scientists excited the atoms to another state so the light beam could travel through the cloud. The team later revived the light pulse and restored its normal speed by shooting an additional laser beam into the cloud. The cold cloud can behave two different ways because the excited atoms have different properties for light absorption and transmission. The phenomenon occurs only when the cloud is cold because the atoms must be in the Bose–Einstein condensate (BEC) state for them to act coherently, so they all respond to the light beam in the same way.

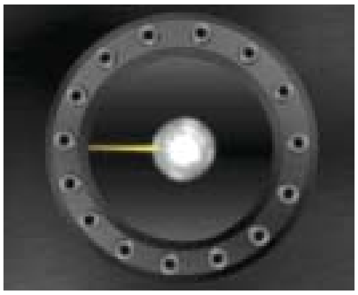
Hau's cold-atom research began in the mid-1990s, when she put ultracold atoms in such cramped quarters that they formed a BEC. In this state, atoms behave oddly, and traditional laws of physics do not apply. Instead of gas atoms' usual behavior of bouncing off each other rather like bumper cars, the atoms join together and function as a unified entity. When atoms of the same material are cooled to extremely low temperatures, they all display the same type of wave, locking together like troops marching in formation instead of flitting around independently. BECs display unusual "quantum" phenomena, including superfluidity, in which fluid substances show no resistance to flow.

The first slow-light breakthrough for Hau and colleagues came in March 1998, when they worked with only a small cloud and not so cold (atoms only partially condensed), so the cloud could not completely stop the beam. Later that summer, they successfully slowed a light beam to about 61 kilometers (about 38 miles) per hour, the speed of suburban traffic. That's 2 million times slower than the speed of light in free space. By tinkering with the system, Hau and her team made light stop completely in the summer of 2000.

These breakthroughs may eventually be applied to advanced optical communications technology. "Light can carry enormous amounts of information through changes in its frequency, phase, intensity or other properties," Hau said. When a light pulse stops, its information is suspended and stored, just as information is stored in the memory of a computer. Light-carrying quantum bits could carry significantly more information than current computer bits. Quantum computers could also be made more secure by encrypting information in elaborate codes that could be broken only by using a laser and complex decoding formulas.



Hau's team is also using slow light as a completely new probe of the very odd properties of BECs. For example, with the light "roadblock" the team created (the cloud of cold atoms stopping the light beam), they can study waves and dramatic rotating-vortex patterns. When a researcher tries to rotate a condensate cloud, at first it will not rotate because certain relations must be satisfied for the motion to comply with the rules of quantum mechanics. As the speed of the rotation attempt increases, eventually a threshold is crossed at which spin motion is excited, and the quantum of spin in these condensates is a vortex. The number of vortices excited increases linearly with the rotation speed above the threshold. The same behavior and vortex structures are seen in superfluid helium, another Bose-condensed medium, in the condensates.

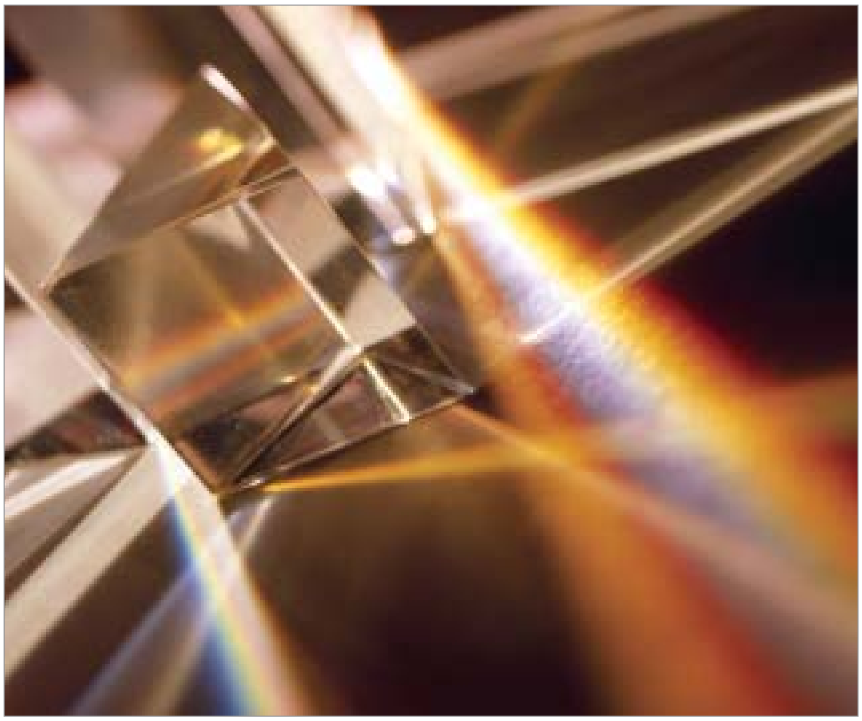


credit: NASA

This artist's concept shows a vacuum-sealed chamber with a cloud of ultracold sodium atoms suspended electromagnetically. When Harvard researchers shot a pulse of light into the cloud, the light slowed dramatically, then stopped completely and shut off. They later revived the light pulse.

The Harvard research team includes Hau; professors Michael Budde, Brian Busch, Zachary Dutton, and Chien Liu; and graduate students Cyrus Behroozi, Naomi Ginsberg, and Christopher Slowe. More information about Hau's research is available at *http://physics.harvard.edu/hau.htm*.

MATERIALS SCIENCE



Materials scientists are on a never-ending quest to transform existing materials such as glass, metals, or ceramics into something better — stronger, lighter, cheaper, or all of the above. NASA's future depends in part on its abilities to develop new materials or adapt original materials to meet its unique needs.

The metal alloys used to build airplanes, the circuits in a computer, the plastic chosen for a heart valve, the metallic-ceramic composites used in industrial turbine blades — each of these materials has specific properties that make it the right choice for the product of interest. No material is perfect, however, so materials scientists are always on the lookout for ways to improve them and to create novel 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 — depend on not only its chemical composition but also its solid structure, whether crystalline or glass. The crystalline structure derives from the method and conditions under which the material is produced. For example, if a mixture of liquid metal and ceramic particles is solidified at one speed, those ceramic particles may congregate in undesired ways, causing the processed material to be brittle and crack easily. But if the same molten mixture is solidified at a different speed, the ceramic particles may be more evenly distributed and thereby strengthen the solidified material. By learning how to alter the conditions of materials processing to obtain desired properties, investigators may be able to manufacture more useful materials than are currently available.

The force of gravity plays a big role here. Because crystalline materials are formed from a liquid melt or a vapor, their production includes steps that are heavily influenced by gravity. Typical gravity-related effects include buoyancy-driven convection (fluid flow caused by

OVERVIEW

Advances in materials science research have improved communications systems, such as those that use these fiber optics, and made service faster and more reliable.

temperature-driven density differences in a material), sedimentation (settling of different materials — liquids, solids, or both liquid and solid — into distinct layers), and hydrostatic pressure (differences in pressure within a quantity of material caused by the material at the top weighing on the material at the bottom).

Observing, monitoring, and studying materials production in microgravity is useful because it allows researchers to isolate some of the mechanisms involved and hence determine how those mechanisms affect a material's structure and properties. Science's fundamental understanding of materials can then be increased, and methods for processing materials on Earth can be improved.

Advances during fiscal year (FY) 2003 went beyond breaking new ground in fundamental ground- and flight-based materials research. Great strides were also made toward establishing an interdisciplinary strategic research program. Long-duration spaceflight entails the need to protect astronauts and equipment from the hazards of space radiation. The Radiation Shielding Materials Program launched in FY 1996 expanded greatly in FY 2003 and was complemented by a program on Advanced Materials for Space Propulsion. Together, these programs address NASA's exploration goals. In addition, the groundwork was laid for an innovative In-Space Fabrication and Repair Program that will support NASA's plans for constructing and repairing equipment while in space or in orbit and will enable humans to both live beyond low Earth orbit and inhabit other planets.

As metals melt and solidify, their properties can be profoundly affected by gravity. Microgravity research reveals a more accurate view of a material's characteristics.

Program Summary

To address the challenges of exploring and inhabiting distant planets, the materials science discipline has launched new initiatives. These initiatives require the development of new materials and techniques for shielding astronauts and equipment from space radiation, basic research into high-performance materials for advanced propulsion systems, scientific approaches to the in-situ fabrication and repair of flight system components, and the study of natural resources on other planetary bodies for their utility as building materials.

With the prospects of crewed spaceflight throughout the solar system and beyond, NASA must continue its research into fundamental materials science if it is not to be stymied by the physics and chemistry involved in making such a journey. During fiscal year (FY) 2003, Marshall Space Flight Center (MSFC), Huntsville, Alabama, has forged ahead with fundamental research in materials science while also launching the strategic materials research program that incorporates the new initiatives associated with safe and efficient space travel.

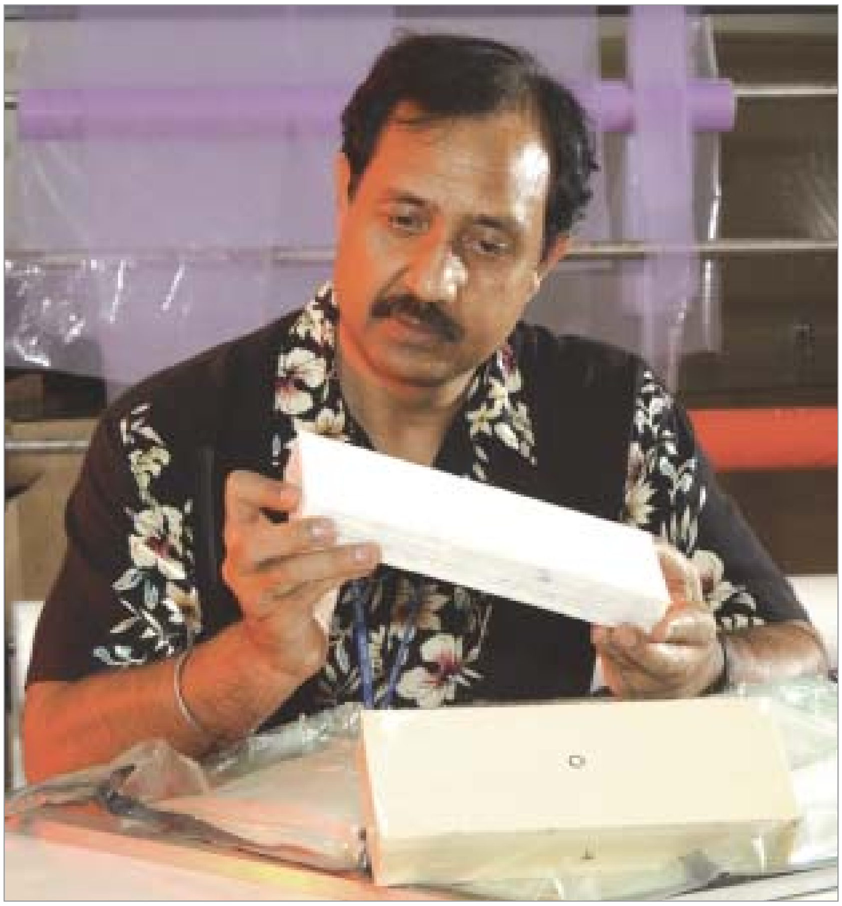
Researchers from universities, industries, and government laboratories across the country compete for funding in the Materials Science Program by submitting research proposals in response to NASA Research Announcements (NRAs). Peer review committees evaluate each proposal and make their selections on the basis of scientific merit, applicability to NASA's goals, and feasibility.

A total of 109 materials science experiments were funded during FY 2003. Ninety-one of these experiments involved fundamental research into the relationships between the structure, processing, and properties of materials; the remainder were funded under the strategic initiative of space radiation shielding materials, five of which are new this fiscal year. Within the experiments funded by the FY 2003 fundamental Materials Science Program, 76 are ground-based investigations, 15 are classified as flight investigations, and 12 are transitioning from ground- to flight-based research. Of the ground-based investigations, four are new grants that specifically target biomaterials. All of the current strategic research investigations are ground-based.

During FY 2003, grants were awarded as a result of three NRAs: one in traditional fundamental materials science and two in the strategic area of space radiation shielding. The NRA for fundamental materials science, NRA-01-OBPR-08-F, was released on December 21, 2001. A dozen grants were awarded on August 31, 2003, of which 10 are being managed by MSFC's Microgravity Science Applications Department (MSAD).

Two NRAs falling under the strategic research program were released and funded; both concern materials for space radiation shielding. The first was NRA-01-OBPR-08-E, released on December 21, 2001. On February 4, 2003, NASA's Office of Biological and Physical Research (OBPR) awarded grants for this NRA, including the topic of space radiation shielding materials. In response to this NRA, 51 researchers submitted proposals, and scientific and technical experts from academia and government reviewed them. Of the 14 grants awarded, 6 will be managed by MSAD.

The second NRA under the strategic research program, NRA-02-OBPR-02, was released on August 30, 2002. This NRA solicited proposals for ground-based



credit: NASA

Scientist Raj Kaul examines "bricks" of radiation shielding material made in his laboratory at Marshall Space Flight Center, Huntsville, Alabama. Kaul, a member of the Space Radiation Shielding Program team, is investigating the effectiveness of materials used to shield spacecraft from harmful radiation.

research in space radiation biology and materials for shielding against space radiation, and 67 responses were received. The proposals were peer reviewed by scientific and technical experts from academia, government, and industry. In June 2003, NASA selected 28 researchers to conduct ground-based research in radiation shielding materials; five of the grants will be managed by MSAD.

Researchers will use the NASA Space Radiation Laboratory (NSRL) incorporating the Alternating Gradient Synchrotron at the Department of Energy's Brookhaven National Laboratory in Upton, New York. The heavy ion beams created by this facility are intended to simulate characteristics similar to those found in space, high-energy ion beams known as HZE. As part of the radiation shielding initiative, these researchers are studying the effectiveness of existing materials and developing new high radiation-shielding, multifunctional spacecraft materials. More information about the NASA Space Radiation Laboratory can be found at *http://server.c-ad.bnl.gov/esfd/nsrl*.

More information about NRA grant selections is available at *http://spaceresearch.nasa.gov/research_projects/selections.html*. A list of all ongoing materials science research projects, along with the names of the investigators conducting the research, is provided in Appendix B. A complete list of funded projects may be viewed from *http://research.hq.nasa.gov/code_u/code_u.cfm*. To complement this research, the Fifth NASA Microgravity Materials Science Conference was held June 25–26, 2002, in Huntsville, Alabama. Conducted biennially, the next such conference is projected for the summer of 2004.

To devise a strategy for conducting physical science research in new strategic areas, hundreds of materials scientists, physicists, and engineers from universities, industry, NASA, and other government agencies attended one of four workshops during FY 2003. The first workshop, a kickoff meeting for the Radiation Shielding Consortia, was held March 17 and 18, 2003, at the National Space Science and Technology Center in Huntsville, Alabama. During those 2 days, physicists laid out plans for developing new analytical models for radiation shielding materials that would protect space crews on longer-duration missions orbiting Earth and eventually on journeys to the Moon and Mars, where radiation levels are even higher. This discussion was led by a group of investigators from the Space Radiation Shielding Program's physics consortia. Participants developed a plan to use NASA's new $34 million Space Radiation Laboratory. Scheduled to begin full operation in fall 2003, this facility simulates the high-energy ionized radiation found in space. More information about this strategic effort may be found at *http://www.radiationshielding.nasa.gov*.

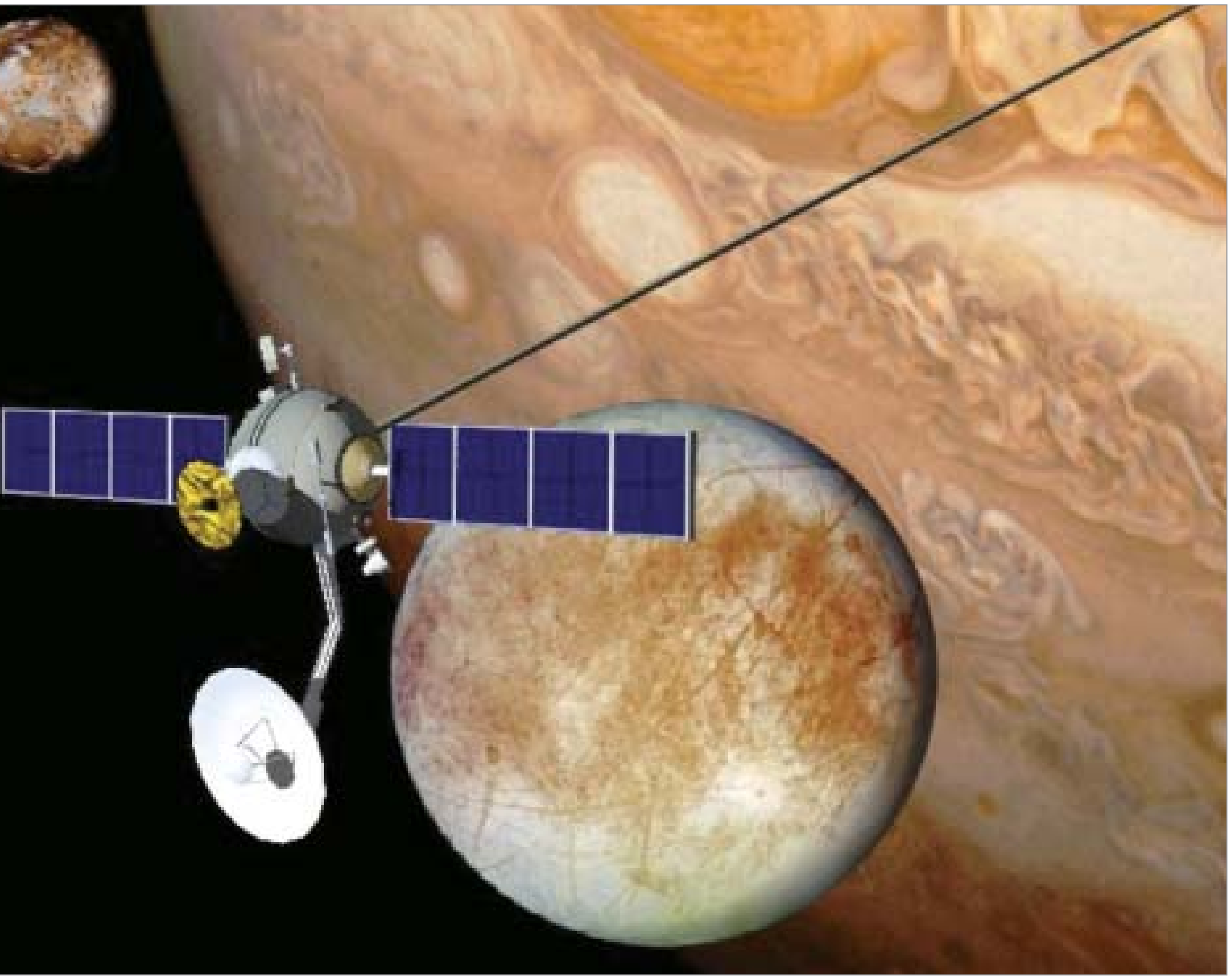
A workshop on materials science for advanced space propulsion was held on May 15–16, 2003, at the Marshall Institute in Huntsville, Alabama. Hosted by OBPR's Physical Sciences Research (PSR) Division, the meeting provided an opportunity for invited experts and customers to generate a road map to direct work in this area. More information on what happened at the workshop may be found at *http://msad.msfc.nasa.gov/workshops/spacepropulsion2003/*.

The In-Space Fabrication and Repair Workshop was held July 8–10, 2003, at the Marshall Institute with the theme "Blazing the Path for In-Space Infrastructure Sustenance and Self-Sufficiency." At this event, also hosted by the PSR Division, invited technical experts and customers assisted OBPR in generating a road map for developing and maturing research on in-space fabrication and repair. Ninety-four attendees split up into break-out sessions to discuss innovative methods that would use resources available in space and require a minimum of materials to be brought from Earth. Additional information about this workshop is available at *http://msad.msfc.nasa.gov/workshops/fabrepair2003/*.

Presentations and splinter-group discussions from the May and July workshops also provided OBPR with input to expand the discussion of materials science for both research initiatives in NRA-02-OBPR-03-E. OBPR released the original NRA in December 2002; the amended Appendix E was released on August 6, 2003.

The fourth materials science workshop was Deep Space Test-Bed for Radiation Shielding Studies, held on June 9–10, 2003, at the National Space Science and Technology Center in Huntsville, Alabama. It provided input for the design of NASA's Balloon-Borne Deep Space Test-Bed (DSTB). The workshop gathered information from the potential user community for the DSTB definition study and initiated coordination between that community and the DSTB design and operations team. One item on the agenda was identifying the requirements of potential investigations to be conducted on the DSTB gondola using suborbital, circumpolar balloon-borne flights. The DTSB achieves an altitude beyond the shielding effects of the Earth's atmosphere, where it will be exposed to galactic cosmic rays. Workshop attendees also discussed requirements for ground support facilities and supplying possible DSTB users with information about polar balloon flight operations. More details about this workshop are available at *http://sd.msfc.nasa.gov/cosmicray/DSTB/meetings/meetings.htm*.

Several notable invitations were extended to participants in the microgravity Materials Science Program in



credit: NASA

NASA's goals for future space exploration and habitation hinge on the development of advanced space propulsion systems and the new materials they will need. The materials science discipline has created a strategic research initiative to focus on such developments. In this futuristic graphic, a spacecraft is using an advanced propulsion system to explore other planets.

FY 2003. Numerous scientists from the program were invited to present papers at the 15th Conference of the American Association of Crystal Growth (AACG), July 20–24, 2003, in Keystone, Colorado. The event was in essence a forum for presenting recent research in all aspects of bulk crystal growth and epitaxial thin-film growth (the growth of the crystals of one material on the crystal face of another material, such that the crystalline orientation of the two materials are well matched), it also included sessions integrating fundamental, experimental, and industrial growth processes, characterization, and applications. Papers were solicited that illumined the role of reduced gravity in factors governing microstructural formation. Also of interest were the results of measuring thermophysical properties and techniques enabled by reduced gravity.

At the AACG conference, Alain Karma of Northeastern University, Boston, Massachusetts, presented "Phase-Field Modeling of Faceted Crystal Growth," coauthored by Jean-Marc Debierre of Université d'Aix-Marseille III, Marseille, France. Phase-field modeling is a technique that tracks locally whether an area is liquid or solid, then assigns it the corresponding property values and governing equations for the physics involved. Martin Glicksman, Rensselaer Polytechnic Institute, Troy, New York, presented "Evolution of Dendritic Mushy Zones"; a mushy zone is defined as a two-phase region consisting of a solid having branchlike (dendritic) extensions and its melt phase. Richard Grugel of MSFC presented "Pore Formation and Mobility Investigation (PFMI): Description and Initial Analysis of Experiments Conducted aboard the International Space Station." More information about PFMI is available in the Highlight "Tiny Bubbles Could Yield Big Results" on page 84. For details on the AACG conference, see *http://www.crystalgrowth.org/conferences/ACCGE15/default.asp*.

Invitations to present the results of materials science research also came from abroad. NASA supported the 3rd Microgravity Transport Processes in Fluid, Thermal, Biological, and Materials Sciences Conference held in Davos, Switzerland, September 14–19, 2003. The meeting's chair and scientific secretary was current NASA materials science PI Satwindar Sadhal, University of Southern California, Los Angeles. Seventeen of the 71 papers presented had NASA-funded materials science personnel as authors or coauthors.

Five researchers from MFSC were invited to speak at the second international workshop of the COmmittee on SPAce Research (COSPAR). Radiation Safety for Manned Mission to Mars was held September 28–October 2, 2003, in Dubna, Russia. John Wilson, Cary Zeitlin, Ram Tripathi, Jack Miller, and Jim Adam presented several papers at the gathering. The COSPAR conference had two overall goals: to identify and analyze issues crucial to space radiation health and protection for human interplanetary travel, and to propose research directed at those issues. Specific topics included

- radiation environment from natural and human-made sources during the Earth-to-Mars transit and on the surface of Mars,

- potential radiobiological effects and risk prediction for radiation exposure of crewmembers (for developing radiation limits for interplanetary flights), and

- scientific requirements and systematic approaches for ensuring the radiation safety of crewmembers.

The Web site for the conference is *http://www.imbp.ru/webpages/engl/Conference/2003/COSPAR/COSPAR.html*.

Other NASA-funded researchers produced notable publications. Ken Kelton and coauthors Geun Woo Lee, Anup Gangopadhyay, Robert Hyers, Tom Rathz, Jan Rogers, Mike Robinson, and D. S. Robinson published "First X-ray Scattering Studies on Electrostatically Levitated Metallic Liquids: Demonstrated Influence of Local Order on the Nucleation Barrier" (*Physical Review Letters*, **90**, May 16, 2003, 195504). Based at Washington University in St. Louis, Missouri, Kelton and coauthors provide new insight into the structural transformations in undercooled liquids. (Undercooling occurs when molten metal is cooled below its melting point without being allowed to solidify.)

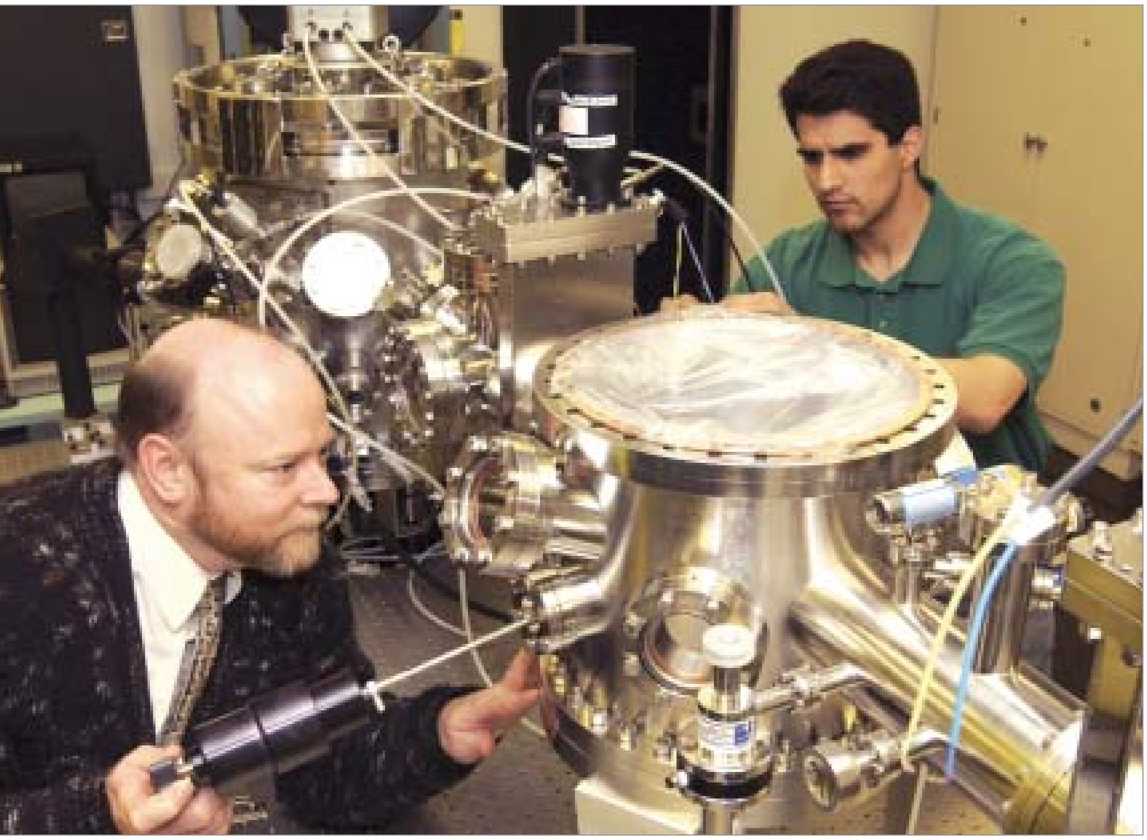
Kelton and his team obtained the first complete proof of a 50-year-old hypothesis that explains how liquid metals resist turning into solids. They used state-of-the-art technology to do so: electrostatic levitation techniques and synchrotron X-ray facilities. The July 2003 issue of *Physics Today* (**56**(*7*), 24–26) featured a paper titled "Experiment Vindicates a 50-Year-Old Explanation of How Liquid Metals Resist Solidification." The article, compiled by Charles Day, an editor at the journal, was based on Kelton's May paper. Kelton's paper also was selected by the editor of *Science* as a "Highlight of Recent Literature for Physics" in the May 30, 2003, issue. Results from this study also support the flight investigation dubbed Quasi-Crystalline Alloys for Space Investigation. For more information about Kelton's research, see the Highlight "Using Levitation to Prove a Theory After More Than 50 Years" on page 85.

Working with scientists from MSFC, Kelton and his team have adapted the unique containerless processing capabilities of Marshall's Electrostatic Levitator (ESL) for use with the high-intensity synchrotron beamline source at the Argonne National Laboratory, Argonne, Illinois. The combination allows molten samples that are suspended (levitated) inside the ESL vacuum chamber to be placed in the direct path of the beam as the sample solidifies, so that X-ray diffraction can be performed instantaneously while the material is in the liquid state. The diffraction patterns enable the structural nature of the material to be determined and indicate how ordered or close to crystallizing it is. Thus, the events of nucleation — the initial formation of a solid within a liquid during solidification — can be monitored, and details of the history of solidification can be faithfully recorded. All of this can occur without risk of contact with a container wall, which might cause a chemical reaction and contaminate the sample or initiate undesired crystallization.

Thanks to this newly developed beamline electrostatic levitation (BESL) unit, researchers can study the structure and phase transformation of high-temperature, highly reactive, undercooled liquids by using conventional electrostatic levitation methods powerfully augmented by X-ray diffraction. The BESL unit can be used for a wide range of materials, including oxides, ceramics, metals, and alloys. This new capability is valuable for OBPR's fundamental and applied strategic research, especially investigating materials for high-temperature applications such as advanced space propulsion.

The ESL facility at MSFC, adapted to accommodate the BESL unit, uses static electricity to suspend otherwise unsupported small samples, which are then melted with lasers and returned to solid form. This process allows researchers to observe how the materials behave in a pure environment without the influence of container walls. Scientists use data from the high-purity ESL processing environment to gain a better understanding of the physical properties of materials including metals, glasses, ceramics, and plastics.

Data gained from the ESL can lead to the development of new materials with enhanced properties. In commercial applications, the research has already been used to improve golf clubs and tennis rackets. NASA researchers have used data from ESL processing to help build a sample



credit: NASA

In the Electrostatic Levitator (ESL), a unique NASA research facility at Marshall Space Flight Center, Huntsville, Alabama, materials science researchers introduce a sample that will be electrostatically suspended and melted. The isolation created in the absence of a container prevents unwanted reactions and allows the observation and collection of accurate data.

collection device for the Genesis probe, which is collecting solar dust to bring back to Earth in late 2004. NASA researchers hope to use ESL data to meet the future challenges of the agency's exploration mission, including developing new materials for advanced propulsion.

In 2003, a new enhanced MSFC ESL was developed to process materials under a broad range of conditions, from high vacuum to high pressure. The ESL facility is unique because samples can be tested in a vacuum or pressurized to about five times Earth's atmosphere. Performing this work in a vacuum or pressure chamber allows scientists to study a sample that is not contaminated by dust or gas such as helium, oxygen, or nitrogen.

Several other materials science researchers had papers published during FY 2003; some example citations follow.

- Christopher Benmore, Richard Weber, S. Sampath, J. Siewenie, J. Urquidi, and J. A. Tangeman. A Neutron and X-ray Diffraction Study of Calcium Aluminate Glasses. *Journal of Physics: Condensed Matter*, **15**(*31*), 13 August 2003, S2413–S2423.

- P. G. Vekilov and A. A. Chernov. The Physics of Protein Crystallization. *Solid State Physics*, **57**, 2002, 1–147.

- Rohit Trivedi, Shan Liu, and Scott Williams. Interface Pattern Formation in Nonlinear Dissipative Systems. *Nature Materials*, **1**, 2003, 157–159.

- J. Miller, C. Zeitlin, F. A. Cucinotta, L. Heilbronn, D. Stephens, and J. W. Wilson. Benchmark Studies of the Effectiveness of Structural and Internal Materials as Radiation Shielding for the International Space Station. *Radiation Research*, **159**, 2003, 381–390.

- Martin Glicksman, A. O. Lupulescu, and M. B. Koss. Melting in Microgravity. *Journal of Thermophysics and Heat Transfer*, **17**, 2003, 69–76.

Scientific accomplishments were awarded to many materials science researchers. Martin Glicksman, Rensselaer Polytechnic Institute, received the 2003 Gold Medal, which was presented at the ASM International Awards Dinner in October 2003. Cited for "pioneering contributions to understanding basic solidification processes, especially dendritic growth, scaling laws, and microstructure development in the design of novel and advanced materials, and for a lifetime of mentoring and training students in their pursuit of materials careers," Glicksman was the PI for the Isothermal Dendritic Growth Experiment, which flew on the second, third, and fourth U.S. Microgravity Payload missions. He is currently the PI on the Evolution of Local Microstructures (ELMS) flight experiment and the follow-on research activities for the Rensselaer Isothermal Dendritic Growth Experiment (RIDGE).

Ken Jackson, University of Arizona, Tucson, received the Bruce Chalmers Award from the Minerals, Metals, and Materials Society (TMS) at its annual meeting March 2–6, 2003, in San Diego, California. The award recognizes outstanding contributions to the field of solidification science. Cited for "outstanding contributions to the science of solidification with physically realistic interpretations and analyses of diverse kinetic phenomena at crystal–liquid interfaces," Jackson is currently a PI for the ground-based project, Growth of Rod Eutectics. With this award, the number of U.S. winners of the Bruce Chalmers Award who are or have been NASA PIs increases to 9 out of 10.

William Johnson, California Institute of Technology, Pasadena, was elected a Fellow of TMS at the 2003 TMS Annual Meeting. The honor is for being "an eminent authority and contributor within a broad field of metallurgy, with a strong consideration of outstanding service to the Society." Specifically recognized for "significant contribution to the science and technology of metallic glasses," Johnson is the PI for the flight experiment Physical Properties and Processing of Undercooled Metallic Glass Forming Melts. His election increases the number of fellows within the NASA program to six. The total number of fellows is limited to 100.

The Southeastern Section of the American Physical Society (SESAPS) has named Jerzy Bernholc, North Carolina State University, Raleigh, winner of the Jesse Beams Award for Outstanding Research for 2003. Since 1973, the award recognizes outstanding research performed at universities and national laboratories in the southeastern United States; Jesse Beams pioneered the centrifuge method for isotope separation of uranium. Bernholc received the award on November 7, 2003, at the annual meeting of SESAPS, Wrightsville Beach, North Carolina. Bernholc is the PI on the materials science ground-based project Growth and Properties of Carbon Nanotubes, which was highlighted on the cover of *Physics Today* in September 1999. Using both classical and quantum molecular dynamics, Bernholc studies fundamental materials issues about the growth and properties of carbon nanotubes.

Many times, research leads beyond journal publications to the creation of technologies or apparatuses that are worthy of patents. Richard Weber's REAl Glass (rare earth–aluminum oxide) technology was issued U.S. Patent No. 6,482,758 on November 19, 2002. REAl Glass has qualities useful for materials to be used in demanding optical applications, such as lasers for surgery or for cutting metal, as well as amplifiers used in optical communications. Alan R. Greenberg's apparatus and method for controlling pore size in thin films and membranes made of polymer were issued U.S. Patent No. 6,479,007 on November 12, 2002. Polymeric membranes have many applications, including breathable garments, surgical dressings, and screen printing.

Flight Experiments

The materials science program conducted its first experiments aboard the International Space Station (ISS) in fiscal year (FY) 2002. The investigations were carried out in the Microgravity Science Glovebox (MSG), a sealed and ventilated workbench-style facility shared among all the disciplines and designed to reduce the risk of contamination to both the astronauts and the experiments. Construction of the MSG was completed during FY 2001 by the European Space Agency (ESA). The facility was launched to the ISS in June 2002 and began operation in July 2002 during Expedition 5 (June 7 through December 5, 2002). In September 2002 the first investigation, Solidification Using a Baffle in Sealed Ampoules (SUBSA), was successfully conducted in the MSG. More information about the MSG appears in the ISS Hardware section of this report (page 102).

A second experiment, the Pore Formation and Mobility Investigation (PFMI), was then installed in the MSG work volume. Expedition 5 Science Officer Peggy Whitson successfully worked with the PFMI team to process several PFMI samples before MSG suffered a power failure in November 2002. During the period that the MSG facility was inoperative, Expedition 6 Science Officer Don Pettit and the ground team devised a schedule that would allow completion of MSG-reliant experiments. The PFMI investigation continued through the remainder of Expedition 6 (November 2002 to April 2003) and Expedition 7 (April to October 2003), with additional samples processed during Expedition 8 (October 2003). The investigator, Richard Grugel designed this experiment to study how bubbles move and interact with one another while a material is melted and solidified in microgravity. When molten metals or alloys are solidified for commercial applications, controlling or eliminating gas pockets is crucial to ensuring the resulting material's strength.

PFMI researchers observe the bubble behavior of a clear, organic compound — in this case, succinonitrile and succinonitrile water (1 percent) mixtures — as the material solidifies. To contain the liquid sample in the event of a breakage of a PFMI sample tube, the PFMI experiments are conducted in the MSG. The main component of the PFMI apparatus is a custom-built furnace, which is versatile

credit: NASA

In preparation for experiment operations, Expedition 6 Science Officer Donald Pettit dons gloves in the Microgravity Science Glovebox.

enough to accommodate other investigations. The success of the current investigation indicates that the furnace will have extended future use. The results support several of NASA's Five Organizing Questions (from the OBPR Research Plan), ReMaP Priorities, and new exploration initiatives. Reprocessing of the PFMI samples was planned to begin in late 2003, with the results expected to complement and expand the present PFMI science results as well as provide insight to future microgravity investigations.

The Coarsening of Solid–Liquid Mixtures 2 (CSLM-2) Facility was tested on the ISS during FY 2003. Experiments were conducted on the new equipment to verify the isothermality of the thermal environment, and to test the efficacy of the quench. The CSLM-2 principal investigator (PI) is Peter Voorhees, Northwestern University, Evanston, Illinois. During Expedition 6 (November 2002 to April 2003), CSLM-2 successfully completed engineering tests in the MSG. The CSLM-2 facility was tested and found to be operational. Additional runs of the facility are currently on hold, pending the arrival of the Minus Eighty Laboratory Freezer for the ISS (MELFI), which is scheduled for launch on Mission UFL-1.

CSLM-2 will examine the so-called competitive growth of microscopic tin particles within a liquid tin–lead matrix. The low-gravity ISS environment will produce data that can be compared directly with theory without interference from convection and sedimentation. The constituent metals of an alloy may cool at different rates, causing competitive particle growth and resulting in less interfacial area (the boundary between different phases) and thus less total energy, through a process called Ostwald ripening. Large particles grow at the expense of smaller ones in a matrix, incorporating atoms from the smaller ones as the microstructure evolves, until the sample consists of a few very large particles crowded around a few remaining small particles. This phenomenon, which occurs by diffusion at high temperatures, is called coarsening.

To gain additional understanding about the coarsening phenomenon in a reasonable time frame, CSLM-2 uses a liquid matrix. On Earth, sedimentation would make such an experiment untenable. The space results, however, can be directly translated to the solid–solid arrangement and directly applied to understanding coarsening in high-temperature alloys. Processing liquid–solid samples in microgravity will accelerate coarsening, thus allowing Voorhees to observe the kinetics of the reactions for periods up to 96 hours and hence test new and conventional theories that describe the phenomenon.

Sent to the ISS aboard a Russian Soyuz capsule in April 2003, the In-Space Soldering Investigation (ISSI) began with the preparation of seven solder coupons (test pieces) during Expedition 7 (April to October 2003) for soldering and completed during Expedition 8 (October 2003). The purpose of the ISSI experiment is to investigate soldering practices and behavior in microgravity — an environment especially relevant to in-space fabrication and repair. In particular, this investigation addresses flow phenomena driven by surface tension forces, interfacial phenomena, and the possible incorporation of bubbles. The results will contribute to the fundamental understanding of soldering as an in-situ repair technique in space.

Investigators for the ISSI are Richard Grugel of MSFC and Fay Hua of Intel Corporation, Santa Clara, California — an important collaboration with industry. Very little research has been conducted on in-situ fabrication and repair. In a microgravity environment, surface tension plays a larger role in joining techniques than it does on Earth. Processes that rely on gravity-driven separations under normal gravity, such as removing gas bubbles from the solder, must use other means in microgravity. Also, cooling rates are affected by the absence of natural convection in microgravity.

The ISSI investigation used hardware already available on the ISS: a battery-operated soldering iron that can heat up to 315.6 °C (600 °F) and the ISS Maintenance Work Area, a portable workbench that includes a debris containment system made out of transparent laminate. The debris containment system could be attached to the ISS's vacuum, to capture and dispose of particulates or liquids that are 6 microns (0.0002 inches) in diameter or larger. After samples were processed, they were returned for material property testing and metallographic examination.

This investigation is one of several with low-to-zero upmass and downmass (weight of equipment during takeoff and landing, a limiting factor for spacecraft) that have been selected for flight after rigorous discipline review. In the selection process, the highest priority was given to candidate experiments of high scientific merit that could be completed in the window of opportunity until space shuttle flights resume. The ISSI experiment is considered to be “fast-track strategic research” because soldering has direct application to PSR’s In-Space Fabrication and Repair initiative. In addition to the experiments already listed, several investigations are still waiting for implementation on the ISS, including Fluid Merging Viscosity Measurements (FMVM), Miscible Fluids in Microgravity (MFMG), and Study of Structure of a Viscous Liquid Foam (FOAM).

Containerless processing is a technique for collecting data in which samples are suspended within but away from contact with a surrounding container or other source of contamination. Edwin Ethridge, a materials scientist at MSFC, and William Kaukler, University of Alabama, Huntsville, are using FMVM to test a new method of measuring the viscosity of containerless fluids aboard the ISS. Their idea is simple: If two floating drops of a liquid touch each other, they will merge to form a single larger drop. The speed of this coalescence is limited by viscosity — water will merge much faster than honey, for example. By measuring the speed with which two drops merge, scientists can calculate the liquid’s viscosity.

Ethridge has selected eight liquids for testing. They have been loaded in syringes that will be launched on a Russian Progress vehicle to the ISS. One of the liquids is ordinary honey. Although it crystallizes very slowly, honey is actually an undercooled liquid. It works very well for proving that this “floating drop” method can accurately measure a liquid’s viscosity. The experiment will be done by squeezing honey (or one of the other test liquids) from its syringe and transferring two drops onto thin strings. (Nomex thread [resistant to high temperatures and many chemicals] and string are available on the ISS and can be used to confine and control the liquid drops in orbit.) The data provided could provide insight into the behavior of glasses prepared in low gravity for potential fabrication on extended missions as well as liquid-phase sintering for strategic in-situ fabrication.

John Pojman, PI from the University of Southern Mississippi, Hattiesburg, is an investigator for two low-mass investigations (collectively referred to as MFMG) that can be loaded in a Progress vehicle, require simple procedures, and are expected to yield valuable strategic information with minimal apparatus requirements. Knowledge gained from these experiments will clarify the role that convection induced by concentration gradients and temperature gradients can play in the industrial processing of miscible (mixable) polymer systems. A demonstration that convection can occur in microgravity in miscible systems has implications for space processing.

There are two versions of MFMG: Isothermal (I; uniform temperature), and Thermal (T; variable temperature). The objective of MFMG-I is to discover whether miscible fluids in an isothermal environment can exhibit transient interfacial phenomena like those observed with immiscible fluids. The objective of MFMG-T is to determine whether miscible fluids in a thermal gradient can exhibit similar behavior.

The approach is simple for both variants of the experiment: A stream of first honey and then honey mixed with water is slowly injected with a modified syringe into water contained in another syringe, whereupon a drop of water containing a dye is injected into both the honey and honey-and-water solutions. The results are captured on video, and digital pictures are taken every 30 seconds.

PI William Johnson, California Institute of Technology, Pasadena, has proposed FOAM, a low-gravity experiment to study how foam structure evolves in a viscous liquid in the absence of gravitational sedimentation and liquid drainage. Foams could well be used for direct fabrication of structures in space. Results of research into foamed metal (specifically, foamed metallic glasses) may be of strategic interest as materials for use in fabricating large structures in space.

Foamed materials have undergone numerous scientific studies over the past several decades. Recent interest in cellular foams has extended to a wide variety of materials, including plastics, ceramics, and metals. Foamed metals, for example, have been developed for technical applications as structural materials, heat exchangers, and energy-absorbing panels. In the case of metals, studies have recently demonstrated that bulk metallic glass–forming liquids with unusually high viscosity are excellent candidates for metal foam production.

An innovative procedure devised by William Kaukler and Chris Veazey, a student of William Johnson’s at the California Institute of Technology, will use the ISS soldering iron to melt a metallic sample. A small pellet of amorphous metal containing a foaming agent is contained inside a copper container that is clamped to the end of the soldering iron tip. The tip has built-in temperature control capability. The battery-driven soldering iron will soften the amorphous metal, which will foam and fill the copper container. After the samples have been processed, they will be stowed for return to Earth, where the scientists will cut the containers open and observe the foam structure. The three FOAM samples were launched on Progress 13 and are waiting to be scheduled for processing on the ISS.

During FY 2003, PI Aleksander Ostrogorsky and his research team at Rensselaer Polytechnic Institute, Troy, New York, have been using computed tomography (the same technology as used for medical CT scans) to conduct ground testing of certain flight samples processed in the MSG in 2002 — namely, the SUBSA samples. Early findings indicate successful positioning and movement of the submerged baffle. Ostrogorsky is now evaluating techniques for measuring dopant distribution throughout the sample. Results will reveal how effective the baffle is in controlling convection in microgravity. Information obtained from the SUBSA experiments will add to our understanding of the solidification process in microgravity and determine how effective baffles can be in producing quality semiconductors in orbit.

In addition to the MSG, the Materials Science Research Rack-1 (MSRR-1) will house microgravity materials science experiments in the U.S. Laboratory Destiny module of the ISS. The MSRR-1 continued to make progress toward completion and installation on the ISS, as did experiment modules designed for the facility. The MSRR-1 is scheduled for launch to the ISS in 2007. Details about the MSRR-1 and its associated modules are in the ISS section of this report (page 101).

Highlights

Tiny Bubbles Could Yield Big Results

When materials such as metals are processed for commercial applications, one of the greatest challenges is ensuring the strength and integrity of resulting products. This includes the need to reduce the number of pores, or bubbles, within the processed material. But fully understanding pore formation is difficult on the ground because bubble movement is strongly influenced by Earth's gravity. The microgravity environment on the International Space Station (ISS), however, gives Richard Grugel at Marshall Space Flight Center in Huntsville, Alabama, an opportunity to study the phenomena that is unavailable on Earth.

Grugel is the Glovebox Investigator (GI) on the Pore Formation and Mobility Investigation (PFMI), which flew to the ISS in June 2002 and was one of the first sets of experiments run in the Microgravity Science Glovebox. As of the end of 2003, all originally planned experiments in the project had been completed.

The PFMI experiments demand a model system that behaves like commercially processed metals but is transparent so scientists can watch and film internal processes. Thus, the team uses a transparent plastic material called succinonitrile (SCN), which solidifies in a crystal structure similar to that of many metals and has a low melting point that simplifies experiments.

The PFMI uses 15 samples of SCN, some with water added as a second material to simulate an alloy. Each sample is encased in a glass tube 13 centimeters (5.1 inches) long by 1 centimeter (0.39 inch) in internal diameter fitted with six thermocouples spaced along its length to measure temperatures at various points. The tube is coated with indium–tin oxide, which is a resistor and acts as a heater. A ring heater and coolant block can move along the sample to control heating and cooling rates as well as temperature gradients. This processing technique, known as controlled directional solidification, is similar to that used in some commercial processes and takes 10 to 12 hours for each sample. Two video cameras record the action for scientists to observe and analyze. Of the 15 samples processed between September 2002 and September 2003, 13 experiments were fully completed without system malfunctions. The experiment will continue into FY 2004.

During each experiment, SCN is heated well above its melting temperature to create a temperature gradient within the tube. Grugel's team's main interest is the formation and fate of bubbles at the interface between liquid and solid SCN. In some cases, they observed that bubbles formed naturally when the solidifying SCN shrank and drew in some of the nitrogen under which the samples were initially processed; in other cases, nitrogen was intentionally added to samples during their initial preparation to ensure the presence of bubbles for investigation.

As with materials processing on Earth, the main parameters controlled during the PMFI experiment are the composition of the material, the velocity at which the material solidifies, and the temperature gradient at the solid–liquid interface. In samples with introduced nitrogen bubbles, for instance, Grugel has found that larger bubbles can significantly influence flow in the liquid while still being attached to the solid.

credit: NASA

Richard Grugel, Glovebox Investigator for Pore Formation and Mobility Investigation on the International Space Station, examines a sample of the succinonitrile, used to simulate metal and metal alloys during materials processing experiments to observe how bubbles form and behave during melting and solidification. Branching treelike dendrites are clearly visible in the sample.

As a result of the temperature gradients set up in the samples, Grugel and his colleagues have observed the consequence of a process called thermal capillary convection, a small but important force usually overwhelmed by buoyancy in Earth's gravity. Capillary convection usually moves bubbles toward hotter regions in the liquid because the side of the bubble closest to the solid is colder than the side closest to the liquid. That temperature gradient across the bubble causes the surface molecules to move and thereby propel the bubble up the temperature gradient.

The researchers also have observed the formation of dendrites, branching treelike structures, during solidification. This process is an important factor in determining a processed material's final properties. Dendrites formed most commonly in the water–SCN "alloy" samples, in some cases affecting the stability of bubbles present.

Overall, the group's observations of the formation of bubbles and the velocity of their movement agreed well with theoretical predictions, says Grugel. Now, with planned processing experiments completed, a new set of experiments on the same samples has been approved. Grugel intends to reexamine some of the initial results, test a wider range of conditions (such as larger temperature gradients), and look for new aspects of dendritic growth.

The team hopes that its PFMI research will contribute to improving the design of future microgravity experiments, because the formation of unwanted bubbles has marred the results of some past materials processing investigations. The PFMI results could also lead to improvements in both mathematical models and commercial processing techniques so that desired material properties can be better achieved during solidification.

Using Levitation to Prove a Theory after More Than 50 Years

Until the 1950s, scientists were baffled by the phenomenon whereby under the right conditions, metals could be "undercooled" — that is, cooled well below their melting point (temperature at which they should solidify) and still remain liquid. In 1952, a British physicist named Charles Frank proposed a theory for how this could happen that sharply contradicted conventional theory about how metals behave, but at the time he could not prove it. Now, by combining the power of two advanced instruments, physicist Kenneth F. Kelton of Washington University in St. Louis, Missouri, and his colleagues have been able to verify Frank's hypothesis definitively. Their work has led to a path of research and the development of techniques that could improve the processing of high-tech aviation alloys and perhaps even lead to methods for manufacturing metal products in space on long-term voyages.

Conventional theory had held that molten metals could not be undercooled because in the liquid phase, the metallic atoms were believed to order themselves in a local structure similar to that in the crystalline solid metal, making the shift to solidification an easy one in thermodynamic terms. To explain undercooling, Frank theorized that an energy barrier must stall the liquid-to-solid shift under the right conditions. He suggested that as a molten metal cools, its atoms naturally arrange themselves in an icosahedron (a solid with 20 triangular faces that in many ways is a three-dimensional analog of a two-dimensional pentagon), the lowest-energy structure possible. But icosahedrons cannot pack regularly in a crystal structure of solid metal without


credit: Kenneth Kelton and Jan Rogers

A drop of molten titanium–zirconium–nickel is suspended in the Electrostatic Levitator at Marshall Space Flight Center in Huntsville, Alabama.

gaps or other defects. Thus, Frank hypothesized, changing phase from molten to solid metal would actually require the addition of energy to allow the atoms to reshuffle yet again into a completely different but stable pattern. That addition of energy would create an energy barrier between the phases, causing molten metal to "resist" solidifying and allowing it to be undercooled.

Proving Frank's theory did not become possible for decades because of limitations in measurement instruments and techniques, such as high-speed X-ray diffraction. Various research teams found evidence supporting Frank's hypothesis in the 1980s discovery of quasicrystals — solids with icosahedral structures — but this theory could not be fully tested and proven until Kelton and his team performed their innovative experiments.

To test Frank's theory, Kelton first needed an alloy that would illustrate the necessary principles, which he found in titanium–zirconium–nickel. This material has a solid quasicrystal phase with icosahedral order that is less stable than the alloy's crystalline phase and forms at a higher temperature than the crystalline phase does. If Frank's theory were correct, then as the liquid alloy cooled, Kelton expected to see its atoms gradually arrange themselves into an icosahedral pattern, making it easier for the quasicrystal to begin to form (nucleate) before entering the stable crystal phase.

Moreover, to prove any of this was happening, Kelton needed to show that the alloy's atoms were locally arranging themselves into the icosahedral pattern when the metal was still liquid. So, he turned to the Electrostatic Levitator (ESL) at the NASA Marshall Space Flight Center in Huntsville, Alabama, which can suspend a small droplet of molten metal away from the walls of the container so as to prevent any impurities in the walls from causing an undercooled droplet to nucleate. (Such impurity-mediated nucleation occurs in almost any normal experimental situation and was the reason scientists were not able to observe undercooling in metals for so many decades.) In the ESL, a solid sample is first levitated by electrostatically charging the metal so it is repelled or attracted by charged elements in the instrument. Lasers then melt the sample.

The second key tool was the Advanced Photon Source (APS) at the Argonne National Laboratory in Argonne, Illinois, which maps out the local atomic order in liquid or solid samples by bombarding them with powerful X-rays and measuring how the paths of the X-rays are altered. By moving the ESL to the APS and using the two tools together — something that had never been done before — Kelton was able to observe clear and complete support for Frank's theory. Over and over again, as molten droplets cooled, Kelton observed that the metal atoms arranged themselves into an icosahedral pattern, making it easy to nucleate the quasicrystal solid phase, which existed only for a brief but observable 2-second interval before melting again and changing to the stable crystalline phase.

The results of Kelton's experiments were reported in the May 2003 issue of *Physical Review Letters* and were the subject of the July 2003 *Physics Today* cover story. During the summer of 2003, Kelton discussed these and subsequent experiments at the Gravitational Effects in Physico-Chemical Systems conference held in New London, Connecticut, and his group is preparing several more papers for publication in major journals.

Besides confirming Frank's theory, Kelton says the work also exposed weakness in classical theory, which does not predict or allow for the intermediate icosahedron stage observed. Accounting for the observations could therefore lead to revisions in the models used to predict crystallization behavior and eventually improve the control of metallic alloys during manufacturing.

Kelton says a more immediate application of the work will be to apply the APS–ESL techniques he developed to other problems. Kelton has also passed the science review for a microgravity experiment to take place on the International Space Station that will further investigate nucleation processes. In addition to providing new basic insights, those studies could lead to a better understanding of how metals behave when processed in space — critical information for long-duration space voyages, during which certain needed parts might have to be manufactured.

Creating a New Class of Glass

It may look no different than the clear or colored glass in a window or a figurine, but REAl Glass is like nothing that has ever been created before. This new family of materials is now in development as a potential component in lasers for metal cutting, surgery, and optical communications as well as other products because of its powerful advantages over currently available products. Experiments conducted at Marshall Space Flight Center's

(MSFC's) Electrostatic Levitator (ESL) enabled some of the fundamental studies that led to the creation of REAl Glass.

Under commercial development by Containerless Research, Inc. (CRI), based in Evanston, Illinois, REAl Glass gets its name from two of the material's main components, rare earth oxides and aluminum oxides. Whereas window glass is about 70 percent silicon oxide or silica — the main component of common sand — REAl Glass is only about 10 to 15 percent silica. Although REAl Glass is produced in various forms depending on the intended application, its main component is instead 50 to 60 percent aluminum oxide, which is also the main component of sapphire. This compound is favored because of its stability and its ability to transmit infrared light well. Perhaps most critically and unlike silica, it also bonds easily with the rare earth oxides such as ytterbium oxide and erbium oxide that make up the balance of the REAl Glass recipe and give the material its range of commercial applications.

The rare earth oxides in the glass function as dopants, that is, intentionally embedded impurities that alter the electrical properties of the manufactured material (such as semiconductor crystals or glass). The type and concentration of dopants used determines the wavelength or range of wavelengths at which light — from a laser, for instance — will transmit from the material.

In a crystal, dopants have to take the place of a normal atom in the crystal lattice, and because the dopants are a different size, they add a degree of instability to the structure. If there are too many dopants, the structure essentially falls apart. Not so with glass. Because glass is amorphous (without a regular crystalline structure), the dopants have little effect on its structural stability, which means that much higher concentrations of dopants can be added.

credit: Containerless Research, Inc.

An employee of Containerless Research, Inc., casts a sample of REAl Glass at the company's facility in Evanston, Illinois.

One of the main potential applications for REAl Glass is in lasers, including those used to cut metal, perform surgery, and send communications signals over optical fibers. REAl Glass components used as energy storage devices in lasers can be tuned more closely than competing YAG (yttrium-aluminum-garnet) crystal components to the wavelength at which other components in the laser operate. This "tunability" dramatically reduces heat loss, so the lasers either can be smaller because they require a smaller cooling apparatus or can be made more powerful than a comparably sized YAG crystal–based instrument.

REAl Glass can also be used to make the infrared transmitting windows used in such devices as the decoys on military aircraft that use infrared beams to create heat sources that "fool" heat-seeking missiles. In addition, REAl Glass is cheaper to produce than crystals, which have to be grown in large blocks that require extensive cutting and shaping, because it can be easily cast to roughly the size of needed components, much like common glass.

In past work to develop aluminum oxide–based glasses, researchers began with silica as a main component. The Weber group instead began by studying aluminum oxide in liquid mixtures that did not include silica, then in mixtures that did, while cooling them to hundreds of degrees below normal solidification temperatures. This "undercooling" forces materials into abnormal configurations that give researchers information about how best to manipulate it during manufacturing. "The more you cool below melting," says Weber, "the more interesting it gets."

This is where the ESL came into play. Materials can generally be undercooled only if there are no contaminants present to facilitate the phase shift from liquid to solid, and containers almost always provide such contaminants. The ESL, however, allows scientists to work with small volumes of material suspended in a vacuum; the material is illuminated by ultraviolet light, which gives its surface a positive static charge, allowing the material to be suspended in the instrument's electrostatic field without contact with a container. Using this system, the team was able to uncover critical information about how to manipulate aluminum oxide to create REAl Glass. One key point was the discovery that ensuring the presence of specific critical forms of aluminum oxides required the addition of ions (charged atoms) of the element lanthanum.

CRI continues to develop REAl Glass through basic research and work to scale up production to commercial levels with funding from the National Science Foundation and continued support from NASA. The group is also working directly with several commercial clients to create specific products using the novel materials.

ACCELERATION MEASUREMENT

credit: NASA

Experiments are usually conducted in microgravity to avoid the by-products of gravity, such as buoyancy-driven convection. Accelerations and other disturbances to the microgravity environment — such as a Russian Progress ship docking or undocking (shown here) with the International Space Station — can interfere with experiment results. The Microgravity Environment Program helps researchers understand the impact of accelerations on their microgravity experiments.

OVERVIEW

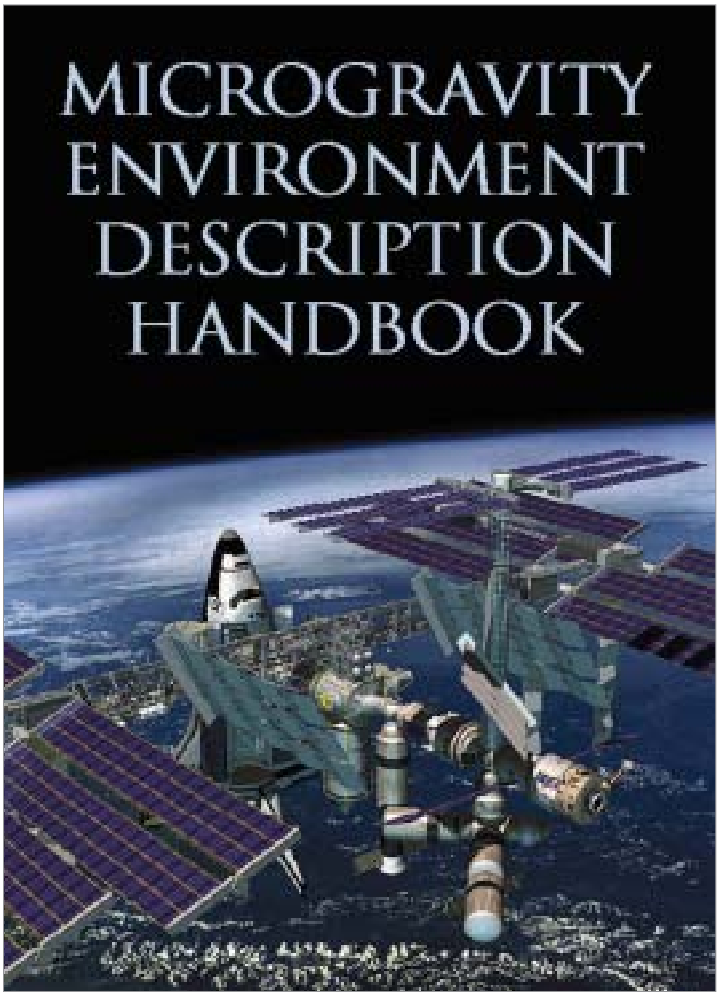
Variations in the quality of a microgravity environment can affect experiment results. Sometimes the very tools that enable an experiment to be conducted in microgravity can be responsible for these variations. Experiment hardware, crewmembers, and even the flight vehicle itself can cause accelerations (commonly known as vibrations) that influence microgravity levels and disturb sensitive experiments. Because accelerations can cause convection, sedimentation, and mixing — 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 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 also can strongly influence the motion of fluids and 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 cooled to temperatures close to absolute zero. The Microgravity Environment Program helps researchers understand the impact of accelerations on their microgravity experiments.

Program Summary

Accurate measurement of the microgravity conditions during a spaceflight is crucial. Principal investigators (PIs) use acceleration data to determine the influence of accelerations on their experiments so they can 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; the Russian space station, *Mir*; sounding rockets; KC-135 parabolic flight aircraft; drop towers; and the International Space Station (ISS).

Accelerometers are used to measure the quality of a microgravity environment onboard the various experiment carriers. 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 complement each other in their measurements. Quasi-steady sensors measure the microgravity environment for low-frequency accelerations. Vibratory sensors measure higher-frequency accelerations (up to 400 hertz).



credit: NASA

Researchers who attend the tutorial run by Principal Investigator Microgravity Services (PIMS) on interpreting the microgravity environment receive a 500-page reference book that serves as a guide for maximizing the success of their microgravity research.

The Space Acceleration Measurement Systems (SAMS) project develops, deploys, and operates its systems to measure, collect, process, and record selected acceleration data for delivery to researchers and other customers; customers in turn use the data to control, monitor, and characterize the microgravity environment on platforms or facilities such as drop towers, aircraft, sounding rockets, space shuttles, and the ISS. SAMS' sister project, Principal Investigator Microgravity Services (PIMS), provides extensive data analysis of the acceleration data on the basis of customer requests and acts as the primary interface of the acceleration data to most researchers.

Current SAMS operational subsystems follow.

- Command and data-handling function:
    - The Interim Control Unit (ICU) is currently performing this function on the ISS. The ICU utilizes a Johnson Space Center Portable Computer System (PCS) installed in an International Subrack Interface Standard (ISIS) Drawer mounted in the continuously powered EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Rack 4.
    - The Control and Data Unit (CDU) is the primary unit provided for ground systems. It utilizes a PC104 bus that is configurable for each user. This unit has been flown on space shuttle and sounding rocket missions.
- Measurement function:
    - The Remote Triaxial System (RTS) is an ISS distributed vibratory system (0.01–400 hertz). Every EXPRESS Rack with Active Rack Isolation System (ARIS) capability contains an RTS, as does the Microgravity Science Glovebox (MSG), and EXPRESS Rack 1 contains two RTS drawers. The RTS is made up of an electronics enclosure (EE) for power conditioning and communications and up to two triaxial sensor enclosures (SEs). It requires a CDU such as a laptop.
    - The Microgravity Acceleration Measurement System (MAMS) is a standalone system on the ISS that uses a quasi-steady sensor (direct current

to 1 hertz) and a vibratory sensor (0.01–100 hertz). It is deployed in EXPRESS Rack 1.

- The Triaxial Sensor Head–Free Flyer (TSH-FF) is used to support ground facilities and aircraft operations (0.01–400 hertz).
- The Parabolic Acceleration Rating System (PARS) is deployed on the KC-135 parabolic flight aircraft, where it provides a rating number to the pilots and acceleration data to the researchers. It uses a TSH-FF sensor head and a CDU.
- The Roll Rate Sensor (RRS) enables the measurement of rotational accelerations by using a fiber-optic gyroscope. It has been used on sounding rocket and space shuttle flights.

The SAMS project team is developing future subsystems to enhance measurement capability and flexibility. The following subsystems currently are under development:

- The Triaxial Sensor Head–Ethernet/Standalone (TSH-ES) has undergone design review and verification readiness review. The first flight unit will be delivered to the Fluids and Combustion Facility (FCF)–Combustion Integrated Rack (CIR) on the ISS in early 2004. The sensor head greatly reduces the size and power required by the RTS to attain the same level of performance.

- The Triaxial Sensor Head–MEMS (TSH-M) is an engineering unit that has been built and tested. The small size of the subsystem and limited power required provide users with another solution to measure the vibratory environment near their experiments.

Helping researchers to better understand the microgravity to which their experiments will be exposed 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 (MEIT). A 1-day introductory MEIT was held October 10, 2002, and the 21st International Microgravity Measurements Group Meeting was held October 11, 2002, as associated events of the World Space Congress in Houston, Texas. The training was a condensed version of the regular 3-day training offered by PIMS.

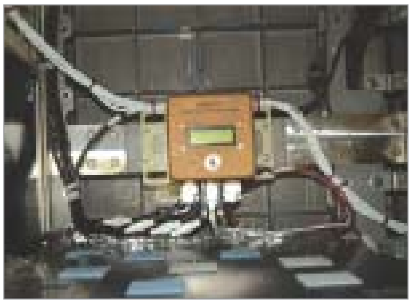
The meeting of the International Microgravity Measurements Group was presented with predictions of ISS microgravity conditions in given situations, improvements to space accelerometers, and environment concerns of experiments as well as discussions by members of the International Partners Program. Offering the training and meetings during the World Space Congress — a once-a-decade event attended by thousands of scientists, engineers, and space science–interested public from around the world — made the events more accessible to many international participants.

For the sixth year, the Acceleration Measurement Program offered its regular MEIT program to PIs and project scientists in the Physical Sciences Research Division during a 3-day session in Cleveland, Ohio, March 4–6, 2003. The tutorial covered topics in accelerometer instrumentation, data collection and analysis techniques, the quality of the microgravity environment on NASA's various carriers, and implications of those environments for microgravity experiments. A 500-page reference book was provided to each participant to serve as a guide to maximizing the success of their microgravity research.

In addition to sharing information with investigators, the acceleration measurement program educates astronauts about the microgravity environment. In early 2003, PIMS conducted a training session with the astronaut candidate class at Johnson Space Center (JSC) in Houston, Texas. Astronaut candidates learned about the effect of accelerations on experiment results, sources of disturbances to the environment, means of maintaining the desired environment, and methods PIMS uses to analyze and present the environment data. The session leaders also explained how the astronauts themselves contribute to the environment (for example, by opening lockers) and offered suggestions for how astronauts can minimize the vibrations they generate as they work in spacecraft. Crews for ISS Expeditions 2–9 were also trained in the operation of SAMS and SAMS subsystems as well as in interpretation of the data.

Flight Experiments

In fiscal year (FY) 2003, the Space Acceleration Measurement Systems (SAMS) project subsystems operated



credit: NASA

Space Acceleration Measurement Systems for Free Flyers (SAMS-FF), pictured here installed on a space shuttle, was originally developed to measure the microgravity environment aboard sounding rockets.

Crew activities, including exercising and inputting data on a computer, can cause disturbances to the microgravity environment aboard a spacecraft. The acceleration measurement program records and analyzes the small vibrations caused by such necessary activities and makes the data available to researchers.

credit: NASA

on the International Space Station (ISS) with very little need for diagnostics or corrective actions. Most operational trouble has been related to rack or ISS subsystem problems associated with the growing pains of operating new equipment on a new space platform. The Principal Investigator Microgravity Services (PIMS) project has analyzed thousands of hours of SAMS and Microgravity Acceleration Measurement System (MAMS) data from the ISS. Analyses have included such activities and conditions as space shuttle dockings to the ISS; Progress dockings to the ISS; ISS systems and subsystems operations; science experiment operations; crew exercise, nominal operations, and sleep periods; ISS vehicle attitudes and methods of control; and spacewalks for ISS assembly and maintenance.

On the ISS, the Remote Triaxial System (RTS) Drawers continued to collect data. All mission success criteria were met. For Expeditions 5 and 6, the SAMS ISS System was available 96.87 percent of the time. Data were collected minimally 90.83 percent of the time from the continuously operated sensors. Researchers using the Microgravity Science Glovebox (MSG) for the Solidification Using a Baffle in Sealed Ampoules (SUBSA) and the Pore Formation and Mobility Investigation (PFMI) experiments received nearly 100 percent of the data they had requested prior to the mission.

In January 2003, space shuttle mission STS-107 was launched with a microgravity science payload. SAMS supported the mission with a Control and Data Unit (CDU), three Triaxial Sensor Head–Free Flyers (TSH-FFs), a Roll Rate Sensor (RRS), and the Orbital Acceleration Research Experiment (OARE). SAMS

/PIMS supplied researchers with real-time data using Combustion Module-2 (CM-2). All SAMS hardware operated nominally.

In December 2001, the Engineering Development Division at Glenn Research Center (GRC) in Cleveland, Ohio, acquired the function of performing predictive analyses of the ISS microgravity environment. Specifically, the Non-Isolated Rack Assessment (NIRA) is currently being performed at GRC. NIRA provides the ISS payload organizations with predictions of the acceleration environment resulting from microgravity disturbances generated by the ISS vehicle and its payloads and crew for scientific experiments located on the nonisolated racks and on attached payload locations. GRC's first full NIRA was completed in December 2003. This microgravity prediction incorporates the latest characterization of the microgravity disturbances, along with the updated finite-element models of the ISS, and is the first NIRA of the ISS environment to be completed since 1999. This effort contributes to ensuring that the ISS and its payloads will be creating a world-class microgravity acceleration environment for the science experiments conducted on board.

Support and assistance to PIs is also offered through experiment modeling and the division's experience with how science experiments can affect and be affected by the microgravity environment. For example, in April 2003, Johnson Space Center (JSC), in Houston, Texas, requested that GRC perform a mini-NIRA for the European Space Agency (ESA). This analysis predicted the microgravity environment for ESA's Atomic Clock Ensemble in Space (ACES) payload that will be located on the external payload facility of the Columbus Orbiting Facility (COF). The predicted microgravity environment at this location was provided to ESA's payload designers in May 2003 for their subsequent evaluation of the suitability of this environment for their ACES payload experiment.

Before experiments and equipment are installed on the ISS, their effect on the microgravity environment can be tested. GRC's Microgravity Emissions Laboratory (MEL) is a one-of-a-kind ground-based laboratory that simulates and characterizes inertial forces generated by ISS payloads and their components, including disk drives, pumps, motors, solenoids, fans, and cameras. MEL uses a low-frequency isolated acceleration measurement system to characterize the rigid body inertial forces generated by various operating components of the ISS. Thirty tests in the laboratory between December 1999 and October 2003 (eight tests in FY 2003) have included ISS subsystem components, payload rack subsystem components, payload components, and entire payloads.

The weight the facility can accept has been increased to accommodate tests of equipment at a weight equivalent to that of an ISS rack. GRC's Fluids and Combustion Facility (FCF) used MEL to test an Input/Output Processor Assembly in September 2002 and a combustion chamber fan in June 2003. The transient characteristics of the FCF solenoid valve were demonstrated in MEL in December 2002. Ames Research Center (ARC), Moffett Field, California, also tested its Space Station Biological Research Project Incubator Chamber and Avionics Fans in MEL in September 2003.

The Physics of Colloids in Space (PCS) experiment data that had been obtained from testing in MEL in May 2000 was used again to define predictions of in-orbit vibratory disturbance in preparation for the return of PCS to the ISS. Payload integrators were given the information they needed to determine PCS compliance with ISS requirements. The MEL test data from the PCS experiment apparatus were given to analysts at Boeing Company, Chicago, Illinois, to aid in determining the microgravity rack responses for surrounding racks and for comparison against flight data.

The FCF project used the MEL laboratory in 2003 to demonstrate the effectiveness of vibration isolators. In June 2003, isolators with the air thermal control unit fan and housing assembly of FCF were tested in MEL, which was subsequently used to define the most effective isolator treatments during the design phase of the engineering-level hardware. Flight design changes were made as a result of the initial MEL characterization of the vibration response expected from component hardware. The project continues to use the MEL component data to predict vibratory disturbances at the flight rack level.

Two papers on MEL were presented at meetings in FY 2003. In June, "Microgravity Emissions Laboratory Testing of the Light Microscopy Module Control Box Fan" was presented at NOISECON 2003, in Cleveland, Ohio (published as A. M. McNelis, S. Samorezov, A. H. Haecker, Microgravity Emissions Laboratory Testing of the Light Microscopy Module Control, NASA publication number NASA/TM-2003-212333; visit *http://www.ntis.gov/* for information about obtaining this publication). In October, "Microgravity Emissions Laboratory Testing of the Physics of Colloids in Space Experiment" was presented at the World Space Congress in Houston, Texas (A. M. McNelis; NASA publication number NASA/TM-2002–211901; visit *http://www.ntis.gov/* for information about obtaining this publication).

Highlights

Minimizing Shake, Rattle, and Roll

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

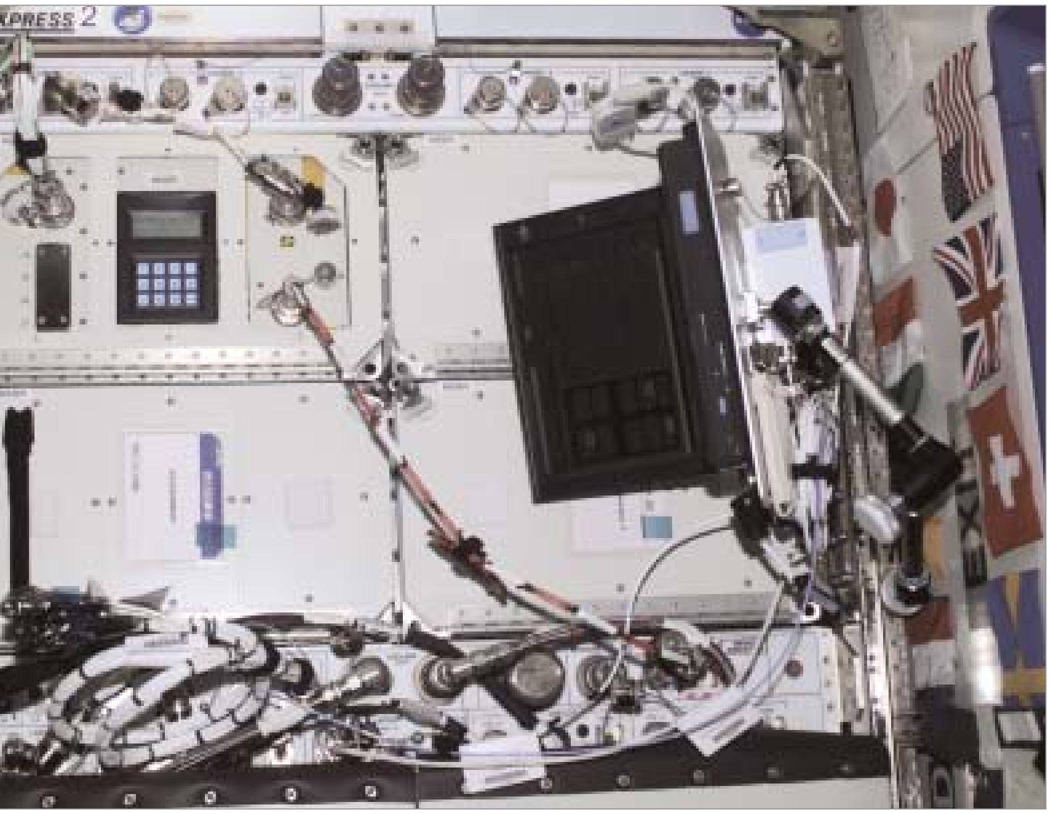
Currently operating on the ISS, the ARIS system is connected to Rack 2 of the EXPRESS (EXpedite the PRocessing of Experiments to Space Station) program. The ability of ARIS to isolate the experiments in EXPRESS Rack 2 from minor disturbances and vibrations was analyzed in an experiment of its own called the ARIS–ISS Characterization Experiment (ICE). The final ICE report is soon to be released, and preliminary data show that ARIS helps to reduce the adverse effects of off-board vibrations to the station rack's science experiment.

The Fluids and Combustion Facility (FCF) Fluids Integrated Rack (FIR) will be equipped with ARIS on the ISS. The FIR flight rack already has the ARIS components installed with the exception of the stowed (for launch) items. ARIS operates by using sensors that detect disturbances on the ISS. When a disturbance is detected, the ARIS actuators deliver a reactive force to the rack to counter the effects detected by the sensors. In effect, ARIS acts as a shock absorber for ISS racks.

ARIS, however, is much more complex than the shock absorbers in a car. ARIS components include accelerometer assemblies that measure disturbances and send that information to the electronic unit, "push rods" that apply force against the ISS framework, and a microgravity rack barrier that prevents accidental disturbances of the ARIS rack by crewmembers.

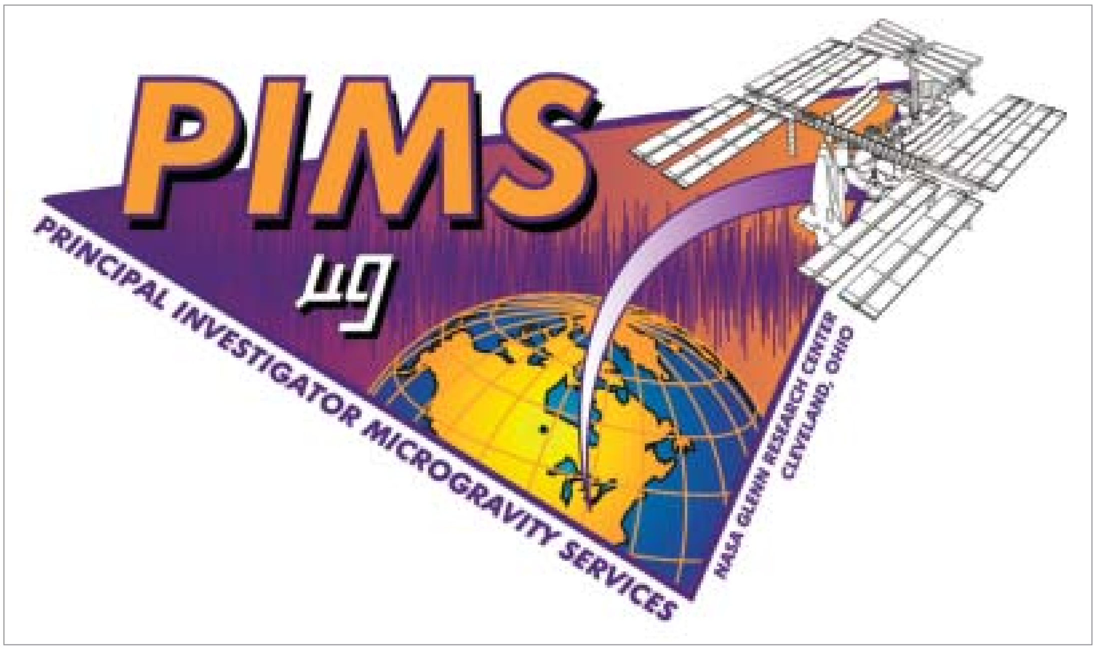
The "shock absorber" integrated into the FCF Combustion Integrated Rack (CIR), PARIS, will help attenuate disturbances seen at the CIR science locations. As "passive" in its name indicates, PARIS does not use an active control system; rather, it is mechanically less complicated than ARIS and minimizes vibrations to the rack through a spring/damper isolator system. The PARIS hardware is currently integrated into the CIR flight rack.

The Fluids and Combustion Microgravity Analyses team at Glenn Research Center in Cleveland, Ohio, has preliminary analytical data from running NASTRAN and Simulink models of the FIR with ARIS and CIR with



credit: NASA

The Active Rack Isolation System (ARIS) mitigates the disturbing effects of vibrations on the microgravity environment of the International Space Station (ISS) by absorbing the shock of motion and thereby protecting experiments from that motion. Here the ARIS-ISS Characterization Experiment (ICE) is shown in the upper left of ISS EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Rack 2. ARIS-ICE works in concert with the Space Acceleration Measurement Systems, Second Generation (SAMS-II) to characterize the vibration environment of the ISS.



credit: NASA

Principal Investigator Microgravity Services (PIMS) supplies researchers with acceleration analyses both during (in real time) and after missions. PIMS also responds to requests to analyze specific aspects of the microgravity (µg) environment from archived data.

PARIS. (NASTRAN and Simulink are software programs that allow users to analyze and manipulate data.) These analyses can be used to determine the disturbance levels at the science locations as a result of both loads on- and off-board and also the disturbance levels that the neighboring station racks will experience because of the CIR and FIR onboard disturbers. The final microgravity assessment to determine compliance with the ISS microgravity requirements for both racks is scheduled to be delivered to the ISS Payload Office at “launch minus 7.5 months.” (The CIR is currently scheduled to launch on STS-123, and the FIR is scheduled to launch on STS-126; both launch dates are under review.)

NASA expects ARIS and PARIS to play key roles in the successful completion of several biological, chemical, and physical science experiments that depend on microgravity for obtaining useful data. Through their ability to help reduce disturbances to the microgravity environment aboard the ISS, ARIS and PARIS will contribute to the advancement of scientific knowledge on Earth and to the success of the ISS as a space-based scientific laboratory.

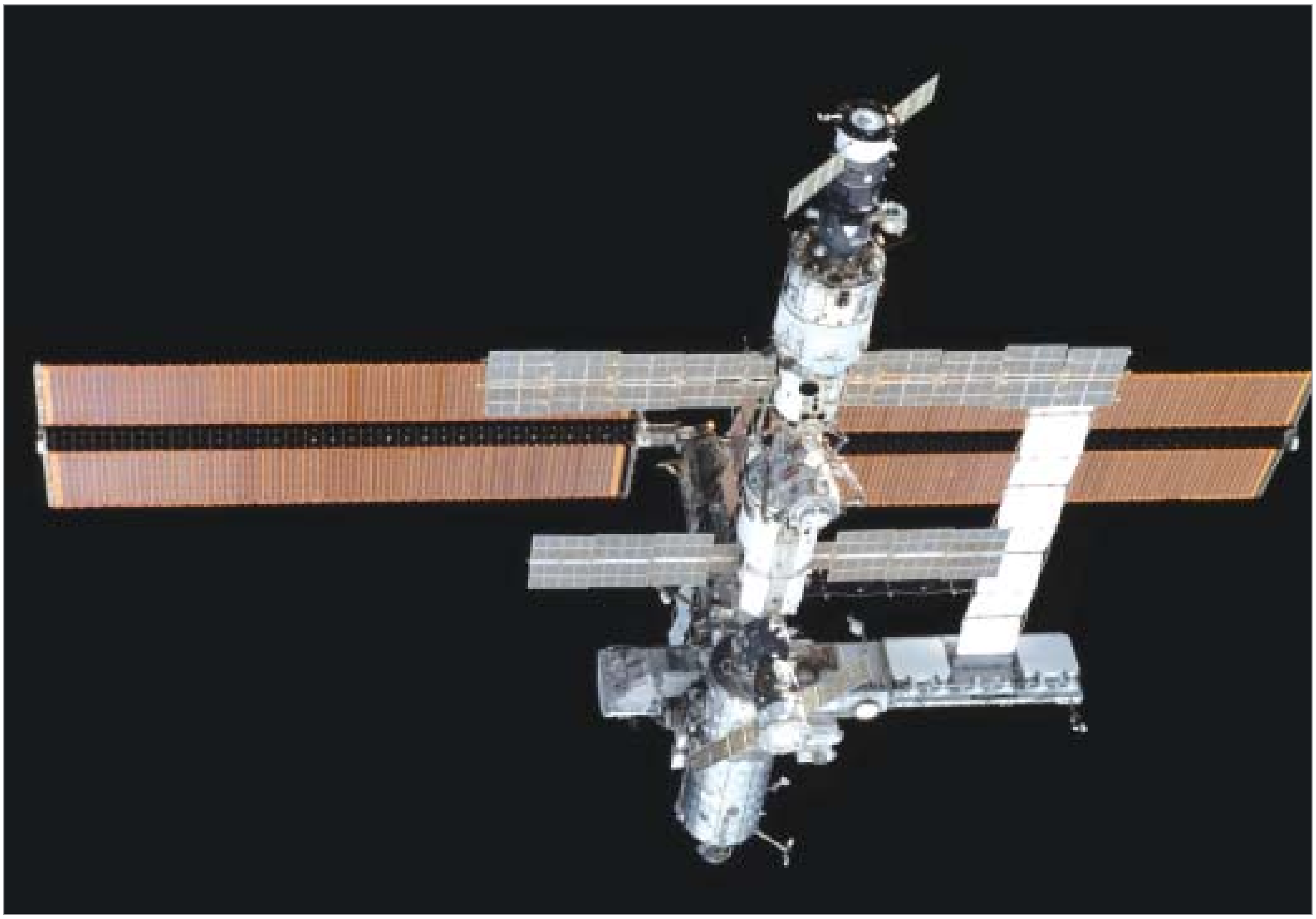
Team Develops Award-Winning Software

Innovative software developed by the Principal Investigator Microgravity Services (PIMS) team received a Space Act Award and was a first runner-up for the Software of the Year Award in 2002. In 2003, the PIMS team was awarded an R&D 100 award given by *R&D Magazine* for the 100 most technologically significant products of research and development during the year.

The new Microgravity Analysis Software System collects, archives, and processes acceleration data on a continuous, untended basis and broadcasts uninterrupted analyses of the microgravity environment over the Internet, giving principal investigators (PIs) in the International Space Statin (ISS) program and other interested parties real-time access to data. The PIMS group has developed new techniques appropriate for analyzing the vast amount of microgravity acceleration environment data being acquired from the complex ISS vehicle and its various operational modes.

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

INTERNATIONAL SPACE STATION



credit: NASA

The International Space Station (ISS) equips researchers with a permanent orbiting laboratory in which one of the fundamental forces of nature — gravity — is greatly reduced. Conducting microgravity research in this facility enables world-class scientists from various discrete fields as well as across a wide range of multidisciplinary pursuits to obtain research results that are impossible to reproduce in any other venue.

The International Space Station (ISS) is a gold mine for researchers, a permanent orbiting laboratory where gravity — a fundamental force of nature — is greatly reduced. Research conducted in this extraordinary situation enables world-class scientists from many discrete fields and across a wide range of multidisciplinary pursuits to obtain results impossible in any other venue. A permanent human presence aboard the ISS is unlikely to be any less consequential. Indeed, it should allow the enhanced understanding of fundamental scientific processes and encourage exciting new applications on Earth and in microgravity.

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

Space Station Facilities for Microgravity Research

Biotechnology Facility (BTF)

The Biotechnology Facility (BTF) is designed to meet the requirements of the science community for conducting low-gravity, long-duration biotechnology experiments. The facility is intended to serve biotechnologists from academic, governmental, and industrial venues in the pursuit of basic and applied research. Changing science priorities and advances in technology are easily accommodated by the BTF's modular design, allowing this facility to support experiments in cell culture, tissue engineering, and fundamental biotechnology.

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

The BTF project staff team was put in place early in fiscal year (FY) 2003. The science requirements, system specifications, and subrack components specifications were baselined in FY 2003. The BTF preliminary design review (PDR) in April 2003 was successful. A new task order and initiation were developed for the new bioastronautics contract on May 1, 2003. All subrack PDRs were successfully completed in summer 2003. The BTF project plan, risk management plan, and configuration plan were baselined between May and July 2003. A detailed design has been initiated and the critical design review is scheduled for early 2005.

Biotechnology research during the early phases of the ISS will be conducted using a modular accommodations rack system known as EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Racks. EXPRESS Racks will hold currently existing biotechnology equipment previously flown on the space shuttle and on *Mir*. They will also accommodate the first operation of equipment built specifically to meet ISS requirements.

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

EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Racks are the standardized payload rack systems that transport, store, and support experiments on the International Space Station (ISS). They are housed in an International Standard Payload Rack (ISPR) — a refrigerator-sized container that provides the shell for the EXPRESS Racks and supplies standard interfaces between the ISS and the payload. An EXPRESS Rack payload can be operated from the payload front panel or the EXPRESS Rack front control panel, and by the ISS crew or researchers on Earth.

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

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

The Apparatus for the Study of Material Growth and Liquids Behavior near Their Critical Point (DECLIC for *Dispositif pour l'étude de la croissance et des liquides critiques*) facility is being developed by the French space agency, Centre National d'Etudes Spatiales (CNES), in cooperation with Glenn Research Center (GRC) in Cleveland, Ohio, to provide a compact autonomous or remote controlled capability for fluids research. The facility consists of two middeck lockers that will fit into an EXPRESS Rack. It will support research on fluids near the critical point and transparent materials systems during solidification, as well as other fluids experiments that are compatible with available imaging, interferometric, and light-scattering diagnostics. Through cooperative interagency agreements signed in early 2000, NASA will provide launch, integration, and resources for DECLIC and will share in the use of the facility. During fiscal year (FY) 2003, DECLIC progressed toward its critical design review; in-orbit operations are expected to begin in 2006.

An experiment-specific insert in development for the DECLIC facility will support research into understanding flows involving binary interfaces of miscible fluids, involved in enhanced oil recovery or within porous media. The insert, known as Miscible Interface Dynamics and Simulation (MIDAS), will also aid predictive tool development and completed a requirements definition review in April 2003. Engineering "breadboard" hardware demonstrated the feasibility of fitting all fluid-handling and diagnostic capabilities needed to implement the proposed experiment within the DECLIC insert's highly constrained volume. Engineering hardware is being fabricated, and a preliminary design review is scheduled for early 2004. MIDAS is expected to be operational in January 2006.

Fluids and Combustion Facility (FCF)

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

The facility will also support experiments from science disciplines other than fluids and combustion as well as commercial and international investigations. Technical feasibility of the facility has been demonstrated, the concept has been defined, and engineering models are nearing completion. A critical design review of the facility was completed in December 2002 and will be followed by the acquisition and assembly of the flight article. More than 100 fluids and combustion experiments are planned during the life of the ISS.

With the development of the CIR, the combustion science program is working on several experiments and their associated hardware for upcoming research flights to the ISS. Detailed engineering is under way for the Multi-User Droplet Combustion Apparatus (MDCA) and the apparatus described as the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS). Each apparatus will enable several experiments to be conducted within the CIR.

The MDCA is intended for droplet combustion research and will be the first research payload in the CIR. Diesel engines, industrial turbine engines, and many other practical devices deliver fuel in droplet form to combustors, whose optimization could improve fuel efficiency and reduce pollution, among other things. Microgravity allows researchers to study spherical fuel droplets, which are much easier to model mathematically than gravitationally influenced droplets, which are tear-shaped.

The initial four research projects using the combined capabilities of the CIR and MDCA systems are the Droplet Combustion Experiment-2 by Forman Williams, University of California, San Diego; the Bi-Component Droplet Combustion Experiment by Benjamin Shaw, University of California, Davis; the Sooting and Radiation Effects in Droplet Combustion Investigation by Mun Choi, Drexel University, Philadelphia, Pennsylvania; and the Dynamic Droplet Combustion Experiment by Vedha Nayagam, Glenn Research Center (GRC), Cleveland, Ohio. Each project has completed its science definition phase and is developing the flight system to perform the science. The MDCA will also remain available for use with new droplet investigations that may be proposed in the future (multiuser hardware such as the MDCA allows effective resource use of the ISS and the CIR).

Six investigations of solid fuels will be conducted in the FEANICS apparatus within the CIR. This research is applicable to the Spacecraft Fire Safety initiative directly in that it contributes to understanding how fire starts, persists, and is extinguished in microgravity. Both thick and thin solid fuels will be studied. The FEANICS hardware contains a flow tunnel for testing fuels at various flow velocities and directions. Within the flow tunnel are several fuel carousels, which are used to introduce fuel samples, one at a time, into the tunnel for combustion testing.

The first six FEANICS investigations are Forced Ignition and Spread Test by Carlos Fernandez-Pello, University of California, Berkeley; Radiative Enhancement Effects on Flame Spread by Paul Ronney, University of Southern California, Los Angeles; Analysis of Thermal and Hydrodynamic Instabilities in Near-Limit Atmosphere by Indrek Wichman, Michigan State University, East Lansing;

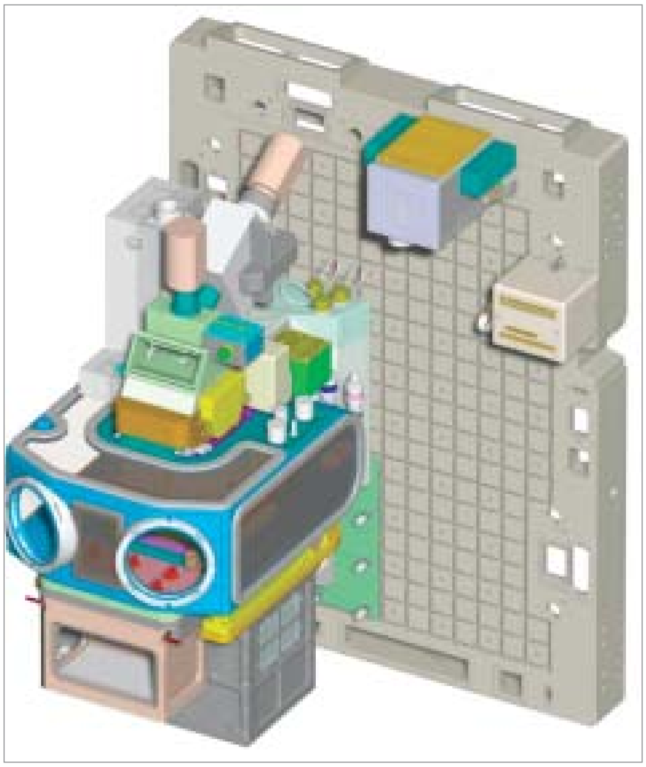
Transition from Ignition to Flame Growth under External Radiation in Three Dimensions by Takashi Kashiwagi, National Institute of Standards and Technology, Gaithersburg, Maryland; Solid Inflammability Boundary at Low Speed by James Tien, Rensselaer Polytechnic Institute, Troy, New York; and Smolder, Transition, and Flaming in Microgravity by Carlos Fernandez-Pello.

Of these experiments, the first five have completed their flight definition peer reviews, but the sixth, which entered the program more recently, is still a candidate for review. FEANICS itself is currently in the engineering model development phase. A three-sided carousel has been built and tested, and two other carousel designs are being fabricated. The next stage will be to test the design and build the flight hardware.

After the FEANICS investigations are completed, the Combustion Science Program will expand into gaseous combustions, addressing flame design, clean flames, and spherical flames. Presently, 14 combustion investigations are to be conducted within the CIR by 2011, with possibly an additional four or more sponsored and developed by commercial and international partners.

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

The GFM will provide three experiment shear apparatuses: a multispeed low–/high–frame rate camera; the ability to supply and remove the spheres used to model granular flow; and systems to control the rotation of the boundaries, stress measurement, and nitrogen flow. It also will allow for in-orbit operations through imbedded software. The software will control experiment operations, data collection, and data transfer to Earth and will also allow for ground control. In-orbit reconfiguration and maintenance that can support follow-on experiments will also be possible.


credit: NASA

The Light Microscopy Module (LMM) will be the first payload integrated into the Fluids Integrated Rack (FIR) aboard the International Space Station and will remain in the FIR for 2 years. The automated, remotely controllable microscope for experiments in complex fluids will conduct five fluid physics experiments. Here, the LMM bench is shown installed on the FIR optics bench in the "open" position.

The ISS and the FIR will provide many significant functions and resources to the GFM. The ISS will provide the space platform and communication to ground for the FIR. The FIR supplies an environmentally controlled space, an optic bench, power, cooling fluid and gas, vacuum exhaust, avionics, image processing, data storage, and additional science diagnostic hardware. The GFM facility is designed to minimize vibration transmission to the experiment shear apparatus, the FIR, and the ISS as well as to minimize crew time, power requirements, and mass.

The Light Microscopy Module (LMM) will be the first payload integrated into the FIR aboard the ISS; it will be installed once it arrives on the ISS and will remain in the FIR for 2 years. An automated, remotely controllable microscope for experiments in complex fluids, the LMM is designed to conduct five fluid physics experiments. It is planned as a subrack facility, allowing flexible scheduling and operation of fluids and biotechnology experiments.

The fluid physics experiments that will be conducted in the LMM by various principal investigators (PIs) are the Constrained Vapor Bubble Experiment by Peter Wayner, Rensselaer Polytechnic Institute, Troy, New York; Physics of Hard Spheres Experiment-2 by Paul Chaikin, Princeton University, New Jersey; Physics of Colloids in Space-2 by David Weitz, Harvard University, Cambridge, Massachusetts; Low-Volume-Fraction Entropically Driven Colloidal Assembly by Arjun Yodh, University of Pennsylvania, Philadelphia; and Micromechanics of Magnetorheological Fluids by Alice Gast, Massachusetts Institute of Technology, Cambridge.

The LMM flight unit features a commercial Leica RXA microscope modified to operate automatically with some interaction from the ground support staff or the astronaut crew. A researcher can choose from six objective lenses of different magnifications and numerical apertures to obtain the required science data. In addition to video microscopy techniques used to record sample features such as basic structures and crystal growth dynamics, enhancements to the microscope provide the following additional capabilities:

- interferometry to measure the thin-film thickness of vapor bubbles,

- laser tweezers for manipulating and patterning sample particles,

- confocal microscopy to visualize sample structures in three dimensions, and

- spectrophotometry to measure photonic properties.

This suite of measurements allows a very broad characterization of fluids, colloids, and two-phase media, including biological samples. The LMM will use cameras and light sources provided by the FIR to apply these imaging techniques.

Also supplied to the LMM by the FIR rack will be power, communications, air and water cooling, vacuum exhaust, avionics, image processing, data storage, and added science diagnostic hardware. The LMM will be installed while the ISS is in orbit and will remain in the FIR for 30 months, performing five separate fluid physics experiments. Other LMM capabilities make it useful for fundamental space biology and cellular biotechnology research. GRC has developed memoranda of agreement with Ames Research Center (the center responsible for the Fundamental Space Biology Program), Moffett Field, California, and Johnson Space Center (JSC; responsible center for the Cellular Biotechnology Program), Houston, Texas, to study and communicate potential use of the LMM in support of their respective research programs.

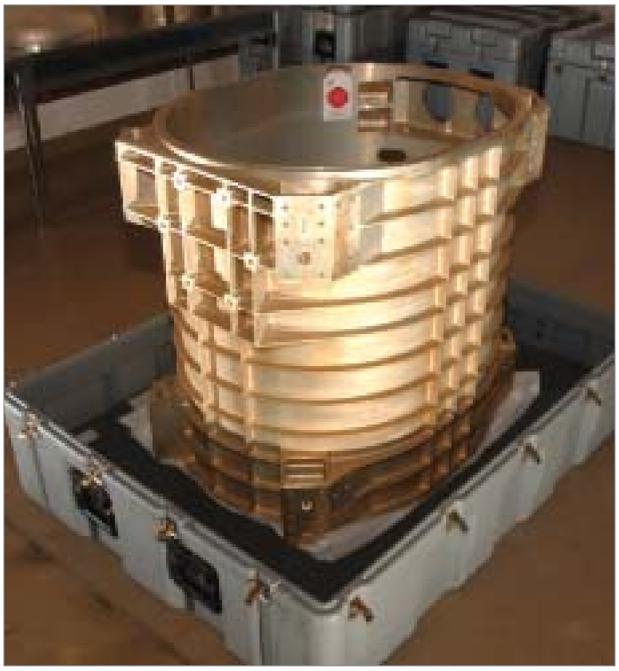
Vibration disturbances were identified as possibly contaminating the microgravity environment for science experiments in the LMM. Accordingly, an integrated FIR-LMM test was conducted at GRC's Acoustics Laboratory in FY 2003 to assess mechanical sources of vibration and their effect on microscopic imaging. The test's main purpose was to characterize the LMM response at the sample location — the X–Y stage within the microscope — to vibrations emitted by the FIR and LMM support structures. Initial measurements indicated that the fans in the Air Thermal Control Unit were the main cause of disturbance in microgravity. Additional data assessment is ongoing.

Low-Temperature Microgravity Physics Facility (LTMPF)

The Low-Temperature Microgravity Physics Facility (LTMPF) is a complete cryogenic laboratory that will be attached to the Japanese Experiment Module–Exposed Facility (JEM-EF) on the International Space Station (ISS). The LTMPF consists of a helium dewar with two instrument inserts, each of which can support multiple experiments. The facility is designed for studies of low-temperature (as low as 1.6 kelvins; -457 ^{o}F) and condensed matter physics.

In February 2003, a decision was made to replace the Microgravity Scaling Theory Experiment (MISTE) instrument with the Superconducting Microwave Oscillator (SUMO) instrument for the first flight of the facility. SUMO was originally scheduled for the facility's second flight, but the instrument change was made to broaden the science return of the first flight. A successful requirements definition review for SUMO was held in August 2003.

The LTMPF project made significant progress in modifying and finalizing the critical design of the facility subsystems for its first mission. In preparation for a system critical design review (CDR), the project successfully held a series of technical peer reviews for all subsystems and the Critical Dynamics in Microgravity Experiment (DYNAMX) instrument during July and August 2003. The peer reviews were thorough and in-depth, validating critical designs in all key areas and examining the plans and readiness for flight fabrication, integration, and testing. The systems CDR was successfully conducted in September 2003. Good progress has been made on schedule-critical hardware developments, with completion of flight dewar machining and welding, engineering model



credit: NASA

The Low-Temperature Microgravity Physics Facility (LTMPF) is a complete cryogenic laboratory that will be attached to the Japanese Experiment Module–Exposed Facility (JEM-EF) on the International Space Station. It consists of a helium dewar with two instrument inserts, each of which can support several experiments. Shown here is the vacuum shell for the LTMPF, which is designed for studies of low-temperature (as low as 1.6 kelvins; -457 °F) and condensed matter physics.

computer and key electronics boards and solid progress made in areas of instrument sensor packages and common flight hardware, such as Superconducting Quantum Interference Device (SQUID) sensors.

The 2-year delay of the JEM-EF launch and a subsequent budget reduction to the LTMPF had an adverse impact on the development schedule. Several flight developments were scaled back, and the project was replanned to accommodate the new budget and schedule. The project is now set to deliver its flight hardware in August 2007. Additional options for attaching the LTMPF to the International Space Station are also being considered.

Materials Science Research Rack-1 (MSRR-1)

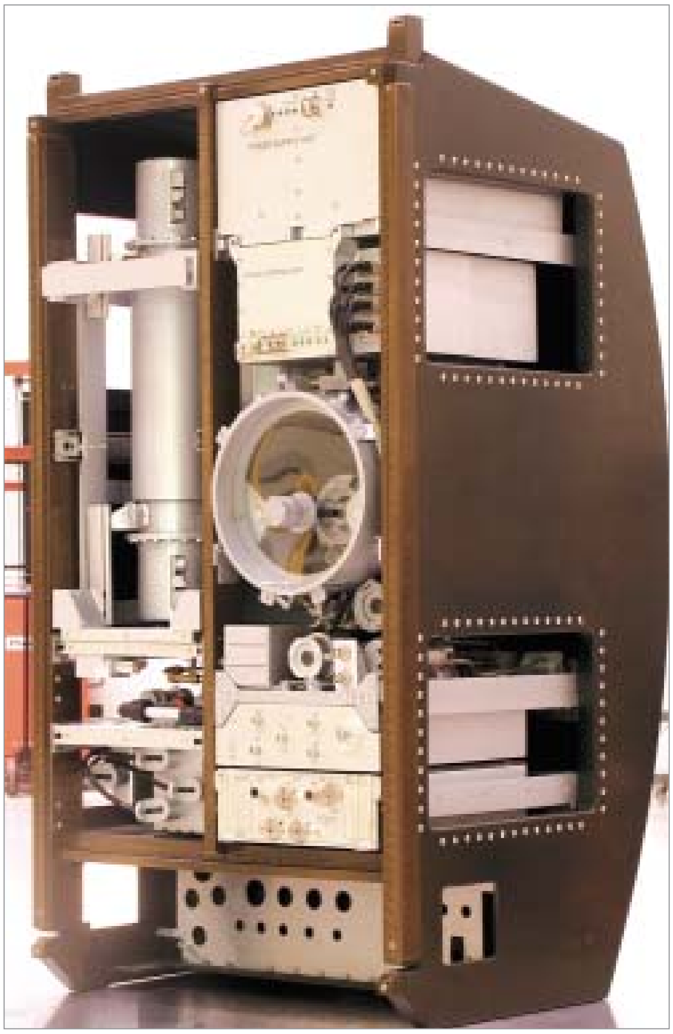
The Materials Science Research Rack-1 (MSRR-1) is being developed to provide a flexible, permanent platform in the Destiny laboratory module of the International Space Station (ISS) dedicated to investigations in materials science. This facility will support research on a range of materials, including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

The first experiment module planned for use in the MSRR-1 is the Materials Science Laboratory (MSL), which is being developed by the European Space Agency (ESA). Occupying about one-half of the rack, the MSL module will be integrated into the MSRR-1 unit in the first quarter of 2004. The MSL will accommodate materials processing inserts that contain experiment-specific hardware.

NASA is building a furnace for the MSL called the Quench Module Insert (QMI). This high-temperature, Bridgman-type furnace will have an actively cooled cold zone. It is being designed to create an extremely steep temperature gradient for the directional solidification processing of metals and alloys. Directional solidification is a process by which a long, thin sample is melted, then slowly solidified, starting at one end of the ampoule and proceeding to the other. The technique is useful for studying the solidification behavior of materials and for the growth of high-quality single crystals.

The QMI also has a feature known as quench capability that allows the furnace to rapidly freeze the sample at the liquid–solid interface, where most of the interesting science takes place during directional solidification. Quenching preserves this liquid–solid interface so that when the samples are returned to Earth, scientists can examine the interface carefully and develop models that recreate and explain exactly what was happening during solidification.

In addition, ESA is developing two module inserts for the MSL: the Low Gradient Furnace (LGF) and the Solidification and Quenching Furnace (SQF). Both furnaces can accommodate processing temperatures up to 1,600 °C (2,912 °F). The LGF is primarily intended for crystal growth experiments in which directional solidification



credit: NASA

With its modular design, the Materials Science Research Rack-1 (MSRR-1) facility will provide a comprehensive, collaborative, international research tool for advanced materials research. It will support research on a range of materials, including metals and alloys, glasses, electronics, ceramics, polymers, and other special-purpose materials. The MSRR-1 will be made up of experiment modules and module inserts that can be delivered to the International Space Station (ISS) by the space shuttle, then integrated and exchanged by crew members aboard the ISS.

processing needs precise temperatures and control of translation speed; the SQF will be used for metallurgical experiments requiring large thermal gradients and rapid quenching of samples. Additional module inserts can be developed and processed over the lifetime of MSL and MSRR-1.

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

Microgravity Science Glovebox (MSG)

In the Microgravity Science Glovebox (MSG) facility, scientists from several disciplines can participate actively in the assembly and operation of experiments in microgravity with much the same degree of involvement they have in their own research laboratories. Developed by the European Space Agency (ESA) and integrated by Marshall Space Flight Center (MSFC), Huntsville, Alabama, the MSG was launched to the International Space Station (ISS) in June 2002. The facility offers an enclosed work area accessible to the crew through sealed glove ports and to ground-based scientists through real-time data links and video. Because the MSG work area can be sealed and held at a negative pressure, the crew can manipulate experiment hardware and samples without the risk of small parts, particulates, fluids, and gases escaping into the open laboratory module.

For conducting investigations, each experiment apparatus is mounted to the floor of the MSG working area (approximately 90 by 50 centimeters [36 by 20 inches]) and connected on the back wall to standard utilities such as power, communications, nitrogen, vacuum, and computer interfaces. The work area unit is designed to slide forward on rails that can extend out of the volume of the rack. This extension forms an enclosed “tabletop” for experiment containment and operation.

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

To facilitate use of the MSG by the scientific community, MSFC maintains an active group of managers, engineers, and support personnel to assist investigators with the complex task of building and operating an experiment in space. ESA completed construction of the MSG in 2001, and the facility was subsequently launched and integrated into the ISS. Before the end of fiscal year (FY) 2003, the unit had been successfully used to complete a series of NASA science experiments in two materials investigations (Solidification Using a Baffle in a Sealed Ampoule [SUBSA] and the Pore Formation and Mobility Investigation [PFMI]) and an important fluids investigation (Investigating the Structure of Paramagnetic Aggregates from Collodial Emulsions [InSPACE]).

ESA also used the facility during the year to support science and commercial programs on the ISS, conducting a series of investigations during the periodic visits of European crewmembers on the Russian Soyuz flights. In all cases, the teamwork concept inherent in the MSG design demonstrated that the scientific return is enhanced when the crew and scientists can easily interact.

For future MSG experiments that are particularly sensitive to low-level vibrations, the new Glovebox Integrated Microgravity Isolation Technology (g-LIMIT) apparatus is in its final phases of development and testing. After the g-LIMIT unit has been delivered to the ISS and has completed in-orbit characterization and testing, vibration-sensitive experiments will be mounted on an electromagnetically levitated top plate of the g-LIMIT unit. Specially designed “umbilical cords” will connect experiments to the MSG utilities.

Additional experiments sponsored by NASA and ESA are planned when the space shuttle returns to flight. New experiments will extend the use of the MSG unit to other disciplines, including biotechnology.

Schedule of Flights

Approximately 30 flight opportunities have been planned to date for the delivery of the Destiny laboratory module of the International Space Station (ISS) and its components (including the microgravity facilities described under “Space Station Facilities for Microgravity Research”), the use of the ISS for microgravity experiments, and the delivery of modules and racks developed by NASA and its international partners.

After the loss of Space Shuttle *Columbia* (STS-107) in February 2003 and during the halt on space shuttle flights that followed, microgravity payloads continued to fly to the ISS on Russian Progress vehicles. A list of milestones, flights, and dates significant to the microgravity program are listed in Table 6. Descriptions of flight hardware to support microgravity experiments are listed in the appendix.

Table 6 — ISS Flights Significant to the Microgravity Program

Milestone	Assembly Flight	STS Flight	Launch Date
U.S. Destiny Laboratory Delivery	5A	STS-98	February 2001
U.S. Destiny Laboratory Outfitting	5A.1	STS-102	March 2001
First two EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Racks, Microgravity Capability	6A	STS-100	April 2001
Phase Two Complete	7A	STS-104	July 2001
U.S. Destiny Laboratory Outfitting, Two Additional EXPRESS Racks	7A.1	STS-105	Aug 2001
Utilization Flight	UF-1	STS-108	Dec 2001
Microgravity Science Glovebox (MSG) Rack	UF-2	STS-111	June 2002
Russian Progress Flight	12P		Aug 2003
Russian Progress Flight	13P		Jan 2004
Russian Progress Flight	14P–17P		Under Review
Logistics Flight, Space Shuttle Return to Flight	LF-1	STS-114	Under Review
European Space Agency (ESA) Automated Transfer Vehicle	ATV-1		Under Review
First Utilization and Logistics Flight	ULF-1.1	STS-121	Under Review
SPACEHAB Flight, Continued U.S. Destiny Laboratory Outfitting	12A.1	STS-116	Under Review
SPACEHAB Flight, Continued U.S. Destiny Laboratory Outfitting	13A.1	STS-118	Under Review
International Space Station (ISS) U.S. Core Complete, Node 2	10A	STS-120	Under Review
Utilization & Logistics Flight, Sixth EXPRESS Rack	ULF-2	STS-122	Under Review
ESA Laboratory (Columbus Module)	1E	STS-123	Under Review
Utilization Flight, Combustion Integrated Rack (CIR)	UF-3	STS-125	Under Review
Utilization Flight	UF-4	STS-126	Under Review
Utilization Flight, Fluids Integrated Rack (FIR), First Materials Science Research Rack (MSRR-1)	UF-5	STS-127	Under Review
Utilization Flight, Express Pallet-1, Alpha Magnetic Spectrometer (AMS)	UF-4.1	STS-128	Under Review
Utilization Flight	UF-6	STS-129	Under Review
Express Pallet-2	1J/A	STS-130	Under Review
Japanese Experiment Module (JEM) Laboratory	1J	STS-131	Under Review
Utilization and Logistics Flight, Biotechnology Facility (BTF)	ULF-3	STS-132	Under Review
Utilization Flight	UF-7	STS-135	Under Review
JEM–Exposed Facility (JEM-EF)	2J/A	STS-136	Under Review
Utilization and Logistics Flight, Seventh EXPRESS Rack	ULF-5	STS-137	Under Review
EXPRESS Pallet-3, Low-Temperature Microgravity Physics Facility (LTMPF)	14A	STS-138	Under Review

GROUND-BASED MICROGRAVITY RESEARCH SUPPORT FACILITIES

credit: NASA

A modified KC-135 turbojet transport is NASA's primary aircraft for ground-based reduced-gravity research. Low-gravity conditions can be obtained for about 18–25 seconds as the aircraft traces a parabolic trajectory, which begins with a shallow dive to increase air speed, followed by a rapid climb (shown here) at up to a 45° to 50° 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° downward angle.

Reduced-Gravity Facilities

Throughout fiscal year (FY) 2003, NASA's ground facilities for reduced-gravity research remained highly productive. These facilities included KC-135 parabolic flight aircraft, the 2.2-Second Drop Tower, and the Zero-Gravity Research Facility. Overall, the reduced-gravity facilities at Glenn Research Center (GRC), Cleveland, Ohio, and Johnson Space Center (JSC), Houston, Texas, have supported numerous investigations addressing several processes and phenomena in several research disciplines. In those facilities, microgravity, a state of apparent weightlessness, can be created by executing a freefall or semi-freefall condition in which the force of gravity on an object is offset by its linear acceleration during the fall — say, 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 interval has been found to be sufficient to advance the scientific understanding of many phenomena. For one thing, experiments in a low-gravity environment can enable new discoveries and new fundamental insights into science. For another, 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. And as a matter of course, experiments scheduled to fly on the space shuttle and the International Space Station (ISS) are frequently tested and validated in the ground facilities before being launched. Table 7 lists the number of experiments supported and the number of drops or trajectories completed in each of the ground-based microgravity facilities.

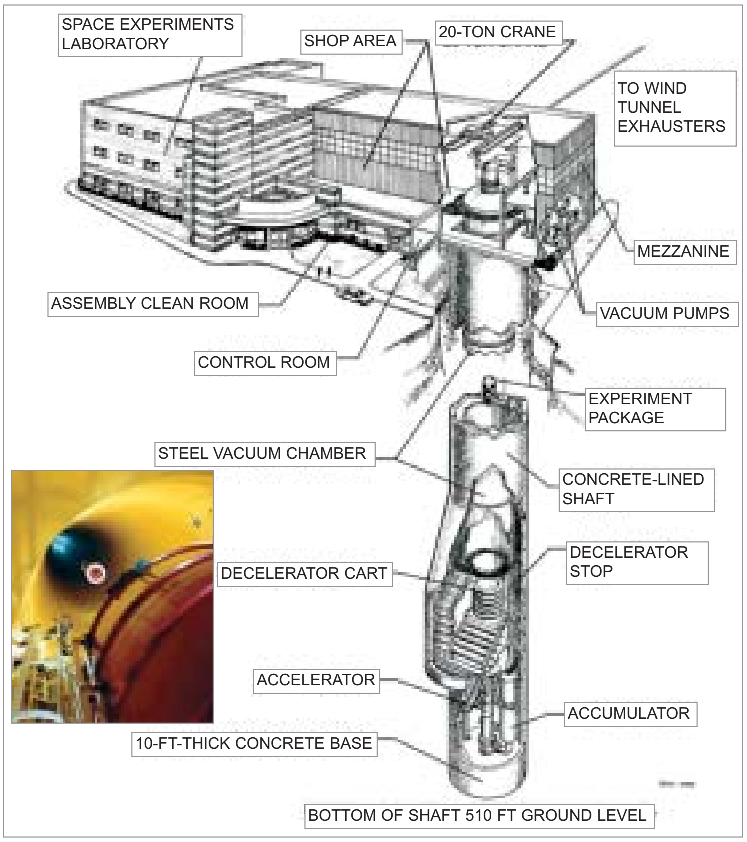
JSC's KC-135 is NASA's primary aircraft for ground-based reduced-gravity research and is the only facility that can provide partial-gravity environments like on the Moon or Mars. The KC-135 can accommodate several experiments during a single flight. Low-gravity conditions

Table 7 — Use of Ground-Based Low-Gravity Facilities in FY 2003

	KC-135	2.2-Second Drop Tower	Zero-Gravity Research Facility
Investigations Supported	48	27	5
Drops or Trajectories	1,783	1,026	153
Flight Hours	94	N/A	N/A

can be obtained for approximately 18–25 seconds as the aircraft traces a parabolic trajectory. A shallow dive to increase air speed is followed by a rapid climb at up to a 45° to 50° 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° downward angle. During the parabola, the plane plunges about 1,800 meters (approximately 6,000 feet). More than 50 parabolas can be performed in a single flight. In FY 2003, 48 experiments were performed during 1,738 trajectories and 94 flight hours. Of the 48 experiments supported, 18 were combustion experiments, 20 were fluid physics experiments, 3 were materials science experiments, and 7 were biomedical experiments.

The GRC 2.2-Second Drop Tower offers a shorter test time than the KC-135, but its simple mode of operation and normal throughput capacity of 12 tests per day make it an attractive and highly used test facility, particularly for performing evaluation and feasibility tests. The drop tower provides gravitational levels that range from 1 percent of Earth’s gravitational acceleration to 0.01 percent. More than 23,300 tests have been performed in the drop tower to date.



credit: NASA

The Zero-Gravity Research Facility, a U.S. registered national historic landmark, provides a quiescent low-gravity environment of 5.18 seconds as experiments are dropped 132 meters (432 feet) inside of a vacuum chamber. The inset shows the drop vehicle as it approaches the landing zone.

Reduced-gravity conditions in the drop tower are created by letting an experiment, with its hardware isolated within an enclosure known as a drag shield, fall freely through 24 meters (79 feet) in an open environment. Twenty-seven experiments were supported during 1,026 drops performed in FY 2003. As in the past, several of these experiments supported the development of research that will be conducted in space. The steady use of the drop tower is expected to continue because many new experiments are in the design and fabrication phases of development for the coming years.

The Zero-Gravity Research Facility, a U.S. registered national historic landmark, provides a quiescent low-gravity environment of 5.18 seconds as experiments are dropped 132 meters (432 feet) inside of a vacuum chamber. Aerodynamic drag on the freely falling experiment is nearly eliminated by dropping it in a vacuum of 0.01 torr. The complexity of facility operations limits testing to at most two drops per day, so that fewer projects can be supported than in the 2.2-Second Drop Tower. However, the longer test duration and lowest gravity levels of any of NASA’s ground-based facilities compensate for the lower experiment throughput rate. In FY 2003, 153 drops were conducted to support five major projects. Many of these drops supported the development of two ISS flight experiments: Radiative Enhancement Effects on Flame Spread (REEFS) and Analysis of Thermal and Hydrodynamic Instabilities in Near-limit Atmosphere.

Improvements to the Zero-Gravity Research Facility implemented in FY 2003 included upgrades to the drop vehicle balance stand and the deceleration material handling system and modernization of the facility control room. Other facility highlights included the development of new Web pages, accessible through both the Glenn Research Facilities Portal and the Glenn Microgravity Science Division home page, and the use of the facility for the shooting of the NASA Connect episode, “Measurement, Ratios, and Graphing: Who Added the ‘Micro’ to Gravity?”

OUTREACH AND EDUCATION

credit: NASA

Physicist and former astronaut Roger Crouch poses with students at the opening of the NASA @ Your Library exhibit at the Enoch Pratt Free Library in Baltimore, Maryland.

Spreading the word about what microgravity researchers do and why they do it is vital to the strength and perceived relevance of NASA's science program. Therefore, the Physical Sciences Research (PSR) Division targets a broad audience with its education and outreach efforts. Included in that audience are researchers


credit: Phil Hunter

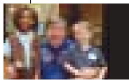
Students in Phil Hunter's eighth-grade physical science class at Johnson Middle School, Westminster, California, learn how to tackle scientific experiments through the Caltech Precollege Science Initiative (CAPSI). Here, students are hard at work writing reflections in their science logs during the unit titled "Matter and Forensic Chemistry." A key element of the CAPSI program is the integration of investigation, reflection, and participation.

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 various educational settings, and last but certainly not least, the general public.

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

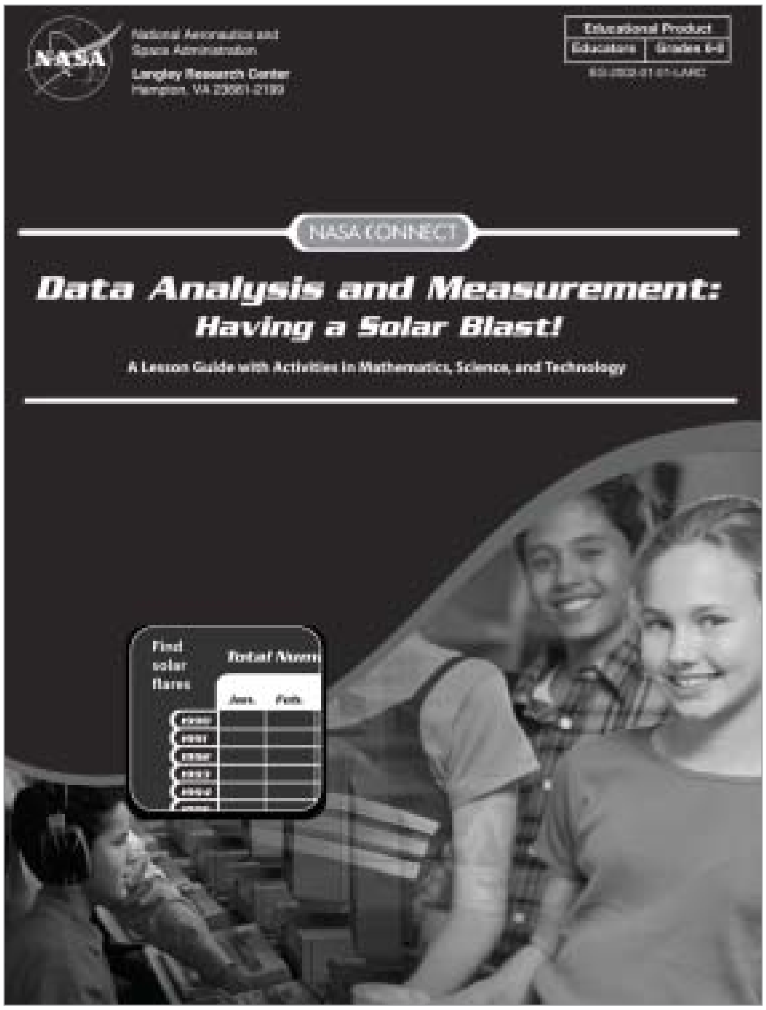
credit: NASA

What more glorious memento could you have of a NASA event than a picture of yourself in a space suit? The Picture Yourself in Space photo booth visited the Inventing Flight: Dayton Air Show 2003, a celebration of 100 years of powered flight. Glenn Research Center's director, Julian Earls, beams at passers-by out of his very own postcard.



Program Summary

The education and outreach team that promotes microgravity research in the physical sciences is as vigorous as ever in communicating how this research mission benefits life on Earth and advances the prospects of long-term human exploration of space. In fiscal year (FY) 2003, this program supported 15 major educational, scientific, and public outreach conferences with speakers, materials, and exhibits. Some events supported include the World Space Congress, National Manufacturing Week, and the 2003 AARP (formerly known as the American Association of Retired Persons) National Event & Expo. Team members also made many visits to schools, museums, and science centers throughout the country.



National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-2199

Educational Product
Educators

NASA CONNECT

Data Analysis and Measurement:
Having a Solar Blast!

A Lesson Guide with Activities in Mathematics, Science, and Technology

credit: NASA

The NASA CONNECT education series' program Measurement, Ratios, and Graphing: Who Added the "Micro" to Gravity? won a 2003 Emmy Award for Children's Programming. In the program, students learn about microgravity and are introduced to combustion science and fire safety as related to the International Space Station. They also learn about materials science and its importance to microgravity research. Shown is the educator's guide that complements the program.

The PSR Division's Outreach and Education Program made efforts to honor the crew of Space Shuttle *Columbia* (STS-107). For example, the Office of Biological and Physical (OBPR) and Public Affairs created a video titled *The Legacy of STS-107*. The video features research accomplishments and highlights from STS-107.

Major national educator conferences give NASA the opportunity to demonstrate new ways to teach students why microgravity matters. More than 75,000 kindergarten through grade 12 (K–12) teachers and administrators attended the five annual meetings of the National Science Teachers Association, the National Council of Teachers of Mathematics, the International Technology Education Association, the National Association of Biology Teachers, and the American Association of Physics Teachers. All five meetings featured booths staffed by PSR Division personnel. Many valuable products were distributed to teachers at these conferences: microgravity science and mathematics posters, teacher's guides, mathematics briefs, microgravity demonstrator manuals and technology guides, microgravity mission and science lithographs, and lists of microgravity resources on the Internet.

The K–12 Educational Outreach Program of the National Center for Microgravity Research (NCMR) and the Microgravity Science Division (MSD) of Glenn Research Center (GRC), both in Cleveland, Ohio, led teacher workshops on original educational materials and products not only at GRC but also at regional workshops, national educator conferences, and special events. In addition, MSD and NCMR worked together with the GRC Education Program Office (EPO) to support workshops for EPO teacher programs, such as NASA Explorer Schools. NCMR also worked closely with the Educator Resource Center and the Speakers Bureau at GRC.

The NCMR K–12 Educational Outreach Program held several workshops that featured its educator's guides *Amusement Park Physics with a NASA Twist, How High Is It?, NASA Student Glovebox*, and *Science in a Box*. NCMR published the *Amusement Park Physics with a NASA Twist* guide in FY 2003. This unique guide for middle school educators "hooks" students on NASA's link to amusement park rides and contains worksheets for seven rides found at most amusement parks. The guide also includes 2 weeks' worth of classroom activities and labs to prepare students to gather data at the park. (For more information on *Amusement Park Physics with a NASA*

Twist, see the Highlight “Taking a Spin with Microgravity” on p. 116.)

Other workshops instructed educators in using the microgravity demonstrator and in teaching about space station science and astronaut training. The demonstrator is a portable tool designed by NASA engineers to convey the principles of microgravity science. It can be taken to classrooms, museums, conferences, and other events. Several scenarios have been designed for the demonstrator so that observers can clearly see what happens to an object or substance during freefall. The demonstrator has a support structure that allows for a drop of at least 2 meters (6.6 feet). A carrier, attached to a rope, has a small charge-coupled device (CCD) camera within it that sends the video signal to a small monitor. The carrier can host a variety of subjects, from magnets to candle flames, each illustrating the effects of microgravity.

This year, more than 5,000 people had the chance to observe and use the microgravity demonstrator. NASA engineers and the microgravity outreach team ran the device at many locations and events in and around Cleveland, Ohio (classrooms, the Great Lakes Science Center, Physics Day at Cedar Point, and Physics Day at Six Flags World of Adventure), as well as a bit farther away (AirVenture in Oshkosh, Wisconsin, and the U.S. Air Force Museum in Dayton, Ohio, celebrating the Centennial of Flight). Another version of the demonstrator, called the wireless drop tower, uses a wireless camera and a laptop with video-editing software for slow-motion playback. This version is also portable and can display the action on any type of monitor (for example, liquid crystal display [LCD], TV, high-definition TV).

The University of Montana hosted the 2003 Office of Biological and Physical Research (OBPR) Strategic Planning Retreat in Missoula, Montana, November 18–21, 2003. Mary Kicza, associate administrator for OBPR, stressed the importance that NASA Administrator Sean O’Keefe and the U.S. Congress attached to the space agency’s ability to inspire a new generation of explorers through education; she noted that they have also recognized that education is part of NASA’s core mission. OBPR workshops were held to determine how to better reach the underserved public in the northwestern region of the country. A public outreach workshop, held on the Tuesday evening of the retreat, drew approximately 500 people. Around 250 people, some of whom traveled several hundred miles to participate, attended the education workshop, held on Thursday evening.

The mock-up of the International Space Station (ISS) U.S. Laboratory Destiny module was exhibited at National Manufacturing Week, held in Chicago, Illinois, March 3–6, 2003. The module drew attention at the National Manufacturing Conference, a public outreach event held during the week that targeted industrial and business audiences. More than 3,500 photographs were taken and distributed from the Picture Yourself in Space photo booth. Attendance at the event was estimated at 20,000 people.

More than 17,000 people attended the 2003 AARP National Event & Expo, held September 5–7, 2003, in Chicago, Illinois. The PSR Division’s exhibit area featured a 6.1-meter (20-foot) OBPR mural, the popular photo booth, and PSR-targeted handouts.

A very popular outreach tool, the Picture Yourself in Space photo booth was developed at Glenn Research Center (GRC), Cleveland, Ohio. Traveling to many outreach events, the photo booth produced more than 49,000 pictures in FY 2003 alone. The tremendous success of the exhibit is evidenced by the number of NASA centers and other groups that have duplicated this effort. Another plus is that anyone can easily be photographed, no matter their age, size, or ability.

On March 29 and 30, 2003, the PSR outreach team had an exhibit at the Centennial of Flight event at the Huntsville Air Show, Huntsville, Alabama. More than 800 visitors got the chance to see a liquid metals demonstration and interact with a classroom glovebox structurally similar to the Microgravity Science Glovebox on the ISS. An estimated 4, 000 people attended the show.

The MSD also supported the year-long Centennial of Flight celebration of the Wright Brothers’ first powered flight. Seven events were supported with the Picture Yourself in Space photo booth, and more than 35,000 photographs were taken during these events alone. The ISS U.S. Laboratory Destiny module mock-up traveled to Inventing Flight: Dayton 2003, a 17-day event in Dayton, Ohio, July 3–20, 2003, and to the Los Angeles County Fair in Pomona, California, a 16-day exhibit held September 12–28, 2003. The thousands of people who explored the module must have left with a better idea of what the ISS is really like on the inside. Many of them carried off a photograph of themselves dressed in an astronaut suit.

The PSR outreach team celebrated Space Day 2003 at Fort Payne High School, located in rural Alabama about 60 miles east of Marshall Space Flight Center (MSFC), Huntsville, Alabama. A total of 175 students from nine classes interacted with the wireless drop tower and learned how freefall influences the behavior of fluids,

credit: NASA

Fiscal year 2003 was the third year that the Dropping in a Microgravity Environment competition was held. Teams from high schools across the country apply to perform an experiment in the 2.2-Second Drop Tower at Glenn Research Center, Cleveland, Ohio. This team from Troy Athens High School, Troy, Michigan — one of the four winning teams in 2003 — submitted a proposal and experiment called Buoyancy in Microgravity.

flames, and magnets. The hands-on lecture included demonstrations of diffusion and convection as well as a multimedia presentation about microgravity and research conducted on the ISS.

The wireless drop tower also starred on the Public Broadcasting Service (PBS) television program called *DragonFly TV*. On the show, students looked at the effects of freefall on the movements of fizzing bubbles, a pendulum, and a wind-up toy.

The *Structures of Life* booklet, originally published in November 2000, now includes a new chapter dedicated to protein and virus crystallography in microgravity. Written in collaboration with NASA and the National Institutes of Health by Alexander McPherson, University of California, Irvine, the chapter highlights macromolecular crystallography in microgravity and depicts ground- and space-grown crystal images. It also profiles a teacher who participated in NASA biological crystallography outreach activities. The document was revised in June 2003.

The *Space Research* newsletter, as in the past, reaches thousands of K–12 teachers, curriculum supervisors, science writers, scientists, principal investigators, and technology developers, among others. Each issue includes a feature on a topic important to the entire enterprise; a research update for each division; short pieces on special events or awards; a list of meetings, research announcements, and selections; and a profile of a member of OBPR's research community. At the end of FY 2003, the distribution for each issue totaled about 24,500 copies, which is an increase of 20 percent over the average for FY 2002. *Space Research* has a subscriber base of 10,550 and is mailed to 38 countries. Archived issues of *Space Research*, *Microgravity News*, and other OBPR publications are available from *http://spaceresearch.nasa.gov/general_info/prespublic.html#newsletters*.

Several of the programs and products produced by MSD and NCMR have been featured in articles published on the Web and in journals. The PBS Web site (*http://www.pbs.org*) showcased the NASA Student Glovebox, the first NASA educational product highlighted on the site. An article about the competition Dropping in a Microgravity Environment (DIME), for high school-aged students, appeared in the December 2002 issue of the *Space Research* newsletter. In May 2003, "Defying Gravity" was a top article on the NASA Portal (*http://www.nasa.gov/ externalflash/m2k4/index1.html)*. The subject was GRC's involvement in "Physics Day" events at amusement parks. NASA connections to amusement park rides were described, and *Amusement Park Physics with a NASA Twist*, a new middle school educator's guide, was highlighted.

In 2003, the NASA CONNECT education series' program Measurement, Ratios, and Graphing: Who Added the "Micro" to Gravity? won an Emmy Award for Children's Programming. In the program, students learn about microgravity and are introduced to combustion science and the importance of fire safety on the ISS. Students also learn about the role chemistry plays in microgravity research. They observe NASA engineers and scientists using measurements, ratios, and graphing to analyze data. Students also conduct a hands-on activity and a Web activity that establishes a connection between NASA research and the mathematics, science, and technology used in the classroom. About 175,000 educators in 50 states representing 6.8 million students are registered users of NASA CONNECT. For more information, see *http://connect.larc.nasa.gov*.

The DIME competition completed its third year in FY 2003 — and the first year that participants spanned all 50 states, the District of Columbia, and Puerto Rico. School teams compete by writing and submitting a proposal for an experiment to be conducted in the 2.2-Second Drop Tower facility at GRC. (Throughout the competition, the students behave like research scientists: They write and submit a proposal, design a microgravity experiment, build the experimental apparatus, test the experiment in a real microgravity research facility, then gather and analyze data.) The four winning teams and their experiments were Sycamore High School, Cincinnati, Ohio (Magnetic Forces in Microgravity); Gettysburg Area High School, Gettysburg, Pennsylvania (Sonoluminescence in Microgravity); Troy Athens High School, Troy, Michigan (Buoyancy in Microgravity); and Cleveland Heights High School, Cleveland Heights, Ohio (Crystal Formation of Super Cooled Water in Microgravity). The teams and their advisors brought experiments to the DIME Drop Days at GRC, held April 29 to May 1, 2003. Each student team was assigned a NASA mentor to assist them through the learning process.

The Drop Days activities were broadcasted live on the Internet via a webcam so that each sponsoring school, the students' parents, and other interested people and organizations could observe the teams' activities in real time. During the webcast, students were interviewed and asked to explain the purpose of their experiments. During the Drop Days, the students also attended microgravity workshops, toured a NASA GRC facility, and participated in a Self-Contained Underwater Breathing Apparatus (SCUBA) training session at a local hotel pool. The SCUBA session simulated neutral buoyancy training undergone by astronauts in preparation for spacewalks.

In fall 2003, NCMR partnered with the Saginaw Valley State University, University Center, Michigan, to offer teachers a course in graduate-level science methods. Anne Tapp, a professor at Saginaw, co-taught her Science Methods class with NCMR Educational Programs Manager Carla Rosenberg using classroom visits, distance learning, and Blackboard, an Internet software program used in distance learning. The focus was on teaching science methods with microgravity science educational materials from NASA. The teacher-students evaluated NASA Web sites, field-tested NCMR educational materials, and developed original activities based on the ISS. The class took a field trip to GRC and toured the center, where teacher-students were paired with scientists to visit labs and find out more about NASA research. The course exposed its participants to many NASA programs and materials and provided useful feedback on materials being developed. The original educational activities developed by the teacher-students may be incorporated into future publications. This course is an excellent example of how NASA can partner with higher-education institutions and teachers to strengthen classroom practices and improve NASA educational products. The course received high evaluations from its participants.

The OBPR Image Archive (*http://obpr.msfc.nasa.gov*), a portal for communicating NASA science to the public through high-quality pictures, graphics, and movies, was completed in September 2003. The online database provides principal investigators and project scientists with a platform for presenting their experiments and results, while supplying the public with an excellent venue to retrieve poster-quality images. Archive users can search the archive by keyword, phrase, research area, theme, or discipline.

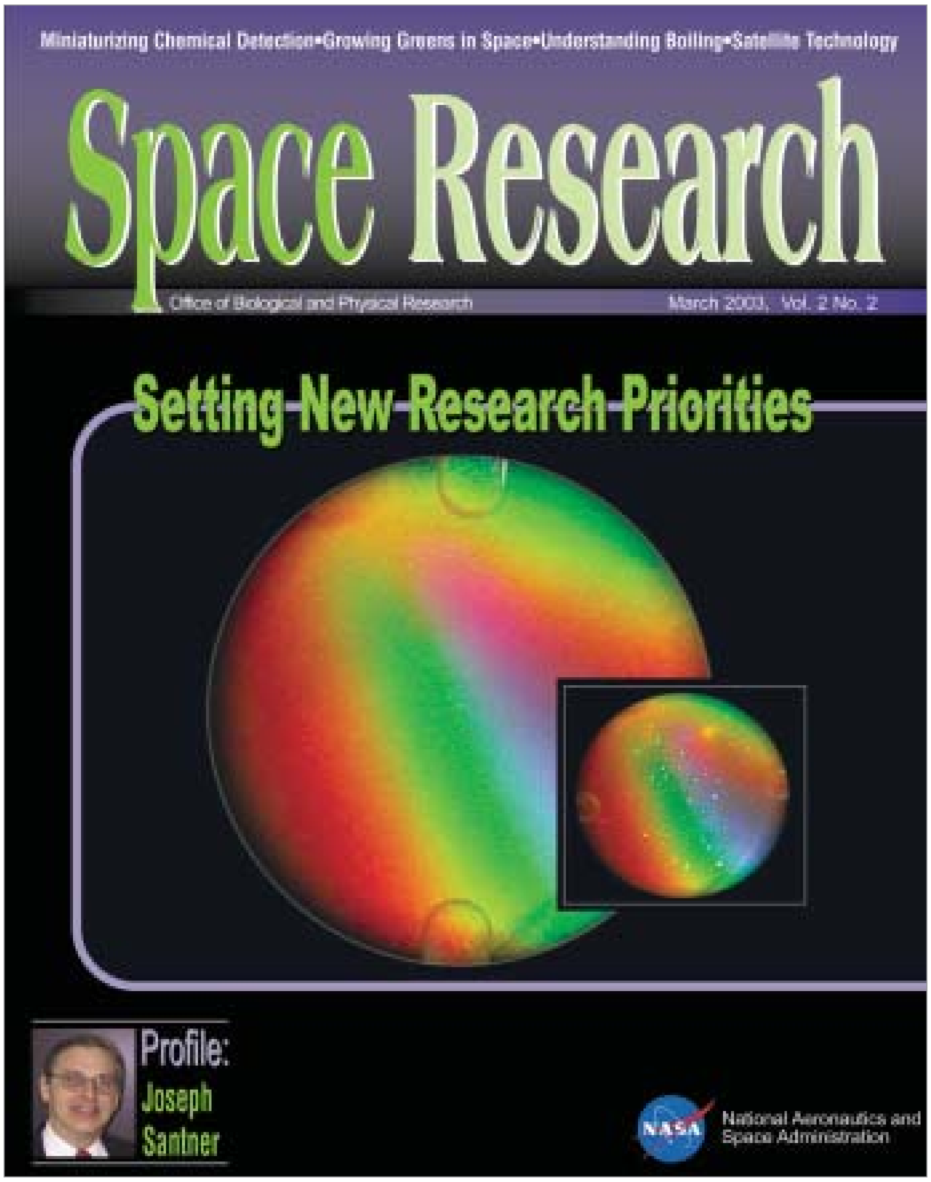
The outreach team of the fundamental physics discipline at NASA Jet Propulsion Laboratory (JPL), Pasadena, California, completed several activities in FY 2003. The team set up displays for the JPL Open House, at which large crowds of visitors were shown the behavior of materials at low temperatures and learned why some experiments must be conducted in the microgravity environment of low Earth orbit.

The team also shared science results with the public by creating four press releases describing new findings by investigators in the fundamental physics program

- **Was Einstein Wrong? Space Station Research May Find Out.**
  Ultraprecise clocks on the ISS and on various missions in microgravity and space may determine whether Albert Einstein's special theory of relativity is correct and could dramatically change humanity's understanding of the universe. Physicist Alan Kostelecky, Indiana University, Bloomington, and his colleagues propose using specific types of clocks aboard the ISS to determine if there are minute changes in their ticking rates. The presence of such changes, easier to measure in microgravity than on Earth, might indicate a flaw in Einstein's theory.

- **Researchers Control Love–Hate Relationship between Atoms.**
  Research that makes ultracold atoms extremely attractive to one another may help test current theories of how all matter behaves — a breakthrough that might lead to advanced transportation systems, more efficient energy sources, and new tests of astrophysical theories. The experiment was conducted by a team led by physicist John Thomas at Duke University, Durham, North Carolina.

- **Frozen Light: Cool NASA Research Holds Promise.**
  Research at Harvard University, Cambridge, Massachusetts, that literally stops light in its tracks may some day lead to breakneck-speed computers that shelter enormous amounts of data from hackers. Conducted by a team led by physicist Lene Hau, the research is one of 12 research projects featured in a special spring 2003 edition of *Scientific American* titled "The Edge of Physics."



Miniaturizing Chemical Detection•Growing Greens in Space•Understanding Boiling•Satellite Technology

Space Research

Office of Biological and Physical Research

March 2003, Vol. 2 No. 2

Setting New Research Priorities

Profile:
Joseph
Santner

National Aeronautics and
Space Administration

credit: *Space Research* newsletter

Space Research*, the successor to the Physical Sciences Research Division's* Microgravity News*, now covers all four research divisions of the Office of Biological and Physical Research.*

- **Lab Research Yields the Biggest Chill.** NASA-funded researchers, led by Nobel Prize–winning scientist Wolfgang Ketterle at the Massachusetts Institute of Technology, Cambridge, have cooled sodium gas to the lowest kinetic temperature ever recorded: one-half-billionth degree above absolute zero. Absolute zero is the point below which no further cooling is possible. This new temperature is six times lower than the previous record, and marks the first time that a gas was cooled below 1 nanokelvin (one-billionth of a kelvin).

An educational activity that was supported by the fundamental physics discipline's Education and Outreach Program was completed in 2003 at Caltech Precollege Science Initiative (CAPSI; Caltech is short for California Institute of Technology, Pasadena). CAPSI finished testing several science teaching modules for middle schools; prepared manuals for teachers, students, and parents; and assembled kits for classroom activities. What's more, it trained pilot teachers in the new pedagogy and philosophy for the modules, including an emphasis on writing, daily use of technology, and modern theories of teaching and learning.

The method sets teams of five or six students to solve a forensic problem that requires them to recall knowledge of scientific principles and properties of matter, record observations in a laboratory notebook, and then use math and English skills to report those observations. Wireless computer notebooks are distributed to the teams for use in gathering data and accessing Internet sites for information about material properties pertinent to the problem. The students use Microsoft PowerPoint slides to report their results to the classroom, integrating English, math, graphing, and presentation skills. The content of each module is coordinated with national science standards.

Ken Fernandez, an engineer at MSFC, was awarded the prestigious NASA Administrator's Fellowship to conduct research at minority institutions. The NASA Administrator's Fellowship Program (NAFP) was designed to enhance the professional development of NASA employees, as well as the science, mathematics, and engineering faculty of minority-serving institutions. It also aims to increase the capability of institutions serving minorities to participate in NASA's research and development programs. Fernandez is conducting his fellowship at Alabama A&M University in Huntsville.

Fernandez will work with Alabama A&M faculty to develop a robotics program within the university's engineering department. His first step will be to develop a two-semester course to help students learn the fundamentals of robotic systems and control methods and demonstrate these principles using simulation software based on his earlier research at Vanderbilt University in Nashville, Tennessee. Students will work in teams to design robotic systems that respond to challenges posed by NASA and industry representatives. Fernandez joins Benjamin Penn, a MSFC scientist who was appointed as an NAFP fellow last year. Penn is currently completing the professional development phase of his fellowship program at the National Space Science and Technology Center in Huntsville, Alabama.

About 800 children visited MSFC during the annual Take Our Children to Work Day held in April 2003. The materials science lab, part of the children's tour, featured games, displays, and activities to spark interest in the research conducted in MSFC's Science Directorate.

The cellular biotechnology discipline hosted 27 Institute of Electrical and Electronics Engineers (IEEE) Pro/Am (Professional/Amateur) college students, who were given research summaries, demonstrations of the NASA bioreactor, and tours of the laboratory facilities at Johnson Space Center (JSC), Houston, Texas. The students were from Rice University, the University of Houston, and Texas Southern University, all in Houston; University of Houston, Clear Lake; and University of Texas Medical Branch, Galveston.

An advanced biological crystallization workshop was conducted February 1–2, 2003, in Cocoa Beach, Florida. Enhanced Gaseous Nitrogen (EGN) Dewar flight samples were loaded, ground controls prepared by batch and vapor diffusion, and coordinate data retrieved and used from the Protein Data Bank. The workshop was conducted by engineers from the University of California/Irvine in Huntsville, Alabama, and Anna Holmes of the University of Alabama, Huntsville. It was jointly sponsored by those two universities; the University of North Florida, Jacksonville; and MSFC. Ewa Ciszak is the project scientist for the EGN flight project. In the past 3 years, thousands of students and teachers across the country have taken part in crystallization workshops under a program established by Principal Investigator (PI) Alexander McPherson, University of California, Irvine.

The Student Access to Space Program, also founded by Alexander McPherson, teaches students how to perform crystallization experiments in the classroom just as they have been conducted on the ISS. The program originally used the EGN Dewar project — an inexpensive, simple, high-capacity system for the crystallization of different samples in space aboard the ISS. EGN Dewar is now a flight simulation project, and the related educational materials are being reworked into a teacher's guide with the preliminary title of *Protein Crystallization, Structural Biology, and Space Travel: What Is the Connection?* This program seeks to reach underserved urban and rural schools, students who are gifted or have special needs, and mainstream schools. Around 58,000 students and almost 1,200 teachers have been involved in the program so far.

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

The Internet is as important as ever for the distribution of microgravity education and outreach products. Efforts were ongoing in FY 2003 to alert educators to all the microgravity research education products that are available online through the MRPO Web site, NASA Spacelink (*http://spacelink.nasa.gov/*), and the NASA Central Operation of Resources for Educators (CORE) education distribution system (*http://core.nasa.gov/)*.

Throughout the year, PSR Division's Outreach and Education Program supports many of its projects by conducting workshops. This enables the projects' organizers to train educators and instructors on the projects, helping them to be more comfortable with the material and more effective when they conduct the projects in their home towns and school systems.

Highlights

Exploring Destiny

More than 20,000 people were able to explore NASA's U.S. Laboratory Destiny module (now attached to the International Space Station [ISS]), when they toured a full-scale mock-up of it. The mock-up was a highlight of

credit: NASA

Betty Grisham of Marshall Space Flight Center, Huntsville, Alabama (right), and Hans and Cisca Roefs from the Netherlands test the Microgravity Science Glovebox during the World Space Congress. Hans is with the European Space Agency (ESA) and was representing ESA during the conference.

the NASA Village at the World Space Congress, which took place October 14–19, 2002, in Houston, Texas. The World Space Congress is held once every 10 years. It provides an opportunity for members of the international space community to show each other and the public what they've been working on and what they hope to be doing in the future. The U.S. Laboratory Destiny module is a combination of both: Although the module was attached to ISS in 2000, it is currently outfitted with only a portion of the research equipment suite that investigators plan for it. The mock-up includes a Now Touch Screen Theater with ISS sound bites to provide a peek inside the real Destiny module. The configuration presented at the congress represents the likely configuration of the module when fully equipped by 2008.

Like the real Destiny module and its research gear, the Destiny mock-up at the World Space Congress was the product of a team effort involving "months of planning and integration with Headquarters, Johnson Space Center (JSC; Houston, Texas), Glenn Research Center (GRC; Cleveland, Ohio), Ames Research Center (ARC; Moffett Field, California), Kennedy Space Center (KSC; Cape Canaveral, Florida), and Marshall Space Flight Center (MSFC; Huntsville, Alabama)," said exhibit manager Betty Grisham of MSFC. (The exhibit has been used in several outreach events and often supports engineering tests as well.)

The Destiny mock-up was developed in the late 1990s by engineers at GRC. It was outfitted with engineering mock-ups of experiment hardware designed for the ISS, to test the fit and function of the designs before committing metal to the machine shop. As the module proved to be highly popular at technical and other conferences, other NASA centers developed high-fidelity representations of their own research gear intended for Destiny. They found that such engineering mock-ups help the public and the research community to see how the plan for scientific research aboard the ISS is coming to life. Indeed, several of the racks in the Destiny mock-up represent scientific experiments that have been operating on ISS since 2001. Racks represented inside or next to the Destiny mock-up include the following.

- Habitat Holding Rack (HHR; designed at KSC and ARC) accommodates habitats and payloads designed specifically for biological research on insects, small animals, aquatic life forms, and individual cells. An important aspect of the HHR is real-time monitoring and automated experiment adjustments by the scientists on Earth.

- Human Research Facility (HRF; designed at JSC) supports testing on the ISS's human crew to learn how humans adapt to and function in orbit. An initial HRF rack is already on the ISS, and a second is planned so crews can run more experiments.

- Window Observational Rack Facility (WORF; designed at JSC) provides a darkened enclosure for photographing Earth from orbit, plus mounting positions for cameras and other gear.

- The Microgravity Science Glovebox (MSG; designed at MSFC) provides a large enclosed environment with the resources necessary for experiments in fluid physics, combustion science, materials science, biotechnology, fundamental physics, and space processing. Using the MSG that was installed aboard the real Destiny in 2001, ISS astronauts have already racked up an impressive experiment record.

- EXpedite the PRocessing of Experiments to the Space Station (EXPRESS; designed at MSFC) Racks accommodate payloads smaller than full experiment racks, specifically those of the size of space shuttle middeck lockers and International Subrack Interface Standard Drawers. That smaller size allows experiment payloads previously flown on the space shuttle to transition to ISS. The MSG and HRF were built up as EXPRESS Racks; other EXPRESS Racks have hosted colloids, the Biomass Production System, and other experiments.

- Material Science Research Rack (MSRR; designed at MSFC) is a multidiscipline facility being developed to accommodate two autonomous material science experiment modules simultaneously. After it is launched, the real MSRR is expected to establish its reputation quickly as the leading laboratory in the arena of materials science investigations in microgravity.

- Combustion Integrated Rack (CIR; designed at GRC) will support combustion experiments in space. It will contain an optics bench, a combustion chamber, other hardware, and software. First to use the CIR will be the Multi-User Droplet Combustion Apparatus (MDCA), designed to accommodate different droplet combustion science experiments. A mock-up of the MDCA also was on display with the CIR.

- Fluids Integrated Rack (FIR; designed at GRC) will accommodate experiments from five major fluid physics disciplines. Furthermore, FIR's flexibility (that is, large volume for experiment hardware, easily reconfigurable diagnostics, customizable software) can accommodate experiments from other disciplines.

- Space Acceleration Measurement Systems (SAMS; designed at GRC) provides visual demonstrations of how even simple movements can cause severe vibration that affects experiments in microgravity. The SAMS project develops, deploys, and operates acceleration measurement systems for everything from drop towers to the ISS. The Principal Investigator Microgravity Services (PIMS) provides extensive data analysis of the acceleration data based on customer requests.

In addition, the Destiny mock-up hosted exhibits of work by the Space Product Development Division, including research on improved metals casting; light-emitting diodes that open new possibilities in cancer therapy; and the AiroCide TiO_2, a revolutionary device that kills 93.3 percent of airborne pathogens that pass through it.

The Destiny mock-up was often a hit during the weeklong World Space Congress, several times being filled with interested visitors while many others waited outside for their chance to explore a corner of NASA's world.

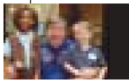
Taking a Spin with Microgravity

Children playing on swings frequently try to see how high they can go, thrilled when they feel weightless, their stomachs feel empty, and their hair floats in midair (as the swing reaches its highest point) — only for an instant — and then disappointed when their weight seems to double (as the swing bottoms out) before the weightless feeling comes again. In this way, the playground often provides a child's unexpected introduction to microgravity and other aspects of acceleration.

Amusement parks have a long history of hosting "Physics Days," and several teacher's guides have been produced by this valuable work. A new guide from NASA published by NASA's Office of Biological and Physical Research (OBPR) in 2003, *Amusement Park Physics with a NASA Twist*, emphasizes the parallels between thrill-rides and launch acceleration and orbital microgravity experienced by space travelers and their experiments. For example, larger roller coasters reach 3.7 gravitational forces (*g*), more than the maximum 3*g* acceleration experienced during a space shuttle launch. Other rides give 2 to 3 seconds of freefall as passengers are dropped 328.1 to 656.2 meters (100 to 200 feet) before decelerating (NASA's largest drop tower provides 5 seconds of freefall with a 131.7-meter [432-foot] drop). Conversely, bumper cars demonstrate Newtonian action and reaction — and the conservation and transfer of momentum — at a most direct level.

Amusement park rides are exciting because of a common element they all share: motion. Motion can change the effect that gravity has on one's body, enough to create a moment of microgravity or a moment of launch. Three types of motion found at amusement parks relate to the sensations of flight: linear motion, curved motion, and circular motion. They all contribute to the chills and thrills of the rides, not to mention an opportunity to learn.

"The idea is to make the ride worksheets useable at any amusement park. The guide itself should make it as easy as possible for teachers to prepare students to collect data at the park," explains Project Manager Carla Rosenberg of the National Center for Microgravity Research (NCMR) in Fluids and Combustion, located at Glenn Research Center (GRC) in Cleveland, Ohio. "We [NASA] offer free training workshops for educators interested in using our guide," she added.



credit: Joe Schwartz

The Physical Sciences Research Outreach and Education Program seeks ways to connect science to the real world.Their teacher's guide, titled Amusement Park Physics with a NASA Twist*, explains physics laws by showing how they apply first to amusement park rides and then to space shuttle launches and flights.*

In the true spirit of scientific inquiry, the purpose of the amusement park trips is not to experience moments of space travel but to learn the inquiry process. Science, after all, is as much about the questions one asks as about the answers one gets. Although most previously published amusement park guides include basic trigonometry or calculus concepts, *Amusement Park Physics* is geared to students in grades 7 through 9 and thus uses more rudimentary tools and basic math skills. Its emphasis is less on getting the correct answer and more on the thinking process leading to reasonable estimations. The guide includes background information for the teacher (but of interest to many students), discussions of basic skills that are needed to carry out the experiments, 2 weeks of activities needed to develop the skills and understand the planned activities, and worksheets for students to use at the park and during tests before and after the visit. Embedded throughout the guide are connections to NASA research and activities, such as microgravity experienced for almost half a minute aboard the KC-135 low-*g* training parabolic aircraft or months at a time on the International Space Station — or the minutes of extra *g*-forces of acceleration needed to get to and from space.

Classroom activities include Pendulums, Collisions, and the Marble Run. “Field work” in the amusement parks includes worksheets on rides that offer moments of freefall, roller coasters, bumper cars, carousels, and pendulum rides. Students build classroom replicas of rides, then calculate how the mini-rides should scale up to the full-sized amusement park rides they will take.

The educator’s guide is designed so teachers can tailor activities to match amusement parks or other facilities that are close enough for a 1-day field trip. Worksheets are provided for students unable to make trips. Typically, teachers propose the field trip in the fall and prepare in March and April. Class work starts in April and culminates with a trip to the amusement park in May. As students experience each ride, they record not only what they feel and but also what they observe with simple devices to calculate ride height, speed, and accelerations.

The 152-page workbook is the result of an informal 4-year partnership between GRC, the National Center for Microgravity Research (NCMR; co-located with GRC in Cleveland, Ohio), and Emerson Middle School in Lakewood, Ohio. During this time, the guide was pilot tested with 10 suburban, urban, and rural schools and more than 1,500 students. Teachers spent a day in training on guide activities and completed extensive written evaluations. The curriculum development team visited classrooms and worked with classes at the parks. All activities in the guide comply with the National Science Education Standards by the National Research Council and Mathematics Principles and Standards for Schools by the National Council of Teachers of Mathematics.

Amusement Park Physics with a NASA Twist can be requested as a printed guide (EG-2003-010-GRC) by contacting the NASA Educator Resource Center Network that serves your geographic region; search the lists at *http://spacelink.nasa.gov/Educational.Services/NASA.Education.Programs/Curriculum.Support.and.Dissemination/Educator.Resource.Center.Network.-.ERCN/*. It also can be downloaded as a PDF from *http://www.ncmr.org/education/k12/amusement_park.html*.

Letting Youngsters Have a Hand in Space Research

Hands-on science museums give children of all ages a chance to experience research aboard the International Space Station (ISS) through a working mock-up of the Microgravity Science Glovebox (MSG) in ISS’s U.S. Laboratory Destiny module. Students can simulate experiments that astronauts are conducting aboard the ISS and learn how research is done in orbit. The museum version of the MSG is a medium-fidelity mock-up designed from the top-level plans for the MSG.

“We wanted to give kids a taste of what it is like for astronauts working with the MSG in orbit,” said Dan Woodard, manager for microgravity outreach and education at Marshall Space Flight Center (MSFC), Huntsville, Alabama. “We had to come up with a blend between making the museum MSG as much like the flight article as possible while making it affordable for us to make multiple copies that could be loaned to museums and schools, or for educational organizations to replicate on their own.”

The MSG was inspired by the highly popular replicas of the Middeck Glovebox (MGBX) flown on space shuttle and Spacelab missions. The smaller MGBX was designed to fit the envelope of two middeck lockers or into a Spacelab single rack. NASA built several mock-ups of it for loan to schools and museums and also developed blueprints and assembly plans so high school shop classes could build their own mock-ups, complete with audio and video monitoring systems. In addition, the plans included simple lab activities that students would carry out inside the glovebox while under the direction of “mission control” — classmates watching on the video link a few feet away.

“We know that kids learn the most when they do things rather than just watching someone else,” Woodard said, “and lots of kids want to be astronauts or at least do things like them. Space is a natural attraction. It’s a natural part of growing up, so we take advantage of that by providing an opportunity for them to learn while imitating some of the work that astronauts do.”

The MSG was designed in the same spirit although the physical hardware is much larger. The flight MSG was built into the envelope of an ISS EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) Rack, which stands about 185.4 centimeters (73 inches) high and 106.7 centimeters (42 inches) wide. The key feature is a large plastic enclosure that slides out of the rack to provide astronauts with access through glove ports in the front,

credit: NASA

Chris McLemore of Cherokee Nation Industries, Inc. guides two young visitors through procedures in the Microgravity Science Glovebox exhibit at the McWane Center Science Museum in Birmingham, Alabama.

allowing students to install equipment and samples through side ports and through a small lockout chamber (somewhat like an airlock) at the bottom.

"Like the flight MSG, we had to design the museum mock-up with users' safety first in mind," said Chris McLemore of Cherokee Nations Industries (the microgravity outreach contractor) at MSFC. "We had to 'kid proof' the design to make sure that the mock-up would survive the normal wear and tear that exhibits get in a museum and still be functional. We also had to guard against finger-pinch hazards, hot lamps, and other possible problems."

Unlike the flight MSG, the museum MSG does not have fluid or vacuum lines or internal power outlets, but it does have interior lighting, ventilation, and audio and video links. The design team decided early on that including full utilities would be an unnecessary complication at the museum level.

An additional component to the MSG is a "mission control" workstation with video and audio connections and computers (to run tutorials, display the experiment plans, or play back video of astronauts working at the MSG in orbit). As the real MSG in orbit sees more and more operational use, videotapes will be edited for playback on the workstation in the museum MSG to exhibit a broader range of the research being conducted aboard the ISS.

The museum MSG is designed for several levels of operation. The simplest is a standalone, untended operation whereby museum visitors can insert their hands into the glovebox and see what it is like to work in gloves. At the same time, a short monitor in the box plays a repeating video that explains the mission of the MSG. Increasingly complex levels of activity include guided tours by museum docents and full-scale simulations with one or two students working at the MSG and guided by classmates at the mission control workstation.

The museum MSG debuted at the McWane Center, a hands-on science museum in Birmingham, Alabama, where dozens of kids tried their hands at it during 2003. The museum MSG then moved on to the Arizona Science Center in Phoenix, where it will be an adjunct to the "International Space Station — The Earth Tour" sponsored by NASA's Office of Biological and Physical Research and initially displayed at the Charlotte, North Carolina, Discovery Center. This exhibit includes a high-fidelity mock-up of the U.S. Laboratory Destiny module as well as other portions of the ISS. NASA is building additional copies of the museum MSG so more museums and schools around the country can give kids their first taste of research in orbit.

Microgravity Web Sites

Fundamental Physics in Space: background material, descriptions, and results for fundamental physics experiments funded by the Microgravity Fundamental Physics Program at the Jet Propulsion Laboratory (*http://funphysics. jpl.nasa.gov*)

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

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

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

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

KC-135 Reduced Gravity Research Program: overview of the program, which uses the KC-135 “Vomit Comet” aircraft to provide brief periods of microgravity for research (*http://jsc-aircraftops.jsc.nasa.gov/kc135/*)

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

Microgravity Research Task Book and Bibliography: links to brief descriptions of all research projects currently funded by the Microgravity Research Program (*http://peer1.nasaprs.com/peer_review/index.cfm*)

Microgravity Science Division at Glenn Research Center (GRC): descriptions of microgravity projects and facilities sponsored by GRC (*http://microgravity.grc.nasa.gov*)

Microgravity Science-Related Meetings and Symposia: list of meetings, conferences, and symposia related to microgravity research (*http://zeta.grc.nasa.gov/ugml/ugmltext.htm*)

Microgravity Sciences and Applications Department at Marshall Space Flight Center: source for information on projects and events within the department (*http://msad.msfc.nasa.gov*)

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

NASA CONNECT: award-winning educational television series on microgravity for educators and students (*http:// connect.larc.nasa.gov*)

NASA Human Spaceflight: a comprehensive source for information about NASA’s spaceflight programs (*http://spaceflight.nasa.gov/*)

NASA Kids: student-oriented educational guide to the wonders of space exploration (*http://www.nasakids.com/*)

NASA Science News: breaking news stories about NASA science research (*http://science.nasa.gov*)

NASA’s Office of Biological and Physical Research (OBPR): goals and organization of OBPR, as well as links to current research opportunities (*http://spaceresearch. nasa.gov/*)

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

Office of Biological and Physical Research Image Archive: source for high-quality pictures, graphics, and movies, available to the public (*http://obpr.msfc.nasa.gov*)

Spacelink: NASA education information, materials, and services (*http://spacelink.msfc.nasa.gov/*)

Space Research: online issues of *Space Research*, a quarterly newsletter about research in microgravity published by NASA’s Office of Biological and Physical Research (*http:// spaceresearch.nasa.gov/general_info/spaceresearchnews .html*)

Space Shuttle Flights: information about space shuttle missions (*http://spaceflight.nasa.gov/shuttle/* and *http://www.ksc.nasa.gov/shuttle/index.htm*)

Program Resources for FY 2003

Funding for the Microgravity Research Program in fiscal year (FY) 2003 totaled $221 million. This figure includes the Microgravity Research Program budget of $79.2 million and $141.8 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 2003 Microgravity Funding Distribution by Science Discipline

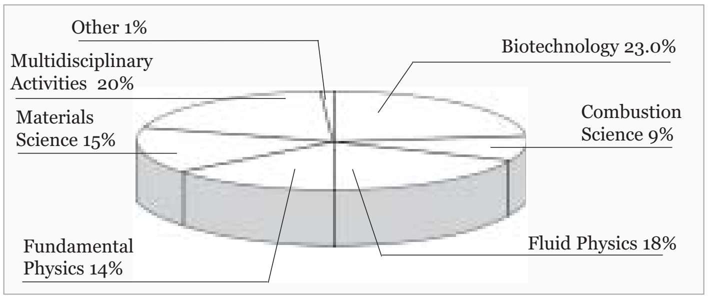


Figure 2 presents the allocation of funding in support of ISS mission planning, development of ISS technology and hardware, development of flight- and ground-based research projects, execution of flight and ground investigations, and development of technology to support those investigations.

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 — bioscience and engineering, 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 2 — FY 2003 Microgravity Funding by Mission Function

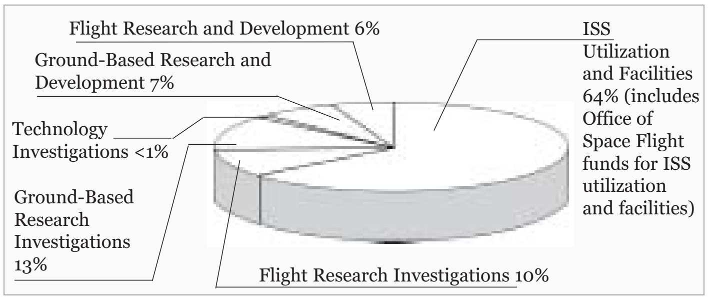
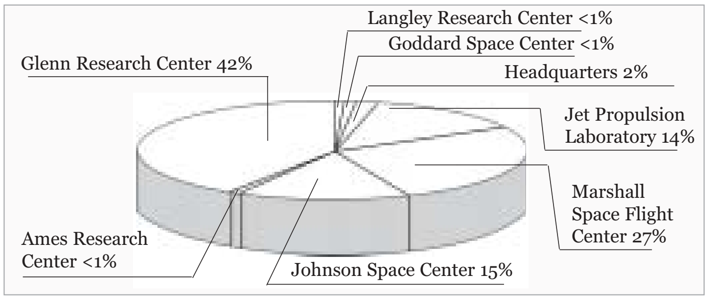


Figure 3 — FY 2003 Microgravity Funding Distribution by NASA Field Centers



Microgravity Experiment Hardware Flights to the International Space Station

Listed below are selected payloads for the International Space Station (ISS) and the associated EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Racks and microgravity facilities in the order of their first flight to the ISS. The principal investigator (PI) names, affiliations, and locations have been included where applicable.

The first list is payloads that have already flown to the ISS; these as-flown payloads primarily consist of EXPRESS Rack payloads and Microgravity Science Glovebox (MSG) investigations. The second list is payloads currently manifested in order of their proposed flights. The third list is payloads that have been approved (or are in development) and are candidates for later flights but have not yet been officially manifested to a particular flight.

Payloads that have flown and operated on the ISS are listed below in order of their flight to the station.

Protein Crystal Growth–Enhanced Gaseous Nitrogen Dewar (PCG-EGN): This apparatus is a gaseous nitrogen dewar that can maintain samples at cryogenic temperature for about 10 days. Frozen liquid–liquid diffusion and batch protein crystal growth experiments are launched in a dewar and then allowed to thaw to initiate the crystallization process in a microgravity environment. The dewar houses a protein crystal growth insert that typically holds approximately 500 protein samples. (Alexander McPherson, University of California, Irvine. First flight: 2A.2B)

Microgravity Acceleration Measurement System (MAMS): MAMS provides measurement of quasi–steady state microgravity acceleration levels at low frequencies (0.01 to 2 hertz) with extreme accuracy. It is an enhanced version of the Orbital Acceleration Research Experiment system used on the space shuttle. Using MAMS data, the microgravity level at any point in the U.S. Laboratory or on the International Space Station (ISS) can be calculated using a transformation matrix and a known center of gravity for the ISS. (Richard DeLombard, Glenn Research Center, Cleveland, Ohio. First flight: 6A)

Space Acceleration Measurement System, Second Generation (SAMS-II): The SAMS-II instrument is an early addition to the International Space Station (ISS) and will most likely remain on board for the life of the station. SAMS-II measures vibratory accelerations (transients) in support of several microgravity science experiments. It also characterizes the ISS microgravity environment for future payloads. (Richard DeLombard, Glenn Research Center, Cleveland, Ohio. First flight: 6A)

Protein Crystal Growth–Single-Locker Thermal Enclosure System (PCG-STES): The PCG-STES hardware is a single EXPRESS (EXpedite the PRocessing of Experiments to Space Station) locker that provides a controlled temperature environment within ±0.5 °C (approximately 1 °F) of a set point in the range of 4 to 40 °C (39 to 104 °F). The PCG-STES houses several apparatuses for protein crystal growth, including the Second-Generation Vapor Diffusion Apparatus, the Diffusion-Controlled Crystallization Apparatus for Microgravity, and the Protein Crystallization Apparatus for Microgravity. (Daniel Carter, New Century Pharmaceuticals, Inc., Huntsville, Alabama. First flight: 6A)

Protein Crystal Growth–Biotechnology Ambient Generic (PCG-BAG): This apparatus flies Second-Generation Vapor Diffusion Apparatus, Diffusion-Controlled Crystallization Apparatus for Microgravity, or Protein Crystallization Apparatus for Microgravity hardware as ambient stowage items within a middeck locker or Cargo Transfer Bag. (Daniel Carter, New Century Pharmaceuticals, Inc., Huntsville, Alabama. First flight: 6A)

Vapor Diffusion Apparatus, Second Generation (VDA-2): VDA-2 uses the vapor diffusion method (hanging drop technique) for protein crystal growth 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 Protein Crystal Growth–Single Thermal Enclosure System (PCG-STES) holds four VDA-2 trays; the Protein Crystal Growth–Biotechnology Ambient Generic (PCG-BAG) holds six. (Daniel Carter, New Century Pharmaceuticals, Inc., Huntsville, Alabama. First flight: 6A, as part of PCG-STES)

Protein Crystallization Apparatus for Microgravity (PCAM): PCAM uses the vapor diffusion method to produce large, high-quality crystals of selected proteins. Each PCAM is a cylindrical stack of nine trays, each with seven chambers, providing 63 total chambers for protein crystal growth. The Protein Crystal Growth–Single Thermal Enclosure System (PCG-STES) holds six cylinders; the Protein Crystal Growth–Biotechnology Ambient Generic (PCG-BAG) holds eight. (Daniel Carter, New Century Pharmaceuticals, Inc., Huntsville, Alabama. 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 techniques. PCS advances understanding of fabrication methods for producing new crystalline materials. (David A. Weitz, Harvard University, Cambridge, Massachusetts. First flight: 6A)

Dynamically Controlled Protein Crystal Growth (DCPCG): The DCPCG apparatus is made up of two components: the command 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. (Lawrence J. DeLucas, University of Alabama, Birmingham. First flight: 7A.1)

Cellular Biotechnology Operations Support System (CBOSS): This hardware provides a platform for the study of basic cell–cell interactions in a quiescent cell culture environment and the role of these interactions in the formation of functional cell aggregates and tissues. The Biotechnology Specimen Temperature Controller (BSTC) operates primarily in the incubation mode. The Biotechnology Refrigerator, Biotechnology Cell Science Stowage, and the gas supply module support BSTC research. (Neal Pellis, Johnson Space Center, Houston, Texas. First flight: 7A.1)

Pore Formation and Mobility Investigation (PFMI): This investigation promotes understanding of detrimental pore formation and mobility during controlled directional solidification processing in a microgravity environment. This Microgravity Science Glovebox investigation uses a transparent material, succinonitrile, so that pore generation and mobility during controlled solidification can be directly observed and recorded. (Richard Grugel, Marshall Space Flight Center, Huntsville, Alabama. First flight: UF-2)

Solidification Using a Baffle in Sealed Ampoules (SUBSA): This investigation was formulated to 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 Microgravity Science Glovebox experiment was intended to resolve several key technological questions and lessen the risk and uncertainties of using a baffle and liquid encapsulation in future major materials science facilities. (Aleksandar Ostrogorsky, Rensselaer Polytechnic Institute, Troy, New York. First flight: UF-2)

Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (InSPACE): InSPACE hardware was designed to be accommodated by the Microgravity Science Glovebox. Three-dimensional microscopic structures of magnetorheological fluids in a pulsed magnetic field were observed. (Alice P. Gast, Stanford University, California. First flight: 11A)

Coarsening of Solid-Liquid Mixtures-2 (CSLM-2): This Microgravity Science Glovebox 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. (Peter Voorhees, Northwestern University, Evanston, IL. First flight: 11A)

Diffusion-Controlled Crystallization Apparatus for Microgravity (DCAM): The DCAM system uses the liquid–liquid diffusion or dialysis method of protein crystal growth to produce high-quality single protein crystals. Three DCAM trays, each with 27 chambers, are flown per PCG-STES or PCG-BAG. (Daniel Carter, New Century Pharmaceuticals, Inc., Huntsville, Alabama. First flight: 11A)

Capillary Flow Experiment (CFE): The CFE hardware consists of two modules that have identical fluid injection mechanisms and similarly sized test chambers. The experiment can be performed in the Microgravity Science Glovebox or as a standalone experiment. Its purpose is to provide fundamental insight into the mechanics of capillary flow that can be immediately applied by designers of low-gravity fluids systems. Specifically, the experiment will produce conclusive data about large-length-scale capillary flows, flow phenomena in complex geometries, and critical damping resulting from moving contact lines. The fluids used are benign, flight-qualified silicone oil and immersion oil. (Mark M. Weislogel, Portland State University, Portland, Oregon. First flight: 13P)

In-Space Soldering Investigation (ISSI): This investigation will study surface tension–driven convection phenomena as well as the microscale physics of the interfacial zone of molten metals. The soldering experiments will consist of systematically investigating several key solidification and fabrication parameters. (Richard Grugel, Marshall Space Flight Center, Huntsville, Alabama. First flight: 12P)

Miscible Fluids in Microgravity (MFMG): The two objectives of this investigation are to determine whether isothermal miscible fluids can exhibit transient interfacial phenomena similar to those observed with immiscible fluids and to determine whether miscible fluids in a thermal gradient can exhibit transient interfacial phenomena similar to those observed with immiscible fluids. (John Pojman, University of Southern Mississippi, Hattiesburg. First flight: 12P)

Binary Colloidal Alloy Test-3 (BCAT-3): BCAT-3 is being developed with the heritage from BCAT and BCAT-2. BCAT-3 is designed to operate as a standalone experiment in the Maintenance Work Area of the International Space Station. In BCAT-3, the long-term behavior of crystals of binary colloidal alloys will be studied in a microgravity environment, where the effects of sedimentation and convection are greatly reduced, to allow a better understanding of colloids and how to engineer their properties. The experiment's predecessor, BCAT-2, was flown on the Russian space station, *Mir*. (David A. Weitz, Harvard University, Cambridge, Massachusetts. First flight: 13P)

Dust Aerosol Measurement Feasibility Test (DAFT): DAFT is a risk mitigation for the future Smoke experiment diagnostic. The DAFT hardware consists of a commercial-off-the-shelf (COTS) ultrafine particle counter (P-Trak from TSI, Inc.) that has been modified to increase its performance in microgravity. To test and verify that performance, a baseline nonenhanced P-Trak particle counter and an alternative particulate measurement device (TSI's DustTrak) are also used. Each of these devices requires batteries. The DAFT hardware also includes equipment to contain and generate 15 particulate aerosol samples. (David L. Urban, Glenn Research Center, Cleveland, Ohio. First flight: 13P)

Fluid Merging Viscosity Measurement (FMVM): FMVM measures the viscosity of viscous liquids by the fluid merging method. The only hardware required is two syringes for each liquid, a means to contain and dispose of the liquids, and tape to secure the syringes while liquid is deployed. The experiment uses various combinations of dye, water, glycerin, honey, and flight-qualified benign silicone oil. (Edwin Ethridge, Marshall Space Flight Center, Huntsville, Alabama. First flight: 13P)

Foam–BMG: The goal of this study is to produce a "foam" material by blowing bubbles in glycerin to study the structure of a viscous liquid foam in a low-gravity environment. It explores the foaming of an undercooled liquid alloy in microgravity and will contribute to the understanding of the effect of coalescence on foam microstructure in the absence of gravity-induced drainage effects. It will determine the change in critical thickness between bubbles formed in Earth's gravity and those formed in microgravity. The foaming effects will take several minutes. (William Johnson, California Institute of Technology, Pasadena. First flight: 14P)

Payloads that are currently manifested are listed below in order of their proposed flight to the station.

Glovebox Integrated Microgravity Isolation Technology (g-LIMIT): G-LIMIT hardware is being developed to attenuate unwanted accelerations within the Microgravity Science Glovebox (MSG); characterize the MSG acceleration environment; and demonstrate high-performance, robust control technology. It also will be available to measure and isolate vibrations for other MSG investigations. (Mark Whorton, Marshall Space Flight Center, Huntsville, Alabama. First flight: ULF-1)

Physics of Colloids in Space Plus (PCS+) Experiment: This investigation complements and extends the research begun with the original Physics of Colloids in Space (PCS) investigation, flown on flight 6A. The PCS+ hardware consists of an avionics section, a test section, auxiliary hardware, operating system hard drives, and mass data storage hard drives. It uses light scattering and rheological measurements to investigate disorder–order transitions in colloidal hard spheres as well as the properties of the resulting ordered phase. (Paul M. Chaikin, Princeton University, Princeton, New Jersey. First flight: 12A.1)

Fiber-Supported Droplet Combustion-3 (FSDC-3): The objective of this investigation using the Microgravity Science Glovebox (MSG) is to provide critical data on the combustion of multicomponent droplets, thus enabling the development of theoretical models for use in multidroplet (spray) applications. The FSDC-3 hardware consists of an experiment module, liquid fuel syringes, deployment needles, droplet tethers, igniters, nozzles, diagnostics, and a computer control interface. (Forman A. Williams, University of California, San Diego. First flight: 12A.1)

Observable Protein Crystal Growth Apparatus (OPCGA): The OPCGA flight investigation hardware is composed of three major components: the mechanical system, the optical system, and the video data-acquisition and control system. The OPCGA hardware provides 96 individual experiment cells with the capability to collect optical data on 72 cells. (Alexander McPherson, University of California, Irvine. First flight: 12A.1)

Metastable Solution Structure in Protein Crystal Growth (XLINK): The XLINK consists of the Low-Temperature, Low-Energy Carrier and Group Activation Pack hardware. The objective of XLINK is to study the presence and distribution of aggregates in solutions that lead to the crystal growth of lysozyme and insulin. The experiment will investigate the effects of gravity on the formation of aggregates, the size distribution of and/or average size of aggregates, and the transport of the aggregates to the crystal surface. (Lori Wilson, Eastern Kentucky University, Richmond. First flight: 12A.1)

Delta-Length (Delta-L): The Delta-L investigation will replace hardware previously known as the Interferometer for Protein Crystal Growth. This Microgravity Science Glovebox (MSG) investigation will study the crystal growth characteristics of biological macromolecules in microgravity. Data from Delta-L will be used to verify the theory that growth rate dispersion plays a role in crystal quality improvement in microgravity. (Russell A. Judge, University of Alabama, Huntsville. First flight: 13A.1)

Smoke Points in Coflow Experiment (SPICE): Using the Microgravity Science Glovebox (MSG), this investigation evaluates the effect of oxidizer and fuel velocities on the laminar smoke point (that is, the propensity of flames to emit soot). SPICE hardware consists of an experiment module, 12 gaseous fuel bottle assemblies, igniters, nozzles, and a video camera. (Gerard M. Faeth, University of Michigan, Ann Arbor. First flight: 13A.1)

Shear History Extensional Rheology Experiment (SHERE): SHERE will study the effects of preshear on the transient evolution of the microstructure and viscoelastic tensile stresses for viscoelastic polymer solutions. The SHERE hardware consists of a rheometer assembly, a camera arm, and a fluid module tray containing 25 fluid modules. Each fluid module contains a single sample for testing. (Gareth H. McKinley, Massachusetts Institute of Technology, Cambridge. First flight: 15A)

Droplet Combustion Experiment-2 (DCE-2): DCE-2 will study single pure fuel droplet combustion in microgravity to better understand combustion kinetics through droplet combustion extinction diameter measurements. It will also improve the understanding of transient liquid- and gas-phase phenomena. DCE-2 will be conducted in the Combustion Integrated Rack (CIR) designed specifically to support advanced combustion research in the microgravity environment. DCE-2 is the first of four experiments to use the Multiuser Droplet Combustion Apparatus (MDCA) in the CIR. (Forman Williams, University of California, San Diego. First flight: ULF-2)

Bi-Component Droplet Combustion Experiment (BCDCE): BCDCE will study bi-component fuel droplet combustion in microgravity, where spherical symmetry is approached in both gas and liquid phases of the droplet, to better understand the transient buildup of the less volatile component on the liquid side of the liquid–gas interface. BCDCE will be conducted in the Combustion Integrated Rack (CIR). BCDCE is the second experiment to use the Multiuser Droplet Combustion Apparatus (MDCA) in the CIR. (Benjamin Shaw, University of California, Davis. First flight: ULF-2)

Candle Flames in Microgravity-2 (CFM-2): CFM-2 will exploit candle geometry as a platform for fundamental science and educational outreach to determine the limiting oxygen concentration for a candle in microgravity, whether a steady microgravity candle flame can exist in air, whether the microgravity flame will oscillate for a prolonged period, and the interactions and extinction behavior between two neighboring flames. CFM-2 will be operated in the Microgravity Science Glovebox (MSG). (Daniel Dietrich, Glenn Research Center, Cleveland, Ohio. First flight: ULF-2)

Microheater Boiling Experiment (MABE): This experiment determines boiling heat-transfer mechanisms and tests the hypotheses that bubble coalescence is the primary bubble removal mechanism, that heat is transferred by small satellite bubbles, and that heat transfer from the small bubbles is not affected by gravity level. Specific experiment hardware consists of a set of miniature heaters and heater controllers installed in the Boiling Experiment Facility (BXF). The BXF itself will be operated in the Microgravity Science Glovebox. (Jungho Kim, University of Maryland, College Park. First flight: ULF-2)

Nucleate Pool Boiling Experiment (NPBX): The objective of this experiment is to validate boiling models with descriptions of such aspects as bubble growth and departure at single nucleation sites, as well as bubble merger, bubble–bubble interaction, and vapor removal from predesigned cavities on a heater surface during quasi-static conditions. This experiment, like the Microheater Boiling Experiment (MABE), will be performed in the Boiling Experiment Facility within the Microgravity Science Glovebox. (Vijay Dhir, University of California, Los Angeles. First flight: ULF-2)

Physics of Colloids in Space-3 (PCS-3): PCS-3 is a follow-on to the Physics of Colloids in Space (PCS) and PCS+ experiments. Using the same techniques of light scattering, PCS-3 will address fundamental questions about nucleation, growth, morphology, and dynamics of binary colloidal crystal alloys, colloid–polymer gels, fractals, anisometric colloids, and colloidal glasses. It will examine samples provided by three separate principal investigators. (David A. Weitz, Harvard University, Cambridge, Massachusetts; Eric Weeks, Emory University, Atlanta, Georgia; and Michael Solomon, University of Michigan, Ann Arbor. First flight: ULF-2)

Payloads that are planned or in development but have not yet been manifested are listed below, in alphabetical order.

Biotechnology Facility (BTF): The next generation of on-orbit cellular biotechnology hardware, BTF serves as a new platform for cellular research. BTF automates many of the functions performed by the crew during the earlier Cellular Biotechnology Operations Support System (CBOSS) experiments and allows for increased science throughput. The Phase I BTF is a two-rack facility that includes three automated stationary culture system units for processing various types of cells as supported by two gas supply module units to supply carbon dioxide–enriched medical-grade air, and an automated culture water assembly to create cell growth media. BTF also provides cold storage at 4, –80, and –180 °C (39, –112, and –292 °F, respectively). The Phase II BTF will add a Multivessel Rotating Bioreactor and data-analysis equipment.

Buoyancy-Driven Instabilities in Single-Bubble Sonoluminescence (BDISL): This experiment will quantify buoyancy-induced instabilities that may play a dominant role in the mechanism for sonoluminescence extinction. The influence of chemical instabilities will be tested by using different gas–water concentrations. BDISL will be operated in the Microgravity Science Glovebox. (Thomas Matula, University of Washington, Seattle)

Capillary Channel Flows (CCF): The purpose of this experiment is to investigate the fundamental physics of flow rate limitations in capillary flows using various geometries. (Michael Dreyer, University of Bremen, Germany)

Colloidal Disorder–Order Transition-3 (CDOT-3) Apparatus: This hardware fits in a glovebox and is used to photograph samples of dispersions of very fine particles as they form various crystalline or gel structures. This hardware was flown previously on the second U.S. Microgravity Laboratory flight (STS-73, 1995) and on STS-95 (1998). (Paul M. Chaikin, Princeton University, Princeton, New Jersey)

Coupled Growth in Hypermonotectics (CGH): Hypermonotectic alloys consist of two separated phases, not only in the solid but also in the liquid. On Earth, in a mixture of liquids that have different densities, the denser phase settles to the bottom. This Materials Science Research Rack (MSRR) payload will help elucidate the theory behind sediment formation and hence will improve the ability to produce desired structures on the ground. (J. Barry Andrews, University of Alabama, Birmingham)

Chain Aggregation Investigation by Scattering (CHAINS): This experiment will investigate the fluctuations and dynamics responsible for the cross-linking of dipolar chains in magnetorheological fluids. CHAINS will be operated in the Microgravity Science Glovebox. (Alice P. Gast, Massachusetts Institute of Technology, Cambridge)

Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments (CSS): The primary purpose of this Materials Science Research Rack (MSRR) payload is to compare the structure and segregation of binary metallic alloys that are directionally solidified in terrestrial and low-gravity environments. (David R. Poirier, University of Arizona, Tucson)

Constrained Vapor Bubble (CVB): This experiment will investigate heat conduction in microgravity as a function of liquid volume and heat flow rate to determine, in detail, the transport process characteristics in a curved liquid film. CVB is being developed to run in the Light Microscopy Module (LMM) within the Fluids Integrated Rack (FIR). (Peter Wayner, Rensselaer Polytechnic Institute, Troy, New York)

Dynamical Selection of Three-Dimensional Interface Patterns in Directional Solidification (DSIP): The objective of this investigation is to establish fundamental principles that govern the spatial–temporal evolution of cellular and dendritic interface patterns in directional solidification. Low-gravity experiments will be used to validate a rigorous numerical model of pattern evolution dynamics that are currently being developed using the phase-field approach. (Rohit Trivedi, Iowa State University, Ames)

Dynamics of Droplet Combustion and Extinction (DDCE): This experiment will investigate the effects of small convective flows on burning droplets to better define the influences of such flows on the extinction process. DDCE extends the knowledge generated in the study of droplet combustion by Droplet Combustion Experiment-2 (DCE-2) and Bi-Component Droplet Combustion Experiment (BCDCE) before it. DDCE is the fourth experiment to use the Multiuser Droplet Combustion Apparatus (MDCA) in the Combustion Integrated Rack (CIR). (Vedha Nayagam, Glenn Research Center, Cleveland, Ohio)

Dynamics of Miscible Interfaces (MIDAS): This experiment will investigate the dynamics of miscible interfaces and document flow fields and concentration gradients near an evolving fluid interface within a precisely controlled, two-fluid flow system. MIDAS will be operated in the DECLIC (“*Dispositif pour l’étude de la croissance et des liquides critiques*”) facility, developed by the French space agency (CNES), in an EXPRESS Rack. (Tony Maxworthy, University of Southern California, Los Angeles)

Foam Optics and Mechanics (FOAM): This experiment is being designed by the European Space Agency (ESA) for operation in the ESA-developed Fluid Science Laboratory. The objective of FOAM is to understand the unusual nature of foam rheology in terms of behavior at the bubble scale, the packing structure, the rearrangement dynamics, and the coarsening of foams via gas diffusion. Video microscopy, multiple light scattering, and rheology techniques will be employed to examine foams as a systematic function of liquid content, shear rate, and foam age. (Douglas Durian, University of California, Los Angeles)

Forced Ignition and Spread Test (FIST): This experiment will validate a proposed new flammability test methodology for homogeneous and composite materials under environmental conditions found only in crew-occupied spacecraft or extraterrestrial habitats. FIST will be conducted in the Combustion Integrated Rack (CIR). FIST is the first of at least five experiments to use the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS) in the CIR. (Carlos Fernandez-Pello, University of California, Berkeley)

Gravity and Granular Materials (GGM): The purpose of this experiment will be directed toward characterizing the stress states of granular materials in an environment that controls the mean density of granular materials in both the dense and dilute phases. In addition to general properties of granular materials, GGM will focus on two phase transitions: the phase transition that occurs for dense sheared granular materials as the density passes through the critical value such that stresses just percolate between the boundaries of a sample and the clustering instability that is predicted to occur as a granular gas cools. (Robert Behringer, Duke University, Durham, NC)

Gravitational Effects on Distortion in Sintering (GEDS): The GEDS apparatus will use the Low Gradient Furnace (LGF). The microgravity Liquid Phase Sintering (LPS) experiments contained in the GEDS apparatus are designed to isolate gravity-porosity interactions with respect to densification, component distortion, and underlying microstructure evolution. Findings from this research will be used to improve modeling of LPS by including gravity-porosity effects. (Randall M. German, Pennsylvania State University, University Park)

Interface Pattern Selection Criteria for Cellular Structures in Directional Solidification (IPSIDS): The objective of this MSRR payload is to obtain benchmark data on cellular and dendritic growth under conditions that produce negligible convection. Precise measurements of interface shape, cell/dendrite tip radius, tip composition, and tip temperature as functions of composition, growth rate, and thermal gradient will be carried out. These measurements will be used to characterize conditions for the planar to cellular, shallow cells to deep cells, and deep cells to dendrites transition. (Rohit K. Trivedi, Iowa State University, Ames)

Kinetics of Nucleation and Crystal Growth in Glass-Forming Melts in Microgravity (CROMIS): CROMIS will investigate why glass forms more easily and is more chemically homogeneous in microgravity than on Earth. The flight experiment will include melting lithium disilicate, a glass with well-known properties, then treating it at selected temperatures for different amounts of time at each temperature. Measurements of the rates of nucleation and crystal growth in microgravity will be compared to those on Earth. (Delbert E. Day, University of Missouri, Rolla)

Levitation Observation of Dendrite Evolution in Steel Ternary Alloy Rapid Solidification (LODESTARS): This payload will help to develop a better understanding of how nucleation and growth of the austenitic phase affect phase selection in ternary steel alloys following formation of a primary metastable ferritic dendritic array. (Merton C. Flemings, Massachusetts Institute of Technology, Cambridge)

Light Microscopy Module (LMM): LMM is a remotely controllable, automated, on-orbit microscope, allowing flexible scheduling and control of physical science and potential biological science experiments within the Fluids Integrated Rack (FIR) on the ISS. Its key features include video microscopy, confocal microscopy, laser tweezers, an oil immersion system, thin-film interferometry, and spectrophotometry.

Low Volume Fraction Entropically Driven Colloidal Assembly (LFCA): The purpose of this investigation is to create new colloidal materials, study their assembly, measure their optical properties, and fix the resulting structures for return to Earth. (Arjun G. Yodh, University of Pennsylvania, Philadelphia)

Microgravity Observations of Bubble Interactions (MOBI): The purpose of this investigation is to study the physics of segregation and re-suspension of bubbles in bubbly suspensions. Outcomes will verify the equations of motion of bubbly suspensions under ideal flow settings. (Ashok Sangani, Syracuse University, Syracuse, New York)

Microgravity Segregation in Collisional Shearing Flows of Binary Mixtures of Inelastic Spheres (µgSEG): The purpose of this investigation is to study two different submechanisms of collisional segregation that usually occur together, the first associated with differences in particle inertia, the second associated with differences in particle geometry. (James Jenkins, Cornell University, Ithaca, New York)

Micromechanics of Magnetorheological Fluids (µMRF): The purpose of this investigation is to study the rheological properties and long range lateral attraction in Magnetorheological (MR) fluids, in addition to the rheological properties of composite chains formed through depletion-induced coalescence. (Alice Gast, Massachusetts Institute of Technology, Cambridge)

Particle Engulfment and Pushing by Solidifying Interfaces (PEP): This investigation, which flew previously in the Middeck Glovebox, will study the effects when two nonmixing alloys (immiscibles such as oil and water) are stirred and frozen in normal gravity and then melted and resolidified in microgravity. PEP will be conducted in the Microgravity Science Glovebox. (Doru Stefanescu, University of Alabama, Tuscaloosa)

Physics of Colloids in Space-2 (PCS-2): The objective of PCS-2 is to carry out further investigation of critical fundamental problems in colloid science and to fully develop the evolving field of "colloid engineering," as well as to create materials with novel properties using colloidal particles as precursors. PCS-2 is being developed to run in the Light Microscopy Module (LMM) in the Fluids Integrated Rack (FIR). (David A. Weitz, Harvard University, Cambridge, Massachusetts)

Physics of Hard Spheres-2 (PHaSE-2): This experiment will investigate the growth, structure, and properties of hard sphere colloidal crystals in microgravity and how applied fields affect these systems. PHaSE-2 is being developed to run in the Light Microscopy Module (LMM) in the Fluids Integrated Rack (FIR). (Paul M. Chaikin, Princeton University, Princeton, New Jersey)

Quasicrystalline Alloys for Space Investigation (QUASI): This payload will perform studies of aluminum-thulium and titanium/zirconium-thulium liquids to better understand the local atomic structure of phases in relation to undercooled liquids, the growth mechanism for complex periodic and ordered nonperiodic phases, and nucleation when the composition of initial and final phases are different. (Kenneth F. Kelton, Washington University, St. Louis, Missouri)

Quench Module Insert (QMI): QMI is being designed for materials science research inside the Materials Science Laboratory in the first Materials Science Research Rack (MSRR-1). QMI is a high-temperature, Bridgman-type furnace with an actively cooled cold zone. The apparatus will create an extremely high-temperature gradient for the directional solidification processing of metals and alloys. It is also capable of rapidly freezing (quenching) samples at the liquid-solid interface, where most of the science takes place during directional solidification.

Radiative Enhancement Effects on Flame Spread (REEFS): This experiment will investigate the transport and chemical effects of various atmospheres on flame spread over solid fuel beds with emphasis on radiative enhancements likely to be present in fires that may occur in microgravity. REEFS is the second experiment to use the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS) in the Combustion Integrated Rack (CIR). (Paul Ronney, University of Southern California, Los Angeles)

Reduction of Defects in Germanium-Silicon (RDGS): The RDGS experiment will likely be conducted in the Low Gradient Furnace (LGF). RDGS investigates the mechanism leading to detached crystal growth in the Bridgman configuration and determines the parameters essential for the controlled use of the furnace for detached growth. A comparison of processing-induced defects in Bridgman, detached Bridgman, and float-zone growth configurations in germanium-silicon crystals will be made. A determination as to whether detached Bridgman or float-zone processing can produce germanium-silicon crystals with fewer defects will also be made, and any differences will be quantified. (Frank R. Szofran, Marshall Space Flight Center, Huntsville, Alabama)

Studies of Gas-Particle Interactions in a Microgravity Flow Cell (SiGMA): The purpose of this investigation is to study the existing theory for flows of gas-solid suspensions by measuring viscous dissipation and viscous drag coefficients. The goal is to understand the essential physics of gas-solid interactions when the flow is not turbulent. (Michel Louge, Cornell University, Ithaca, New York)

Smoke: Increasing mission durations and the expanded size of habitable space aboard spacecraft require enhanced fire detection capability. This experiment will improve the ability to detect spacecraft fires by studying the particle size distribution of smoke generated in microgravity. Results from research conducted as part of the United States Microgravity Payload in 1996, indicate that smoke structure changes significantly in low gravity. Current ISS and space shuttle smoke detectors were designed based upon data collected in Earth's gravity. The Smoke experiment is being designed for operation in the Microgravity Science Glovebox (MSG). (David L. Urban, Glenn Research Center, Cleveland, Ohio)

Sooting and Radiation Effects in Droplet Combustion (SEDC): This experiment will investigate the effects of sooting and radiation influences on the overall burning behavior of droplets by means of optical and intrusive techniques. SEDC extends the knowledge generated in the study of droplet combustion by the second Droplet Combustion Experiment (DCE-2) and before it. SEDC is the third experiment to use the Multiuser Droplet Combustion Apparatus (MDCA) in the Combustion Integrated Rack (CIR). (Mun Choi, Drexel University, Philadelphia, PA)

Spaceflight Holography Investigation in a Virtual Apparatus (SHIVA): SHIVA will record particle motion in a fluid using holographic data. SHIVA plans to use the Microgravity Science Glovebox (MSG) and possibly Glovebox Integrated Microgravity Isolation Technology (g-LIMIT). (James Trolinger, MetroLaser, Inc., Irvine, California)

Transient Interfacial Phenomena in Miscible Polymer Systems (TIPMIPS): This experiment will measure the fluid flow induced by a temperature gradient along the interface between a polymer and its monomer and the fluid flow induced by a variation in the initial width of the interface between a polymer and its monomer. TIPMIPS will also determine if Marangoni instability can occur at a miscible interface and if a bubble driven by a temperature gradient penetrates a miscible interface. (John Pojman, University of Southern Mississippi, Hattiesburg)

Ultraviolet-Visible-Infrared Spectrophotometer (UVIS): This experiment will provide spectrophotometry capabilities from 200 nanometers to 2,400 nanometers to determine the photonic band structures of crystals and support future fluid physics and biotechnology experiments. UVIS will be operated in the Microgravity Science Glovebox (MSG). (Arjun Yodh, University of Pennsylvania, Philadelphia)

Water Mist: This experiment will investigate how different sizes and concentrations of droplets will affect a thin layer of flame, known as a laminar flame. The Water Mist investigation is developed by the Center for Commercial Applications of Combustion in Space and will be conducted in the Combustion Integrated Rack (CIR). (Thomas McKinnon, Colorado School of Mines, Golden)

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 Microgravity Science Glovebox (MSG).

The Physical Sciences Research Division currently has two unpressurized payload candidates in addition to the Low-Temperature Microgravity Physics Facility. These payloads are described below.

Primary Atomic Reference Clock in Space (PARCS): The PARCS investigation will measure various predictions of Einstein's Theory of General Relativity, including gravitational frequency shift and the local position invariance on the rate of clocks. PARCS will also achieve a realization of the second, a fundamental unit of time, as a function of the energy difference between two atomic levels in a cesium atom at an order of magnitude better than that achievable on Earth. (Donald Sullivan, National Institute of Standards and Technology, Gaithersburg, MD)

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 International Space Station (ISS). (Kurt Gibble, Pennsylvania State University, University Park)

The following international payloads are planned for the International Space Station (ISS).

Apparatus for the Study of Material Growth and Liquids Behavior near Their Critical Point (DECLIC): The DECLIC ("*Dispositif pour l'étude de la croissance et des liquides critiques*") facility is being developed by the French space agency, Centre National d'Etudes Spatiales (CNES), in cooperation with Glenn Research Center in Cleveland, Ohio, to provide an autonomous or remotely operated capability at middeck locker scale to accommodate research on high-pressure samples of fluids near their critical points, transparent materials systems during solidification, and other fluids experiments that are compatible with available diagnostics. Through cooperative interagency agreements, NASA will provide launch, integration, and resources for DECLIC and will share use of the facility.

Fluid Science Laboratory (FSL): The FSL is part of the European Space Agency's (ESA's) Microgravity Facilities for Columbus Programme. It will support basic and applied research in fluid physics under microgravity conditions. The design provides easy exchange of FSL modules for upgrades and modifications. The facility can be operated in fully automatic mode, following a preprogrammed sequence of commands, or in semiautomatic telescience (remotely operated) mode, enabling the user to interact with the facility in quasi–real time from the ground. This flexibility will allow scientists to follow the evolution of their experiments and to provide feedback on the data they receive at the ground station.