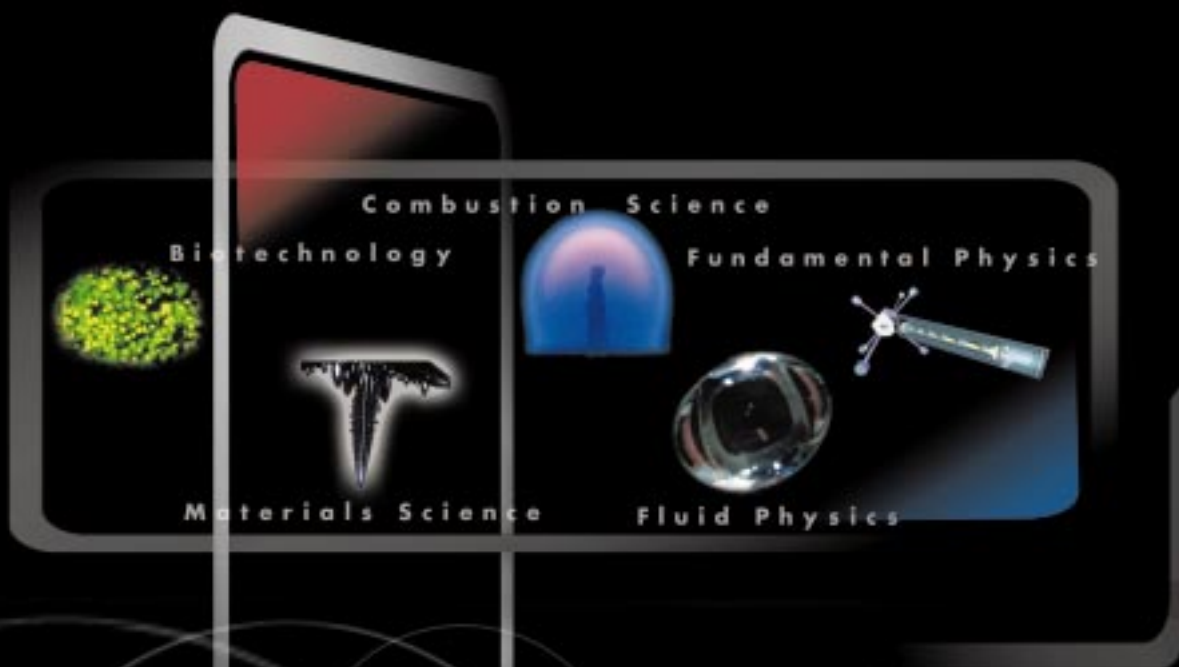


NASA'S MICROGRAVITY RESEARCH PROGRAM



Microgravity Research

Annual
Report
1999

NASA'S MICROGRAVITY RESEARCH PROGRAM

1999



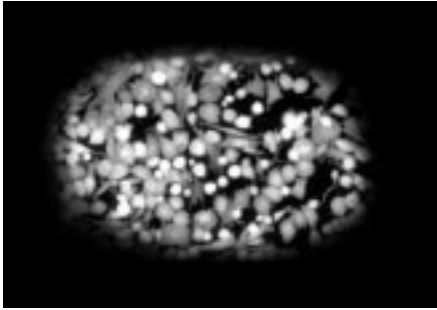
NASA/TM – 2000-210615



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Space Administration

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Marshall Space Flight Center, Alabama 35812

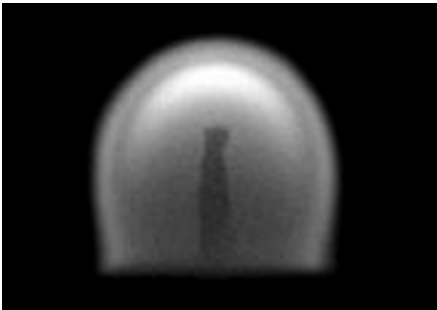
On the front cover...



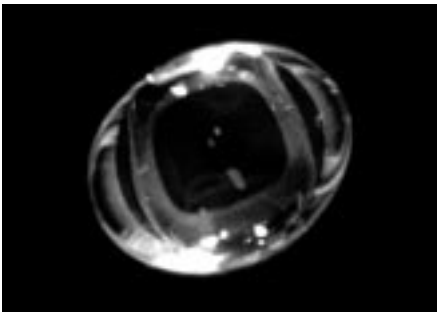
In FY 99, the microgravity biotechnology program investigated the structure of macromolecules through Earth- and space-grown crystals and conducted experiments in tissue engineering and basic cellular functions both in ground laboratories and in orbit. These cells were isolated from cartilage grown on Russian Space Station *Mir*. Gray areas (green on cover) indicate the presence of esterase, a key metabolic enzyme.



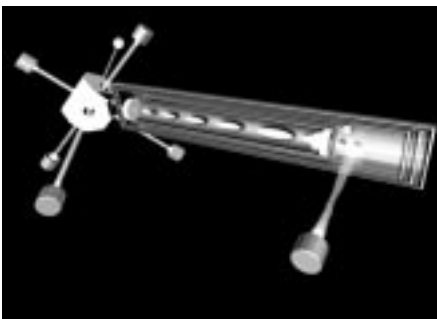
Discovering how processing affects the structure and properties of materials is the focus of the materials science discipline. A microgravity environment allows a simpler view of the relationship of processing to structure. Several experiments have been conducted and are planned for investigating the formation of dendrites, a common microstructure in metals. This dendrite of pivalic acid was formed during a microgravity shuttle mission.



The study of combustion science in microgravity contributes to the basic understanding of the combustion process and of how to prevent and control burning on Earth and in space. This photo was taken during an experiment on candle flames that took place on *Mir*.



Fluid physicists participate in the microgravity program to understand the fundamentals of fluid behavior under various conditions. Microgravity experiments investigating liquid drops have contributed to our knowledge of microscopic and macroscopic processes, from the way atomic nuclei undergo fission to how planets are formed. This photo was taken during a drop experiment conducted on the space shuttle.

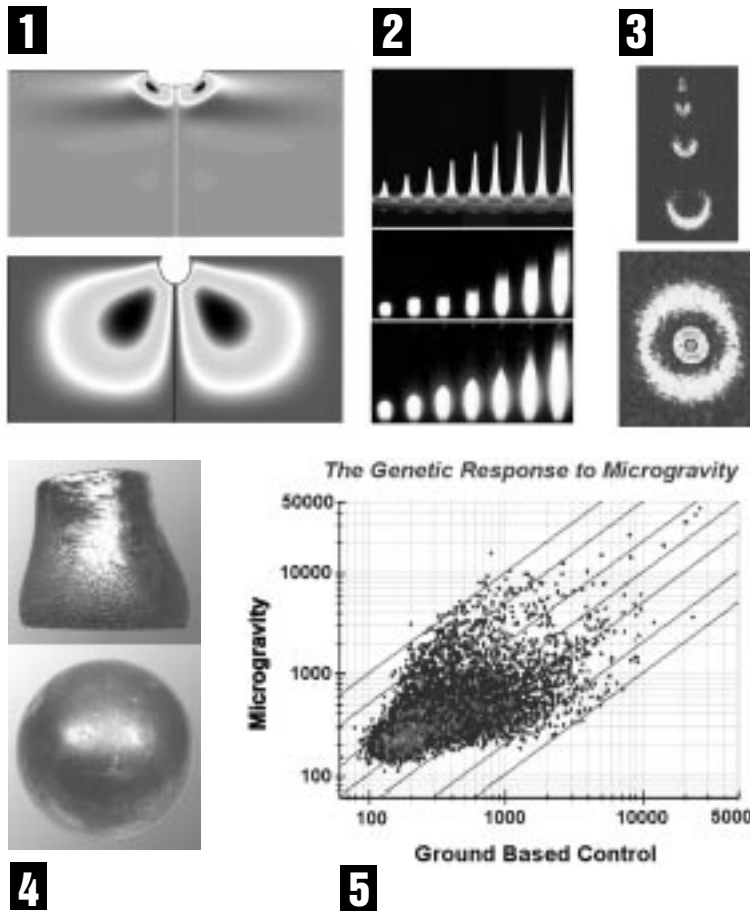


Physicists use a microgravity environment to help them discover and understand the laws governing our universe. Accurate clocks are important research tools in such experiments. Physicists in the microgravity program are developing a clock to be flown on the International Space Station that will be the most accurate clock to date and will be available to everyone as a research tool. An artist's rendering of this clock is pictured here.

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On the back cover...



1 Thermocapillary flow induced by a bubble on Earth is greatly influenced by its inevitable interactions with buoyancy-driven convection. These pictures show steady-state flow fields generated by an air bubble in a surrounding fluid (silicone oil) in normal gravity (top) and microgravity (bottom).

2 Due to a reduction in buoyancy-induced flows, flames in microgravity experience a change in the onset of soot release and a change in flame shape when compared to flames in normal gravity. The top series of images shows onset of soot release occurring in the annular shell at the flame tip (3rd flame from right). The middle series of low-velocity microgravity flames shows that the onset of soot release occurs in the annular layer, but that the flame shape is flat before the onset (4th flame from right). The bottom series of high-velocity microgravity flames shows that the onset of soot release occurs at the center of the flame (third flame from left).

3 In an atom laser on the ground, atoms fall under the influence of gravity, producing a nonlinear dispersion of matter waves (top). An artist's concept of an atom laser in space (bottom) shows that coherent matter waves propagate free from gravity's perturbation.

4 Many materials are available only as a powder. To achieve high density in components shaped from these materials a process known as liquid-phase sintering is often used. However, when the liquid forms, the component can distort under its own weight (top photo). The same type of compact when sintered in microgravity generally attains a spherical shape (bottom).

5 Some genes respond to microgravity as evidenced by this graph of spaceflight experiment results, which shows that of 10,000 genes expressed by human kidney cells, 1,600 genes changed their expression levels when in microgravity. (Shear stress and heat shock proteins are shown as green dots, transcription factors as red dots. A change in expression is denoted by movement along the x and y axes.)

To use the microgravity environment of space as a tool to advance knowledge; to use space as a laboratory to explore the nature of physical phenomena, contributing to progress in science and technology on Earth; and to study the role of gravity in technological processes, building a scientific foundation for understanding the consequences of gravitational environments beyond Earth's boundaries.
— From the Microgravity Research Program's Mission Statement

Marshall Space Flight Center (MSFC), located in Huntsville, Alabama, serves as NASA's lead center for the Microgravity Research Program (MRP). To support that work, MSFC's Microgravity Research Program Office (MRPO) is responsible for advancing the microgravity mission through the coordination of microgravity science research at NASA field centers, at universities, and with industry partners. Basic and applied research in the five microgravity disciplines (biotechnology, combustion science, fluid

physics, fundamental physics, and materials science) and work conducted on behalf of the MRP's acceleration measurement, glovebox, and technology programs are managed by the MRPO and implemented at the following NASA centers: the Jet Propulsion Laboratory in Pasadena, California, which manages investigations in fundamental physics and is responsible for microgravity technology development and transfer activities; Johnson Space Center in Houston, Texas, which manages the cellular biotechnology discipline; Glenn Research Center in Cleveland, Ohio, which manages studies in the combustion science and fluid physics disciplines as well as microgravity measurement and analysis support services for all the microgravity science disciplines; and MSFC, which, in addition to serving as NASA's lead center for the MRP, manages research in the macromolecular biotechnology and materials science disciplines and is responsible for the microgravity glovebox program. The MRP's program goals for fiscal year (FY) 1999 follow:

Goal 1

Sustain a leading-edge research program focused in the areas of biotechnology, combustion science, fluid physics, fundamental physics, and materials science that effectively engages the national research community.

Goal 2

Foster an interdisciplinary community to promote synergy, creativity, and value in carrying out the research program.

Goal 3

Enable research through the development of an appropriate infrastructure of ground-based facilities, diagnostic capabilities, and flight facilities/opportunities, and promote the use of smaller apparatus.

Goal 4

Promote the exchange of scientific knowledge and technological advances among academic, governmental, and industrial communities. Disseminate results to the general public and to educational institutions.

Goal 5

Raise the awareness of the microgravity research community regarding the long-term direction of NASA's Human Exploration and Development of Space Enterprise, and discuss with the community the role of microgravity research in support of agency objectives.

Performance Goals

While the five program goals listed above are qualitative and program-oriented, the MRP has also developed a set of performance goals that describe specific activities, methods for implementation, and planned outcomes. In addition to guiding the progress of the program, these goals will also serve as measuring sticks, allowing quantitative evaluation of the program. The performance goals were developed in response to the general call to reinvent government and the Government Performance and Results Act of 1993, which directs agencies within the executive branch to develop customer-focused strategic plans that align their activities with concrete mission and goal statements. Performance goals have been developed that

support the MRP mission to use the microgravity environment of space as a tool to advance knowledge; to use space as a laboratory to explore the nature of physical phenomena, contributing to progress in science and technology on Earth; and to study the role of gravity in technological processes, building a scientific foundation for understanding the consequences of gravitational environments beyond Earth's boundaries.

The MRP performance goals were finalized in FY 1998 in fulfillment of Congress' mandate and were used in FY 1999 to assess the program's progress. The MRP performance goals and an update on progress in FY 1999 are listed in **Table 1**. Further information on projects supporting each goal is available online at: <http://microgravity.hq.nasa.gov/research.htm>.

Table 1 MRP Performance Goals and Progress in FY 1999

Goal	Progress in FY 1999
1.21 — Sustain a leading biotechnology research program that will assure continued scientific and technical leadership.	103 biotechnology investigations were supported in FY 1999.
1.22 — Enable increased combustion system efficiency, reduced pollution, and mitigation of fire risks through insights and databases obtainable only through microgravity experiments.	72 combustion science investigations were supported in FY 1999.
1.23 — Pursue groundbreaking basic research in fluid physics and transport phenomena to provide fundamental understanding of natural phenomena affected by gravity for increased efficiency and effectiveness of space-based and industrial processes.	86 fluid physics investigations were supported in FY 1999.
1.24 — Unlock mysteries of the universe by exploring the frontiers of physics obscured by Earth's gravity, using laboratories in space.	49 fundamental physics investigations were supported in FY 1999.
1.25 — Use microgravity to establish and improve quantitative and predictive relationships between the structure, processing, and properties of materials.	105 materials science investigations were supported in FY 1999.
1.9 — Successfully test a fundamental tenet of general relativity by completing an internationally funded Satellite Test of the Equivalence Principle project by 2005.	1 fundamental physics investigation was supported in FY 1999.
2.2 — Identify materials processing issues and propose/test processing strategies to enable human operations on the surface of the Moon/Mars using In-Situ Resource Utilization (ISRU) concepts.	2 investigations were supported in FY 1999.

2.4 — Develop methods, databases, and validating tests for material flammability characterization, hazard reduction, and fire detection/suppression strategies for spacecraft and extraterrestrial habitats.	8 investigations were supported in FY 1999.
2.5 — Advance the state of knowledge sufficiently to enable dust-control technologies and bulk materials handling for extraterrestrial habitats and/or ISRU.	8 investigations were supported in FY 1999.
2.6 — Advance the state of knowledge sufficiently to allow development of reliable and efficient heat transfer technology for space and extraterrestrial operations.	19 investigations were supported in FY 1999.
2.7 — Advance the state of knowledge sufficiently to allow development of effective fluid management technology for space and extraterrestrial and industrial operations.	3 investigations were supported in FY 1999.
2.8 — Establish the knowledge base required to design chemical process systems for exploration missions.	12 investigations were supported in FY 1999.
2.9 — Determine the potential use of bioreactors to provide biological materials supporting long-duration space travel.	12 investigations were supported in FY 1999.
2.10 — Develop new probe technologies that use living cells or subcellular components to survey the impacts of extreme environments on terrestrial life.	5 investigations were supported in FY 1999.
2.11 — Adapt precision measurement and control technologies developed by fundamental physics research activities to solve the needs of human and robotic exploration of space.	2 investigations were supported in FY 1999.
4.1 — Involve Americans in the adventure of space exploration by sharing discoveries; expand educational opportunities by opening participation in NASA's Microgravity Research Program.	Microgravity educational products were down-loaded from microgravity web sites by more than 168,000 users.

Program Highlights in FY 1999

- The MRP conducted broad, productive, Earth- and space-based research, including the first-ever expression of new genes under microgravity conditions in the bioreactor during the STS-90 mission, which flew in March 1998. This research revealed that the microgravity environment of space fundamentally affects cellular processes and alters gene expression. The research represents the first application of recently developed gene array techniques to the understanding of changes in cellular function in space.
- Exciting fundamental research results from fluid physics colloids experiments were obtained on the STS-95 mission, which flew in October 1998. The Colloidal Gelation experiment yielded insight into the formation of gels, near-rigid networks of particles. This work is the essential first step in the synthesis of new materials from colloidal particles. The Colloidal Disorder-Order Transition experiment yielded insight into the physics of the structure of materials at the atomic scale. Colloid systems were used to macroscopically model particle interactions among atoms.

- Spacecraft fire safety data were verified through cooperative American/Russian experiments on Russian Space Station *Mir*. The flammability of selected United States-supplied plastic materials was tested under microgravity conditions in a combustion tunnel supplied by Russia. The data were compared to reference testing of the flammability, heat release, thermal properties, and combustion products of identical materials in ground laboratories at both the Russian Keldysh Research Center and at Johnson Space Center's White Sands Test Facility.
- Spacecraft radiation safety was advanced with an understanding of the fundamental processes and appropriate materials for shielding the spacecraft from space radiation. Progress included the development of transport code and a nuclear database for evaluation of spacecraft shielding; the assembly of a database of 75 important materials, which are being characterized according to their shielding properties; and an understanding of the production of neutrons from collisions with spacecraft shielding materials.
- Optical particle manipulation technologies called laser tweezers and laser scissors, which were developed for colloids research, are being applied to in-vitro fertilization research at University Hospital in Cleveland, Ohio. Interest in using the "tweezers" as a noncontact method for manipulating gametes and embryos in the laboratory prompted the collaboration with NASA microgravity researchers. In addition, cell fusion studies using laser tweezers and scissors may be performed by bringing two cells into contact and ablating the cell wall where they touch.
- Feasibility testing of the Magneto-Optical Trap for studies in fundamental physics was completed with the successful ground demonstration of the technology. This technology will enable significant increases in timekeeping and enable a broad range of general relativity experiments in microgravity. The technology has been baselined for upcoming fundamental physics research on the International Space Station.
- Furthering the MRP's continuing efforts to communicate and interact with the industrial sector, an Industry Liaison Board was formed through an initiative of the National Center for Microgravity Research on Fluids and Combustion. The board, convened by William Ballhaus, vice president of Lockheed Martin Corporation, made an initial set of recommendations for how NASA could enhance the value of its microgravity research on fluids and combustion for the industrial sector.
- Through NASA's Graduate Student Research Program, 14 graduate students received funding to perform ground-based microgravity research, supporting a commitment to encourage the next generation of microgravity researchers.
- Microgravity science posters, teacher's guides, mathematics briefs, microgravity demonstrator manuals, and supplemental curricular materials were made available to more than 44,700 elementary and secondary school teachers and administrators in attendance at annual meetings of science, technology, and mathematics teacher's associations.

Reaching out to the community in order to increase the awareness of NASA's microgravity activities is mandated by the MRP's mission statement and program goals and helps to maintain the strength and relevance of its science program. The following are highlights of education and outreach activities in FY 1999:

- *Microgravity News*, a quarterly update on NASA's Microgravity Research Program, reached increasing numbers of people in the past year. The total distribution for each issue of the newsletter grew to more than 10,800 copies in calendar year 1999.

This fiscal year (FY) 1999 report describes key elements of the NASA Microgravity Research Program (MRP) as conducted by the Microgravity Research Division (MRD) within NASA's Office of Life and Microgravity Sciences and Applications. The program's goals, approach taken to achieve those goals, and available resources are summarized. A "snapshot" of the program's status at the end of FY 1999 and a review of highlights and progress in ground- and flight-based research are provided. Also described are major space missions that flew during FY 1999, plans for utilization of the research potential of the International Space Station, technology development, and various education and outreach activities. The MRP supports investigators from academia, industry, and government research communities needing a space environment to study phenomena directly or indirectly affected by gravity.

Because they are natural extensions of traditional Earth-based laboratory science, the experiments conducted under the MRP benefit from the stable, long-duration microgravity environment available on orbiting spacecraft. The microgravity environment affords substantially reduced buoyancy forces, hydrostatic pressures, and sedimentation rates, allowing gravity-related phenomena to be isolated and controlled, and permitting measurements to be made with an accuracy that cannot be achieved in ground-based laboratories.

Table 2 summarizes information from the *Microgravity Science and Applications Program Tasks and Bibliography for FY 1999* that may be of particular interest to the reader. Data for FY 1995–1998 are shown for comparison with FY 1999 statistics.

Table 2 **FY 1995–1999 Research Task Summary: Overview Information and Statistics**
(includes some continuing projects at no additional cost)

	FY 1995	FY 1996	FY 1997	FY 1998	FY 1999
Number of principal investigators	290	358	329	377	409
Number of co-investigators	287	396	375	446	487
Number of research tasks	347	508	414	465	485
Total number of bibliographic listings	1,200	1,573	1,428	1,868	2,280
■ Proceeding papers	140	237	177	305	350
■ Journal articles	526	600	576	683	905
■ NASA technical briefs	11	14	10	31	30
■ Science/technical presentations	509	706	647	823	962
■ Books/chapters	14	16	18	26	33
Number of patents applied for or awarded	1	2	4	8	26
Number of students funded	534	780	748	853	969
Number of degrees granted based on MRD-funded research	178	247	243	277	368
Number of states with funded research (including District of Columbia)	34	35	36	36	36
FY MRD Budget (\$ in millions)	163.5	159	105.3	100.4	113.7

The Microgravity Research Program supports both basic and applied research in five key areas:

- **Biotechnology** — focusing on macromolecular crystal growth as well as the use of the unique space environment to assemble and grow mammalian tissue.
- **Combustion science** — focusing on the processes of ignition, flame propagation, and extinction during combustion of gaseous, liquid, and solid fuels, and on combustion synthesis in a low-gravity environment.
- **Fluid physics** — including aspects of fluid dynamics and transport phenomena affected by the presence of gravity.
- **Fundamental physics** — including the study of critical phenomena; low-temperature, atomic, and gravitational physics; and other areas of fundamental physics where significant advantages exist for studies in a low-gravity environment.
- **Materials science** — including electronic and photonic materials, glasses and ceramics, polymers, and metals and alloys.

Experiments in these areas are typically directed at providing a better understanding of gravity-dependent physical phenomena and exploring phenomena obscured by the effects of gravity. Scientific results are used to challenge or validate contemporary scientific theories, identify and describe new experimental techniques that are unique to the low-gravity environment, and engender

the development of new theories explaining unexpected results. These results and the improved understanding accompanying them can lead to improved combustion efficiency and fire safety; reduced combustion-generated pollutants; the development of new technologies in industries as varied as medicine, chemical processing, and materials processing; the development or improvement of pharmaceuticals; and the expansion of fundamental knowledge in a broad range of science disciplines destined to become the foundation for scientific and technological discoveries in the future.

A complementary document to this MRP annual report is the *Microgravity Research Division Program Tasks and Bibliography for FY 1999*, available online at <http://microgravity.hq.nasa.gov/research.htm>. Detailed information on the research tasks funded by the MRD during FY 1999 is listed in that report, which serves as an excellent reference for supplementary information to this annual report. Also of interest is the *NASA Microgravity Science and Applications Program Strategic Plan*, issued in June 1993, a guide for development and implementation of the MRP plans and activities to the year 2000. The *Marshall Space Flight Center (MSFC) Strategic Implementation Plan*, January 1996, describes MSFC's lead center role for the MRP.

Table 3 lists the number of research tasks and types performed at each NASA center for FY 1995–1999.

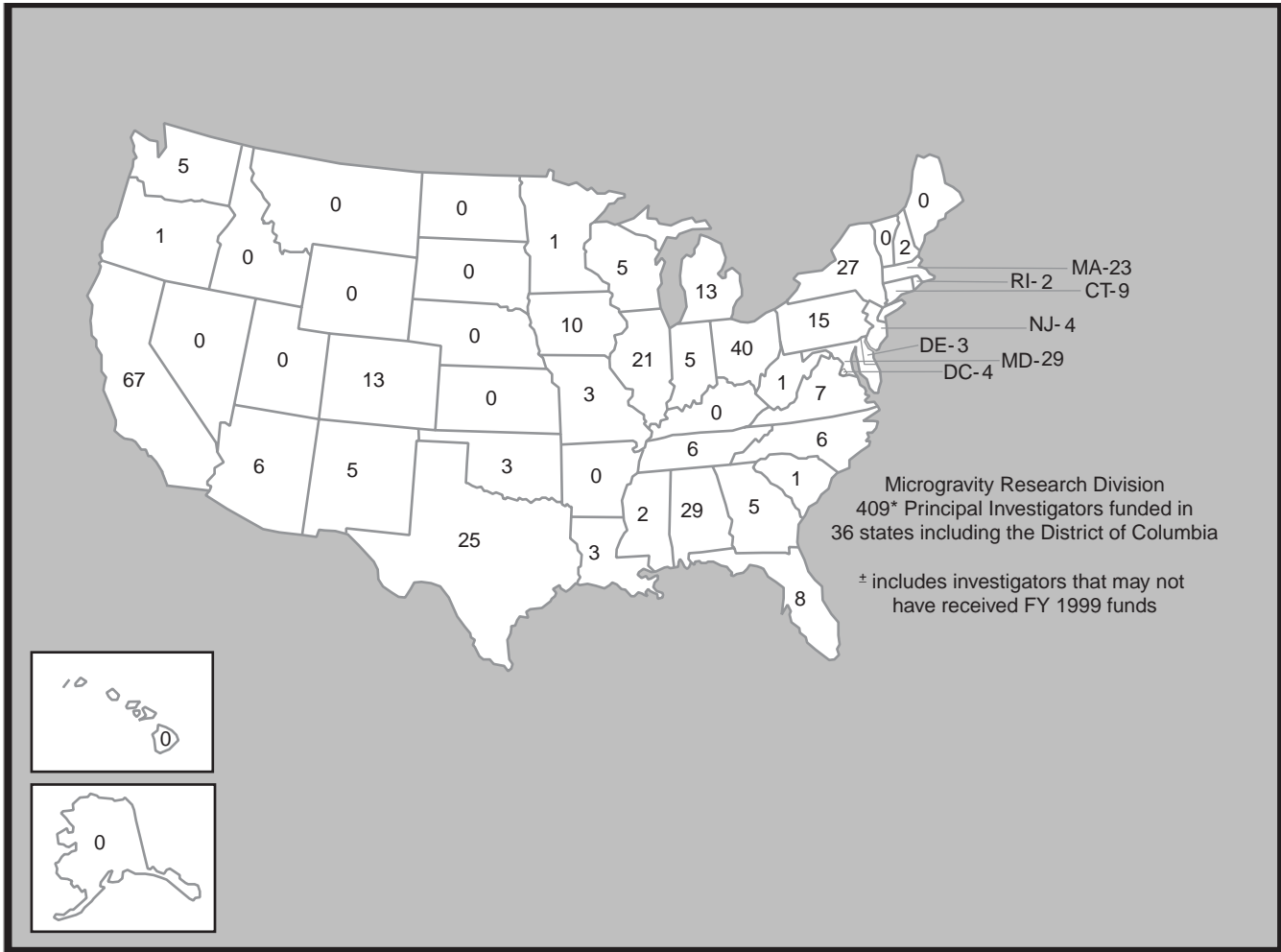
Table 3 Microgravity Research Tasks and Types by Fiscal Year
(responsibilities by center)

Center	Ground					Flight					ATD*					Center Totals				
	95	96	97	98	99	95	96	97	98	99	95	96	97	98	99	95	96	97	98	99
Glenn Research Center	125	203	137	152	163	32	46	40	44	43	6	6	7	6	5	163	255	184	202	211
Jet Propulsion Laboratory	28	45	23	42	40	5	7	5	9	9	3	3	3	3	3	36	55	31	54	52
Johnson Space Center	34	32	42	37	55	1	1	1	1	2	0	1	1	1	1	35	34	44	39	58
Marshall Space Flight Center	76	124	117	127	135	25	32	31	39	39	6	4	5	3	4	107	160	153	169	178
Research Task Totals	266	406	319	358	393	65	87	78	93	93	16	15	17	13	13	347	508	414	464	499

* *Advanced Technology Development*

Table 4 shows the distribution of principal investigators by state, including the District of Columbia.

Table 4 FY 1999 Microgravity Research Division Principal Investigators by State



3 Microgravity Research Conducted in FY 1999

In fiscal year (FY) 1999, researchers in the Microgravity Research Program's five science disciplines — biotechnology, combustion science, fluid physics, fundamental physics, and materials science — worked to advance human understanding of fundamental physical phenomena and processes through their investigations, which quantify the effects of and overcome the limitations imposed by gravity. Ground-based experiments, coupled with experiments selected for flight definition, comprise a compelling and coherent strategy for understanding and using the microgravity space environment. Highlights of research activity in FY 1999 are presented for each science discipline.

Biotechnology

Biotechnology is the application of knowledge concerning biological systems for the production of consumer goods or services. The Microgravity Research Program's biotechnology discipline furthers the advancement of biotechnology by sponsoring research activities involving both spaceflight and ground-based experiments. The fields most affected by this research are medicine and agriculture. Biotechnology also supports a broad range of manufacturing industries, since processes that use biological components or mimic biological systems can be used for a variety of purposes including the creation of new materials, the removal of contaminants, and the improvement of the efficiency of chemical reactions. In addition, biotechnology applications are important to NASA because they provide enabling technology for space exploration.

Research in the microgravity biotechnology program includes investigations in both molecular science and cellular science. Marshall Space Flight Center (MSFC) serves as the managing center for the biotechnology discipline and directly oversees molecular research within the discipline. The Johnson Space Center arm of the program manages projects involving cellular and tissue research. Sponsored projects emerge from three categories: (1) projects that use the space environment for research purposes; (2) ground-based experiments that improve our ability to use space as a research tool; and (3) research that enables space exploration. Currently funded research projects include studies of cellular development, tissue engineering, biomaterials, radiation effects, the crystallization of biological materials, molecular structure, and the purification of biological materials.

Large, living organisms are constructed of systems of organs, each of which comprises specific tissues. These in turn are composed of cells, which contain billions of biological molecules. These biological molecules are much larger and more complex than nonbiological molecules. The unique chemical traits of these molecules are the foundation of life. A primary goal of the biological sciences is to determine how these molecules are constructed. This allows scientists to determine how they interact and react with other molecules, and in turn, to understand how cells function, how tissues form, and how an organism grows, lives, and dies. The research conducted under the biotechnology discipline focuses on the fundamental bases of how an organism functions at the molecular and cellular levels.

Molecular Science Overview

The shape and chemical components of biological macromolecules determine their function. These molecules, mostly proteins and nucleic acids, perform or regulate all the functions necessary to maintain life. Thus, how a living organism functions must be comprehended at the molecular level. Understanding the function of a living organism is a complex task. About 100,000 different types of biological macromolecules are at work in the human body. Substructures that make up these molecules are called folds. There are an estimated 10,000 different types of folds found in nature.

An organism's genetic code controls the production of its molecules. Small differences between codes can result in major differences between organisms. For example, humans and apes share over 99 percent of the same genetic code. Small errors in an organism's code can cause misformed molecules that can result in genetic defects and susceptibility to disease.

The most common way to study the structure of biological molecules is called crystallography. Scientists first produce and purify a significant amount of a molecule and then grow crystals of the material. If the crystals are of sufficient quality, an X-ray beam shining through the crystal can be used to produce a distinct pattern of diffracted light. This diffraction pattern is unique to the molecules that make up the crystal. Computer codes can then be used to decipher the pattern and estimate the size, shape, and structural composition of the molecule. The quality of the estimate is largely determined by the quality of the crystal. This structural information is vital in understanding how the molecule works. The shape and composition of the molecule determines what other molecules can and will interact with it. The analogies of a key fitting in a lock or a hand in a glove are often used to describe how one molecule in the body interacts with another.

Scientists from a number of different fields specialize in the study of biological macromolecules. Drug designers are particularly interested in molecules found in the human body. If a drug is of the wrong molecular shape, size, or chemical function it is likely to have no effect, or even worse, react with molecules that it was not designed for. Molecular information is also important to genetic engineers, scientists who chemically alter genetic codes to make species with desirable properties. For example, yeast has been engineered to make insulin, the molecule used to treat diabetes. In addition, genetic engineering is used to make crop plants more productive. Molecular knowledge is also the key to understanding how some species function, survive, and thrive in extreme environments such as arctic regions, volcanic vents, and

nuclear reactors. An example of this ability to survive in extreme conditions is found in a cold-water fish that produces a natural antifreeze in its blood.

Living organisms make large, complex, and in many cases, multifunctional molecules that cannot be produced using non-living materials. Therefore, materials scientists may require the use of living systems to make some types of complex materials. For example, one class of molecules, known as enzymes, catalyzes chemical reactions. Enzymes could be used in industrial processes to chemically convert waste or pollutants to innocuous or useful material. An enzyme can be viewed as a molecular-sized manufacturing plant — it takes other molecules and converts them to something else. In this sense, enzymes are the ultimate in nanotechnology.

The microgravity biotechnology program has sponsored research devoted to improving the ability of scientists to obtain information about biological molecules. The primary thrust of the research has been to use the spaceflight environment to perform experiments. In orbit, the effects of buoyancy are nearly negligible. Fluid flows due to density differences are greatly reduced. Sedimentation virtually disappears. The reduction of these effects can be a big advantage to a scientist. For example, crystals grown slowly from a solution tend to be of better quality. However, buoyancy-driven fluid flows inherent on Earth tend to speed the formation of solution-grown crystals. In addition, when an investigator tries to purify molecules by separating them from impurities on Earth, buoyancy-driven fluid flows may keep the impurities and molecules mixed. Spaceflight offers researchers an opportunity to avoid these problems.

The biotechnology discipline also funds a robust program of ground-based molecular research. Sponsored studies include the analysis of biological crystals, methods to control the quality of crystals, the formation of substrates made from biological materials, catalytic decomposition of sewage, separation technology, and studies of molecules found in species living in extreme conditions.

Molecular Science Program Highlights in Fiscal Year (FY) 1999

- Gray Bunick, of Oak National Laboratory, reported at the American Crystallographic Association (ACA) meeting that his laboratory had determined the structure of the nucleosome core particle to high resolution. The structure was determined using crystals grown in the Diffusion-Controlled Crystallization Apparatus for Microgravity (DCAM) during the series of space shuttle flights to Russian Space Station *Mir*. The nucleosome core particle is found in all cells around the DNA, but its function is poorly understood.
- Crystals of the enzymes RNase P and 8-oxo-dGTPase grown by the University of Alabama, Birmingham (UAB), on the STS-95 mission in October 1998 diffracted to better resolution than had been achieved previously. The enzymes regulate RNA production and repair of DNA, respectively.

- Development of high-brilliance X-ray diffraction equipment continued. Diffraction systems that rely on tens of watts of power as opposed to kilowatts of power were tested and shown to be feasible. The work was performed in a cooperative agreement with New Century Pharmaceuticals, Inc., and the National Institutes of Health (NIH). Several diffraction data sets have been obtained.
- Research conducted by Denis Wirtz, of Johns Hopkins University, was published in the prestigious journal *Nature*. The article, titled “Dynamics of Individual Flexible Polymers in a Shear Flow,” describes how the shape of large molecules can be affected by fluid flow. Polymeric material was observed to exhibit large changes in shape depending on the fluid shear. These observations may be applicable to biological molecules.
- A patent was issued for a blood replacement/expander product co-owned by NASA and New Century Pharmaceuticals. Walter Reed Army Hospital has signed a cooperative agreement with the pharmaceutical company and will conduct tests on the blood substitute. The patent resulted from research conducted by Daniel Carter, of New Century Pharmaceuticals, on serum albumin.
- A team consisting of Edward Snell, of the Universities Space Research Association; Craig Kundrot, of MSFC; Gloria Borgstahl, of the University of Toledo; and Henry Bellamy, of Stanford University, has been awarded 40 days of beamtime over the next two years at the Stanford Synchrotron. The project supports three current NASA Research Announcement (NRA) grants for which Snell, Kundrot, and Borgstahl serve as either principal investigators or co-investigators. Approximately half of all molecular structures reported are determined using data from synchrotrons. Despite the difficulty in obtaining beamtime, use of the facility is sought after because its high-intensity beams enable most difficult structures to be determined.

Molecular Science Meetings, Awards, and Publications

The 18th General Assembly of the International Union of Crystallography, held once every three years, took place in Glasgow, Scotland, August 4–13, 1999. More than 2,200 crystallographers from 53 different countries attended. NASA, in coordination with the ACA and the International Center for Diffraction Data, funded more than 20 U.S. crystallographers to attend and present their results. Many expressed their thanks to NASA in the ACA newsletter. NASA also sponsored a session chaired by Edward Snell titled “New Frontiers in Macromolecular Crystallization.” A number of NASA-funded experiments were presented to the international community at the meeting, including talks by flight investigators Craig Kundrot and Lawrence DeLucas, of UAB. NASA ground-based researchers were also well-represented at the meeting, with several talks and many posters in the sessions.

Three meetings were held with a task group of the National Academy of Science of the National Research Council (NRC). This task group was established to examine NASA's plans for biotechnology research on the International Space Station (ISS). The task group is expected to provide critical assessments of all aspects of the biotechnology program during the group's year-long review, which will culminate in a formal published report in the spring of 2000. Chairing the task group was Paul Sigler, of Yale University. Membership on the panel includes experts in macromolecular science and cell science.

The NASA biotechnology program assisted and partially funded the ACA's annual meeting. Several NASA investigators served as session chairs and presenters. Most of the research groups performing molecular-based science and funded by the biotechnology discipline were represented and made presentations on their research.

Onofrio Annunziata, of Texas Christian University, and his research team, including John Albright, won the Linus Pauling prize at the ACA annual meeting. The award recognized a poster presentation describing measurements of diffusivities of biological macromolecules. The measurement technique was shown to be useful for determining the electrostatic charge on the molecules.

Peter Vekilov, of the University of Alabama, Huntsville, was one of 12 Americans invited to be speakers at the Third International Conference on Molecular Structural Biology. The conference is one of the most respected in the field of molecular science.

At NASA headquarters in June 1999, NASA Administrator Daniel Goldin presented Alexander McPherson, of the University of California, Irvine (UCI), with the Exceptional Scientific Achievement Medal, which was awarded to just three scientists this year. McPherson is considered the nation's foremost authority on macromolecular crystallization. The McPherson Laboratory at UCI serves as a hub for scientific cooperation among scientists from Canada, France, Germany, Japan, Russia, and the United States.

Molecular Science Flight Experiments

Nine types of biological macromolecules were flown on STS-95 in October 1998 using the **Protein Crystallization Apparatus for Microgravity (PCAM)**. The principal investigator (PI) for the experiment was Daniel Carter.

Crystals of EF hand proteins grown using PCAM on the first Microgravity Science Laboratory (MSL-1) mission were found to diffract to 0.9-angstrom resolution. This is one of the higher resolutions ever achieved with a biological macromolecule. EF hand proteins are important in regulating calcium and magnesium ions involved in signaling in the nervous system. This research, conducted by Declercq (Université Catholique de Louvain) and its partners, was published in *Protein Science* and the *Journal of Crystal Growth*.

Crystals grown in DCAM during the *Mir*/shuttle flight series are being studied by neutron diffraction. Carter, the PI for the experiments, reports that one molecular structure has been

determined using neutron diffraction, and two others are in progress. Only 12 structures of biological molecules have ever been attempted by this technique. The technique requires exceptionally large crystals, which have been successfully produced in spaceflight experiments in DCAM.

Nineteen types of biological molecules were flown on STS-95 using the **Vapor-Diffusion Apparatus** and the **Commercial Vapor-Diffusion Apparatus**. Lawrence DeLucas, the PI for the experiments, reports that 13 of the molecules produced diffraction-quality crystals.

Crystals of **NAD synthetase** grown by UAB on STS-95 diffracted to 0.9-angstrom resolution, which indicates crystals of exceptional quality. This resolution allows even hydrogen, the smallest atom, to be found in the molecular structure. NAD synthetase is vital to the life cycle of all bacteria. The information obtained from these crystals may be used in antibiotic research.

Proteinase K, grown by UAB on STS-95, diffracted to 0.98 angstroms. These data allowed resolution of the protein's chemically active site. A paper on this experiment has already been published in the *Journal of Crystal Growth*.

Cell Science Overview

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 aqueous solution of chemicals. The simplest forms of life are solitary cells that propagate by dividing in two. Higher organisms, such as humans, are like cellular cities in which groups of cells perform specialized functions and are linked by intricate communications systems. Cells occupy a halfway point in the scale of biological complexity. We study them to learn, on the one hand, how they are made from molecules, and on the other, how they cooperate to make an organism as complex as a human being.

There are more than 200 different types of cells in the human body. These are assembled into a variety of different types of tissue such as epithelia, connective tissue, muscle, and nervous tissue. Most tissues contain a mixture of cell types. Cells are small and complex. A typical animal cell is about five times smaller than the smallest visible particle. It is hard to see their structure, hard to discover their molecular composition, and harder still to find out how their various components function. Differentiated cells perform specialized functions. Specialized cells interact and communicate with one another, setting up signals to govern the character of each cell according to its place in the structure as a whole.

What can be learned about cells depends on the available tools. The culture of cells is one of the most basic tools used by medical researchers. Growth of human cells outside the body enables the investigation of the basic biological and physiological

phenomena that govern the normal life cycle and many of the mechanisms of disease. In traditional methods, researchers culture mammalian cells using vessels in which cells settle to the bottom surface of the vessels under the influence of gravity. This results in a thin sheet, or monolayer, of cells. Cells in human tissues, however, are arranged in complex, three-dimensional structures. When cells are grown in a monolayer, they do not function as they would in a three-dimensional tissue. Although much valuable information is gained from monolayer cell cultures, further understanding of the processes that govern gene expression and cellular differentiation is limited because the cells are not arranged as they are in the human body. When the influence of gravity is decreased, the cells are able to form more tissue-like, three-dimensional aggregates. Until the cellular biotechnology program developed a unique technology, the NASA bioreactor, experiments to form three-dimensional cell formations were confined to the microgravity of space.

The NASA bioreactor is an analog of microgravity cell culture. The completely filled cylindrical vessel rotates about a horizontal axis, suspending the cells in a low-shear culturing environment. This allows for cell aggregation, differentiation, and growth. The NASA bioreactor affords researchers exciting opportunities by creating three-dimensional cell cultures that are similar to tissues found in the human body. Using both space- and ground-based bioreactors, scientists are investigating the prospect of developing tissues that can be used in medical transplantation to replace failed organs and tissues. Additionally, investigators are striving to produce models of human disease to be used in the development of novel drugs and vaccines for the treatment and prevention of disease, to devise strategies to re-engineer defective tissues, and to develop new hypotheses for the emergence of diseases such as cancer. Finally, cells exposed to simulated and true microgravity respond by making novel adaptational changes that give new insights to cellular processes, establish a cellular basis for the human response to microgravity and the space environment, and open the way for cell biology research in space on the transition of terrestrial life to low-gravity environments.

Cell Science Program Highlights in FY 1999

- The NASA rotating bioreactor is not only a microgravity cell culture analog, but it also engenders novel approaches in tissue engineering. Lisa Freed and Gordana Vunjak-Novakovic, both of the Massachusetts Institute of Technology (MIT), used the bioreactor to engineer cardiac tissue with techniques similar to those used to culture functional cartilage tissue. These latest results from the MIT tissue engineering effort are the first steps toward engineering heart muscle tissue that may one day be used to patch damaged human hearts.
- J. Milburn Jessup, of the University of Texas Health Science Center Medical School, used the bioreactor to develop a model for metastasis of colon cancer cells to the liver. Jessup's

group subsequently analyzed the effects of the tumor marker Carcinoembryonic antigen (or CEA, which is produced by human colorectal carcinoma) and how it enhances the ability of weakly metastatic carcinoma cells to implant and survive in the liver. They've also found that CEA induces production of the cytokine IL-10 (Interleukin-10, which down-regulates some immune responses) and are currently beginning to apply this to the clinical situation by testing whether IL-10 may be modulated by CEA.

- Wei-Shou Hu, of the University of Minnesota, and colleagues are developing a bioartificial liver and investigating manufacturing tissue-like liver cells in the bioreactor for use in clinical investigations.
- Several research efforts are under way to benefit the future of microgravity research by developing technology that will continuously monitor and control the cell culture environment in bioreactors operating on orbit. Sophisticated sensors are an important part of space exploration as well as of research on cell culture. These sensors are needed to achieve a physiologically balanced culture environment that will enable growth of tissues for transplantation. David Murhammer, of the University of Iowa, and colleagues are investigating the use of near-infrared spectroscopy for real-time, noninvasive monitoring of selected parameters that are critical for animal cell cultures. Melody Anderson, of Johnson Space Center (JSC), and coworkers successfully developed and validated a photometric-based pH sensor in a ground-based bioreactor for a period greater than 90 days. Glenn Spaulding, of the Clear Lake Medical Foundation, Inc., is working on optical sensors that monitor cell culture media remotely.
- Joshua Zimmerberg and Leonid Margolis, both of the NASA/NIH Three-Dimensional Tissue Laboratory, have established cell culture models of immune dysfunction using human tonsillar tissue.
- Thomas Goodwin, of JSC, presented the first stable cell cultures of bowhead whale kidney, an important step in investigating the environmental toxicology of heavy metals. Discovery that bowhead whale metallothionein (MTH) protein is homologous to human MTH protein resulted from the development of three-dimensional tissue cultures. MTH is the primary site for binding heavy metals and other toxins. The genetic sequence for this protein was logged with the National Gene Bank.
- Timothy Hammond, of Tulane University, demonstrated the vast array of genes affected when cells transition to microgravity.
- H. Alan Wood, of Cornell University, demonstrated the unique glycosylations that occur in bioreactor cultures of insect cells expressing human genes. His finding opens new possibilities in the production of biologically active human glycoproteins.
- Neal Pellis and Alamelu Sundaresan, both of JSC, further characterized the signal transduction lesion in cells exposed to microgravity analog culture.

- The fluid environment of space- and ground-based bioreactors was characterized independently by Paul Neitzel, of the Georgia Institute of Technology, and Stanley Kleis, of the University of Houston.
- Three patents were approved and five patents are pending in the cellular biotechnology program in FY 1999.
- Fifty-nine investigations in cell science were funded for 1999 from the NRA in biotechnology (97-HEDS-02) released in December 1997.

Cell Science Meetings, Awards, and Publications

One of the most important events of FY 1999 for the cellular biotechnology program was the evaluation of NASA's Biotechnology Facility for the ISS, conducted by the NRC's task group. The cellular biotechnology program provided presentations in three meetings that specifically identified the science requirements for the facility, the selection process for research to be conducted in the facility, and the potential output of a dedicated facility. The NRC task group examined the use of the ISS as a platform for biotechnology research. The final report will be released in the spring of 2000.

The cellular biotechnology program manager, Neal Pellis, was a guest speaker at the annual meeting of the American Association of Clinical Endocrinologists' Upstate New York Chapter and the joint International Juvenile Diabetes Foundation and Diabetes Research Foundation's Open Meeting on the New Age of Diabetes Research and Care.

Twenty-two presentations covering ground and flight research in basic cell science, tissue engineering, and protein crystal growth were discussed at the 1999 Biotechnology Cell Science Program Investigators' Working Group Meeting in Houston, Texas.

Gordana Vunjak-Novakovic and colleagues at MIT presented a talk titled "Microgravity Studies of Cells and Tissues: From *Mir* to ISS" at the conference on International Space Station Utilization — Biotechnology on the ISS, held in Albuquerque, New Mexico.

The future of research relevant to improving the quality of increased longevity and how space life sciences will contribute to that aim was discussed at the Media Forum on Aging Research at the National Press Club in conjunction with the Association for Aging Research.

A report on the development of a model for the study of heavy metals in cetaceans (whales) was presented at the International Whaling Commission's annual meeting.

Cell science papers were presented at the Biannual Meeting and General Assembly of the European Low-Gravity Research Association, held in Rome, Italy, and at a session titled "Out of This World Biotechnology — The NASA Connection" at the Bio '99 International Biotechnology Meeting and Exhibition in Seattle, Washington.

Cell science investigators presented research results at the following meetings and conferences in FY 1999: the 39th Annual American Society for Cell Biology meeting, the 1999 Annual American Association for the Study of Liver Diseases meeting, the 15th Annual Meeting of the American Society for Gravitational and Space Biology, the International Mechanical Engineering Congress and Exposition/American Society of Mechanical Engineers meeting, the Laboratory of Cellular and Molecular Biophysics Laboratory Retreat, the 15th Congress of the International Federation of Associations of Anatomists and Fourth International Malpighi Symposium, the 217th American Chemical Society Annual Meeting, the 90th Annual Meeting of the American Association for Cancer Research, the Sixth World Biomaterials Congress and 2000 Society for Biomaterials Joint Meeting, the 1999 Transcriptional Regulatory Mechanisms Symposium, the meeting of the Society for In-Vitro Biology, the American Institute of Aeronautics and Astronautics meeting, the meeting of the American Chemical Society, the American Institute of Chemical Engineers meeting, the American Diabetes Association Annual Meeting, the Materials Research Society Fall Meeting, the meeting of the American Physical Society, the National Institute for Science and Technology — Biomaterials Group Seminar, the North American Hyperthermia Society 18th Annual Meeting, and the meeting of the American Association for the Study of Liver Diseases.

Thomas Goodwin, of JSC, received the NASA Group Achievement Award for outstanding contributions to the NASA/*Mir* Phase 1 space station program.

Neal Pellis received the NASA Group Achievement Award from the NASA/*Mir* Phase 1 Microgravity Science Team for exceptional dedication to the science planning, development, and operations support of microgravity experiments that have flown onboard *Mir* as part of the Phase 1 program.

"Gene Expression in Space," by Timothy Hammond, et al., was published in the April issue of *Nature Medicine*. The article describes the influence of various gravitational environments on gene expression by human renal cells in culture.

A team of researchers led by Lisa Freed published their findings on engineered cardiac tissue in the *American Journal of Physiology and Biotechnology and Bioengineering*.

An article discussing the research of Goodwin and collaborators on heavy metal contamination in arctic whales was published in *The Scientist*.

In FY 1999, cell science researchers published in such diverse journals as *Nature Medicine*, *Cancer Research*, *Advances in Space Research*, the *Journal of Immunology*, the *Journal of Clinical Investigation*, *Pharmacological Research*, *Biomaterials*, the *Journal of Membrane Biology*, *In Vitro Cellular and Developmental Biology — Animal*, (Federation of American Societies for Experimental Biology), *Analytical Chimica Acta*, *Oncogene*, the *Journal of Immunotherapy*, *International Reviews of Immunology*, *Immunopharmacology*, *Gastroenterology*, and the *Applied Spectroscopy Journal*.

Cell Science Flight Experiments

Evaluation of data from the first attempt to construct a **three-dimensional vascularized tumor model** in microgravity on STS-89/Mir-7 has indicated the beginning stages of angiogenesis. Further data analysis is under way as preparations continue for the repeat of this experiment on the ISS.

The following cell science payloads are under consideration for early flights aboard the ISS: the **Biotechnology Specimen Temperature Controller (BSTC)** on flight for 7A.1, the BSTC on the first Utilization Flight (UF-1), and the **Rotating Wall Perfused System** on UF-2.

The FY 1999 ground and flight tasks for biotechnology are listed in **Table 5**. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1999*, available online at <http://microgravity.hq.nasa.gov/research.htm>.

Table 5 **Biotechnology Tasks Funded by the Microgravity Research Division in FY 1999**
(includes some continuing projects at no additional cost)

Flight Experiments

Protein Crystal Growth Facility–Based Microgravity Hardware: Science and Applications

Daniel C. Carter
New Century Pharmaceuticals, Inc.; Huntsville, AL

Microgravity Studies of Medically Relevant Macromolecules

Lawrence J. DeLucas
University of Alabama, Birmingham; Birmingham, AL

Protein Crystal Growth in Microgravity

Lawrence J. DeLucas
University of Alabama, Birmingham; Birmingham, AL

A Microgravity-Based, Three-Dimensional Transgenic Cell Model to Quantify Genotoxic Effects in Space

Steve R. Gonda
Johnson Space Center; Houston, TX

Growth, Metabolism, and Differentiation of MIP-101 Carcinoma Cells

J. Milburn Jessup
University of Texas Health Science Center Medical School
San Antonio, TX

Macromolecule Nucleation and Growth Rate Dispersion Studies: A Predictive Technique for Crystal Quality Improvement in Microgravity

Russell Judge
Marshall Space Flight Center; Huntsville, AL

Optimizing the Use of Microgravity to Improve the Diffraction Quality of Problematic Biomacromolecular Crystals

Craig E. Kundrot
Marshall Space Flight Center; Huntsville, AL

An Observable Protein Crystal Growth Flight Apparatus

Alexander McPherson Jr.
University of California, Irvine; Irvine, CA

Enhanced Dewar Program

Alexander McPherson Jr.
University of California, Irvine; Irvine, CA

Effects of Convective Transport of Solute and Impurities on Defect-Causing Kinetics Instabilities in Protein Crystallization

Peter G. Vekilov
University of Alabama, Huntsville; Huntsville, AL

Investigation of the Particle Dynamics in the Vicinity of Crystal Surfaces: Depletion Zone Dynamics

Keith B. Ward
Naval Research Laboratory; Washington, DC

Ground-Based Experiments

Experimental Assessment of Multicomponent Effects in Diffusion-Dominated Transport in Protein Crystal Growth and Electrophoresis and Chiral Separations

John G. Albright
Texas Christian University; Forth Worth, TX

Crystallization Mechanisms of Membrane Proteins

James P. Allen
Arizona State University; Tempe, AZ

Novel Concepts in Acoustophoresis for Biotechnology Applications

Robert E. Apfel
Yale University; New Haven, CT

Real-Time Monitoring of Protein Concentration in Solution to Control Nucleation and Crystal Growth

Mark A. Arnold
University of Iowa; Iowa City, IA

The Use of Bioactive Glass Particles as Microcarriers in Microgravity Environment

Portonovo S. Ayyaswamy
University of Pennsylvania; Philadelphia, PA

Protein Crystal-Based Nanomaterials

Jeffrey A. Bell
Rensselaer Polytechnic Institute; Troy, NY

An Acoustically Assisted Bioreactor for Terrestrial and Microgravity Applications

Joanne M. Belovich
Cleveland State University; Cleveland, OH

Expansion and Differentiation of Cells in Three-Dimensional Matrices Mimicking Physiological Environments

Rajendra S. Bhatnagar
University of California, San Francisco; San Francisco, CA

Searching for the Best Protein Crystals: Synchrotron-Based Mosaicity Measurements of Crystal Quality and Theoretical Modeling

Gloria Borgstahl
University of Toledo; Toledo, OH

Reversible Cryogenic Storage of Macromolecular Crystals Grown in Microgravity

Gerard J. Bunick
University of Tennessee; Oak Ridge, TN

Development of an Insulin-Secreting, Immunoprivileged Cell-Cell Aggregate Utilizing the NASA Rotating Wall Vessel

Donald F. Cameron
University of South Florida, College of Medicine; Tampa, FL

Quantitative, Multivariate Methods for Preflight Optimization and Postflight Evaluation of Macromolecular Crystal Growth

Charles W. Carter
University of North Carolina, Chapel Hill; Chapel Hill, NC

Quantitative, Statistical Methods for Preflight Optimization and Postflight Evaluation of Macromolecular Crystal Growth

Charles W. Carter
University of North Carolina, Chapel Hill; Chapel Hill, NC

Origin of Imperfections in Growing Protein Crystals by In-Situ Rocking Curve Analysis

Alexander A. Chernov
Universities Space Research Association, Marshall Space Flight Center; Huntsville, AL

Infrared Signatures for Mammalian Cells in Culture

Krishnan K. Chittur
University of Alabama, Huntsville; Huntsville, AL

Differentiation of Three-Dimensional Cocultures of Myofibroblasts, Preneoplastic Epithelial and Mononuclear Cells

Vimlarani Chopra
University of Texas Medical Branch; Galveston, TX

Microgravity-Simulated Prostate Cell Culture

Leland W. Chung
University of Virginia; Charlottesville, VA

Modeling Prostate Cancer Skeletal Metastasis and Cell Therapy

Leland W. Chung
University of Virginia; Charlottesville, VA

Ions and Protein Association: aw and Protein Crystals

Kim D. Collins
University of Maryland Medical School; Baltimore, MD

Design, Synthesis, and Characterization of Well-Defined, Biomimetic Polypeptide Networks

Vincent P. Conticello
Emory University; Atlanta, GA

Investigation of Neuronal Physiology in Simulated Microgravity Using Smart Fluorescent Microcarriers and Bulk Near-Infrared Sensors

Gerard L. Cote
Texas A&M University; College Station, TX

Noninvasive, Near-Infrared Sensor for Continual Cell Glucose Measurement

Gerard L. Cote
Texas A&M University; College Station, TX

A Comprehensive Investigation of Macromolecular Transport During Protein Crystallization

Lawrence J. DeLucas
University of Alabama, Birmingham; Birmingham, AL

Development of Robotic Techniques for Microgravity Protein Crystal Growth

Lawrence J. DeLucas
University of Alabama, Birmingham; Birmingham, AL

Macromolecular Crystallization: Physical Principles, Passive Devices, and Optimal Protocols

George T. DeTitta
Hauptman-Woodward Medical Research Institute; Buffalo, NY

Use of Microgravity-Based Bioreactors to Study Intercellular Communication in Airway Cells

Ellen R. Dirksen
University of California, Los Angeles; Los Angeles, CA

Microbial Resistance to Solar Radiation: DNA Damage and Application of Repair Enzymes in Biotechnology

Jocelyne Diruggiero
University of Maryland, Biotechnology Institute; Baltimore, MD

Laser Scattering Tomography for the Study of Defects in Protein Crystals

Robert S. Feigelson
Stanford University; Stanford, CA

Novel Strategy for Three-Dimensional In-Vitro Bone Induction

John A. Frangos
University of California, San Diego; La Jolla, CA

Role of Fluid Shear on Three-Dimensional Bone Tissue Culture

John A. Frangos
University of California, San Diego; La Jolla, CA

Microgravity Tissue Engineering

Lisa E. Freed
Massachusetts Institute of Technology; Cambridge, MA

Epitaxial Growth of Protein Crystals on Self-Assembled Monolayers

Jonathan M. Friedman
University of Houston; Houston, TX

Protein and DNA Crystal Lattice Engineering

D. T. Gallagher
Center for Advanced Research in Biotechnology; Rockville, MD

In-Situ Optical Waveguides for Promoting and Monitoring Protein Crystal Growth

Ursula Gibson
Dartmouth College; Hanover, NH

Microgravity-Based Three-Dimensional Transgenic Cell Models

Steve R. Gonda
Johnson Space Center; Houston, TX

Lymphocyte Invasion Into Tumor Models Emulated Under Microgravity Conditions In Vitro

Thomas J. Goodwin
Johnson Space Center; Houston, TX

Application of Bioreactor Technology for a Preclinical Human Model of Melanoma

Elizabeth A. Grimm
M.D. Anderson Cancer Center, University of Texas; Houston, TX

Application of Bioreactor Technology for Analysis and Counter Measure Development of Microgravity-Induced Suppression of Innate Immunity

Elizabeth A. Grimm
M.D. Anderson Cancer Center, University of Texas; Houston, TX

Differentiation of Cultured Normal Human Renal Epithelial Cells in Microgravity

Timothy G. Hammond
Tulane University Medical Center; New Orleans, LA

Production of 1-25-diOH D3 by Renal Epithelial Cells in Simulated Microgravity Culture

Timothy G. Hammond
Tulane University Medical Center; New Orleans, LA

Determining the Conditions Necessary for the Development of Functional Replacement Cartilage Using a Microgravity Reactor

Carole A. Heath
Iowa State University; Ames, IA

New Cell Culture Technology

Charles E. Helmstetter
Florida Institute of Technology; Melbourne, FL

The Effects of Microgravity on Viral Replication

John H. Hughes
Ohio State University; Columbus, OH

Use of NASA Bioreactor to Study Cell Cycle Regulation

J. Milburn Jessup
University of Texas Health Science Center Medical School
San Antonio, TX

Use of Rotating Wall Vessel to Facilitate Culture of Norwalk Virus

Philip C. Johnson
University of Texas Medical School; Houston, TX

Stabilization and Preservation of Crystals for X-Ray Diffraction Experiments

Frances Jurnak
University of California, Irvine; Irvine, CA

Protein Crystallization in Complex Fluids

Eric W. Kaler
University of Delaware; Newark, DE

Applications of Atomic Force Microscopy to Investigate Mechanisms of Protein Crystal Growth

John H. Konnert
Naval Research Laboratory; Washington, DC

Differentiation and Maintenance of Skeletal and Cardiac Muscle in Simulated Microgravity

William E. Kraus
Duke University Medical Center; Durham, NC

Regulation of Skeletal Muscle Development and Differentiation In Vitro by Mechanical and Chemical Factors

William E. Kraus
Duke University Medical Center; Durham, NC

Nutritional Immunomodulation in Microgravity: Application of Ground-Based In-Vivo and In-Vitro Bioreactor Models to Study Role and Mechanisms of Supplemental Nucleotides

Anil D. Kulkarni
University of Texas Health Science Center; Houston, TX

Development of a Noninvasive Glucose Monitor

James L. Lambert
Jet Propulsion Laboratory; Pasadena, CA

PC12 Pheochromocytoma Cells: A Proven Model System for Optimizing Three-Dimensional Cell Culture Biotechnology in Space

Peter I. Lelkes
University of Wisconsin Medical Center; Milwaukee, WI

Multidisciplinary Studies of Cells, Tissues, and Mammalian Development in Simulated Microgravity

Elliot M. Levine
Wistar Institute; Philadelphia, PA

Analysis of Electrophoretic Transport of Macromolecules Using Pulsed Field Gradient NMR

Bruce R. Locke
Florida State University; Tallahassee, FL

Quantitative Analysis of Surfactant Interactions During Membrane Protein Crystallization

Patrick J. Loll
University of Pennsylvania School of Medicine; Philadelphia, PA

Cellular Oxygen and Nutrient Sensing in Microgravity Using Time-Resolved Fluorescence Microscopy

Henryk Malak
Microcosm, Inc.; Columbia, MD

Ground-Based Program for the Physical Analysis of Macromolecular Crystal Growth

Alexander J. Malkin
University of California, Irvine; Irvine, CA

Growth Processes and Defect Structure of Macromolecular Crystals

Alexander J. Malkin
University of California, Irvine; Irvine, CA

Thyroid Follicle Formation in Microgravity: Three-Dimensional Organoid Construction in a Low-Shear Environment

Andreas Martin
Mount Sinai Medical Center; New York, NY

Microgravity Regulation of Oncogene Expression and Osteoblast Differentiation

Laura R. McCabe

Michigan State University; East Lansing, MI

Biological Particle Separation in Low Gravity

D. J. Morré

Purdue University; West Lafayette, IN

Continuous, Noninvasive Monitoring of Rotating Wall Vessels and Application to the Study of Prostate Cancer

David W. Murhammer

University of Iowa; Iowa City, IA

Monitoring and Control of Rotating Wall Vessels and Application to the Study of Prostate Cancer

David W. Murhammer

University of Iowa; Iowa City, IA

Diffusion, Viscosity, and Crystal Growth of Proteins in Microgravity

Allan S. Myerson

Polytechnic University; Brooklyn, NY

Control of Transport in Protein Crystal Growth Using Restrictive Geometries

Robert J. Naumann

University of Alabama, Huntsville; Huntsville, AL

Insect-Cell Cultivation in Simulated Microgravity

Kim C. O'Connor

Tulane University; New Orleans, LA

Extremophilic Interfacial Systems for Waste Processing in Space

Tonya L. Peeples

University of Iowa; Iowa City, IA

Microgravity and Immunosuppression: A Ground-Based Model in the Slow-Turning Lateral Vessel Bioreactor

Neal R. Pellis

Johnson Space Center; Houston, TX

Fluorescence Studies of Protein Aggregation in Under- and Over-Saturated Solutions

Marc L. Pusey

Marshall Space Flight Center; Huntsville, AL

The Role of Specific Interactions in Protein Crystal Nucleation and Growth Studied by Site-Directed Mutagenesis

Marc L. Pusey

Marshall Space Flight Center; Huntsville, AL

Stem Cell Expansion in Rotating Bioreactors

Peter J. Quesenberry

University of Massachusetts Medical Center; Worcester, MA

Islet Cell Assembly and Function in a NASA Microgravity Bioreactor

Arun S. Rajan

Baylor College of Medicine; Houston, TX

Heterozygous Ataxia-Telangiectasia Human Mammary Cells as a Microgravity-Based Model of Differentiation and Cancer Susceptibility

Robert C. Richmond

Marshall Space Flight Center; Huntsville, AL

Evaluating Oxidative Stress in Virally Infected Cells in Simulated Microgravity

Victor G. Rodgers

University of Iowa; Iowa City, IA

Impact of Microgravity on Immunogenicity Associated With Biostructural Changes in Pancreatic Islets

Lynne P. Rutzky

University of Texas Health Science Center; Houston, TX

Cartilage Tissue Engineering: Circumferential Seeding of Chondrocytes Using Rotating Reactors

Robert L. Sah

University of California, San Diego; La Jolla, CA

Enhancement of Cell Function in Culture by Controlled Aggregation Under Microgravity Conditions

W. M. Saltzman

Cornell University; Ithaca, NY

Use of NASA Bioreactors in a Novel Scheme for Immunization Against Cancer

Cherylyn A. Savary

M.D. Anderson Cancer Center, University of Texas; Houston, TX

Electrohydrodynamics of Suspensions

Dudley A. Saville

Princeton University; Princeton, NJ

Influence of Impurities on Protein Crystal Growth

Constance A. Schall

University of Toledo; Toledo, OH

Microgravity and the Biology of Neural Stem Cells

William J. Schwartz

University of Massachusetts Medical School; Worcester, MA

Gastric Mucosal Cell Culture in Simulated Microgravity

Adam J. Smolka

Medical University of South Carolina; Charleston, SC

Electrophoretic Focusing

Robert S. Snyder

New Century Pharmaceuticals, Inc.; Huntsville, AL

Application of pH, Glucose, and Oxygen Biosensors to NASA Rotating Culture Vessels

Glenn F. Spaulding

Clear Lake Medical Foundation, Inc.; Houston, TX

Influence of Microgravity Conditions on Gene Transfer Into Expanded Populations of Human Hematopoietic Stem Cells

F. M. Stewart

University of Massachusetts Medical Center; Worcester, MA

Production of Recombinant Human Erythropoietin by Mammalian Cells Cultured in Simulated Microgravity

Arthur J. Sytkowski

Beth Israel Deaconess Medical Center; Boston, MA

Defects, Growth, and Elastic Properties of Protein Crystals

Robert E. Thorne

Cornell University; Ithaca, NY

Impurity Effects in Macromolecular Crystal Growth

Robert E. Thorne

Cornell University; Ithaca, NY

Mechanisms for Membrane Protein Crystallization: Analysis by Small Angle Neutron Scattering

David M. Tiede

Argonne National Laboratory; Argonne, IL

Preparation and Analysis of RNA Crystals

Paul Todd
University of Colorado; Boulder, CO

Development of Microflow Biochemical Sensors for Space Biotechnology

Bruce C. Towe
Arizona State University; Tempe, AZ

Self-Renewal Replication of Hematopoietic Stem Cells in Microgravity

Christie M. Traycoff
Indiana Cancer Research Institute; Indianapolis, IN

Experimental Studies of Protein Crystal Growth Under Simulated Low-Gravity Conditions

Eugene H. Trinh
National Aeronautics and Space Administration; Washington, DC

Protein Precipitant-Specific Criteria for the Impact of Reduced Gravity on Crystal Perfection

Peter G. Vekilov
University of Alabama, Huntsville; Huntsville, AL

Two-Dimensional Protein Crystallization at Interfaces

Viola Vogel
University of Washington; Seattle, WA

Two-Dimensional Crystal Growth in Microgravity

Theodore G. Wensel
Baylor College of Medicine; Houston, TX

Rejuvenation of Spent Media via Supported Emulsion Liquid Membranes

John M. Wiencek
University of Iowa; Iowa City, IA

Thermodynamics of Protein Crystallization and Links to Crystal Quality

John M. Wiencek
University of Iowa; Iowa City, IA

Membrane Protein Crystallization Screens Based Upon Fundamental Phenomenology of Detergent and Protein-Detergent Solutions

Michael C. Wiener
University of Virginia Health Sciences Center; Charlottesville, VA

Metastable Solution Structure and Optimization Strategies in Protein Crystal Growth

Lori J. Wilson
East Tennessee State University; Johnson City, TN

A Rational Approach for Predicting Protein Crystallization

W. W. Wilson
Mississippi State University; Mississippi State, MS

Novel Approaches Regarding Protein Solubility

W. W. Wilson
Mississippi State University; Mississippi State, MS

Novel Microgravity Optical Technique for Molecularly Engineering Electrophoretic Media

Denis Wirtz
Johns Hopkins University; Baltimore, MD

The Effects of Microgravity/Low Shear on Glycosylation and Eukaryotic DNA Virus Replication

H. A. Wood
Cornell University; Ithaca, NY

Ex-Vivo Hemopoiesis in a Three-Dimensional Human Bone Marrow Culture Under Simulated Microgravity

J. H. David Wu
University of Rochester; Rochester, NY

Freely Suspended Liquid Films and Their Applications in Biological Research

Xiao-lun Wu
University of Pittsburgh; Pittsburgh, PA

Liver Tissue Engineering in Microgravity Environment

Boris Yoffe
Baylor College of Medicine; Houston, TX

Particle Interaction Potentials and Protein Crystal Quality

Charles F. Zukoski
University of Illinois, Urbana-Champaign; Urbana, IL

Combustion Science

Combustion and the results of combustion processes affect each of us every day. The majority of the world's electric power production, home heating, and ground and air transportation are made possible by combustion. Unfortunately, combustion by-products are major contributors to air pollution and global warming. Additionally, unintentional fires claim thousands of lives and cost billions of dollars in property damage. Improved control of combustion would be of great benefit to society, yet beneficial control of combustion is impeded by a lack of fundamental understanding of combustion processes. Combustion research is hampered more than other areas of science by the effects of gravitational forces on Earth, since combustion intrinsically involves the production of high-temperature gases in which low densities trigger buoyant flows. These flows cause the reaction zone to collapse into very thin, sheet-like regions that are impenetrable by current or anticipated instrumentation. Conducting experiments in microgravity eliminates buoyancy and expands the reaction zone, thereby improving the measurement resolution. The resulting data are used to verify combustion theory, validate numerical models, and develop fresh insight into elemental phenomena, all of which can be applied to Earth-based combustion processes. Specific potential benefits that may ensue, in part, from microgravity combustion research include the following:

- Increased conversion efficiency of chemical energy stored in fuels to useful heat and work in combustion devices, leading to economic savings, reduced dissipation of scarce fuel reserves, and lower greenhouse gas emissions.
- Reduction of combustion-related effluents that pollute the atmosphere.
- Reduction of fire and explosion hazards.
- Improved hazardous waste incineration processes.
- Development of improved materials via combustion synthesis for use in widely diverse applications such as bone replacement, electrical components, and engines.

The microgravity combustion science program, in conjunction with the combustion science discipline working group, has defined the following high-priority areas for microgravity research and is supporting research in each area:

Combustion-turbulence interactions — The majority of practical combustion devices involve turbulent flows. Microgravity uniquely limits the range of turbulent length and time scales to those large enough to be tractable experimentally.

Soot processes — Soot is a critical element in many combustion systems because it can have a strong effect on combustor lifetime, efficiency, peak power output, and pollution generation. The lack of buoyancy-induced flow acceleration in a microgravity environment results in longer periods of time in which primary soot formation, soot clustering, cluster-cluster agglomeration, and oxidation can be investigated.

Diagnostics — Investment in technological improvements in measurement capabilities is of high priority due to the payoff in scientific data return from space experiments. Historically, spin-off opportunities have also resulted from successful development of combustion diagnostics.

Pressure effects — High pressure and/or supercritical operation of combustors yields improved thermodynamic efficiency at the expense of increased generation of pollutants. Conventional diesel engines operate at 50 atmospheres (atm), but most research has been conducted at near-ambient conditions (1 atm). Research at higher pressure levels is important because the influence of buoyancy on combustion processes increases with pressure.

Benchmark data on laminar flames — Flames in practical devices, although highly turbulent, operate in the “laminar flamelet” regime; that is, their flames are typically smooth and steady like butane lighters and gas stoves. Advances in understanding laminar flame structure and associated characteristics will have a direct impact on the modeling of turbulent flames.

Spray and aerosol cloud combustion — This type of combustion, typical of the way cars burn fuel, accounts for 25 percent of the world's energy use yet remains poorly understood from both fundamental and practical perspectives. Microgravity not only offers a quiescent, nonbuoyant environment for the study of spray and cloud combustion, it also overcomes the problem of droplet settling in a 1 g environment.

Combustion synthesis — Flame-synthesized products include valuable vapors (e.g., acetylene), ultrafine particles (e.g., fullerenes, silicon oxides, and titanium oxides), coatings (e.g., diamonds), and monolithic solids (e.g., boron carbide and titanium boride). These materials are rapidly expanding in breadth of use and value, but their production remains very much an art, rather than a science. Sedimentation and buoyant plumes lead to short residence times and interfere with investigation into the mechanisms of material production. Current research is geared toward interpreting the differences between normal- and low-gravity processing and toward improving the products.

Surface flame spread — Large-scale fires and fire spread on Earth are complicated by buoyancy-fed turbulent processes and thermal radiative interactions with surrounding materials, terrain, and building structures. Current models of flame spread generally omit thermal radiation because of the limited understanding of this transport mechanism. Laboratory-scale experiments in microgravity have begun to elucidate the importance of thermal radiation and indicate that these results might be utilized in modeling large-scale fires.

Transient processes in gaseous flames — Microgravity experimentation can provide insights into flame instabilities, such as ignition, extinction, and imposed perturbations that are often masked by buoyancy in normal gravity.

Spacecraft fire safety — Models used to study spacecraft fire safety are still considered “primitive.” Further research is

required in the areas of microgravity flammability, fire spread, fire and smoke detection, fire suppression, and postfire cleanup.

To aid in disseminating results to date and to engage in discussion of potentially new investigation areas, the Fifth Microgravity Combustion Workshop was held in Cleveland, Ohio, May 18–20, 1999, and was attended by 280 scientists and engineers from around the world. The workshop briefed potential investigators on the opportunity to respond to the 1999 NASA Research Announcement for combustion science (99-HEDS-04) and focused on research opportunities that will soon be enabled by the International Space Station (ISS). Current ground-based and flight investigators presented research results to date in 16 sessions during the three-day workshop. The proceedings of this workshop are available online at <http://www.ncmr.org/events/combustion1999.html>.

Meetings, Awards, and Publications

Merrill King, of NASA Headquarters, and Jose Torero, of the University of Maryland, chaired two microgravity combustion sessions of the 37th Aerospace Sciences Meeting in Reno, Nevada, in January 1999. Sixteen papers on combustion science research were presented.

Howard Ross, of Glenn Research Center (GRC), and Frank Schowengerdt, of the Center for Commercial Applications of Combustion in Space, chaired the microgravity combustion session of the 1999 Space Technology and Applications International Forum in Albuquerque, New Mexico, in January 1999. Five papers on combustion science research and hardware capabilities were presented.

A special issue of *Combustion and Flame* was devoted to microgravity combustion research. The issue included results from the first Microgravity Science Laboratory (MSL-1) mission, flown in April and July 1997; from a Get Away Special Canister experiment on smoldering; and from ground-based facilities.

The cover of the January 1999 issue of *Physics Today* highlighted a picture of “fingering” in combustion. The image was followed by a two-page article. The article prominently referenced research conducted by Takashi Kashiwagi, of the National Institute of Standards and Technology (NIST), and Sandra Olson, of GRC, in the Radiative Ignition and Transition to Flame Spread Investigation. In addition, modeling work on flame front cellularity and development of instabilities in combustion in porous media by Bernard Matkowsky, of Northwestern University, was referenced and discussed. This work was also funded by the microgravity combustion science program.

In a White House ceremony, Howard Pearlman, a resident researcher in the GRC Microgravity Science Division and assistant professor at the University of Southern California, was awarded a Presidential Early Career Award for Scientists and Engineers (PECASE) in recognition of his research on the combustion of

fuel-oxidizer mixtures under near-limit conditions and his research in the area of cool flames leading to the development of cleaner, more efficient engines. In his work, Pearlman discovered the first evidence of a gas-phase diffusive thermal oscillation behavior in a premixed fuel-oxidizer mixture. The PECASE, the highest honor bestowed by the U.S. government to scientists and engineers, was created to recognize exceptional potential for leadership at the frontiers of scientific knowledge.

Flight Experiments

Nineteen flight investigations were funded in fiscal year (FY) 1999. Additionally, a number of flight system designs were initiated in an effort to work toward achieving research goals aboard the ISS.

Experimental verification of material flammability in space research was conducted as an international cooperative project aboard the Russian space station, *Mir*. The flammability of selected U.S.-supplied plastic materials was tested under microgravity in a Russia-supplied combustion tunnel operated on the space station. Reference testing of the flammability, heat release, thermal properties, and combustion products of identical materials was conducted in ground laboratories at both the Russian Keldysh Research Center and at Johnson Space Center’s White Sands Test Facility. The *Mir* tests were conducted on samples of three different materials: Delrin (polyacetal), PMMA (polymethyl methacrylate), and high-density polyethylene. Postflight ground tests were performed at Keldysh and at White Sands using on-orbit atmospheric oxygen levels as comparative data points. All three materials showed a limiting velocity, defined as the minimum velocity below which flame propagation is not possible. Polyethylene burned rapidly and smoothly. Combustion of Delrin and PMMA samples was less steady, with melting and particle ejection. All samples showed a limiting air velocity for flame propagation on the order of 0.3 to 0.5 cm/s. These data and their corrections for the variable *Mir* oxygen concentrations have been reported by the Keldysh investigators.

FY 1999 signaled the transition from space research conducted on short-duration microgravity platforms to planning for research to be conducted aboard the permanently inhabited ISS. Preparations for conducting combustion research on the station were complemented by the readying of the Combustion Module-2 hardware for launch aboard a shuttle SPACEHAB mission in early 2001. The **Combustion Integrated Rack (CIR)**, the first of three racks that will make up the Fluids and Combustion Facility on the ISS, continued to undergo design and development towards its 2003 launch. To effectively utilize the capabilities of the CIR, two insert apparatus devices are also progressing through the flight system design phase.

One of these devices, the **Multiuser Droplet Combustion Apparatus (MDCA)**, will be the first research payload in the CIR. The MDCA, which is capable of supporting four investigations

simultaneously, entered its preliminary design stage in FY 1999. Multiuser hardware such as the MDCA allows more effective resource utilization of the ISS and the CIR; this hardware will remain available for use with new investigations that may be proposed in the future. The following four investigations have been identified as the initial set of research experiments to use the combined capabilities of the CIR and MDCA systems:

- The goals of the **Droplet Combustion Experiment-2 (DCE-2)**, conceived by Forman Williams, of the University of California, San Diego, and Frederick Dryer, of Princeton University, are to study combustion kinetics relevant to droplet combustion, controlling mechanisms in droplet burning (transient and quasisteady), radiative heat loss, and extinction phenomena.
- The **Bi-Component Droplet Combustion Experiment (BCDCE)**, conceived by Benjamin Shaw, of the University of California, Davis, will study bi-component fuel droplets where spherical symmetry is approached in the gas and liquid phases. BCDCE will result in a better understanding of transient behaviors between liquid and gas interfaces in droplets that are composed of two components with different boiling and capillary properties.
- The **Sooting and Radiation Effects in Droplet Combustion Experiment**, conceived by Mun Choi, of Drexel University, is designed to study the effects of sooting and radiation influences on the overall burning behavior of droplets by means of optical and intrusive techniques. Investigation results will improve our understanding of soot processes, thermophoresis, and radiative feedback from the flame to the fuel surface.
- The **Dynamics of Droplet Combustion and Extinction Experiment (DDCE)**, conceived by Vedha Nayagam, of the National Center for Microgravity Research on Fluids and Combustion, will study the effects of small convective flows on burning droplets and better define the effects of flow on the burning and extinction process. DDCE is relevant to practical combustors in which droplets are always injected with nonzero velocities.

Work on the preliminary design for the second insert for the CIR, the **Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS)** apparatus, has been initiated and will result in a platform well-suited to the study of ignition and flammability limits of thin and thick solid materials. These investigations have direct applicability to terrestrial and spacecraft fire safety and will be focused on the phenomena of combustion of solid materials. Such investigations are highly relevant to the understanding of ignition, flammability, and the extinction of fires over real materials and are crucial to the increased understanding of terrestrial and spacecraft fire safety activities. The following five investigations are currently under consideration for selection for the initial research experiments in the FEANICS:

- The **Solid Inflammability Boundary at Low Speed (SIBAL)** investigation, by James T'ien, of Case Western Reserve University, is a study of flame spread under conditions of

very low induced air velocity. SIBAL will determine the spread rate dependence and limiting conditions for spread.

- The **Transition From Ignition to Flame Growth Under External Radiation in Three Dimensions (TIGER-3D)** investigation is led by Takashi Kashiwagi, of NIST. TIGER-3D is a study of the transition from momentary ignition to flame spread. By studying radiatively ignited fuels, the conditions that control the onset of flame spread or extinction will be determined.
- The **Flammability Diagrams of Combustible Materials in Microgravity (FIST)** investigation, guided by Carlos Fernandez-Pello, of the University of California, Berkeley, is a study of the ignitability of practical materials. FIST will extend NASA's current pass/fail acceptance program for spacecraft materials to the consideration of the limiting conditions for ignitability of materials.
- The **Radiative Enhancement Effects on Flame Spread (REEFS)** investigation is headed by Paul Ronney, of the University of Southern California. REEFS is a study of the radiative participation of combustion product gases in flame spread. The hot gas above the flame can participate in the flame spread, depending upon the radiative properties of the gases. This research is relevant for spacecraft fire safety, since carbon dioxide, which is used to extinguish fires, is a strong absorber and emitter in the infrared.
- The **Investigation of Diffusion Flame Tip Thermo-Diffusive and Hydrodynamic Instability Under Microgravity Conditions** experiment, led by Indrek Wichman, of Michigan State University, studies flame spread at the limits of breakup of the flame tip into smaller flamelets. Existence of these flamelets represents the limiting conditions for flame spread.

The FY 1999 ground and flight tasks for combustion science are listed in **Table 6**. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1999*, available online at <http://microgravity.hq.nasa.gov/research.htm>.

Table 6 **Combustion Science Tasks Funded by the Microgravity Research Division in FY 1999**
(includes some continuing projects at no additional cost)

Flight Experiments

Flame Design — A Novel Approach to Clean, Efficient Diffusion Flames

Richard L. Axelbaum
 Washington University; St. Louis, MO

Gravitational Effects on Laminar, Transitional, and Turbulent Gas Jet Diffusion Flames

M. Y. Bahadori
 Science and Technology Development Corporation
 Los Angeles, CA

Experiments and Model Development for Investigation of Sooting and Radiation Effects in Microgravity Droplet Combustion

Mun Y. Choi
 University of Illinois; Chicago, IL

Candle Flames in Microgravity

Daniel L. Dietrich
 Glenn Research Center; Cleveland, OH

Investigation of Laminar Jet Diffusion Flames in Microgravity: A Paradigm for Soot Processes in Turbulent Flames

Gerard M. Faeth
 University of Michigan; Ann Arbor, MI

Flammability Diagrams of Combustible Materials in Microgravity

A. Carlos Fernandez-Pello
 University of California, Berkeley; Berkeley, CA

Fundamental Study of Smoldering Combustion in Microgravity

A. Carlos Fernandez-Pello
 University of California, Berkeley; Berkeley, CA

Combustion Characteristics of Fully Modulated, Turbulent Diffusion Flames in Reduced Gravity

James C. Hermanson
 Worcester Polytechnic Institute; Worcester, MA

Ignition and the Subsequent Transition to Flame Spread in Microgravity

Takashi Kashiwagi
 National Institute of Standards and Technology; Gaithersburg, MD

Structure and Response of Spherical Diffusion Flames

Chung K. Law
 Princeton University; Princeton, NJ

Dynamics of Droplet Extinction in Slow Convective Flows

Vedha Nayagam
 National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

The High-Lewis Number Diffusive-Thermal Instability in Premixed Gas Combustion and Low-Temperature Hydrocarbon Oxidation and Cool Flames

Howard G. Pearlman
 Glenn Research Center; Cleveland, OH

Studies of Premixed Laminar and Turbulent Flames at Microgravity

Paul D. Ronney
 University of Southern California; Los Angeles, CA

Transport and Chemical Effects on Concurrent- and Opposed-Flow Flame Spread at Microgravity

Paul D. Ronney
 University of Southern California; Los Angeles, CA

Ignition and Flame Spread of Liquid Fuel Pools

Howard D. Ross
 Glenn Research Center; Cleveland, OH

Combustion Experiments in Reduced Gravity With Two-Component Miscible Droplets

Benjamin D. Shaw
 University of California, Davis; Davis, CA

Combustion of Solid Fuel in Very Low-Speed Oxygen Streams

James S. T'ien
 Case Western Reserve University; Cleveland, OH

Investigation of Diffusion Flame Tip Instability in Microgravity

Indrek S. Wichman
 Michigan State University; East Lansing, MI

Droplet Combustion Experiment

Forman A. Williams
 University of California, San Diego; La Jolla, CA

Ground-Based Experiments

Effects of Energy Release on Near-Field Flow Structure of Gas Jets

Ajay K. Agrawal
 University of Oklahoma; Norman, OK

Formation of Carbon Nanotubes in a Microgravity Environment

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

Radiant Extinction of Gaseous Diffusion Flames

Arvind Atreya
 University of Michigan; Ann Arbor, MI

High-Pressure Combustion of an Unsupported, Sooting Fuel Droplet in Microgravity

C. T. Avedisian
 Cornell University; Ithaca, NY

Multicomponent Droplet Combustion in Microgravity: Soot Formation, Emulsions, Metal-Based Additives, and the Effect of Initial Droplet Diameter

C. T. Avedisian
 Cornell University; Ithaca, NY

Gas-Phase Combustion Synthesis of Metal and Ceramic Nanoparticles

Richard L. Axelbaum
 Washington University; St. Louis, MO

Carbon Monoxide and Soot Formation in Inverse Diffusion Flames

Linda G. Blevins
 National Institute of Standards and Technology; Gaithersburg, MD

Combustion of Metals in Reduced-Gravity and Extraterrestrial Environments

Melvyn C. Branch
 University of Colorado, Boulder; Boulder, CO

Ignition and Combustion of Bulk Metals in Microgravity

Melvyn C. Branch

University of Colorado, Boulder; Boulder, CO

A Numerical Model for Combustion of Bubbling Thermoplastic Materials in Microgravity

Kathryn M. Butler

National Institute of Standards and Technology; Gaithersburg, MD

Heterogeneous Combustion of Porous Solid Fuel Particles Under Microgravity: A Comprehensive Theoretical and Experimental Study

Harsha K. Chelliah

University of Virginia; Charlottesville, VA

Numerical Study of Buoyancy and Differential Diffusion Effects on the Structure and Dynamics of Triple Flames

Jyh-Yuan Chen

University of California, Berkeley; Berkeley, CA

Buoyancy Effects on the Structure and Stability of Burke-Schumann Diffusion Flames

L.- D. Chen

University of Iowa; Iowa City, IA

Reflight of Enclosed Laminar Flames Investigation

L.- D. Chen

University of Iowa; Iowa City, IA

Gravitational Effects on Premixed Turbulent Flames: Microgravity Flame Structures

Robert K. Cheng

Lawrence Berkeley National Laboratory; Berkeley, CA

Investigation of Strain/Vorticity and Large-Scale Flow Structure in Turbulent, Nonpremixed Jet Flames

Noel T. Clemens

University of Texas; Austin, TX

Turbulent Flame Processes via Vortex Ring-Diffusion Flame Interaction

Werner J. Dahm

University of Michigan; Ann Arbor, MI

Combustion of Interacting Droplet Arrays in a Microgravity Environment

Daniel L. Dietrich

Glenn Research Center; Cleveland, OH

Interaction of Burning Metal Particles

Edward L. Dreizin

New Jersey Institute of Technology; Newark, NJ

Flame Vortex Interactions in Microgravity to Assess the Theory of Flame Stretch

James F. Driscoll

University of Michigan; Ann Arbor, MI

Applications of Electric Field in Microgravity Combustion

Derek Dunn-Rankin

University of California, Irvine; Irvine, CA

Aerodynamic, Unsteady, Kinetic, and Heat Loss Effects on the Dynamics and Structure of Weakly Burning Flames in Microgravity

Fokion N. Egolfopoulos

University of Southern California; Los Angeles, CA

Detailed Studies on the Structure and Dynamics of Reacting Dusty Flows at Normal and Microgravity

Fokion N. Egolfopoulos

University of Southern California; Los Angeles, CA

Quantitative Studies on the Propagation and Extinction of Near-Limit Flames Under Normal and Microgravity

Fokion N. Egolfopoulos

University of Southern California; Los Angeles, CA

Effects of Gravity on Sheared and Nonsheared Turbulent, Nonpremixed Flames

Said E. Elghobashi

University of California, Irvine; Irvine, CA

Flow/Soot Formation in Nonbuoyant, Laminar Diffusion Flames

Gerard M. Faeth

University of Michigan; Ann Arbor, MI

Soot Processes in Freely Propagating, Laminar Premixed Flames

Gerard M. Faeth

University of Michigan; Ann Arbor, MI

Thickness Effects on Fuel Flammability

Paul Ferkul

National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Large Eddy Simulation of Gravitational Effects on Transitional and Turbulent Gas Jet Diffusion Flames

Peyman Givi

State University of New York; Buffalo, NY

Studies on the Behavior of Highly Preheated Air Flames in Microgravity

Ashwani K. Gupta

University of Maryland, College Park; College Park, MD

The Extinction of Low-Strain Rate Diffusion Flames by an Agent in Microgravity

Anthony Hamins

National Institute of Standards and Technology; Gaithersburg, MD

Characteristics of Nonpremixed Turbulent Flames in Microgravity

Uday Hegde

National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Combustion Synthesis of Fullerenes and Fullerenic Nanostructures in Microgravity

Jack B. Howard

Massachusetts Institute of Technology; Cambridge, MA

Quantitative Interpretation of Optical Emission Sensors for Microgravity Experiments

Jay B. Jeffries

SRI International; Menlo Park, CA

Real-Time, Quantitative, Three-Dimensional Imaging of Diffusion Flame Species

Daniel J. Kane

Southwest Sciences, Inc.; Santa Fe, NM

The Impact of Buoyancy and Flame Structure on Soot, Radiation, and NO_x Emissions From a Turbulent Diffusion Flame

Ian M. Kennedy

University of California, Davis; Davis, CA

Aerodynamics and Chemical Kinetics of Premixed Flames at High Pressures

Chung K. Law

Princeton University; Princeton, NJ

Computational and Experimental Study of Laminar Diffusion Flames in a Microgravity Environment

Marshall B. Long

Yale University; New Haven, CT

Dynamics of Liquid Propellant Combustion at Reduced Gravity

Stephen B. Margolis
Sandia National Laboratories; Livermore, CA

Filtration Combustion for Microgravity Applications: (1) Smoldering, (2) Combustion Synthesis of Advanced Materials — PHASE 2

Bernard J. Matkowsky
Northwestern University; Evanston, IL

Simulation of Combustion Systems With Realistic G-Jitter

William E. Mell
National Institute of Standards and Technology; Gaithersburg, MD

Gravitational Influences on Flame Propagation Through Nonuniform, Premixed Gas Systems (Layers)

Fletcher J. Miller
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

A Fundamental Study of the Combustion Synthesis of Ceramic-Metal Composite Materials Under Microgravity Conditions — Phase III: Effect of Gravity on the Combustion Synthesis of Advanced, Engineered, Porous Materials

John J. Moore
Colorado School of Mines; Golden, CO

Kinetics and Structure of Superagglomerates Produced by Silane and Acetylene

George Mulholland
National Institute of Standards and Technology; Gaithersburg, MD

Stretched Diffusion Flames in Von Karman Swirling Flows

Vedha Nayagam
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Low-Stretch Diffusion Flames Over a Solid Fuel

Sandra L. Olson
Glenn Research Center; Cleveland, OH

Gravitational Effects on Partially Premixed Flames

Ishwar K. Puri
University of Illinois; Chicago, IL

Hyperspectral Imaging of Flame Spread Over Solid Fuel Surfaces Using Adaptive Fabry-Perot Filters

W. T. Rawlins
Physical Sciences, Inc.; Andover, MA

Development of Methods for Producing and Utilizing Alternate Fuel/Oxidizer Combinations Associated With Mars to Support ISRU-Based Propulsion and Power Systems

Eric E. Rice
Orbital Technologies Corporation; Madison, WI

Combustion of Individual Bubbles and Submerged Gas Jets in Liquid Fuels

Daniel E. Rosner
Yale University; New Haven, CT

Combustion of Unconfined Droplet Clusters in Microgravity

Gary A. Ruff
Drexel University; Philadelphia, PA

Flame Spreading and Extinction in Partial-Gravity Environments

Kurt R. Sacksteder
Glenn Research Center; Cleveland, OH

Combustion of Han-Based Monopropellant Droplets in Reduced Gravity

Benjamin D. Shaw
University of California, Davis; Davis, CA

Quantitative Species Measurements in Microgravity Combustion Flames

Joel A. Silver
Southwest Sciences, Inc.; Santa Fe, NM

Acoustically Forced, Condensed-Phase Fuel Combustion Under Microgravity Conditions

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

Computational and Experimental Study of Energetic Materials in a Counterflow Microgravity Environment

Mitchell D. Smooke
Yale University; New Haven, CT

Combustion of Rotating, Spherical, Premixed, and Diffusion Flames in Microgravity

Siavash H. Sohrab
Northwestern University; Evanston, IL

Investigation of Velocity and Temperature in Microgravity Laminar Jet Diffusion Flames

Peter B. Sunderland
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Reaction Kernel Structure and Diffusion Flame Stabilization

Fumiaki Takahashi
University of Dayton Research Center; Dayton, OH

Diffusion Flame Structure, Shape, and Extinction: Geometrical Considerations

Jose L. Torero
University of Maryland, College Park; College Park, MD

The Synthesis of Graphite-Encapsulated Metal Nanoparticles and Metal Catalytic Nanotubes

Randall L. Vander Wal
Glenn Research Center; Cleveland, OH

Laser Velocimeter for Studies of Microgravity Combustion Flowfields

Philip Varghese
University of Texas, Austin; Austin, TX

Mechanistic Studies of Combustion and Structure Formation During Synthesis of Advanced Materials

Arvind Varma
University of Notre Dame; Notre Dame, IN

High-Pressure Combustion of Binary Fuel Sprays

Forman A. Williams
University of California, San Diego; La Jolla, CA

Fluid Physics

Fluid physics is the study of the motion of fluids and the effects of such motion. Since of the four states of matter, three (gas, liquid, and plasma) are fluid, and even the fourth (solid) behaves like a fluid under many conditions, fluid physics encompasses a wide spectrum of industrial and natural processes and phenomena. Fluid motion is responsible for most of the transport and mixing that take place in the environment, in industrial processes, in vehicles, and in living organisms. The ultimate goal of research in fluid physics is to improve our ability to predict and control the behavior of fluids in all of the above instances so as to improve our ability to design devices and operate them. Fluid motion, in most situations, is strongly influenced by gravity. The low-gravity environment of space offers a powerful research tool for the study of fluid physics, enabling the observation and control of fluid phenomena in ways not possible on Earth. Experiments conducted in this environment have clearly demonstrated the value of microgravity by revealing results that are either completely unexpected or unobservable in Earth's gravitational field. These results are providing new insight into the behavior of fluids in terrestrial environments.

The microgravity fluid physics program currently has four major research areas: complex fluids, interfacial phenomena, dynamics and instabilities, and multiphase flows and phase change. There are 90 ground-based and 21 flight/flight-definition principal investigators (PIs) conducting experimental research and developing the theoretical framework for understanding the effects of gravity on processes involving fluids. Work in complex fluids covers colloids, foams, granular media, rheology of non-Newtonian fluids, and emulsions and suspensions. Interfacial phenomena include liquid-vapor interface configurations, contact line dynamics, capillary-driven flows, and the shape stability and breakup of liquid bridges and drops. Dynamics and instabilities include thermocapillary and thermosolutal flows, biofluid mechanics, geological fluid flows, pattern formation, and electrokinetics and electrochemistry. Multiphase flows and phase change include flow patterns in liquid-vapor/gas flows in microgravity, nucleate boiling and its control using acoustic and electric fields in microgravity, and flows of gas-solid and liquid-solid mixtures in microgravity.

A total of 297 proposals were received in response to the NASA Research Announcement for microgravity fluid physics (98-HEDS-03) that was released in November 1998. The proposals are undergoing peer review, and selections are to be made in early fiscal year (FY) 2000. A listing of all of the fluid physics grants, along with the PIs who received them, is provided in **Table 7**.

NASA is in the process of defining a strategy for exploring Mars and other planets in the "better, faster, and cheaper" framework. These missions pose considerable challenges, in that they require humans and associated life support systems to be subjected to prolonged exposure to microgravity during the interplanetary transit phase, and to reduced gravity while on the planet's surface. As one might expect, fluid physics and transport phenomena play

a major role in many of the research and technology development needs identified for exploration of Mars. The Microgravity Research Division (MRD) has developed specific performance goals that support these needs. The performance goals, which represent new opportunities for the microgravity fluid physics and transport phenomena community, are listed below:

1. Advance the state of knowledge sufficiently to enable dust control technologies and bulk material handling for extraterrestrial habitats and/or in-situ resource utilization.
2. Advance the state of knowledge sufficiently to allow development of reliable and efficient heat transfer technologies for space and extraterrestrial operations.
3. Advance the state of knowledge sufficiently to allow development of effective fluid management technology for space and extraterrestrial and industrial applications.
4. Establish the knowledge base required to design chemical process systems for exploration missions.

Some of the highlights of microgravity fluid physics research conducted in space as well as on Earth in FY 1999 are included below.

- *Physics Today*, the monthly magazine of the American Institute of Physics, featured as its cover story an article authored by microgravity fluid physics PIs Alice Gast, of Stanford University, and William Russel, of Princeton University. The article appeared in the December 1998 issue. Titled "Simple Ordering in Complex Fluids: Colloidal Particles Suspended in Solution Provide Intriguing Models for Studying Phase Transitions," the article reports findings of spaceflight experiments as well as ground-based work sponsored by the microgravity fluid physics program. Results from the Colloidal Disorder-Order Transition glovebox investigation and the Physics of Hard Spheres Experiment were prominently cited, and photographs of colloidal crystals formed in space were included.
- Bruce Ackerson, of Oklahoma State University, has filed a patent application titled "A Fiber-Optic Multiple Scattering Suppression Device." The patent is based on work performed under an MRD-funded grant. The invention provides a method and apparatus for estimating single scattering functions, particularly in concentrated solutions. The instant method utilizes two light detectors that are spatially and/or angularly separated which simultaneously record the speckle pattern from a single sample. The recorded patterns from two detectors are then cross-correlated at zero-lag to produce one point on a composite single/multiple scattering function curve. By collecting and analyzing cross-correlation measurements that have been taken at a plurality of different spatial/angular positions, the signal representative of single scattering may be differentiated from the signal representative of multiple scattering, and a near-optimum detector angle for use in taking future measurements can be determined.

The technique is used for measuring colloid particle size in concentrated solutions, where multiple scattering confounds measurements.

- K.R. Sridhar, of the University of Arizona, is developing solid oxide electrolysis (zirconia cells), which is one of the leading concepts for producing oxygen from the Mars atmosphere for propulsion and life support needs. A proof-of-concept experiment investigating this process is manifested to fly on the Mars 2001 lander as part of an in-situ resource utilization demonstration experiment. In this process, the predominantly carbon dioxide atmosphere of Mars is used as a feed gas to produce oxygen and carbon monoxide. The oxygen produced is separated as a 100 percent pure product by the zirconia electrolyte, using solid state ionic conduction. A laser texturing method was adopted to increase the surface area of the cells and to control the dimensions of the valleys and peaks. Tests show a marked improvement in the performance of cells using a laser-textured surface.
- John Goree, of the University of Iowa, and German colleagues led by Gregor Morfill, at the Max Planck Institute Für Extraterrestrische Physik, discovered a new phenomenon: mach cones in a dusty plasma. Dusty plasma consists of highly charged monodisperse microspheres levitated in a charge-neutral laboratory plasma. The researchers are using this system as a physical model to study the microscopic structure and dynamics during the melting transition between crystalline and liquid phases in two-dimensional ground-based experiments and three-dimensional microgravity experiments. The newly discovered mach cones are shock waves produced by an object moving faster than the speed of sound through the dusty plasma. They are like the V-shaped shock cones produced in gas dynamics by a supersonic aircraft. In this case, the relevant sound speed is the speed of compressional waves in the suspension of 'dust,' or particulates. The spacing between particles is compressed by the shock wave, and the charge on the dust particles, due to exposure to a plasma, provides an interparticle repulsion, which leads to a sound propagation at a very low velocity of typically a few centimeters per second.
- Harry Swinney, of the University of Texas Center for Nonlinear Dynamics, authored a chapter titled "Emergence and Evolution of Patterns" in the book *Critical Problems in Physics*. Swinney reports on findings from his work funded by a NASA microgravity fluid physics grant on "Surface Tension-Driven Convection" in this book.
- Van Carey, of the University of California, Berkeley, has successfully demonstrated the effectiveness of using Marangoni effects to enhance pool boiling using binary liquid mixtures. The data obtained in this investigation imply that the Marangoni effects arising from the surface tension gradients due to concentration gradients are an active mechanism in the boiling of binary mixtures such as 2-propanol/water. At a

molar concentration of 0.015 of 2-propanol in water, where the surface tension gradient is highest among the concentrations tested, the critical heat flux is a factor of three greater than that of pure water for similar conditions under normal gravity. Models of pool boiling heat transfer and the critical heat flux condition for binary mixtures are tested to correlate the data. Comparison of boiling curves and critical heat flux obtained at different orientations of the heater surface indicates that there is a strong gravity-independent mechanism of boiling heat transfer in these mixtures. This finding makes binary mixtures attractive for microgravity applications. Carey is continuing work to develop an improved understanding of this phenomenon at a microscale level.

- Mark McDowell and Thomas Glasgow, both of Glenn Research Center (GRC), have been awarded a U.S. patent for the Stereo Imaging Velocimetry technique developed under the Advanced Technology Development (ATD) program. The technique provides a full-field, quantitative, three-dimensional map of any optically transparent fluid that is seeded with tracer particles. This technique has been applied to track the motion of the flame balls in the Structure of Flame Balls at Low Lewis Number experiment, which flew on the first Microgravity Science Laboratory mission (MSL-1).
- A patent application for "Microfluidic Controller and Microvalve" has been filed by Alice Gast, of Stanford University, and her research team. The patent represents a method for synthesizing permanently linked monodisperse paramagnetic chains by both covalently linking surface-functionalized polystyrene particles and physically linking electrostatically stabilized paramagnetic emulsion droplets. These anisotropic magnetoresponsive materials should be of interest for their unique rheological, optical, electronic, and micromechanical properties. Stanford has elected to retain the title for this invention.
- Robert Behringer, of Duke University, reported a key finding: the existence of a well-defined strengthening/softening transition in the dynamic behavior of two-dimensional granular systems. Experiments on a slowly sheared two-dimensional granular material show a continuous transition as the packing fraction passes through a critical value of 0.776. The mean stress plays the role of an order parameter. As the packing fraction approaches this critical value from above, (1) the compressibility becomes large, (2) a slowing down of the mean velocity occurs, (3) the force distributions change, and (4) the network of stress chains changes from intermittent long radial chains near the critical packing fraction to a tangled, dense network for larger packing fractions. This finding has potential for significant impact in understanding the spatial character of stress chains in granular media.
- The August 1999 issue of *Notices of the American Mathematical Society* includes the feature article "Capillary Surface Interfaces" by Robert Finn, of Stanford University, a

co-investigator funded by the Microgravity Research Program. The colorful images on the front cover show results from the Interfacial Configuration Experiment glove-box investigation, conducted on the second United States Microgravity Laboratory (USML-2) mission and on the Russian space station, *Mir*, along with data obtained from the GRC drop tower. Capillary action is governed by highly nonlinear equations. Some recently discovered formal consequences of these equations are at variance with predictions from formal expansions, and experiments were conducted on NASA and *Mir* flights to determine what actually occurs. The article sketches the history of the problems, some of the current theory, and relevant experimental results. Paul Concus, of the University of California, Berkeley, is the PI for this project, and Mark Weislogel, formerly of GRC, was also a co-investigator for these investigations.

- Research conducted by Noel Clark, of the University of Colorado, was featured on the cover of the June 1999 *Journal of Materials Chemistry*, published by the Royal Society of Chemistry. The accompanying article is titled “The Case of Thresholdless Antiferroelectricity: Polarization-Stabilized Twisted Smc* Liquid Crystals Give V-Shaped Electro-Optic Response.”

Meetings, Awards, and Publications

The 1998 Annual Meeting of the American Institute of Chemical Engineers featured a special session titled “Fundamental Research Fluid Mechanics II.” The session honored the 70th birthday of microgravity fluid physics PI Andrea Acrivos, of the City College of the City University of New York, on November 18, 1998. This special session was chaired by Gary Leal, of the University of California, Santa Barbara, and Robert Davis, of the University of Colorado, both fluid physics PIs.

Harry Swinney, of the University of Texas Center for Nonlinear Dynamics, was elected fellow of the American Association for the Advancement of Science in January 1999. Swinney is also a member of the microgravity fluid physics discipline advisory group.

Nancy Hall, of GRC, was selected to receive the 1999 National Society of Black Engineers Pre-College Community Service Award. The award was presented during the second annual Golden Torch Awards Ceremony on March 26, 1999, in Kansas City, Missouri. The Golden Torch Award Ceremony is the premier award and recognition program for African-American engineers, scientists, and technologists. The primary goal of the award is to recognize excellence among African-American technical professionals; corporate, government, and academic leaders; and university and pre-college students. Hall’s extensive commitment and dedicated service to the pre-college student and teaching communities through numerous educational outreach activities were the basis for her nomination for this award.

The first international workshop on “Scientific Research Against Sand Encroachment” was held in Medenine, Tunisia, April 19–24, 1999. The meeting gathered American, Danish, French, German, Icelandic, Mauritanian, Moroccan, and Tunisian scientists from disciplines ranging from geology to engineering and physics. Funding for the non-African participants was provided by CNRS (France’s national research organization), NASA, and the National Science Foundation. The organization of the meeting was shared by CNRS and Tunisia’s Institute des Regions Arides (Institute of Arid Regions). Fluid physics PI James Jenkins, of Cornell University, led a scientific contingent from the United States. The present understanding of dune formation and migration was reviewed, and several phenomena critical to the problems of sand encroachment and desertification were identified as requiring improved understanding, including grain transport in extremely high winds, the onset and run-out of intermittent avalanches, and the percolation and evaporation of water in sand. A second conference is planned for 2001 in Mauritania. Fluid physics PI Michel Louge, of Cornell University, also participated and presented a paper.

A conference titled “Interfaces for the Twenty-First Century: New Research Directions in Fluid Mechanics and Materials Science” was held August 16–18, 1999, in Monterey, California. Many fluid physics PIs played key roles in the conference. This conference was also an opportunity to highlight and celebrate the contributions to interface research in fluid mechanics and materials science made by Stephen Davis, of Northwestern University, on the occasion of his 60th birthday. Davis is a fluid physics PI and past chair of the microgravity fluid physics discipline working group.

Rafat Ansari, of the National Center for Microgravity Research on Fluids and Combustion (NCMRFC) at GRC, was awarded the NASA Public Service Medal on September 13, 1999, at the NASA Honor Award ceremony at GRC. Ansari was honored for “pioneering work in the use of a compact, fiber optic-based, laser light-scattering probe for the detection and prevention of eye diseases.” The basis for this compact fiber-optic probe technology was developed for spaceflight experiments under the ATD program. This probe is currently being used at the National Institutes of Health for human clinical trials for the treatment of cataracts and at the Federal Drug Administration on animal models for diabetes research.

John Brady, professor of chemical engineering and executive officer for chemical engineering at the California Institute of Technology, was elected to the National Academy of Engineering (NAE). NAE membership is one of the highest professional distinctions accorded engineers, honoring 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 “unusual accomplishments in the pioneering of new and developing fields of technology.”

Peter Wayner, of Rensselaer Polytechnic Institute, was awarded the American Institute of Chemical Engineers’ Heat

Transfer and Energy Conversion Division Award at the November 1998 meeting in Miami, Florida. The award recognizes an individual's outstanding chemical engineering contributions and achievement in heat transfer or energy conversion.

Andrea Prosperetti, of Johns Hopkins University, was appointed associate editor of the *International Journal of Multiphase Flow* and to the editorial board of the *Physics of Fluids* journal.

A paper in the area of fluid physics has been selected for the 1998 GRC Distinguished Publication Award. The paper is titled "Equilibration Near the Liquid-Vapor Critical Point in Microgravity." The authors are Allen Wilkinson, of GRC; Gregory Zimmerli, of NCMRFC; Michael Moldover and Robert Berg, both of the National Institute of Standards and Technology; William Johnson, of Westminster College; and Hong Hao, Richard Ferrell, and Robert Gammon, all of the University of Maryland. The paper reports the results of a spaceflight experiment that was the first to measure and verify the hypothesized density changes associated with late-stage thermal equilibration near the liquid-vapor critical point. The results are the closest ever to the critical point by nearly two orders of magnitude and approach within 1.4 millikelvins. The experiment was performed on the first International Microgravity Laboratory (IML-1) mission in January 1992.

Jeffrey Allen, of NCMRFC, was awarded the 1998 Manuel Luan Jr. Student Paper Award at the Space Technology and Applications International Forum in Albuquerque, New Mexico. The award recognized his paper titled "A Study of the Fundamental Operation of a Capillary-Driven Heat Transfer Device in Both Normal and Low Gravity, Part I: Liquid Slug Formation in Low Gravity." His co-author and academic adviser is Kevin Hallinan, of the University of Dayton. The paper is based on results obtained from the Capillary Heat Transfer glovebox investigation, which was carried out on MSL-1 in April and June 1997. The experiments were performed by Payload Specialist Roger Crouch, of NASA headquarters.

Simon Ostrach, director of NCMRFC, organized and hosted the first meeting of the Industry Liaison Board, which was chaired by William Ballhaus Jr., vice president of science and engineering at Lockheed Martin. The membership of the Industry Liaison Board consists of 12 vice president-level representatives of a number of leading U.S. corporations. The board was briefed on the technical content of the microgravity combustion science and fluid physics programs and asked to provide feedback on how these programs can better benefit industry. The board was "pleasantly surprised at the breadth, depth, and quality of microgravity science." They also made a number of recommendations to strengthen ties with industry.

NCMRFC has organized a lecture series on fluid physics and transport phenomena. The lectures will address topics of increasing importance to microgravity and industrial research, and are intended to broaden the perspective of attendees and provide a basis for further work on these more modern aspects of fluid mechanics. Information and online registration are available

at the NCMRFC web site,
<http://www.ncmr.org/events/fluid-annc.html>.

Microgravity fluid physics PIs published numerous papers in prestigious journals, such as *Science*, *Nature*, the *Journal of Fluid Mechanics*, *Physical Review Letters*, *Physical Review*, *Langmuir*, *Physics of Fluids*, *International Journal of Heat and Mass Transfer*, and the *Journal of Colloids and Interface Science*.

The following meetings and conferences of note also took place during FY 1999:

Meeting/Conference	Date
American Society of Mechanical Engineers' Fluids Engineering Conference	June 1998
National Heat Transfer Conference	August 1998
11th International Heat Transfer Conference	August 1998
American Physical Society's Fluid Dynamics Meeting	November 1998
American Institute of Chemical Engineers' Annual Meeting	November 1998
American Society of Mechanical Engineers' International Mechanical Engineering Congress and Exhibition	November 1998
American Institute of Aeronautics and Astronautics' Microgravity Science and Space Processing Meeting	January 1999
Space Technology and Applications International Forum — First Conference on Application of Thermophysics in Microgravity	January 1999
Interfaces for the Twenty-First Century, New Research Directions in Fluid Mechanics and Materials Science	August 1999
Microgravity Fluid Physics and Heat Transfer Meeting	September 1999

Flight Experiments

The **Internal Flow in a Free Drop (IFFD)** glovebox investigation was conducted on STS-95 in October 1998. The crew was successful in deploying and manipulating the acoustically positioned drops. Good video images with optimal resolution of the internal tracer particles will allow the accurate measurement of the internal motion of the liquid. The first demonstration of noncontact fissioning of a single drop into two parts was obtained with a static sound field. In addition, the new technique for accurate, acoustically assisted drop deployment in microgravity has been verified together with the feasibility of quiescently positioning a partially wetted drop at the end of a sting. A preliminary review of the flight tapes indicated that thermocapillary flows were clearly observed within a free drop in microgravity. Clear evidence of an increase in the internal circulation in the drop has

been detected as the sting heater was activated in the vicinity of the drop. Further analysis of the data is continuing. The PI for IFFD is Satwindar Sadhal, of the University of Southern California, and the co-investigator is Eugene Trinh, formerly of the Jet Propulsion Laboratory.

The **Growth and Morphology of Supercritical Fluids (GMSF)** experiment, also known as Growth and Morphology, Boiling, and Critical Fluctuations in Phase-Separating Supercritical Fluids, is a collaborative experiment between the United States and France that was run in the French Alice-II facility on the Russian space station, *Mir*, from 1998 to 1999. The American PI is John Hegseth, of the University of New Orleans. The French co-investigators are Daniel Beysens, of the French Atomic Energy Commission in Grenoble, France, and Yves Garrabos, of the University of Bordeaux. GMSF consists of three experiments. One experiment distinguished two growth rate laws that depend on the density deviation from the critical point standard state and the size of the temperature step in going from a one-phase fluid to a two-phase fluid. A second experiment examined rapid interface dynamics when going from a two-phase state to a one-phase state (supercritical boiling) using the same fluid as the first experiment. The third experiment sought to quantify the randomness of density fluctuation structures that are smaller than the “correlation length” very close to the liquid-vapor critical density and temperature. This experiment was conducted over a 20-day period. The first experiment was successful and is under analysis. The second experiment revealed differences from previous low-gravity experiments, and results are being published. The third experiment failed due to a hardware malfunction.

The **Extensional Rheology Experiment (ERE)**, designed by Gareth McKinley, of the Massachusetts Institute of Technology, is intended to provide the first unambiguous quantitative measurements of the transient uniaxial extensional viscosity for a viscoelastic polymer solution and to examine the relaxation behavior following extensional deformation. The test fluid selected for ERE is a Boger fluid composed of 0.025 weight percent of high molecular weight monodisperse polystyrene dissolved in oligometric polystyrene. The complete test matrix involves eight non-Newtonian tests on the Boger fluid covering the Deborah number range of 0.10 to 10.0, and two Newtonian tests using the oligometric polystyrene only. The experiments will be conducted on a Terrier Black-Brant sounding rocket with an MK70 booster. A total of five flights are needed to complete the 10-test matrix (two tests per flight). Assembly of the ERE flight hardware was complete in 1999. Design changes to the force measurement system and optics systems (flow-induced birefringence and digital particle image velocimetry) were implemented, and system functional testing was completed. The ERE payload completed flight acceptance vibration testing in November 1999. Payload thermal testing was started in 1999 and completed in early 2000. Delays encountered during testing resulted in the first sounding rocket launch schedule slip to July 2000.

The **Physics of Colloids in Space (PCS)** experiment, designed by David Weitz, of Harvard University, and Peter Pusey, of the University of Edinburgh, is slated to become the first fluid physics

experiment to be carried out on the International Space Station (ISS). This experiment will be conducted in the Expedite Processing of Experiments to Space Station (EXPRESS) rack, located in the U.S. Laboratory Module. The scientific goals of this experiment are to study fundamental colloid physics questions, colloid engineering (using colloids as precursors for the fabrication of novel materials), and the properties of new materials and their precursors. Weitz and Pusey plan to conduct tests on eight colloid samples of selected binary colloidal crystals, colloid/polymer mixtures (gels and crystals), and fractal colloidal gels. The flight experiment hardware has been assembled, and system verification testing has been initiated. All the science diagnostic operations, which include fiber dynamic and static light scattering, Bragg imaging, and low-angle imaging dynamic and static light scattering, have been performed with the flight system and on the flight samples. The experiment is completing the final verifications and preparations for shipment to Kennedy Space Center for rack integration and integrated rack testing. PCS is scheduled to be launched on ISS assembly flight 6A.

Preparation is under way for the third flight of the **Mechanics of Granular Materials (MGM-III)** experiment. The PI is Stein Sture, of the University of Colorado, Boulder. A total of nine very successful triaxial compression experiments were performed on dry sand specimens during the STS-79 (September 1996) and STS-89 (January 1998) missions. The results have generated great interest in related scientific and engineering communities. In October 1999, MGM received the authority to proceed for another flight after successfully completing an investigation continuation review in October 1998. MGM-III experiments will be conducted aboard the space shuttle during the STS-107 mission and will investigate the constitutive and stability behavior of water-saturated sand specimens in microgravity, where the science team will employ a new specimen-reforming technique that enables recycling the same specimen for additional experiments. The experiments are expected to provide the first-ever measurements of sand strength and stiffness modulus properties and induced pore water pressures during cyclic loading similar to strong ground motion observed during earthquakes. The newly devised specimen-reforming technique will be of great importance for future space station-based research, as it enables the reuse and retesting of the same sample many times under controlled initial conditions. The Office of Life and Microgravity Sciences and Applications has ranked MGM one of its top discoveries and accomplishments in 1999.

Collisions Into Dust Experiment-2 (COLLIDE-2) is a Complex Autonomous Payload experiment that studies the effects of particle collisions on the formation of planetary rings and protoplanetary disks. The PI is Joshua Colwell, of the University of Colorado. In the experiment, data are obtained on the outcome of low-velocity collisions into a fine volcanic powder that simulates regolith, the dust and small particles that coat the surfaces of most bodies in the Solar System, such as asteroids, ring particles, and the Moon. COLLIDE-2 continues the study that began with COLLIDE, a Get Away Special payload that flew on STS-90 in April 1998. Results from that experiment showed an absence of any significant dust ejecta in the impact energy regime studies.

COLLIDE-2 will expand the experimental parameter space in order to find the transition from purely accretional impacts to those with some dust ejecta and to characterize the amount and velocity of ejecta as a function of impact velocity and energy. COLLIDE-2 is being designed and built at the Laboratory for Atmospheric and Space Physics in Boulder, Colorado, with a significant amount of student involvement. Hardware design modifications have been completed, and the flight hardware is in the process of being built and tested. The launcher mechanisms were

successfully tested on the KC-135 aircraft to verify the projectile launch velocities as a function of launcher settings. The flight battery boxes have been fabricated, and camera container boxes have been fabricated and pressure tested.

The FY 1999 ground and flight tasks for fluid physics are listed in **Table 7**. Further details regarding these tasks may be found in the complementary document *Microgravity Research Division Program Tasks and Bibliography for FY 1999*, available online at <http://microgravity.hq.nasa.gov/research.htm>.

Table 7 **Fluid Physics Tasks Funded by the Microgravity Research Division in FY 1999**
(includes some continuing projects at no additional cost)

Flight Experiments

The Dynamics of Disorder-Order Transitions in Hard Sphere Colloidal Dispersions

Paul M. Chaikin
Princeton University; Princeton, NJ

Collisions Into Dust Experiment-2

Joshua E. Colwell
University of Colorado, Boulder; Boulder, CO

Investigations of Mechanisms Associated With Nucleate Boiling Under Microgravity Conditions

Vijay K. Dhir
University of California, Los Angeles; Los Angeles, CA

The Melting of Aqueous Foams — Foam Optics and Mechanics

Douglas J. Durian
University of California, Los Angeles; Los Angeles, CA

Microscale Hydrodynamics Near Moving Contact Lines

Stephen Garoff
Carnegie Mellon University; Pittsburgh, PA

Growth and Morphology, Boiling, and Critical Fluctuations of Phase Separating Supercritical Fluids

John J. Hegseth
University of New Orleans; New Orleans, LA

An Experimental Study of Richtmyer-Meshkov Instability in Low Gravity

Jeffrey W. Jacobs
University of Arizona, Tucson; Tucson, AZ

Particle Segregation in Collisional Shearing Flows

James T. Jenkins
Cornell University; Ithaca, NY

Magnetorheological Fluids: Rheology and Nonequilibrium Pattern Formation

Jing Liu
California State University; Long Beach, CA

Studies of Gas – Particle Interactions in a Microgravity Flow Cell

Michel Y. Louge
Cornell University; Ithaca, NY

Microgravity Experiments to Evaluate Electrostatic Forces in Controlling Cohesion and Adhesion of Granular Materials

John R. Marshall
Ames Research Center; Moffett Field, CA

The Dynamics of Miscible Interfaces: A Space Flight Experiment

Tony Maxworthy
University of Southern California; Los Angeles, CA

Extensional Rheology Experiment

Gareth H. McKinley
Massachusetts Institute of Technology; Cambridge, MA

Industrial Processes Influenced by Gravity

Simon Ostrach
Case Western Reserve University; Cleveland, OH

Diffusing Light Photography of Containerless Ripple Turbulence

Seth J. Putterman
University of California, Los Angeles; Los Angeles, CA

Behavior of Rapidly Sheared Bubbly Suspensions

Ashok S. Sangani
Syracuse University; Syracuse, NY

Studies in Electrohydrodynamics

Dudley A. Saville
Princeton University; Princeton, NJ

Thermal Control and Enhancement of Heat Transport Capacity of Cryogenic Capillary-Pumped Loops and Heat Pipes With Electrohydrodynamics

Jamal Seyed-Yagoobi
Texas A&M University; College Station, TX

Mechanics of Granular Materials

Stein Sture
University of Colorado, Boulder; Boulder, CO

A Study of the Constrained Vapor Bubble Heat Exchanger

Peter C. Wayner Jr.
Rensselaer Polytechnic Institute; Troy, NY

Physics of Colloids in Space

David A. Weitz
Harvard University; Cambridge, MA

Colloidal Assembly in Entropically Driven, Low Volume–Fraction Binary Particle Suspensions

Arjun G. Yodh
University of Pennsylvania; Philadelphia, PA

Ground-Based Experiments

Experimental and Analytical Study of Two-Phase Flow Parameters in Microgravity

Davood Abdollahian
S. Levy Inc.; Campbell, CA

The Synergism of Electrorheological Response, Dielectrophoresis, and Shear-Induced Diffusion in Flowing Suspensions

Andreas Acrivos
City College of the City University of New York; New York, NY

Dynamics and Statics of Nonaxisymmetric Liquid Bridges

J. Iwan D. Alexander
National Center for Microgravity Research on Fluids and Combustion
Case Western Reserve University; Cleveland, OH

Ultrasonic Thermal Field Imaging of Opaque Fluids

C. D. Andereck
Ohio State University; Columbus, OH

Scientific Studies and Technological Potential of Acousto-Electrically Generated Drop or Particle Clusters and Arrays

Robert E. Apfel
Yale University; New Haven, CT

Fluid Physics of Foam Evolution and Flow

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

Marangoni Instability-Induced Convection in Evaporating Liquid Droplets

V. S. Arpaci
University of Michigan; Ann Arbor, MI

Two-Phase Gas-Liquid Flows in Microgravity: Experimental and Theoretical Investigation of the Annular Flow

Vemuri Balakotaiah
University of Houston; Houston, TX

Numerical Simulation of Electrochemical Transport Processes in Microgravity Environments

Sanjoy Banerjee
University of California, Santa Barbara; Santa Barbara, CA

Control of Flowing Liquid Films by Electrostatic Fields in Space

S. G. Bankoff
Northwestern University; Evanston, IL

Forced Oscillation of Pendant and Sessile Drops

Osman A. Basaran
Purdue University; West Lafayette, IN

Dynamics of Granular Materials

Robert P. Behringer
Duke University; Durham, NC

Investigation of Drop Formation by a Vortex Ring in Microgravity

Luis P. Bernal
University of Michigan; Ann Arbor, MI

Dynamic Modeling of the Microgravity Flow

Jeremiah U. Brackbill
Los Alamos National Laboratory; Los Alamos, NM

Inertial Effects in Suspension Dynamics

John F. Brady
California Institute of Technology; Pasadena, CA

Marangoni Effects on Near-Bubble Microscale Transport During Boiling of Binary Fluid Mixtures

Van P. Carey
University of California, Berkeley; Berkeley, CA

Structure, Hydrodynamics, and Phase Transitions of Freely Suspended Liquid Crystals

Noel A. Clark
University of Colorado, Boulder; Boulder, CO

Dusty Plasma Dynamics Near Surfaces in Space

Joshua E. Colwell
University of Colorado, Boulder; Boulder, CO

Interface Morphology During Crystal Growth: Effects of Anisotropy and Fluid Flow

Sam R. Coriell
National Institute of Standards and Technology; Gaithersburg, MD

Scaling of Multiphase Flow Regimes and Interfacial Behavior at Microgravity

Christopher J. Crowley
Creare Inc.; Hanover, NH

Phoretic and Radiometric Force Measurements on Microparticles Under Microgravity Conditions

E. J. Davis
University of Washington; Seattle, WA

Cell and Particle Interactions and Aggregation During Electrophoretic Motion

Robert H. Davis
University of Colorado, Boulder; Boulder, CO

Thermocapillary-Induced Phase Separation of Dispersed Systems With Coalescence

Robert H. Davis
University of Colorado, Boulder; Boulder, CO

Theory of Solidification

Stephen H. Davis
Northwestern University; Evanston, IL

Spectral-Element Simulations of Thermal Convection in a Rotating, Hemispherical Shell With Radial Gravity and Comparison With Space-Laboratory Experiments

Anil Deane
University of Maryland, College Park; College Park, MD

Attenuation of Gas Turbulence by a Nearly Stationary Dispersion of Fine Particles

John K. Eaton
Stanford University; Stanford, CA

Effects of Gravity on Sheared Turbulence Laden With Bubbles or Droplets

Said E. Elghobashi
University of California, Irvine; Irvine, CA

Evaporation, Boiling, and Condensation on/in Capillary Structures of High Heat Flux, Two-Phase Devices

Amir Faghri
University of Connecticut; Storrs, CT

The Influence of Gravity on Colloidal Crystallization and Field-Induced Aggregation

Alice P. Gast
Stanford University; Stanford, CA

Definition of Dust Aggregation and Concentration System for the Microgravity Space Environment

Frank J. Giovane
Naval Research Laboratory; Washington, DC

Material Instabilities in Particulate Systems

Joe D. Goddard
University of California, San Diego; La Jolla, CA

Thermoacoustic Effects at a Solid-Fluid Boundary: The Role of a Second-Order Thermal Expansion Coefficient

Ashok Gopinath
Naval Postgraduate School; Monterey, CA

Plasma Dust Crystallization

John A. Goree
University of Iowa; Iowa City, IA

Capillary-Elastic Instabilities in Microgravity

James B. Grotberg
University of Michigan; Ann Arbor, MI

Determination of the Accommodation Coefficient Using Vapor/Gas Bubble Dynamics in an Acoustic Field in Microgravity Conditions

Nail A. Gumerov
Dynaflow, Inc.; Fulton, MD

Instability Mechanisms in Thermally Driven Interfacial Flows in Liquid-Encapsulated Crystal Growth

Hossein Haj-Hariri
University of Virginia; Charlottesville, VA

A Study of the Microscale Fluid Physics in the Near-Contact Line Region of an Evaporating Capillary Meniscus

Kevin P. Hallinan
University of Dayton; Dayton, OH

Engineering of Novel Biocolloidal Suspensions

Daniel A. Hammer
University of Pennsylvania; Philadelphia, PA

A Geophysical Flow Experiment in a Compressible Critical Fluid

John J. Hegseth
University of New Orleans; New Orleans, LA

Experimental Investigation of Pool Boiling Heat Transfer Enhancement in Microgravity in the Presence of Electric Fields

Cila Herman
Johns Hopkins University; Baltimore, MD

Rheology of Foam Near the Order-Disorder Transition

R. G. Holt
Boston University; Boston, MA

Sonoluminescence in Space: The Critical Role of Buoyancy in Stability and Emission Mechanisms

R. G. Holt
Boston University; Boston, MA

Problems in Microgravity Fluid Mechanics: Thermocapillary Instabilities and G-Jitter Convection

George M. Homsy
Stanford University; Stanford, CA

Surfactant-Based Critical Phenomena in Microgravity

Eric W. Kaler
University of Delaware; Newark, DE

Bubble Generation in a Flowing Liquid Medium and Resulting Two-Phase Flow in Microgravity

Yasuhiro Kamotani
Case Western Reserve University; Cleveland, OH

Bubble Dynamics on a Heated Surface

Mohammad Kassemi
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Studies in Thermocapillary Convection of the Marangoni-Bénard Type

Robert E. Kelly
University of California, Los Angeles; Los Angeles, CA

Two-Phase Annular Flow in Helical Coil Flow Channels in a Reduced-Gravity Environment

Edward G. Keshock
Cleveland State University; Cleveland, OH

Investigation of Pool Boiling Heat Transfer Mechanisms in Microgravity Using an Array of Surface-Mounted Heat Flux Sensors

Jungho Kim
University of Maryland, College Park; College Park, MD

Weakly Nonlinear Description of Parametric Instabilities in Vibrating Flows

Edgar Knobloch
University of California, Berkeley; Berkeley, CA

Molecular Dynamics of Fluid-Solid Systems

Joel Koplik
City College of the City University of New York; New York, NY

Thermocapillary Convection in Low Pr Materials Under Simulated Reduced-Gravity Conditions

Sindo Kou
University of Wisconsin; Madison, WI

Electric Field-Induced Interfacial Instabilities

Robert E. Kusner
Glenn Research Center; Cleveland, OH

Microscopic Visualization of Fluid Flow in Evaporating Droplets and Electro-Osmotic Flows

Ronald Larson
University of Michigan; Ann Arbor, MI

Interaction Forces and the Flow-Induced Coalescence of Drops and Bubbles

L. G. Leal
University of California, Santa Barbara; Santa Barbara, CA

The Micromechanics of the Moving Contact Line

Seth Lichter
Northwestern University; Evanston, IL

Absolute and Convective Instability and Splitting of a Liquid Jet at Microgravity

Sung P. Lin
Clarkson University; Potsdam, NY

Rheology of Concentrated Emulsions

Michael Loewenberg
Yale University; New Haven, CT

The Dissolution of an Interface Between Miscible Liquids

James V. Maher
University of Pittsburgh; Pittsburgh, PA

Using Surfactants to Enhance Thermocapillary Migration Bubbles and Drops and Facilitate Drop Spreading to Hydrophobic Surfaces

Charles Maldarelli
City College of New York; New York, NY

Passive or Active Radiation Stress Stabilization of (and Coupling to) Liquid Bridges and Bridge Networks

Philip L. Marston
Washington State University; Pullman, WA

Single Bubble Sonoluminescence in Low Gravity and Optical Radiation Pressure Positioning of the Bubble

Philip L. Marston
Washington State University; Pullman, WA

Fundamental Processes of Atomization in Fluid-Fluid Flows

Mark J. McCready
University of Notre Dame; Notre Dame, IN

An Interferometric Investigation of Contact Line Dynamics in Spreading Polymer Melts and Solutions

Gareth H. McKinley
Massachusetts Institute of Technology; Cambridge, MA

Study of Two-Phase Gas-Liquid Flow Behavior at Reduced-Gravity Conditions

John McQuillen
Glenn Research Center; Cleveland, OH

Fluid Dynamics and Solidification of Molten Solder Droplets Impacting on a Substrate in Microgravity

Constantine M. Megaridis
University of Illinois; Chicago, IL

Determination of Interfacial Rheological Properties Through Microgravity Oscillations of Bubbles and Drops

Ali Nadim
Boston University; Boston, MA

NMRI Measurements and Granular Dynamics Simulations of Segregation of Granular Mixtures

Masami Nakagawa
Colorado School of Mines; Golden, CO

Noncoalescence Effects in Microgravity

G. P. Neitzel
Georgia Institute of Technology; Atlanta, GA

Production and Removal of Gas Bubbles in Microgravity

Hasan N. Oguz
Johns Hopkins University; Baltimore, MD

Waves in Radial Gravity Using Magnetic Fluid

Daniel R. Ohlsen
University of Colorado, Boulder; Boulder, CO

On the Boundary Conditions at an Oscillating Contact Line: A Physical/Numerical Experimental Program

Marc Perlin
University of Michigan; Ann Arbor, MI

Experimental Studies of Multiphase Materials Using Nuclear Magnetic Resonance (NMR) and NMR Imaging

Robert L. Powell
University of California, Davis; Davis, CA

Dynamics of Accelerated Interfaces: Parametric Excitation and Fluid Sloshing in Closed Containers and Open Tanks

Constantine Pozrikidis
University of California, San Diego; La Jolla, CA

Acoustic Bubble Removal From Boiling Surfaces

Andrea Prosperetti
Johns Hopkins University; Baltimore, MD

Containerless Ripple Turbulence

Seth J. Putterman
University of California, Los Angeles; Los Angeles, CA

Complex Dynamics in Marangoni Convection With Rotation

Hermann Riecke
Northwestern University; Evanston, IL

Decoupling the Role of Inertia and Gravity on Particle Dispersion

Chris B. Rogers
Tufts University; Medford, MA

Design/Interpretation of Microgravity Experiments to Obtain Fluid/Solid Boundary Conditions in Nonisothermal Systems

Daniel E. Rosner
Yale University; New Haven, CT

Ground-Based Studies of Internal Flows in Levitated, Laser-Heated Drops

Satwindar S. Sadhal
University of Southern California; Los Angeles, CA

Terrestrial Experiments on G-Jitter Effects on Transport and Pattern Formation

Michael F. Schatz
Georgia Institute of Technology; Atlanta, GA

Free-Surface and Contact-Line Motion of Liquids in a Microgravity Environment

Leonard W. Schwartz
University of Delaware; Newark, DE

Drop Breakup in Flow Through Fixed Beds as Model Stochastic Strong Flows

Eric S. Shaqfeh
Stanford University; Stanford, CA

Lateral Motion of Particles and Bubbles Caused by Phoretic Flows Near a Solid Interface

Paul J. Sides
Carnegie Mellon University; Pittsburgh, PA

Fluid Physics and Transport Phenomena Research Support

Bhim Singh
Glenn Research Center; Cleveland, OH

The Development of Novel, High-Flux, Heat Transfer Cells for Thermal Control in Microgravity

Marc K. Smith
Georgia Institute of Technology; Atlanta, GA

Dynamics of the Molten Contact Line

Ain A. Sonin
Massachusetts Institute of Technology; Cambridge, MA

Modeling of Transport Processes in a Solid Oxide Electrolyzer Generating Oxygen on Mars

K. R. Sridhar
University of Arizona, Tucson; Tucson, AZ

Marangoni Effects on Drop Deformation and Breakup in an Extensional Flow: The Role of Surfactant Physical Chemistry

Kathleen J. Stebe
Johns Hopkins University; Baltimore, MD

Stability of Shapes Held by Surface Tension and Subjected to Flow

Paul H. Steen
Cornell University; Ithaca, NY

Instabilities in Surface Tension–Driven Convection

Harry L. Swinney
University of Texas, Austin; Austin, TX

Crystal Growth and Fluid Mechanics Problems in Directional Solidification

Saleh Tanveer
Ohio State University; Columbus, OH

Microgravity Effects on Transendothelial Transport

John M. Tarbell
Pennsylvania State University; University Park, PA

The Pool Boiling Crisis From Flat Plates: Mechanism(s) and Enhancement

Theofanis G. Theofanous
University of California, Santa Barbara; Santa Barbara, CA

Studies of Particle Sedimentation by Novel Scattering Techniques

Penger Tong
Oklahoma State University; Stillwater, OK

Acoustic Streaming in Microgravity: Flow Stability and Heat Transfer Enhancement

Eugene H. Trinh
National Aeronautics and Space Administration; Washington, DC

Computations of Boiling in Microgravity

Gretar Tryggvason
University of Michigan; Ann Arbor, MI

Fluid Physics in a Stochastic Acceleration Environment

Jorge Viñals
Florida State University; Tallahassee, FL

Enhanced Boiling on Microconfigured Composite Surfaces Under Microgravity Conditions

Nengli Zhang
Ohio Aerospace Institute; Cleveland, OH

The Small-Scale Structure of Turbulence

Gregory Zimmerli
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Fundamental Physics

Science is driven by human curiosity about nature. In the study of fundamental physics, scientists wish to uncover and understand the basic underlying principles that govern the behavior of the world around us. Fundamental physics, therefore, establishes a foundation for many other branches of science and provides the intellectual underpinning needed to maintain and further develop our highly technological society. Researchers in the discipline have two quests that motivate laboratory studies and experiments in space. First, they seek to explore and understand the fundamental physical laws governing matter, space, and time. Deep examination of the smallest and largest building blocks that make up the universe will yield a better understanding of the basic ideas, or theories, that describe the world. The space environment provides access to different space-time coordinates and frees experimenters from the disturbing effects caused by gravity on Earth. Second, researchers seek to discover and understand the organizing principles of nature from which structure and complexity emerge. While the basic laws of nature may be simple, the universe that has arisen under these laws is amazingly complex and diverse. By studying nature apart from Earth's gravity, we can better understand how the universe developed and how best to employ these principles in service to humanity.

The pursuit of these quests will greatly benefit society over the long run. For example, the study of physical laws and natural principles with unprecedented precision requires advances in instrumentation that provide the foundation for tomorrow's breakthrough technologies. These advances contribute to the competitiveness of American industry and further support and enhance the presence of humans in space. The pursuit of knowledge also serves to educate tomorrow's scientists and technologists and to fulfill the innate human desire to understand our place in the universe. Humankind's concept of the universe is changing rapidly as the tools that NASA places in space, such as the Hubble Space Telescope, detect new astronomical objects and novel events; the understanding of the details of these phenomena depends strongly on our understanding of fundamental forces such as gravity.

To address the two long-term quests discussed above, research is currently being pursued in three areas: gravitational and relativistic physics, laser cooling and atomic physics, and low-temperature and condensed matter physics. There is significant synergy across the three research areas in terms of both scientific overlap and overlap in experimental techniques. It is anticipated that research in other areas, such as biological physics and high-energy physics, may be pursued in the future.

Gravitational and relativistic physics is perhaps the most fundamental area of physics. Physicists have determined that there are four kinds of forces that operate on matter: gravity, electromagnetism, and the "strong" and "weak" forces within atomic nuclei. Gravity is the weakest of these forces, yet paradoxically the most dominant, as it can act over very great distances. In fact, the entire history of the universe illustrates the struggle to counteract the gravitational force with the predictable eventuality that all matter will succumb to it. In this regard, the gravitational

force is the most fundamental of all forces in nature. Every bit of matter in the universe is under the influence, even if infinitesimally so, of every other bit of matter. Relativity theories propose that gravitational forces apply equally to all bodies. Furthermore, Einstein's Theory of General Relativity puts gravity at the heart of the structure of the universe, proposing that even the orderly space-time structure of the universe can be "warped" near a body of large mass, such as the Sun or Earth. This warp would even affect clocks. While these changes to the very fabric of space and time near a large body are dramatic in their importance, they are very subtle and difficult to measure accurately. Still, they are large enough that they must be taken into account in even routine astronomy observations and in measuring the position of satellites and planets. Advanced technologies must be used to detect and characterize these minute changes so that the corrections due to relativistic phenomena can be precise. The fundamental physics program currently is sponsoring the development of several experiments designed to improve accuracy in the measurements of these effects and to test the basic foundations for Einstein's theory.

While studies in gravitational and relativistic physics examine the most fundamental laws describing the universe on a large scale, it is equally important to look at the tiny building blocks of matter and how they manifest the same fundamental laws. Laser cooling and atomic physics examines this area. Atoms are the smallest systems in which we can study the basic principles of the universe. New techniques allow the use of laser light to cool and probe individual atoms as a starting point for exploration. Careful study of individual atoms bridges the gap between the actions of the smallest pieces of matter and the complex behavior of large systems. Conducting these experiments in space allows researchers to remove the influence of gravity and manipulate matter freely, without having to counteract "falling" of the specimens within the instruments. The ability to observe the behavior of atoms while they are completely under the experimenter's control promises novel results and new insights previously hidden from view in Earth-bound laboratories. The NASA microgravity fundamental physics program is developing space experiments to study clouds of atoms cooled by laser light to very near absolute zero, yet freely floating without the forces that would be needed to contain them on Earth. These novel conditions allow longer observation times and measurements of higher precision. These techniques are also employed to develop improved clocks, both for testing basic theories of nature and for use in technological applications in space.

Like laser cooling and atomic physics, low-temperature and condensed matter physics is the study of fundamental laws of nature on a small scale, at the atomic level. Condensed matter physicists examine the properties of solids and liquids, the states of matter in which atoms are condensed, or packed closely together. Of particular interest to physicists is the behavior of matter near a critical point, or conditions of pressure and temperature at which the properties of two different phases become similar. For example, a substance at the liquid-vapor critical point exhibits no distinction between the liquid phase and the

vapor phase. Properties of a substance often display anomalies at a critical point. Many of the unusual phenomena exhibited at critical points can best be studied at low temperatures, where thermal noise (heat-induced vibration) is much reduced. By understanding the complex critical behavior of low-temperature materials, such as liquid helium, we will learn more about the critical properties of many systems, such as metallic alloys, magnetic materials, and groups of fundamental particles, and even learn about larger-scale phenomena, such as the percolation of water or the movement of weather patterns, all of which exhibit critical point behavior. Because critical point behavior is a function not only of temperature but also of pressure, the pressure must be uniform throughout the sample under observation. Earth's gravity causes pressure differences in a sample, so critical point phenomena on the ground can only be observed in a very small region. If an experiment is conducted in microgravity, the pressure can be uniform across the sample, and much more comprehensive measurements can be made. Furthermore, in microgravity, a drop of sample material can be freely suspended without the interference of a container. This freedom from external constraints is not possible in an Earth-bound laboratory.

Ongoing investigations sponsored by the fundamental physics program study critical point behavior in mixtures and in confined media and test the universality of critical phase transitions and the scaling laws at such points. In addition, the dynamic behavior of materials at critical points is studied to detect predicted nonlinear responses to driving forces, and the effects of finite size and of boundaries are studied near critical points. For example, studies of large-scale quantum systems are being performed to learn the hydrodynamics of such systems and of the melting and freezing of quantum crystals.

Again this year, the list of discoveries and first observations of new phenomena for the fundamental physics investigators is impressive. Research discoveries have been published in the most prestigious journals, such as *Nature*, *Science*, and *Physical Review Letters*. Following are highlights of the microgravity fundamental physics program in fiscal year (FY) 1999:

- Robert Berg, of the National Institute of Standards and Technology (NIST), demonstrated in the Critical Viscosity of Xenon experiment aboard the space shuttle that a non-polymer fluid could be viscoelastic. The key to observing xenon's viscoelasticity was to bring the sample very close to the critical point state, which is only possible in a freefall environment.
- John Hall, of the University of Colorado, has filed two patents that relate to his group's work developing stable oscillators employing laser-cooled atoms.
- Daniel Heinzen, of the University of Texas, generated ultracold molecules using a Bose-Einstein condensate of a dilute atomic gas.
- Jason Ho, of Ohio State University, developed a theoretical model for the superfluid state of optically trapped fermions.

- Randy Hulet, of Rice University, and his group have successfully demonstrated their "atom skimmer" for loading ${}^6\text{Li}$ atoms into a magneto-optical trap. This process allows for the atomic beam source to be physically separated from the trapping region so that ultrahigh vacuum conditions can be maintained in the trap.
- Juha Javanainen, of the University of Connecticut, has demonstrated theoretically that, by simply sweeping the frequency of a photo-associating laser, a condensate of atoms can be converted into a condensate of molecules. This discovery may prove to be a key to establishing a molecular condensate.
- Mark Kasevich, of Yale University, demonstrated the highest sensitivity reported thus far for a gravity gradiometer, with an instrument based on atom interferometry.
- Wolfgang Ketterle, of the Massachusetts Institute of Technology (MIT), observed excitation of standing and rotating surface modes and domains of different spin orientations in a Bose-Einstein condensate. The structure of these domains is established by applied magnetic fields and by orientation-dependent interactions between the atoms. The MIT researchers also measured "zero-point motion" in a sodium Bose-Einstein condensate for the first time.
- John Lipa, of Stanford University, and his team have completed their data analysis of the Confined Helium Experiment flight results and data from different confinement sizes. The results agree qualitatively with theoretical models describing the nature of confinement effects.
- Lipa and his team report a tenfold improvement from previous measurements in searching for the existence of a new force acting in the 0.3 mm range. So far, the experiment has been a null result.
- Horst Meyer, of Duke University, and his group directly observed for the first time the predicted "adiabatic temperature gradient" effect in ${}^3\text{He}$ in a ground-based experiment.
- Richard Packard, of the University of California, Berkeley, and his group have observed Shapiro steps in superfluid weak links and have discovered an exotic current-phase relation in superfluid weak links.
- William Phillips, of NIST, made the first observation of four-wave mixing with atom waves resulting from the collision of three Bose-Einstein condensates to form a fourth one.
- Alvin Sanders, of the University of Tennessee, has been awarded two patents related to his Satellite Energy Exchange project.

Meetings, Awards, and Publications

The American Physical Society held its centennial meeting in Atlanta, Georgia, March 20–26, 1999. With 11,400 physicists from more than 60 countries in attendance, this was the largest physics meeting in history. Most of the microgravity fundamental physics investigators participated in the meeting. Among the

exhibits that accompanied the meeting was a booth presenting an overview of microgravity research to be performed aboard the International Space Station. A tutorial titled “The Physics of Cold Atoms at Millikelvin, Microkelvin and Nanokelvin Temperatures” was organized by Wolfgang Ketterle at the meeting.

The 1999 Frequency Control Symposium was held jointly with the European Frequency and Time Forum in Besançon, France, April 13–16, 1999. Laser cooling flight project team members attended the conference, which featured sessions on space clocks, laser-cooled frequency standards, and time-transfer techniques.

A mini-workshop discussing recent advances in studies of ^4He in a heat current near the superfluid transition, organized by Robert Duncan, of the University of New Mexico, was held in Washington, D.C., on April 28, 1999.

The 1999 NASA/Jet Propulsion Laboratory (JPL) International Conference on Fundamental Physics in Space was held April 29–May 1 in Washington, D.C. One hundred thirty scientists representing all subdiscipline areas participated in the meeting, which consisted of 38 oral presentations and 47 poster presentations. A special opening session saw Congressman Vernon Ehlers, R-Mich., reporting on the House Science Committee’s work on updating our outdated National Science Policy. Arnauld Nicogossian, of NASA headquarters; William Phillips, of NIST; Kip Thorne, of the California Institute of Technology; and Humphrey Maris, of Brown University, gave keynote speeches. Maurice Jacobs, the European Space Agency (ESA) Fundamental Physics Advisory Group chair, gave the banquet speech. A breakfast meeting with Congressmen Ehlers; Congressman Alan Mollohan, D-W.Va.; and Congressman Rush Holt, D-N.J.; congressional aides Lee Alman and Richard Oberman; Office of Management and Budget Representative Douglas Comstock; and Office of Science and Technology Policy Representative Colleen Hartman was sponsored by Stanford University and held during the first day of the conference.

The 1999 Conference on Lasers and Electro-Optics and the 1999 Quantum Electronics Laser Science Conference were held jointly May 23–28, 1999, in Baltimore, Maryland. Several investigators in the low-temperature and condensed matter physics area attended and presented papers at the conference, which featured a wide selection of topics in atomic and optical physics.

The Inner Space/Outer Space conference was held at the Fermi National Accelerator Laboratory May 26–29, 1999. NASA Code S and the Department of Energy jointly organized this conference. Discussions were held with participants regarding Code UG collaborations in the high-energy physics area.

Approximately 10 investigators participated in the Second International Conference on Low-Temperature Physics held in Chernogolovka, Russia, July 28–August 2, 1999.

Fundamental physics investigators presented more than 25 papers at the 22nd International Conference on Low-Temperature Physics held in Helsinki, Finland, August 4–11, 1999. A number of fundamental physics investigators were invited speakers at the conference.

Jason Ho and Mark Kasevich organized a workshop on Bose-Einstein condensation, held at the Aspen Center for Physics June 14–July 4, 1999. The workshop gathered more than 40 participants from all over the world to discuss the latest developments in the field.

The number of presentations and publications by fundamental physics investigators increased by 30 percent over last year. The 250 publications during 1999 comprised 114 journal articles, 53 presentations, 66 proceedings articles, 4 patents, 12 NASA New Technology Reports, and 1 book.

Fundamental physics investigators garnered several awards during FY 1999:

- John Dick, of JPL, received the 1999 European Time and Frequency Award. The award, granted every two years by the French Society of Microtechnology and Chronometry, recognizes exceptional contributions in fundamental advances for present or future applications.
- Robert Duncan was elected vice chair of the American Physical Society’s (APS) Topical Group on Instrumentation and Measurement.
- Shin Inouye, a graduate student in Wolfgang Ketterle’s laboratory, won the 1999 Deutsch Award for Excellence in Experimental Physics. The Deutsch Award is given every other year to one graduate student at MIT.
- Ketterle was awarded the very prestigious Fritz London Prize in Low-Temperature Physics at the 22nd International Conference on Low-Temperature Physics in Helsinki, Finland.
- Daniel Stamper-Kurn, a graduate student working in Ketterle’s laboratory, won the 1998 New Focus Student Award of the Optical Society of America.
- William Phillips, of NIST, was awarded the 1998 APS Arthur L. Schawlow Prize in Laser Science for his work in developing methods for magnetic trapping of laser-cooled atoms.

Flight Experiments

The data analysis phase for the **Confined Helium Experiment (CHeX)**, which had a successful flight as part of the fourth United States Microgravity Payload (USMP-4) mission November 19–December 5, 1997, has been completed. Principal Investigator John Lipa’s results demonstrate good agreement with theories of finite size effect and with finite size scaling. A manuscript summarizing the findings has been accepted for publication in *Physical Review Letters*. A successful investigation continuation review was held with a recommendation for a CHeX reflight to study confinement in cylindrical pores with a diameter roughly equal to the two-dimensional spacing from the first flight. Unfortunately, the program has been unable to generate the required funds and flight opportunity to implement the reflight.

The objective of the **Critical Viscosity of Xenon-2 (CVX-2)** experiment, designed by Robert Berg, builds on the original CVX experiment, launched on August 7, 1997, which met all scientific

objectives. Raw data converted to values of viscosity yielded accurate results to test viscoelasticity theory. The principal investigator submitted a paper titled "Viscoelasticity of Xenon Near the Critical Point," which was accepted by *Physical Review Letters*. Based on results from CVX, Berg proposed a follow-on experiment to measure shear thinning predicted to occur near the critical point of a pure fluid. CVX-2 uses the CVX flight hardware, with some modifications, to achieve the viscometer precision and temperature stability required. The flight hardware has been completed, and all modifications have been tested. The same sample cell used for CVX will also be used for CVX-2. The flight timeline includes three passes through the critical temperature. CVX-2 was modified to accommodate programmable viscometer frequencies and amplitudes, and also to allow the principal investigator to make timeline changes in real time. The first action of the experiment is to locate the critical point to within 3 millikelvins while taking a series of viscometer measurements. Primary viscosity data are acquired during a series of measurements at a single viscometer operating frequency and four different amplitudes. A third data set will repeat the measurements at two different viscometer frequencies. A flight has not been identified for CVX-2, and the hardware is currently in storage.

The six candidate experiments for the **Low-Temperature Microgravity Physics Experiments Project** made significant progress in their flight-definition activities. The Microgravity Scaling Theory Experiment (MISTE) and the Superfluid Universality Experiment (SUE) held successful science concept reviews (SCRs) in December 1998. A nonadvocate science panel and a nonadvocate engineering/programmatic panel reviewed the experiments' science significance, needs for microgravity, preliminary science requirements, and preliminary experiment implementation plans. MISTE, SUE, and the Critical Dynamics in Microgravity experiment will compete for the two experiment slots on the first mission (M1) of the Low-Temperature Microgravity Physics Facility at their requirements definition reviews (RDRs), planned for November 1999. The other three experiments, Boundary Effects on the Superfluid Transition, Experiments Along Coexistence near Tricriticality, and Superconducting Microwave Oscillator, are working towards their SCRs, which are planned for February 2000. Two of these experiments will be selected for the M2 mission.

The multinational **Satellite Test of the Equivalence Principle (STEP)** project completed the definition of science requirements and put them under configuration control. Based on the maturity of the project definition, the experiment's SCR and RDR were completed. STEP also defined the spacecraft and payload interface requirements, allowing ESA to select Martra Marconi Space, of the United Kingdom, to perform the spacecraft service module study with a completion date of April 2000. STEP is currently focusing its efforts on retiring key technical risks in the science instrument by prototyping.

Once onboard the International Space Station (ISS), the **Primary Atomic Reference Clock in Space (PARCS)** project will measure various predictions of Einstein's Theory of General

Relativity, including gravitational frequency shift and local position invariance, on the rate of clocks. PARCS will also achieve a realization of the "second" (the fundamental unit of time tied to the energy difference between two atomic levels in cesium) at an order of magnitude better than is achievable on Earth and will disseminate this accuracy to laboratories across the globe. The PARCS SCR was successfully held in January 1999.

Utilizing the microgravity environment aboard the ISS, the **Rubidium Atomic Clock Experiment (RACE)** will interrogate rubidium (^{87}Rb) atoms with precision one to two orders of magnitude better 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 limitations, and distribute accurate time and frequency from the ISS. The RACE SCR has been scheduled for June 2000.

The FY 1999 ground and flight tasks for fundamental physics are listed in **Table 8**. Further details regarding these tasks may be found in the complementary document *Microgravity Research Division Program Tasks and Bibliography for FY 1999*, available online at <http://microgravity.hq.nasa.gov/research.htm>.

Table 8 **Fundamental Physics Tasks Funded by the Microgravity Research Division in FY 1999**
(includes some continuing projects at no additional cost)

Flight Experiments

Boundary Effects on Transport Properties and Dynamic Finite-Size Scaling Near the Superfluid Transition Line of ^4He

Guenter Ahlers
 University of California, Santa Barbara; Santa Barbara, CA

Microgravity Test of Universality and Scaling Predictions Near the Liquid-Gas Critical Point of ^3He

Martin B. Barmatz
 Jet Propulsion Laboratory; Pasadena, CA

Critical Viscosity of Xenon-2

Robert F. Berg
 National Institute of Standards and Technology; Gaithersburg, MD

Critical Dynamics in Microgravity

Robert V. Duncan
 University of New Mexico; Albuquerque, NM

Investigation of Future Microgravity Atomic Clocks

Kurt Gibble
 Yale University; New Haven, CT

Experiments Along Coexistence Near Tricriticality

Melora E. Larson
 Jet Propulsion Laboratory; Pasadena, CA

A New Test of Critical Point Universality by Measuring the Superfluid Density Near the Lambda Line of Helium

John A. Lipa
 Stanford University; Stanford, CA

Confined Helium Experiment

John A. Lipa
 Stanford University; Stanford, CA

Fundamental Physics Experiments With Superconducting Cavity-Stabilized Oscillators on Space Station

John A. Lipa
 Stanford University; Stanford, CA

Primary Atomic Reference Clock in Space

Donald Sullivan
 National Institute of Standards and Technology; Boulder, CO

Ground-Based Experiments

The Superfluid Transition of ^4He Under Unusual Conditions

Guenter Ahlers
 University of California, Santa Barbara; Santa Barbara, CA

New Phenomena in Strongly Counterflowing He-II near T_1

Stephen T. Boyd
 University of New Mexico; Albuquerque, NM

Prediction of Macroscopic Properties of Liquid Helium From Computer Simulation

David M. Ceperley
 University of Illinois, Urbana-Champaign; Urbana, IL

Droplets of ^3He - ^4He Mixtures

Siu-Tat Chui
 University of Delaware; Newark, DE

The Lambda Transition Under Superfluid Flow Conditions

Talso C. Chui
 Jet Propulsion Laboratory; Pasadena, CA

Nucleation of Quantized Vortices From Rotating Superfluid Drops

Russell J. Donnelly
 University of Oregon; Eugene, OR

Kinetic and Thermodynamic Studies of Melting-Freezing of Helium in Microgravity

Charles Elbaum
 Brown University; Providence, RI

Satellite Test of the Equivalence Principle

C. W. F. Everitt
 Stanford University; Stanford, CA

Critical Dynamics of Ambient-Temperature and Low-Temperature Phase Transitions

Richard A. Ferrell
 University of Maryland, College Park; College Park, MD

Fundamental Physics Using Frequency-Stabilized Lasers as Optical "Atomic Clocks"

John L. Hall
 University of Colorado, Boulder; Boulder, CO

Precision Measurements With Trapped Laser-Cooled Atoms in a Microgravity Environment

Daniel J. Heinzen
 University of Texas, Austin; Austin, TX

Gravitational Effects in Bose-Einstein Condensate of Atomic Gases

Tin-Lun Ho
 Ohio State University; Columbus, OH

A Quantum Degenerate Fermi Gas of ^6Li Atoms

Randall G. Hulet
 Rice University; Houston, TX

Dynamic Measurements Along the Lambda Line of Helium in a Low-Gravity Simulator on the Ground

Ulf E. Israelsson
 Jet Propulsion Laboratory; Pasadena, CA

Turbidity and Universality Around a Liquid-Liquid Critical Point

Donald T. Jacobs
 The College of Wooster; Wooster, OH

Bose-Einstein Condensate and Atom Laser: Coherence and Optical Properties

Juha Javanainen
 University of Connecticut; Storrs, CT

Atom Interferometry in a Microgravity Environment

Mark A. Kasevich
 Yale University; New Haven, CT

Towards Precision Experiments With Bose-Einstein Condensates

Wolfgang Ketterle
 Massachusetts Institute of Technology; Cambridge, MA

Second Sound Measurements Near the Tricritical Point in ^3He - ^4He Mixtures

Melora E. Larson

Jet Propulsion Laboratory; Pasadena, CA

Static Properties of ^4He in the Presence of a Heat Current in a Low-Gravity Simulator

Melora E. Larson

Jet Propulsion Laboratory; Pasadena, CA

Studies of Atomic Free Radicals Stored in a Cryogenic Environment

David M. Lee

Cornell University; Ithaca, NY

A Renewal Proposal to Study the Effect of Confinement on Transport Properties by Making Use of Helium Along the Lambda Line

John A. Lipa

Stanford University; Stanford, CA

A Test of Supersymmetry Theory by Searching for Anomalous Short-Range Forces

John A. Lipa

Stanford University; Stanford, CA

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

John A. Lipa

Stanford University; Stanford, CA

Theoretical Studies of Liquid ^4He Near the Superfluid Transition

Efstathios Manousakis

Florida State University; Tallahassee, FL

Density Equilibration in Fluids Near the Liquid-Vapor Critical Point

Horst Meyer

Duke University; Durham, NC

Indium Mono-Ion Oscillator II

Warren Nagourney

University of Washington; Seattle, WA

Superfluid Gyroscopes for Space

Richard E. Packard

University of California, Berkeley; Berkeley, CA

Search for Spin-Mass Interaction With A Superconducting Differential Angular Accelerometer

Ho Jung Paik

University of Maryland, College Park; College Park, MD

The Effect of Thermal History, Temperature Gradients, and Gravity on Capillary Condensation of Phase-Separated Liquid ^3He - ^4He Mixtures in Aerogel

Jeevak M. Parpia

Cornell University; Ithaca, NY

Nonlinear Relaxation and Fluctuations in a Nonequilibrium, Near-Critical Liquid With a Temperature Gradient

Alexander Z. Patashinski

Northwestern University; Evanston, IL

Evaporative Cooling and Bose Condensates in Microgravity: Picokelvin Atoms in Space

William D. Phillips

National Institute of Standards and Technology; Gaithersburg, MD

A Microgravity Helium Dilution Cooler

Pat R. Roach

Ames Research Center; Moffett Field, CA

Finite Size Effects Near the Liquid-Gas Critical Point of ^3He

Joseph Rudnick

University of California, Los Angeles; Los Angeles, CA

Research and Analysis in Support of Project Satellite Energy Exchange: Test of the Equivalence Principle and Measurement of Gravitational Interaction Parameters in an Ultra-Precise Microgravity Environment

Alvin J. Sanders

University of Tennessee; Knoxville, TN

Dynamics and Morphology of Superfluid Helium Drops in a Microgravity Environment

George M. Seidel

Brown University; Providence, RI

Precise Measurements of the Density and Critical Phenomena of Helium Near Phase Transitions

Donald M. Strayer

Jet Propulsion Laboratory; Pasadena, CA

^3He - ^4He Mixtures and Droplets Stabilized in Cesium Containers

Peter Taborek

University of California, Irvine; Irvine, CA

Ground-Based Investigations With the Cryogenic Hydrogen Maser

Ronald L. Walsworth

Smithsonian Institution; Cambridge, MA

Materials Science

The goal of the microgravity materials science research program is to establish and improve the quantitative and predictive relationships among the structure, processing, and properties of materials. Production processes for most materials include steps that are very heavily influenced by the force of gravity. Typical gravity-related effects on materials science research include buoyancy-driven convection, sedimentation, and hydrostatic pressure. The opportunity to observe, monitor, and study material production in low gravity promises to increase our fundamental understanding of production processes and their effects on the properties of the materials produced. Through careful modeling and experimentation, the mechanisms by which materials are formed can be better understood and can result in improved processing controls. In this way, materials scientists can design and manufacture new metal alloys, semiconductors, ceramics, glasses, and polymers with better properties, such as increased strength and durability. These new materials can be used to improve the performance of a wide range of products, including complex computers.

In fiscal year (FY) 1999, the materials science program continued work on projects in support of the Human Exploration and Development of Space Enterprise Strategic Plan. The plan includes goals, performance measurements, and metrics. The current status of efforts put forth toward meeting these goals was presented to the associate administrator for life and microgravity sciences and applications as part of the materials science program's annual assessment. In addition, the materials science office at Marshall Space Flight Center (MSFC) was restructured under a single department to enable better communications and organizational efficiency among the science, systems engineering, and the projects implementing the program.

To ensure that investigations get approved for flight, the materials science program has placed emphasis on providing NASA resources to the principal investigator teams in the flight-definition phase to help investigators through the science concept review (SCR) and the requirements definition review (RDR) processes in a timely manner. Multiple project science and engineering teams were established to assist the PI teams with experiment concept development, technology identification, modeling, breadboarding, and hardware prototyping. Additionally, support for building apparatus for KC-135 aircraft, drop tube, and electrostatic levitator operation was provided.

Due to the agency's emphasis on initial hardware assembly for the International Space Station (ISS) and the dedication of space shuttle flights to build the station, no materials science research missions or individual flight experiments were conducted this year. Our flight researchers from prior space shuttle and Spacelab flights concluded their analyses and published final postflight results.

Development of the Materials Science Research Facility continued in FY 1999. This development effort includes independent racks and components comprising experiment and insert modules that can be interchanged and replaced on orbit. The inserts include both low- and high-temperature instruments and diagnostics

devices that accommodate a wide range of applications. An envelope of potential experiment requirements for both current and future investigations is being developed for Materials Science Research Racks (MSRRs) #2 and #3 for the facility. These data will be used for architectural system trade studies.

MSRR #1 completed its project definition review in June 1999 with the rack subsystems and the Quench Module Insert. Activities have begun for the integrated design review, which will be conducted in mid-2000. Currently the first rack is scheduled for launch on the third Utilization Flight (UF-3) to the ISS. Work continued with the European Space Agency (ESA) on finalizing the scope of the Materials Science Laboratory module. These efforts produced a significant step forward in establishing design interfaces with our international partner engineering team.

Implementation of apparatus for two glovebox investigations, Pore Formation and Mobility, and Solidification Using a Baffle in Sealed Ampoules, was initiated. The two experiments are scheduled for flight on UF-1. Flight hardware delivery is expected in mid-2001.

All SCRs for experiments selected from the 1994 NASA Research Announcement (NRA) for microgravity materials science were completed in FY 1999. Requirements definition for these investigations will continue throughout FY 2000. During this year, some project formulation support activities for the RDR milestones were adjusted due to reduced levels of station funding and delays in obtaining flight opportunities. An investigation continuation review (ICR) for the Coarsening in Solid-Liquid Mixtures investigation was conducted. A delta ICR to address certain specific engineering changes will be held in early FY 2000.

Work continued on the investigation definition for the 10 experiments selected from the 1996 NRA for materials science. SCRs for these investigations will be held in FY 2000.

The evaluation of proposals in response to the 1998 NRA for microgravity materials science (98-HEDS-05) was completed, and award letters will be issued by the end of calendar year 2000. It is anticipated that the total number of grants awarded will increase slightly over prior annual cycles.

The Electrostatic Levitator (ESL) became fully operational at MSFC this year. The ESL is a state-of-the-art containerless processing tool used by multiple materials science investigators. With this new capability, MSFC can provide critical resources to the materials science community to continue and enhance ground-based research in support of the development of experiments during the transition to ISS flight opportunities. Processing levitated materials represents an important area of research that allows access to the metastable state of undercooled melts. By levitating materials so that they are free from contact with the container wall, a high-purity environment can be obtained for the study of reactive, high-temperature materials for experiments on refractory solids and melts. William Johnson, of the California Institute of Technology, uses data obtained from the ESL to develop alloy systems for an exciting new class of materials, bulk metallic glasses. FY 1999 highlights from research conducted in

the ESL include the extension of processing capabilities to oxide glasses, such as Pyrex. Several facility upgrades contributed to this success. Of these upgrades, the most critical were improvements to the sample positioning and control system and an improved ultraviolet charging system. These upgrades continue to enhance ESL processing capabilities for metals and alloys.

The developmental dendrite growth hardware, installed in the Microgravity Development Laboratory last year, continues to provide an important test platform for materials science investigations and engineering breadboarding. Data were provided to evaluate transient and time-dependent dendritic growth by employing the relatively large Clapeyron pressure/melting temperature effect in succinonitrile. Preliminary tests of the feasibility of this idea confirmed the basic scientific concept. Significant achievements also have been made in meeting imaging diagnostics requirements, including the challenge of tracking the dendrite tip radii. In parallel, both conventional optics and holography are being developed and tested as a means of achieving the stringent optics requirements of materials science investigations.

The prototype furnace for the Bridgman Unidirectional Dendrite in a Liquid Experiment (BUNDLE) is being utilized to investigate the fundamentals of unidirectional solidification of metal alloy samples. Unique to the furnace design is an in-situ quench capability that ensures freezing without disturbing the interfacial sample morphology. Increased throughput is achievable by "bundling" multiple furnace cores together. An extensive test program was initiated for a wide range of thermal parameters. The BUNDLE furnace has successfully processed various samples and sample configurations for more than 225 hours and 45 heat-up cycles, at temperatures up to 1,100° C. The sharp delineation between the growing dendrites and the eutectic structure in the interfacial region proved the efficacy of the in-situ quench method.

Some notable scientific achievements during FY 1999 are listed below:

- While conducting preparatory research for his Frontal Polymerization in Microgravity investigation, John Pojman, of the University of Southern Mississippi, was able to produce in the tensiometer an interface between a monomer and its polymer. This may be the first time an interface of this type between miscible liquids has been stabilized and examined.
- Delbert Day, of the University of Missouri, and his team have developed a new experimental method for determining the nucleation rate, crystal growth rate, and concentration of quenched-in nuclei in glasses using differential thermal analysis. This new method is about 10 times faster and requires only one-tenth the sample size while yielding comparable accuracy, allowing otherwise unusable, damaged samples to be successfully analyzed.
- Richard Weber, of Containerless Research, Inc., reported several significant accomplishments in FY 1999, including the discovery of a method for controlling phase separation in rare earth aluminate glasses, measuring the first X-ray-weighted structure factor and radial distribution function for a deeply

undercooled rare earth aluminate liquid, and establishing conditions for synthesizing bulk orthosilicate glass (forsterite, Mg_2SiO_4).

- Randall German, of Pennsylvania State University, has begun identification of the sequence of events that occur during sintering in normal gravity, showing that densification and distortion take place in series. Improved understanding of the sintering process will allow the production of high-performance sintered materials with improved dimensional control.

Meetings, Awards, and Publications

Richard Weber presented the invited keynote paper on the investigation of liquid oxides under extreme conditions at the American Ceramic Society Meeting in Cocoa Beach, Florida, in January 1999.

The 37th American Institute of Aeronautics and Astronautics' Aerospace Sciences Meeting and Exhibit was held January 11–14, 1999, in Reno, Nevada. This meeting highlighted 21 areas dealing with aeronautical, astronautical, and educational aspects of materials science, including sessions on microgravity and space processing. The meeting brought together scientists and engineers to discuss fundamental science issues, technological challenges, and basic research associated with aerospace engineering. Carlos Coimbra, of Drexel University, and Roger Rangel, of the University of California, Irvine, won the best paper award for their work titled "Spherical Particle Motion in Unsteady Viscous Flows." The paper is based on work being done to support the Spaceflight Holography Investigation in a Virtual Apparatus project, headed by James Trolinger, of MetroLaser, Inc.

The Martin E. Glicksman Symposium on Solidification and Crystal Growth of the Minerals, Metals, and Materials Society's (TMS) Annual Meeting was held in San Diego, California, March 3, 1999. A workshop on containerless processing was also conducted as part of the conference.

The Pittsburgh Conference '99, an annual major conference and trade show on analytical chemistry and applied spectroscopy, was held in Orlando, Florida, March 8–11, 1999. Donald Gillies, of MSFC, gave an invited talk titled "Materials Science on Space Station" as part of the symposium "Analytical Chemistry on the Space Station and Beyond." Approximately 30,000 people attended the conference.

During the Powder Metallurgy and Particulate Materials conference held in Vancouver, Canada, June 20–24, 1999, three presentations based on results obtained from the Gravitational Effects on Distortion in Sintering experiment were given by a Pennsylvania State University research team led by Randall German. Although focusing on different material systems, all three presentations concerned the role of porosity while sintering in the presence of a liquid phase.

The Society for Photo-Optical Instrumentation Engineers' International Symposium on Optical Science and Instrumentation took place in Denver, Colorado, July 18–23,

1999. The meeting featured a three-day conference on materials research in low gravity, chaired by Narayanan Ramachandran, of the Universities Space Research Association (USRA). The conference emphasized the use of external fields in materials processing. Separate sessions were devoted to glasses, alloys, and melts; in-situ monitoring and diagnostics; and analysis and modeling.

Doru Stefanescu, of the University of Alabama, was the plenary speaker at the Fourth Pacific Rim International Conference on Modeling of Casting and Solidification, held in Seoul, South Korea, September 4–8, 1999. Stefanescu's talk was titled "An Interface Tracking Numerical Model for Solidification of Pure Metals and Alloys," and was co-authored by Adrian Catalina, of USRA. In this paper, the investigators proposed a two-dimensional numerical model able to accurately track sharp solid/liquid interfaces during the solidification of pure metals and alloys.

Two principal investigators from the materials science program were installed as Fellows of the American Society for Metals (ASM) at its annual meeting in Cincinnati, Ohio, November 1, 1999. Arun Gokhale, of the Georgia Institute of Technology, was recognized "for outstanding contributions to the field of stereology and its applications to quantitative microstructural characterization." Jogender Singh, head of the Electron Beam–Physical Vapor Deposition Coating Center at Pennsylvania State University, was honored "for exceptional contributions in the applications of laser beam processing to the synthesis of nanoparticles, coatings, surface modifications, thin welds, welding, and cutting."

Randall German received numerous awards, including the 1999 Outstanding Paper Award by the Metal Powder Industries Federation; the Sauver Award by ASM International, Boston Section; and the Lectureship Award by the Japan Institute for Materials Technology. German gave an invited keynote presentation on "Innovations in Sintering" at the National Institute for Standards and Technology's Advanced Technology Program in November 1999 and was named the first Nanyang Professor by the Nanyang Technological University in Singapore. German was also awarded the Jubilee Tesla Medal for outstanding contribution to the field of natural science.

The 1999 Space Technology and Applications International Forum was held in Albuquerque, New Mexico, in October. Sharon Cobb, of MSFC, presented a paper titled "Preliminary Concepts for the Materials Science Research Facility." The materials science session included presentations on planned payloads and experiments for the ISS, as well as updates on the predicted microgravity environment and the Active Rack Isolation System.

Rohit Trevidi, of Iowa State University, who is the principal investigator (PI) for the Interface Pattern Selection Criteria for Cellular Structures in Directional Solidification project, was honored with the David R. Boylan Eminent Faculty Award for Research, given by the College of Engineering at Iowa State University. Trevidi was also named Consultant Professor by Northwestern Polytechnical University in Xian, China.

TMS presented several awards to researchers active in the materials science research program. Reza Abbaschian, of the University of Florida, was cited as the Structural Materials Division

Distinguished Scientist/Engineer for his outstanding scientific and technical contributions in the solidification and processing of composites, leadership in materials science and engineering education activities, and service to TMS. Abbaschian was also the recipient of the 1999 Leadership Award for outstanding academic leadership and contributions to the materials profession through TMS-sponsored and national activities.

TMS' Educator Award for 1999 was awarded to Merton Flemings, of the Massachusetts Institute of Technology. Flemings was cited for outstanding contributions to the unification of the fields of materials science and engineering and for disseminating information on the contributions of leaders in materials processing and solidification.

Flight Experiments

The Coarsening in Solid-Liquid Mixtures-2 (CSLM-2) investigation is designed to investigate the factors controlling the morphology of solid-liquid mixtures during Ostwald ripening, or coarsening. Coarsening occurs in a wide variety of two-phase mixtures, ranging from multiphase solids to multiphase liquids, and has a significant impact on the high-temperature stability of many technologically important materials. The objectives of the experiment are (1) to produce coarsening data that for the first time can be compared directly to theory with no adjustable parameters, and (2) to support the development and accuracy of theoretical models of the process. This investigation, which will fly aboard the ISS in 2001, is a modified reflight of the CSLM experiment, which flew on STS-83 and STS-94 in April and July 1997, respectively. In particular, experiments with longer coarsening times will be carried out to eliminate possible transient effects. An improved furnace will provide minimal gradients (less than $0.02^\circ\text{C}/\text{cm}$) in order to control grain formation over longer processing periods necessary for correlation theory. The experiment will be carried out in the ISS Microgravity Science Glovebox. The PI, Peter Voorhees, of Northwestern University, has tested the new furnace and has found it greatly improved over the previous design. The PI and engineering team are preparing to conduct an investigation continuation review, after which an authority-to-proceed review will be scheduled.

The Coupled Growth in Hypermonotectics (CGH) experiment uses microgravity to establish and improve quantitative and predictive relationships among the structure, processing, and properties of materials. Engineering alloys typically consist of a mixture of two or more metals that are melted together to form a mixture with enhanced properties. However, there is a large group of alloys that do not mix when melted. Instead, these immiscible, or hypermonotectic, alloys form two separate liquids, resulting in a situation similar to that seen when oil is added to water. When hypermonotectic alloys are melted and solidified on Earth, the heavier of the two liquids sinks to the bottom and limits the usefulness of the alloy. Low-gravity conditions can prevent the heavier liquid from sinking and allow the formation of internal

microstructures ideal for many engineering applications. The CGH project uses low-gravity conditions to enhance our understanding of these intriguing and potentially beneficial alloys in an attempt to improve the ability to produce the desired structures on Earth. Immiscible alloys have potential beneficial characteristics for use in superconductors, catalysts, bearings, electrical contacts, magnetic materials, and microelectronic circuits. Barry Andrews, of the University of Alabama, Birmingham, and his team are preparing CGH for operations aboard the ISS in 2003. This experiment is projected for processing in the Quench and High-Gradient Directional Solidification Furnace module insert of the Materials Science Research Facility.

The primary objective of the **Particle Engulfment and Pushing by a Solid/Liquid Interface (PEP)** experiment is to develop the understanding of the pushing and engulfment of particles by planar liquid/solid interfaces during the solidification of metallic alloys. Composite materials, mixtures of two or more materials which, when combined, provide specific, desired properties, are developed to make new, superior materials that take advantage of the properties of each component material. Ground-based investigations have been inconclusive in accurately

understanding the physics of the problem due to convection and sedimentation occurring in the liquid metal under terrestrial gravity. Metal matrix composites, which consist of combinations of metallic and ceramic components, have widespread applications in the automotive and aerospace industries. To optimize properties, it is essential to process the composite materials in such a way that they produce a uniform dispersion of ceramic particles within the metal matrix. During processing, the particles are either pushed or engulfed. New understanding will also help in other fields that see particles pushed by solidifying interfaces. The investigation team, led by Doru Stefanescu, is preparing to conduct flight investigations on the ISS in 2003. Findings from this investigation may improve techniques for processing metal alloys on Earth, resulting in stronger, lighter materials for use in industry. PEP may also provide an understanding of how and why potholes form on road surfaces and how to prevent them.

The FY 1999 ground and flight tasks for materials science are listed in **Table 9**. Further details regarding these tasks may be found in the complementary document *Microgravity Research Division Program Tasks and Bibliography for FY 1999*, available online at <http://microgravity.hq.nasa.gov/research.htm>.

Table 9 **Materials Science Tasks Funded by the Microgravity Research Division in FY 1999**
(includes some continuing projects at no additional cost)

Flight Experiments

In-Situ Monitoring of Crystal Growth Using MEPHISTO

Reza Abbaschian
University of Florida; Gainesville, FL

Coupled Growth in Hypermonotectics

J. B. Andrews
University of Alabama, Birmingham; Birmingham, AL

Fundamental Aspects of Vapor Deposition and Etching Under Diffusion-Controlled Transport Conditions

Klaus J. Bachmann
North Carolina State University; Raleigh, NC

Self-Diffusion in Liquid Elements

R. M. Banish
University of Alabama, Huntsville; Huntsville, AL

Thermophysical Property Measurements of Te-Based II-VI Semiconductor Compounds

R. M. Banish
University of Alabama, Huntsville; Huntsville, AL

Investigation of the Relationship Between Undercooling and Solidification Velocity

Robert J. Bayuzick
Vanderbilt University; Nashville, TN

Equiaxed Dendritic Solidification Experiment

Christoph Beckermann
University of Iowa; Iowa City, IA

Kinetics of Nucleation and Crystal Growth in Glass-Forming Melts in Microgravity

Delbert E. Day
University of Missouri; Rolla, MO

Measurement of the Viscosity and Surface Tension of Undercooled Melts Under Microgravity Conditions and Supporting Magnetohydrodynamic Calculations

Merton C. Flemings
Massachusetts Institute of Technology; Cambridge, MA

Microgravity Growth of PbSnTe

Archibald L. Fripp
Langley Research Center; Hampton, VA

Gravitational Effects on Distortion in Sintering

Randall M. German
Pennsylvania State University; University Park, PA

Isothermal Dendritic Growth Experiment

Martin E. Glicksman
Rensselaer Polytechnic Institute; Troy, NY

Evolution of Local Microstructures: Spatial Instabilities of Coarsening Clusters

Martin E. Glicksman
Rensselaer Polytechnic Institute; Troy, NY

Physical Properties and Processing of Undercooled, Metallic, Glass-Forming Melts

William L. Johnson
California Institute of Technology; Pasadena, CA

Thermophysical Properties of Metallic Glasses and Undercooled Liquids

William L. Johnson
California Institute of Technology; Pasadena, CA

Transient Dendritic Solidification Experiment

Matthew B. Koss
Rensselaer Polytechnic Institute; Troy, NY

Orbital Processing of Eutectic Rod-Like Arrays

David J. Larson Jr.
State University of New York; Stony Brook, NY

Crystal Growth of II-VI Semiconducting Alloys by Directional Solidification

Sandor L. Lehoczky
Marshall Space Flight Center; Huntsville, AL

Growth of Solid-Solution, Single Crystals

Sandor L. Lehoczky
Marshall Space Flight Center; Huntsville, AL

Diffusion Processes in Molten Semiconductors

David H. Matthiesen
Case West Reserve University; Cleveland, OH

Space- and Ground-Based Crystal Growth Using a Baffle

Aleksandar G. Ostrogorsky
University of Alabama, Huntsville; Huntsville, AL

Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments

David R. Poirier
University of Arizona, Tucson; Tucson, AZ

Frontal Polymerization in Microgravity

John A. Pojman
University of Southern Mississippi; Hattiesburg, MS

Particle Engulfment and Pushing by Solidifying Interfaces

Doru M. Stefanescu
University of Alabama, Tuscaloosa; Tuscaloosa, AL

Crystal Growth of ZnSe and Related Ternary Compound Semiconductors by Vapor Transport

Ching-Hua Su
Marshall Space Flight Center; Huntsville, AL

Reduction of Defects in Germanium-Silicon

Frank R. Szofran
Marshall Space Flight Center; Huntsville, AL

Interface Pattern Selection Criterion for Cellular Structures in Direction Solidification

Rohit K. Trivedi
Iowa State University; Ames, IA

Spaceflight Holography Investigation in a Virtual Apparatus

James D. Trolinger
MetroLaser, Inc.; Irvine, CA

Coarsening in Solid-Liquid Mixtures-2

Peter W. Voorhees
Northwestern University; Evanston, IL

Microgravity Studies of Liquid-Liquid Phase Transitions in Undercooled Alumina-Yttria Melts

Richard Weber
Containerless Research, Inc.; Evanston, IL

Identification and Control of Gravity-Related Defect Formation During Melt Growth of Electro-Optic Single Crystals: Sillenites ($\text{Bi}_{12}\text{SiO}_{20}$), BSO

August F. Witt
Massachusetts Institute of Technology; Cambridge, MA

Ground-Based Experiments

Microgravity Impregnation of Fiber Preforms

M. C. Altan
University of Oklahoma; Norman, OK

An Electrochemical Method to Visualize Flow and Measure Diffusivity in Liquid Metals

Timothy J. Anderson
University of Florida; Gainesville, FL

The Effect of Convection on Morphological Stability During Coupled Growth in Immiscible Systems

J. B. Andrews
University of Alabama, Birmingham; Birmingham, AL

Nucleation and Growth Mechanisms Underlying the Microstructure of Polymer Foams Produced by Dynamic Decompression and Cooling

Robert E. Apfel
Yale University; New Haven, CT

Growth and Properties of Carbon Nanotubes

Jerry Bernholc
North Carolina State University; Raleigh, NC

Dispersion Microstructure and Rheology in Ceramics Processing

John F. Brady
California Institute of Technology; Pasadena, CA

Combustion Synthesis of Materials in Microgravity

Kenneth Brezinsky
University of Illinois; Chicago, IL

Application of Parallel Computing for Two- and Three-Dimensional Modeling of Bulk Crystal Growth and Microstructure Formation

Robert A. Brown
Massachusetts Institute of Technology; Cambridge, MA

Study of Development of Polymer Structure in Microgravity Using Ellipsometry

Peggy Cebe
Tufts University; Medford, MA

Three-Dimensional Velocity Field Characterization in a Bridgman Apparatus: Technique Development and Effect Analysis

Soyoung S. Cha
University of Illinois; Chicago, IL

Morphological Stability of Stepped Interfaces Growing From Solution

Alexander A. Chernov
Universities Space Research Association, Marshall Space Flight Center; Huntsville, AL

Dynamic Reduction and the Creation of Fine-Grained Ceramics From Inviscid Oxide/Silicate Melts

Reid F. Cooper
University of Wisconsin; Madison, WI

Gravity-Induced Settling in Interconnected Liquid-Solid Systems

Thomas H. Courtney
Michigan Technological University; Houghton, MI

Improved Radiation Transport Code and Nuclear Database for Evaluation of Spacecraft Shielding

Francis A. Cucinotta
Johnson Space Center; Houston, TX

Fundamental Studies of Solidification in Microgravity Using Real-Time X-Ray Microscopy

Peter A. Curreri
Marshall Space Flight Center; Huntsville, AL

Adaptive-Grid Methods for Phase-Field Models of Microstructure Development

Jonathan A. Dantzig
University of Illinois, Urbana-Champaign; Urbana, IL

Atomistic Simulations of Cadmium Telluride: Toward Understanding the Benefits of Microgravity Crystal Growth

Jeffrey J. Derby
University of Minnesota; Minneapolis, MN

Theoretical Analysis of Three-Dimensional, Transient Convection and Segregation in Microgravity Bridgman Crystal Growth

Jeffrey J. Derby
University of Minnesota; Minneapolis, MN

Surface Transformation of Reactive Glass in a Microgravity Environment

Paul Ducheyne
University of Pennsylvania; Philadelphia, PA

White Beam X-Ray Topography and High-Resolution Triple Axis X-Ray Diffraction Characterization

Michael Dudley
State University of New York; Stony Brook, NY

Reverse Micelle-Based Synthesis of Microporous Materials in Microgravity

Prabir K. Dutta
Ohio State University; Columbus, OH

Gas Phase Polymerization and Nucleation Experiments in Microgravity

M. S. El-Shall
Virginia Commonwealth University; Richmond, VA

Studies on Nucleation, Polymerization, and Nanoparticle Composites in Supersaturated Vapors Under Microgravity Conditions

M. S. El-Shall
Virginia Commonwealth University; Richmond, VA

Exploiting the Temperature Dependence of Magnetic Susceptibility to Control Convection in Fundamental Studies of Solidification Phenomena

James W. Evans
University of California, Berkeley; Berkeley, CA

Theoretical and Experimental Investigation of Vibrational Control of the Bridgman Crystal Growth Technique

Alexandre I. Fedoseyev
University of Alabama, Huntsville; Huntsville, AL

Investigation of the Crystal Growth of Dielectric Materials by the Bridgman Technique Using Vibrational Control

Robert S. Feigelson
Stanford University; Stanford, CA

Development of Anionic Polyelectrolytes for Solid-State Battery Applications

Andrienne C. Friedli
Middle Tennessee University; Murfreesboro, TN

Melt Stabilization of PbSnTe in a Magnetic Field

Archibald L. Frupp
Langley Research Center; Hampton, VA

Solidification of II-VI Compounds in a Rotating Magnetic Field

Donald C. Gillies
Marshall Space Flight Center; Huntsville, AL

Effect of Gravity on the Evolution of Spatial Arrangement of Features in Microstructure: A Quantitative Approach

Arun M. Gokhale
Georgia Institute of Technology; Atlanta, GA

Influence of Solutocapillary Convection on Macrovoid Defect Formation in Polymeric Membranes

Alan R. Greenberg
University of Colorado, Boulder; Boulder, CO

Novel Directional Solidification Processing of Hypermonotectic Alloys

Richard N. Grugel
Marshall Space Flight Center; Huntsville, AL

Utilizing Controlled Vibrations in a Microgravity Environment to Understand and Promote Microstructural Homogeneity During Floating-Zone Crystal Growth

Richard N. Grugel
Marshall Space Flight Center; Huntsville, AL

Interdiffusion in the Presence of Free Convection

Prabhat K. Gupta
Ohio State University; Columbus, OH

Metal Nanoshell Functionalization and Materials Assembly: Effects of Microgravity Conditions

Naomi J. Halas
Rice University; Houston, TX

Radiation-Transmission Properties of In-Situ Materials

Lawrence H. Heilbronn
Lawrence Berkeley National Laboratory; Berkeley, CA

Microgravity Processing of Oxide Superconductors

William H. Hofmeister
Vanderbilt University; Nashville, TN

Dimensional Stability of Supermatrix Semiconductors

Douglas E. Holmes
Electronic Materials Engineering; Camarillo, CA

Porosity and Variations in Microgravity Aerogel Nanostructures

Arlon Hunt
Lawrence Berkeley National Laboratory; Berkeley, CA

Nonequilibrium Phase Transformations

Kenneth A. Jackson
University of Arizona, Tucson; Tucson, AZ

The Role of Dynamic Nucleation at Moving Boundaries in Phase and Microstructure Selection

Alain S. Karma
Northeastern University; Boston, MA

Determination of Gravity-Related Effects in Crystal Growth From Melts With an Immiscibility Gap

Mohammad Kassemi
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Effect of Marangoni Convection Generated by Voids on Segregation During Low-Gravity and Normal-Gravity Solidification

Mohammad Kassemi
National Center for Microgravity Research on Fluids and Combustion; Cleveland, OH

Measurement of Liquid-to-Solid Nucleation Rates in Undercooled Metallic Melts

Joseph L. Katz
Johns Hopkins University; Baltimore, MD

Phase Formation and Stability: Sample Size Effects

Kenneth F. Kelton
Washington University; St. Louis, MO

Physical Simulation of Marangoni Convection in Weld Pools

Sindo Kou
University of Wisconsin; Madison, WI

Colloidal Stability in Complex Fluids

Jennifer A. Lewis
University of Illinois, Urbana-Champaign; Urbana, IL

A Comparative Modeling Study of Magnetic and Electrostatic Levitation in Microgravity

Ben Q. Li
Washington State University; Pullman, WA

Study of Magnetic Damping Effect on Convection and Solidification Under G-Jitter Conditions

Ben Q. Li
Washington State University; Pullman, WA

Influence of Natural Convection and Thermal Radiation on Multicomponent Transport and Chemistry in MOCVD Reactors

Samuel A. Lowry
CFD Research Corporation; Huntsville, AL

Numerical and Laboratory Experiments on the Interactive Dynamics of Convection, Flow, and Directional Solidification

Tony Maxworthy
University of Southern California; Los Angeles, CA

A Phase-Field/Fluid Motion Model of Solidification: Investigation of Flow Effects During Directional Solidification and Dendritic Growth

Geoffrey B. McFadden
National Institute of Standards and Technology; Gaithersburg, MD

Microgravity Investigation on the Formation of Oxides and Adsorbed Oxygen Films in Solder Jetting Applications Pertinent to the Electronics Manufacturing Industry

Constantine M. Megaridis
University of Illinois; Chicago, IL

Thermodynamic and Spectroscopic Studies of Secondary Nucleation in Microgravity

Allan S. Myerson
Polytechnic University; Brooklyn, NY

Reduction of Convection in Closed-Tube Vapor Growth Experiments

Robert J. Naumann
University of Alabama, Huntsville; Huntsville, AL

Gravitational Effects on the Morphology and Kinetics of Photodeposition of Polydiacetylene Films From Monomer Solutions

Mark S. Paley
Universities Space Research Association, Marshall Space Flight Center; Huntsville, AL

Investigation of Convective Effects in Crystal Growth by Physical Vapor Transport

Witold Palosz
Universities Space Research Association, Marshall Space Flight Center; Huntsville, AL

Analysis of Containerless Processing and Undercooled Solidification Microstructures

John H. Perepezko
University of Wisconsin; Madison, WI

Improved Crystal Quality by Detached Solidification in Microgravity

Liya L. Regel
Clarkson University; Potsdam, NY

Thermophysical Property Measurement of Molten Semiconductors in Normal-Gravity and Reduced-Gravity Conditions

Won-Kyu Rhim
Jet Propulsion Laboratory; Pasadena, CA

Undercooling Limits and Thermophysical Properties in Glass-Forming Alloys

Won-Kyu Rhim
Jet Propulsion Laboratory; Pasadena, CA

Carbon-Based Reduction of Lunar Regolith

Eric E. Rice
Orbital Technologies Corporation; Madison, WI

A Study of the Undercooling Behavior of Immiscible Metal Alloys in the Absence of Crucible-Induced Nucleation

Michael B. Robinson
Marshall Space Flight Center; Huntsville, AL

Determination of the Surface Energy of Liquid Crystals From the Shape Anisotropy of Freely Suspended Droplets

Charles S. Rosenblatt
Case Western Reserve University; Cleveland, OH

Modeling of Macroscopic/Microscopic Transport and Growth Phenomena in Zeolite Crystal Solutions Under Microgravity

Albert Sacco Jr.
Northeastern University; Boston, MA

Thermophysical Properties of High-Temperature Liquid Metals and Alloys

Robert J. Schaefer
National Institute of Standards and Technology; Gaithersburg, MD

Gravitational Effect on the Development of Laser Weld-Pool and Solidification Microstructure

Jogender Singh
Pennsylvania State University; University Park, PA

Flight Experiment to Study Double Diffusive Instabilities in Silver-Doped Lead Bromide Crystals

N. B. Singh
Northrop-Grumman Corporation; Baltimore, MD

Kinetics of Nucleation and Growth From Undercooled Melts

Frans A. Spaepen
Harvard University; Cambridge, MA

Development of Superior Materials for Layered, Solid Oxide Electrolyzers Based on Mechanical and Thermal Failure Testing and Analysis

K. R. Sridhar
University of Arizona, Tucson; Tucson, AZ

Magnetic Damping of Solid-Solution Semiconductor Alloys

Frank R. Szofran
Marshall Space Flight Center; Huntsville, AL

The Features of Self-Assembling, Organic Bilayers Important to the Formation of Anisotropic, Inorganic Materials in Microgravity Conditions

Daniel R. Talham

University of Florida; Gainesville, FL

Dynamically Induced Nucleation of Deeply Supercooled Melts and Measurement of Surface Tension and Viscosity

Eugene H. Trinh

National Aeronautics and Space Administration; Washington, DC

Investigate the Influence of Microgravity on Transport Mechanisms in a Virtual Spaceflight Chamber

James D. Trolinger

MetroLaser Inc.; Irvine, CA

Models of Magnetic Damping for Bridgman Semiconductor Crystal Growth in Microgravity

John S. Walker

University of Illinois, Urbana-Champaign; Urbana, IL

Process-Property-Structure Relationships in Complex Oxide Melts

Richard Weber

Containerless Research Inc.; Evanston, IL

Use of Microgravity to Control the Microstructure of Eutectics

William R. Wilcox

Clarkson University; Potsdam, NY

Improved Spacecraft Materials for Radiation Shielding

John Wilson

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Ground-Based Experiments in Support of Microgravity Research Results — Vapor Growth of Organic, Nonlinear Optical Thin Film

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4 Acceleration Measurement

Acceleration measurement is the process by which data that describe the quality of a microgravity environment are acquired, processed, analyzed, and passed on to microgravity principal investigators (PIs). Because accelerations (commonly referred to as vibrations) cause disturbances such as convection, sedimentation, and mixing within microgravity science experiments — effects that researchers experimenting in microgravity conditions wish to avoid — information about accelerations is critical to the interpretation of science experiment results.

Experiments are usually conducted in microgravity to avoid fluid flow as much as possible; however, accelerations can strongly influence fluid motion. 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. In some fluids experiments, fluid movement due to accelerations may mask fluid characteristics, such as surface tension, that the experimenter wishes to observe. Mechanical vibrations over a wide range of frequencies may cause drastic temperature changes in low-temperature physics experiments, where the samples are at temperatures close to absolute zero. Accurately measuring the microgravity conditions of a microgravity science experiment is crucial. PIs use acceleration data to determine the influence of accelerations on their experiments and thus gain a more accurate picture of the phenomena under observation. The primary objective of the acceleration measurement program is to characterize the reduced-gravity environment of the various experiment carriers, such as the space shuttle, Russia's Space Station *Mir*, sounding rockets, parabolic flight aircraft, and the International Space Station (ISS).

The device most frequently used to measure the quality of a microgravity environment on the space shuttle has been the Space Acceleration Measurement System (SAMS), which flew on 20 missions from its first flight on STS-40 in June 1991 until the landing of its last flight on STS-87 in December 1997. The seven SAMS units recorded high-frequency accelerations and have flown in support of microgravity science experiments in the shuttle middeck, in the Spacelab module, on the Spacelab Mission Peculiar Experiment Support Structure, and in the SPACEHAB module. SAMS units on the space shuttle have supported experiments from all of the microgravity science disciplines (biotechnology, combustion science, fluid physics, fundamental physics, and materials science). After flying on two shuttle missions, SAMS unit E was installed on *Mir* in 1994, where it was operated intermittently as required to support U.S. and Russian microgravity science and mechanical structure experiments. Having traveled in orbit for three years and 10 months (approximately 532 million miles), the unit was returned to Earth on STS-91 in June 1998. The unit, along with its data disks, crew log books, summary reports, photographs, and drawings, was donated to the National Air and Space Museum in Washington, D.C. Originally designed for 14-day shuttle flights, the success of the unit for nearly four years of on-orbit operations amazed its engineers. The seven SAMS units have been retired from active use on shuttle missions, but critical components, such as acceleration

sensors, are being recycled for use with the SAMS-II and SAMS for Free Flyers (SAMS-FF) systems. The last spaceflight for a SAMS unit was the return of unit E from *Mir*. The last mission of a SAMS unit was in August 1999, when unit A flew on the KC-135 parabolic flight aircraft.

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

The microgravity program also uses an instrument called the Orbital Acceleration Research Experiment (OARE) to measure very low-frequency accelerations in support of microgravity research. The OARE has flown on 10 missions since its first flight on STS-40.

The Principal Investigator Microgravity Services (PIMS) project works with other Microgravity Research Program participants, such as vibration isolation programs, to lend assistance with data processing, interpretation, and analysis. The information collected and produced by the acceleration measurement program is made available through the PIMS project in mission summary reports, data files on CD-ROM and on Internet file servers, and specialized analysis reports for scientists. Some of the highlights of the fiscal year (FY) 1999 acceleration measurement program are discussed below.

Sounding Rockets

The SAMS-FF team supported the launch of the first Terrier-Orion sounding rocket microgravity mission on December 17, 1999. The SAMS-FF system collected microgravity data in support of the University of Maryland Microscale Heaters payload and characterized the environment for future microgravity science experiments. The rocket was launched at Wallops Flight Facility in Virginia. This flight served as the initial demonstration of a lower-cost sounding rocket for microgravity payloads and was the first of 10 planned flights. The flight offered approximately 3.5 minutes of high-quality microgravity. This amount of time is adequate for a number of payloads, including many combustion experiments.

Successful operation of the SAMS-FF system was verified in real time by the telemetry downlink. The sensor data was also recorded onboard the sounding rocket by the Control and Data Acquisition Unit, which controlled the operation of the SAMS-FF system. The system passed postmission testing and calibration and was placed in storage for the next flight opportunity. The data were analyzed and are presently available to interested parties. The data indicated that this sounding rocket platform offers high-quality microgravity for payloads requiring a very low-acceleration environment.

KC-135

During FY 1999, several SAMS units provided support for KC-135 flights. SAMS unit A, which has been retired from spaceflight after five successful shuttle missions, was used during three weeks of flight for microgravity experiments on NASA's newest KC-135 aircraft. SAMS unit A mapped the low-gravity environment of the parabolic flight aircraft and provided payload-specific support on the KC-135 aircraft. Presently, software is being developed by the SAMS-FF project to rate each parabola in the KC-135's flight path in terms of quality and duration. Immediately after the flight, the software will produce a concise table summarizing data on each parabola. This information will help experimenters to consider with more efficiency the impact of the microgravity environment on their experiments.

USMP-4

A mission summary report for the fourth United States Microgravity Payload (USMP-4) mission, STS-87, was issued by the PIMS team in January 1999. The report describes the microgravity environment for the STS-87 mission, which included a SPARTAN satellite deployment and various experiments conducted in the shuttle middeck. The accelerometers for this mission were the SAMS units F and G, and the OARE.

STS-89

The PIMS mission summary report for STS-89 was released in June 1999. This report describes the microgravity environment for the STS-89 mission, which included nearly five days during which the space shuttle was docked with the *Mir* space station. Accelerometers involved with this mission were the SAMS unit mounted in the SPACEHAB module in the shuttle cargo bay and the SAMS unit on *Mir*. The SAMS unit in the SPACEHAB module successfully supported the Mechanics of Granular Materials experiment during the mission.

STS-95

Data from the SAMS-FF operations on STS-95 were analyzed to support the Hubble Space Telescope Orbital Systems Test (HOST) payload and to characterize the acceleration environment for the mission. The STS-95 mission was the first space shuttle mission supported by the SAMS-FF acceleration measurement system. A total of 43 measurement sessions were conducted during the HOST mission, corresponding to various operating cycles of the HOST cryocooler. The SAMS-FF data were analyzed by PIMS and provided to the HOST team. These data have been invaluable in determining the cryocooler's potential effect on the precise alignment capabilities of the Hubble telescope. The data indicated that vibrations caused by the cryocooler were not a problem, and the decision was made to install the cryocooler on the telescope during the third servicing mission.

ISS

Development of SAMS-II, a system for conducting acceleration measurements on the ISS, continued this year and moved into the deployment phase. Flight designs and buildup of the Interim Control Unit (ICU) and Remote Triaxial Sensor (RTS) drawers were completed. The flight ICU and RTS drawers are undergoing verification testing and will be completed in early 2000. Operational activities continued for interfacing SAMS-II with the ISS. Plans for acceleration data handling were developed by the PIMS project team and the Telescience Support Center. Successful tests were performed with the SAMS-II and PIMS teams to demonstrate the data handling and analysis interfaces.

SAMS successfully supported the Active Rack Isolation System Initial Capability Experiment on the ISS by supplying SAMS-II engineering hardware. A capability test with the flight hardware is planned for 2000. SAMS has a draft agreement with the Physics of Colloids in Space experiment to provide a Remote Triaxial Sensor Enclosure. SAMS is also working with the Microgravity Science Glovebox and Fluids and Combustion Facility projects to create similar agreements.

The Microgravity Acceleration Measurement System (MAMS) was instituted to verify that the ISS produces a microgravity environment in accordance with ISS program requirements. MAMS has independent high-frequency and quasi-steady (low-frequency) sensor subsystems. MAMS low-frequency data will be used to support microgravity science payloads. In FY 1999, the MAMS flight unit was completed and verification testing was initiated. MAMS flight software interfaces were verified using the Suitcase Test Environment for Payloads provided by the ISS program. Crew activation procedures have been developed, and ground operations planning has been completed. MAMS will be delivered to Kennedy Space Center (KSC) in FY 2000 for integration into the ISS Expedite Processing of Experiments to Space Station (EXPRESS) Rack #1 and launch on ISS assembly flight 6A.

The acceleration measurement discipline scientist served as a co-chair for the Microgravity Constraints Tiger Team, which was formed in July 1999 and continues to meet weekly. The team comprises representatives for all ISS payloads, including payloads from all of the NASA divisions and those from the international partners. The team worked to develop an acceptable set of acceleration level requirements applicable to all ISS payloads.

Meetings and Conferences

The second annual Microgravity Environment Interpretation Tutorial was presented at Glenn Research Center (GRC) in September 1998 to a select group of scientists and microgravity personnel. The response from the participants was very positive. Excellent suggestions were also received for the third tutorial, which was conducted in December 1999. Discipline project scientists from GRC, the Jet Propulsion Laboratory (JPL), and Marshall Space Flight Center (MSFC), as well as some PIs and other Microgravity Research Program (MRP) representatives,

participated in the sessions. The tutorials were held over two-and-a-half days and covered the following topics: definitions and accelerometer instrumentation, data collection and analysis techniques, the measured environment of microgravity platforms, and implications for microgravity experimenters. A 500-page reference book was given to each participant. This tutorial will continue in future years to reach MRP PIs through the program's project scientists.

Papers titled "Experiment-to-Experiment Disturbance of Microgravity Environment" and "Principal Investigator Microgravity Services Role in the ISS Acceleration Data Distribution" were presented at the American Institute of Aeronautics and Astronautics' 37th Aerospace Sciences Meeting and Exhibit in Reno, Nevada, in January 1999. The acceleration measurement discipline scientist coordinated and chaired the "Microgravity Environment" session, which included eight papers on various aspects of the shuttle and *Mir* microgravity environments and the expected environment of the ISS. Coordination of a similar session was completed in preparation for the 38th meeting, scheduled for January 2000.

The inaugural "Microgravity Environment Familiarization Briefing" was presented in April 1999 to the 25 members of the 1998 astronaut class as part of their tour of GRC. This briefing introduced class members to the concepts of the microgravity environment on the ISS and the effect the crew may have on that environment. Class members got a chance for hands-on demonstrations of functioning SAMS-II and SAMS-FF engineering hardware. A briefing similar to this will be presented to each astronaut class to familiarize future ISS crew members with the impact of their activities on the microgravity environment in an effort to improve the quality of the environment during microgravity science operations.

Papers titled "Comparison Tools for Assessing the Microgravity Environment of Orbital Missions, Carriers, and Conditions" and "SAMS-II — Microgravity Instrumentation for the International Space Station Research Community" were presented at the 19th Institute of Electrical and Electronics Engineers' (IEEE's) Instrumentation and Measurement Technology Conference, held May 24–26, 1999, in Venice, Italy. Acceleration measurement discipline personnel served as chairs for two sessions at the conference. Before the IEEE conference, the acceleration measurement discipline scientist presented two seminars at the Microgravity Advanced Research and Support Center of the Università Degli Studi di Napoli Federico II in Napoli, Italy.

The 18th Microgravity Measurements Group meeting was conducted in June 1999 in Cocoa Beach, Florida. Approximately 40 attendees from various disciplines within the international microgravity community heard talks on a variety of microgravity environment topics, including the ISS, acceleration measurement and analysis results, science effects from microgravity accelerations, vibration isolation, free-flyer satellites, and parabolic flight aircraft. A 540-page summary of the meeting presentations was prepared and mailed to all participants after the meeting.

The series of talks at the meeting provided a forum for exchanging information and ideas about the microgravity environment and microgravity acceleration research in the MRP. Investigators in all areas of microgravity research, including PIs, project scientists, numerical modelers, instrumentation developers, and acceleration data analysts, participated. The attendees included representatives from NASA headquarters; GRC; JPL; Johnson Space Center; KSC; MSFC; the Canadian Space Agency (CSA); the French space agency (CNES); the German space agency (DLR); the Japanese space agency (NASDA); universities in Germany, Italy, Russia, and the United States; and commercial companies in Germany, Russia, and the United States. A tour of the Space Station Processing Facility (SSPF) at KSC was a feature of the meeting. In the near future, participants at this meeting will be characterizing the acceleration environment of the flight hardware seen in the SSPF.

A poster titled "Impacts of the Microgravity Environment on Experiments (and Vice Versa), Case Studies from the NASA STS and Shuttle/*Mir* Programs" was presented at the Gordon Research Conference on Gravitational Effects on Physico-Chemical Systems, at New England College in Henniker, New Hampshire. The conference was held June 27–July 2, 1999.

A paper titled "Effects of Exercise Equipment on the Microgravity Environment" was published in the November 1999 issue of *Advances in Space Research*. This paper had been presented at the 32nd COSPAR Scientific Assembly, which was held July 12–19, 1998. COSPAR is the Committee on Space Research of the International Council of Scientific Unions.

A paper titled "Measurement and Data Distribution for Microgravity Acceleration on the International Space Station" was presented at the 50th International Astronautical Congress, held October 4–8, 1999, in Amsterdam, the Netherlands. The paper was presented as part of the sessions on microgravity engineering sciences.

Advanced Technology Development Program

The Advanced Technology Development (ATD) Program was developed in response to the challenges researchers face when defining microgravity experiment requirements and designing associated hardware. Technology development projects addressed both focused and broad-based scientific concerns. Focused development projects ensured the availability of technologies to satisfy the science requirements of specific microgravity flight- or ground-based programs. Broad-based development projects encompassed a long-term, proactive approach to meeting the needs of future projects and missions within the Human Exploration and Development of Space Enterprise. In fiscal year (FY) 1999, the ATD Program was canceled due to budgetary constraints; however, ATD projects already in progress were permitted to continue until their originally scheduled completion dates. A plan for the Microgravity Integrated Technology Program, leveraging other NASA and non-NASA technology programs, is under development.

Historically, ATD projects have encompassed a broad range of activities. Funded projects included the development of diagnostic instrumentation and measurement techniques, observational

instrumentation and data recording methods, acceleration characterization and control techniques, and advanced methodologies associated with hardware design technology.

In FY 1999, five NASA centers were involved in the Microgravity Research Program–sponsored ATD Program: Glenn Research Center (GRC), Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), Johnson Space Center (JSC), and Marshall Space Flight Center (MSFC). The FY 1999 projects, listed in **Table 10**, illustrate the breadth of technologies covered by the ATD Program.

Table 10 FY 1999 ATD Projects

Magnetostrictive Cryogenic Actuators

Jennifer Dooley, JPL

The objective of this ATD project is to use the unique “giant” magnetostrictive properties of terbium-dysprosium polycrystalline alloys as the prime mover in a series of actuators and mechanisms that include low-temperature valves, heat switches, precision positioners, and lead screwdrivers. These materials and a family of devices are being developed for low-temperature use based on their unique properties of long stroke and high power with negligible energy dissipation. This work is centered at JPL and the California Institute of Technology in collaboration with researchers at GSFC, the American Superconducting Corporation, and the Naval Surface Warfare Center. The success of this work has been demonstrated through two U.S. patent applications filed by the investigators and JPL for the production of the magnetostrictive polycrystalline terbium-dysprosium materials by deformation processes and the use of these materials in several cryogenic devices. Eleven New Technology Awards have been issued for this work. A recent development in this work is the possibility of using magnetostrictive polycrystalline materials in passive cryogenic dampers. A primary focus of the continued efforts will be on damping vibrations in low-temperature space structures such as telescopes and large antennas.

Hydrofocusing Bioreactor

Steve Gonda, JSC

The goal of this project is to develop a space bioreactor that provides the capability to maintain a low-shear culture environment on-orbit while simultaneously removing air bubbles from the

bioreactor vessel. This technology will enable the removal of ubiquitous air bubbles formed in the culture fluid during on-orbit operation, without degrading the delicate three-dimensional tissue assemblies.

Space Bioreactor Bioproduct Recovery System

Steve Gonda, JSC

The purpose of this ATD effort is to develop a Bioproduct Recovery System (BRS) that allows the selective removal of molecules of interest from space bioreactors, thus enhancing the productivity of those bioreactors. The BRS will be miniaturized to meet volume and power constraints, and will be designed to operate in microgravity.

Space Bioreactor Media Reclamation System

Steve Gonda, JSC

The overall goal of this project is to develop a media reclamation system (MRS) that will enhance and extend the utility of space bioreactors for long-duration, on-orbit operation while concomitantly reducing on-orbit resources. The MRS will integrate online into the space bioreactor perfusion loop and provide continuous real-time conditioning and revitalization of culture medium by supplementing specific media components and removing specific toxic molecules.

Advanced Diagnostics for Combustion

Paul Greenberg, GRC

The goal of this ATD project is to develop a series of more sophisticated measurement techniques applicable to the general

area of microgravity combustion science in order to improve the accuracy and spatial/temporal yield of the data acquired and to extend the range of applicability and access to the relevant parameters presently inaccessible through current methods.

Small High-Resolution Thermometer

Inseob Hahn, JPL

Smaller and lighter high-resolution thermometers (HRTs) have been developed under this ATD project for lambda point experiments. In the Low-Temperature Microgravity Physics Facility on the International Space Station (ISS), multiple experiments will be performed within the same instrument package to reduce the average cost per experiment; the new, smaller HRTs will benefit these experiments.

Multiple Scattering Concerns in Dynamic Light Scattering

William Meyer, National Center for Microgravity Research on Fluids and Combustion (NCMRFC), GRC
Maryjo Meyer, GRC

This ATD project provides a simple and novel optical scheme that overcomes multiple scattering effects in turbid media. In addition, ways to experimentally measure and provide a full analytical solution for double, triple, and higher-order scattering are being developed.

A Robust Magnetic Resonant Imager for Ground- and Flight-Based Measurements of Fluid Phenomena

Benjamin Ovrin, Department of Mechanical and Aerospace Engineering, Case Western Reserve University, NCMRFC, GRC

One of the primary factors that has limited the use of magnetic resonance imaging for measurement has been the lack of a user-friendly, versatile, inexpensive nuclear magnetic resonance (NMR) machine that could be utilized by members of the scientific community who have little or no knowledge of NMR. To rectify this situation, a user-friendly NMR imager will be developed under this ATD project for use with myriad projects of relevance to NASA's scientific community. Ultimately, this type of machine should be suitable for use on the ISS.

Solid-Liquid Interface Characterization Hardware

Palmer Peters, MSFC

This ATD project focuses on the real-time characterization of temperature distributions within samples during directional solidification. Present technologies are limited for many applications, especially those having nonplanar interfaces, by the size of the thermocouples, when discrete thermocouples are used, and by interpretation of the Seebeck signal. To overcome these limitations, arrays of micron-sized thin film thermocouples, all deposited simultaneously with uniform properties and protective coatings, will be developed.

A Diffractometer for Reciprocal Space Mapping of Macromolecular Crystals

Marc Pusey, MSFC

The primary objective of this ATD project is to develop technology both instrumentally and theoretically for routine use in macromolecular crystal studies in the research laboratory. This technology will enable the researcher to accurately and repeatably characterize macromolecular crystal quality through X-ray mosaicity

measurements, topography, reciprocal space mapping, and direct three-dimensional reciprocal lattice point measurements. The results can then be used to quantitatively examine the effects of microgravity and different growth regimes on protein crystal growth.

Application of Superconducting Cavities to Microgravity Research

Don Strayer, JPL

This ATD project has two main objectives: (1) to use modern microwave electronics; high quality factor, low-temperature superconducting cavities; and high-resolution temperature control to develop an ultrastable oscillator system that will provide a comparison oscillator for the laser-cooled atomic oscillators now under development in the Microgravity Research Program; and (2) to develop high-temperature superconductor materials, high quality factor cavities, and electronics that can be integrated with a small cryocooler to provide an easy-to-use materials characterization system for use on the ISS.

Transient Torque Viscometer for Viscosity and Electrical Conductivity Measurements

Ching-Hua Su, MSFC

Obtaining data on the thermophysical properties of electrically conducting melts is required for any meaningful investigation of metallurgical or semiconductor processing. The principal objective of this ATD project is to develop a novel technique that will allow for the simultaneous measurement of the viscosity and electrical conductivity of electrically conducting melts. An essential feature of this technique is the utilization of a rotating magnetic field.

A Pulsed Tunable Laser System for Combustion

Randall Vander Wal, NCMRFC, GRC
Howard Ross, GRC

The objective of this ATD project is to design, construct, and demonstrate a pulsed solid state laser system in a microgravity environment. High peak intensities and multiple wavelength generation capabilities, characteristic of pulsed laser light, would enable fluorescence, incandescence, and scattering measurements in a wide range of combustion processes.

Vibration Isolation and Control System for Small Microgravity Payloads

Mark Whorton, MSFC

This project will deliver an active isolation device to provide a quiescent acceleration environment required for investigations to be carried out on the ISS.

A New Ultrahigh-Resolution Near-Field Microscope for Observation of Protein Crystal Growth

William Witherow, MSFC

The primary objective of this ATD project is to build and test a new optical method for observing protein crystals as they nucleate and grow. The method is based on a tapered-fiber probe in a near-field scanning optical microscope.

Experiment Hardware Flown on Space Shuttle and *Mir* Flights

The Microgravity Research Program Office has established itself as a leader in research with a history of highly successful flights onboard the space shuttle and Russian Space Station *Mir*. Table 11 lists these flights in chronological order. Following this

list are short descriptions of some of the investigations flown on these missions and of the flight experiment apparatus that supported these missions.

Table 11 Shuttle Missions With Major Microgravity Experiments Onboard, Chronologically by Launch Date

Launch Date	Flight	Mission	Full Name
April 1985	STS-51	SL-3	Spacelab-3
Jan. 1986	STS-61C		Materials Science Demonstrations
Jan. 1992	STS-41	IML-1	International Microgravity Laboratory-1
June 1992	STS-50	USML-1	United States Microgravity Laboratory-1
Oct. 1992	STS-52	USMP-1	United States Microgravity Payload-1
March 1994	STS-62	USMP-2	United States Microgravity Payload-2
July 1994	STS-65	IML-2	International Microgravity Laboratory-2
June 1995	STS-71	<i>Mir</i> -1	Shuttle/ <i>Mir</i> -1
July 1995	STS-70		Shuttle
Sept. 1995	STS-69	*	Wake Shield Facility, Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN)
Oct. 1995	STS-73	USML-2	United States Microgravity Laboratory-2
Nov. 1995	STS-74	<i>Mir</i> -2	Shuttle/ <i>Mir</i> -2
Feb. 1996	STS-75	USMP-3	United States Microgravity Payload-3
March 1996	STS-76	<i>Mir</i> -3	Shuttle/ <i>Mir</i> -3
June 1996	STS-78	LMS	Life and Microgravity Spacelab
Sept. 1996	STS-79	<i>Mir</i> -4	Shuttle/ <i>Mir</i> -4
Jan. 1997	STS-81	<i>Mir</i> -5	Shuttle/ <i>Mir</i> -5
April 1997	STS-83	MSL-1	Microgravity Science Laboratory-1
May 1997	STS-84	<i>Mir</i> -6	Shuttle/ <i>Mir</i> -6
July 1997	STS-94	MSL-1R	Microgravity Science Laboratory-Reflight
Aug. 1997	STS-85		CRISTA-SPAS-2, Japanese Experiment Module Flight Demonstration
Sept. 1997	STS-86	<i>Mir</i> -7	Shuttle/ <i>Mir</i> -7
Nov. 1997	STS-87	USMP-4	United States Microgravity Payload-4
Jan. 1998	STS-89	<i>Mir</i> -8	Shuttle/ <i>Mir</i> -8
March 1998	STS-90		Neurolab
Oct. 1998	STS-95		Shuttle

* *Middeck and Get Away Special (GAS) microgravity payloads only. GAS payloads also flew on STS-40, STS-41, STS-43, STS-45, STS-47, STS-54, STS-57, STS-60, STS-63, STS-64, STS-66, STS-72, and STS-77.*

Advanced Automated Directional Solidification Furnace: This instrument was a modified Bridgman-Stockbarger furnace for directional solidification and crystal growth. (USMP-2, USMP-3, USMP-4)

Biotechnology Refrigerator (BTR): The BTR had a refrigerated volume of 0.57 cubic feet for cold storage of culture medium, reagents, and specimens in support of biotechnology experiments. The BTR provided a temperature range of 4–12° C. (Shuttle/Mir-6, Shuttle/Mir-7, Neurolab)

Biotechnology Specimen Temperature Controller (BSTC): BSTC was a thermally controlled, single-locker module designed to incubate multiple small cell cultures. It had a single chamber capable of maintaining an internal temperature within the range of 36–40° C and the capability of monitoring carbon dioxide concentrations within the chamber in the range of 0–20 percent. BSTC was able to deliver custom-blended air/carbon dioxide gas mixtures, was programmable, and was able to be operated either independently or in conjunction with facility computers. (Shuttle/Mir-6, Neurolab)

Biotechnology System: This instrument was composed of a rotating wall vessel bioreactor, a control computer, a fluid supply system, a gas supply system, and a refrigerator for sample storage. (*Mir*)

Combustion Module-1: This module was developed to perform multiple combustion experiments in orbit. The first two experiments were the Laminar Soot Processes experiment and the Structure of Flame Balls at Low Lewis Number experiment. (MSL-1, MSL-1R)

Comparative Soot Diagnostics: This Middeck Glovebox investigation studied the combustion intermediates and products from an assortment of materials as measured by the space shuttle fire-detection system and the proposed International Space Station fire-detection system. Results of this work will be used in the design and operation of future spacecraft smoke-detection systems. (USMP-3)

Confined Helium Experiment Apparatus: This apparatus provided a thermometer resolution better than 100 picodegrees in measuring properties of helium samples confined to a two-dimensional state. It flew in the Low-Temperature Platform, where it was used to test finite size effects under controlled conditions to uncover underlying fundamental principles. (USMP-4)

Critical Fluid Light Scattering Experiment Apparatus: This apparatus provided a microkelvin-controlled thermal environment for performing dynamic light scattering and turbidity measurements of room-temperature critical fluids. (USMP-2, USMP-3)

Critical Viscosity of Xenon Experiment Apparatus: This apparatus provided a precision-controlled thermal environment (microkelvin) and an oscillating screen viscometer to perform viscosity measurements of room-temperature critical fluids. (STS-85)

Crystal Growth Furnace: This instrument was a modified Bridgman-Stockbarger furnace for crystal growth from a melt or vapor. (USML-1, USML-2)

Diffusion-Controlled Crystallization Apparatus for Microgravity (DCAM): The DCAM hardware, which was designed for long-duration protein crystal growth, combined liquid-liquid diffusion and dialysis methods to effect protein crystal growth. Each DCAM tray assembly consisted of 27 DCAM experiment chambers containing precipitant solutions and protein sample solutions. (USML-2, five *Mir* flights)

Drop Physics Module: This apparatus was designed to investigate the surface properties of various suspended liquid drops, to study surface and internal features of drops that are being vibrated and rotated, and to test a new technique for measuring the surface tension between two immiscible fluids. (USML-1, USML-2)

Enclosed Laminar Flames (ELF): This Middeck Glovebox investigation was performed to improve the fundamental understanding of the effects of flow environment on flame stability. ELF investigated the effect of convective flows on the stability of laminar (nonturbulent) jet-diffusion flames in a ducted, co-flow environment. (USMP-4)

Engineering Development Unit (EDU): The EDU was a rotation cylinder bioreactor supported by subsystems that provided media perfusion and exchange; continuous measurement and control of nutrient media, pH, glucose, oxygen, and carbon dioxide; incubator temperature control; and data storage. It was useful for the investigation of cell science and tissue engineering. (STS-70, Shuttle/Mir-4, STS-85, Shuttle/Mir-8)

Experiment Control Computer (ECC): The ECC was designed to provide the computer control resources required for automated, long-duration cell science and tissue engineering investigations on orbit. The ECC provided interfaces for communication and control of experiment equipment, execution of experiment protocol, and recording and archiving of experiment data and equipment performance data. (STS-70, STS-85, Shuttle/Mir-7)

Forced Flow Flame Spreading Test: This Middeck Glovebox investigation studied the effects of low airspeed and bulk fuel temperature on flammability, ignition, flame growth, and flame spreading behavior on solid fuels in a microgravity environment. (USMP-3)

Gas Supply Module (GSM): The GSM delivered research-grade gases to the bioreactor and the ECC. This hardware housed and provided air, nitrogen, carbon dioxide, and other gases at required concentrations and pressures for long-duration, on-orbit cell culture and tissue engineering investigations. (Shuttle/Mir-4, Shuttle/Mir-8)

Gaseous Nitrogen (GN₂) Dewar Protein Crystal Growth Experiment Apparatus: The GN₂ dewar was a device capable of maintaining samples at cryogenic temperatures for about 13 days. Frozen liquid-liquid diffusion and batch protein crystal growth experiments were launched in the GN₂ dewar and then allowed to thaw to initiate the crystallization process in a microgravity environment. The GN₂ dewar housed a protein crystal growth insert that typically held approximately 200 protein samples. (*Mir*)

Geophysical Fluid Flow Cell: This instrument used electrostatic forces to simulate gravity in a radially symmetric vector field, centrally directed toward the center of the cell. This allowed investigations to perform visualizations of thermal convection and other research-related topics in planetary atmospheres and stars. (Spacelab-3, USML-2)

Interferometer for Protein Crystal Growth (IPCG): The IPCG was an apparatus designed to operate in the Microgravity Glovebox to measure details of how protein molecules move through a fluid and then form crystals. The IPCG comprised three major systems designed to produce images showing density changes in a fluid as a crystal forms: an interferometer, six fluid assemblies, and a data system. (Shuttle/Mir-7)

Isothermal Dendritic Growth Experiment Apparatus: This apparatus was used to study the growth of dendritic crystals in transparent materials that simulate the solidification of some aspects of pure metals and metal alloy systems. (USMP-2, USMP-3, USMP-4)

Lambda Point Experiment Apparatus: This apparatus provided temperature control in the part-per-billion range of a bulk helium sample near the superfluid transition at 2 K for testing the theory of critical phenomena under well-controlled static conditions. It flew in the Low-Temperature Platform. (USMP-1)

Mechanics of Granular Materials Experiment Apparatus: This instrument used microgravity to gain a quantitative understanding of the mechanical behavior of cohesionless granular materials under very low confining pressures. (Shuttle/Mir-4, Shuttle/Mir-8)

Microencapsulation Electrostatic Processing System: This was an automated system that formed multilayered, liquid-filled microcapsules containing pharmaceuticals. The unit automatically controlled fluid flows, recorded video of fluid interfaces as the microcapsules were formed, harvested the capsules, and used electrostatic deposition to apply a thin coating of an ancillary polymer. The system was also used for select fluid physics experiments. (STS-95)

Microgravity Glovebox: This was a modified Middeck Glovebox designed for *Mir* that enabled the collection of scientific and technological data prior to major investments in the development of more sophisticated scientific instruments. (*Mir*)

Microgravity Smoldering Combustion Apparatus: This apparatus was used to determine the smoldering characteristics of combustible materials in microgravity environments. (STS-69)

Middeck Glovebox: This apparatus was a multidisciplinary facility used for small scientific and technological investigations. (USMP-3, USMP-4, STS-95)

Orbital Acceleration Research Experiment Apparatus: This instrument was developed to measure very low-frequency accelerations on orbit such as atmospheric drag and gravity gradient effects. (Multiple missions)

Particle Engulfment and Pushing by a Solid-Liquid Interface: This Middeck Glovebox investigation studied the solid-liquid (freezing) interface as it moved, either pushing ahead of or engulfing suspended particles into a solid material. (USMP-4)

Physics of Hard Spheres Experiment Apparatus: This hardware supported an investigation to study the processes associated with liquid-to-solid and crystalline-to-glass phase transitions. (MSL-1)

Pool Boiling Experiment Apparatus: This apparatus was capable of autonomous operation for initiating, observing, and recording nucleate pool boiling phenomena. (Multiple missions)

Protein Crystallization Apparatus for Microgravity (PCAM): PCAM was used to evaluate the effects of gravity on vapor-diffusion protein crystal growth and to produce improved protein crystals in microgravity for the determination of molecular structures. Each PCAM cylinder contained nine crystallization trays, each with seven sample chambers, for a total of 63 chambers per cylinder. The total number of samples that could be flown in a Single-Locker Thermal Enclosure System (STES) unit was 378. (Seven shuttle flights)

Radiative Ignition and Transition to Spread Investigation: This Middeck Glovebox investigation studied the processes involved in the transition to fire growth with a particular kind of ignition source — radiative heating. The microgravity flame behavior was compared with predictions from three-dimensional numerical computations. (USMP-3)

Second-Generation Vapor-Diffusion Apparatus (VDA-2): The VDA-2 trays were protein crystal growth devices based on a syringe assembly design to provide mixing of protein and precipitant solutions in microgravity. A mixing chamber (third barrel) was added to the original double-barreled VDA syringes to improve mixing during activation of vapor-diffusion protein crystal growth flight experiments. An STES held four VDA-2 trays. Each VDA-2 tray had 20 sample chambers, for a total of 80 samples per STES. (Five shuttle flights)

Single-Locker Thermal Enclosure System: The STES replaced a single middeck locker and provided a controlled temperature environment within $\pm 0.5^\circ\text{C}$ of a set point in the range of 4–40° C. The STES housed a variety of protein crystal growth experiment apparatus, including DCAM, PCAM, and VDA-2. (10 shuttle flights)

Solid Surface Combustion Experiment Apparatus: This instrument was designed to determine the mechanism of gas-phase flame spread over solid fuel surfaces in the absence of buoyancy-induced or externally imposed gas-phase flow. (Multiple missions)

Space Acceleration Measurement System: This instrument measured and recorded the acceleration environment in the space shuttle middeck and cargo bay, in the Spacelab, in SPACEHAB, and on *Mir*. (Multiple missions)

Surface Tension-Driven Convection Experiment Apparatus: This apparatus was designed to provide fundamental knowledge of thermocapillary flows and fluid motion generated by surface tension and temperature gradients along a free surface. (USML-1, USML-2)

Transitional/Turbulent Gas Jet Diffusion Flames Experiment

Apparatus: This instrument was used to study the role of large-scale flame structures in microgravity transitional gas jet flames. (Get Away Special experiment)

Wetting Characteristics of Immiscibles: This Middeck Glovebox investigation studied the effects when two nonmixing alloys (immiscibles such as oil and water), which had been stirred and frozen in normal gravity, were melted and resolidified in microgravity. (USMP-4)

Experiment Hardware Flights to the International Space Station

Below are two lists of selected payloads for the International Space Station (ISS) and the associated EXPRESS (Expedite Processing of Experiments to Space Station) racks and microgravity facilities in the order of their flight to the station. Early on, microgravity research is limited to EXPRESS payloads and Microgravity Science Glovebox investigations, as reflected in the first list, which includes investigations currently manifested. The second list comprises payloads in development that are candidates for later flights. Future flights to the ISS with major significance to microgravity science are listed chronologically by launch date in **Table 12**.

Protein Crystal Growth — Enhanced Gases Nitrogen Dewar:

This apparatus is a GN₂ dewar that can maintain samples at cryogenic temperature for about 10 days. Frozen liquid-liquid diffusion and batch protein crystal growth experiments are launched in a dewar and then allowed to thaw to initiate the crystallization process in a microgravity environment. The dewar houses a protein crystal growth insert typically holding approximately 200 protein samples. (First flight: 5A; proposed future flight: 2A.2b)

Microgravity Acceleration Measurement System (MAMS):

MAMS provides quasi-steady state microgravity acceleration levels at low frequencies (0.01 to 2 Hz) with extreme accuracy. It is an enhanced version of the Orbital Acceleration Research Experiment space shuttle system. Using MAMS data, the microgravity level at any point in the U.S. Laboratory or on the ISS can be calculated using a transformation matrix and a known center of gravity for the station. (First flight: 6A)

Space Acceleration Measurement System, Second Generation (SAMS-II): The SAMS-II instrument will be an early addition to the ISS and will most likely remain onboard for the life of the station. SAMS-II will measure vibratory accelerations (transients) in support of a variety of microgravity science experiments. It will also characterize the ISS microgravity environment for future payloads. (First flight: 6A)

Protein Crystal Growth — Single Thermal Enclosure System (PCG-STES): The PCG-STES hardware is a single EXPRESS locker that provides a controlled temperature environment within $\pm 0.5^\circ\text{C}$ of a set point in the range from 4–40 $^\circ\text{C}$. The PCG-STES

houses a variety of protein crystal growth apparatus including VDA-2, DCAM, and PCAM. (First flight: 6A)

Protein Crystal Growth — Biotechnology Ambient Generic (PCG-BAG): This apparatus flies PCAM, DCAM, or VDA-2 hardware as ambient stowage items within a middeck locker or Cargo Transfer Bag. (First flight: 7A)

Vapor Diffusion Apparatus, Second Generation (VDA-2): VDA-2 uses the vapor diffusion method (hanging drop technique) for protein crystal growth in order to produce large, high-quality crystals of selected proteins. The 20 growth chambers need to be activated to start the process and deactivated to stop it. The PCG-STES holds four trays, the PCG-BAG holds six trays. (First flight: to be determined)

Diffusion-Controlled Crystallization Apparatus for Microgravity (DCAM): The DCAM system can use the liquid-liquid diffusion or dialysis method of protein crystal growth to produce high-quality single crystals of selected proteins. Three DCAM trays, each with 27 chambers, are flown per PCG-STES or PCG-BAG. (First flight: to be determined)

Protein Crystallization Apparatus for Microgravity (PCAM): PCAM uses the vapor-diffusion method to produce large, high-quality crystals of selected proteins. Each PCAM is a cylindrical stack of nine trays, each with seven chambers, to provide 63 chambers for protein crystal growth. The PCG-STES holds six cylinders; the PCG-BAG holds eight. (First flight: to be determined)

Physics of Colloids in Space (PCS): The PCS experiment hardware supports investigations of the physical properties and dynamics of formation of colloidal superlattices and large-scale fractal aggregates using laser light scattering. PCS advances understanding of fabrication methods for producing new crystalline materials. (First flight: 6A)

Dynamically Controlled Protein Crystal Growth (DCPCG): The DCPCG apparatus comprises three components: the control locker, the vapor locker, and the temperature locker. The command locker controls experiment processes in both the temperature and vapor lockers. It also collects data, performs telemetry functions, and is programmable from the ground. The vapor locker holds 40 protein samples; the temperature locker holds 50 protein samples. (First flight: 7A.1)

Lab Support Equipment — Digital Thermometer: This instrument is an off-the-shelf digital thermometer that will be used by ISS payloads to measure temperatures by utilizing a variety of thermocouple probes. (First flight: 7A.1)

Biotechnology Specimen Temperature Controller (BSTC): This apparatus will provide a platform for the study of basic cell-to-cell interactions in a quiescent cell culture environment and the role of these interactions in the formation of functional cell aggregates and tissues. BSTC will operate primarily in the incubation mode. The Biotechnology Refrigerator (BTR), Biotechnology Cell Science Stowage (BCSS), and the Gas Supply Module (GSM) support BSTC research. (First flight: 7A.1)

Pore Formation and Mobility: This investigation promotes understanding of detrimental pore formation and mobility during controlled directional solidification processing in a microgravity environment. This Microgravity Science Glovebox (MSG) investigation will utilize a transparent material, succinonitrile, so that direct observation and recording of pore generation and mobility during controlled solidification can be made. (First flight: first Utilization Flight (UF-1))

Glovebox Integrated Microgravity Isolation Technology (g-LIMIT): The g-LIMIT hardware was developed to provide attenuation of unwanted accelerations within the MSG; to characterize the glovebox acceleration environment; and to demonstrate high-performance, robust control technology. (First flight: UF-1)

Solidification Using a Baffle in Sealed Ampoules: This investigation will test the performance of an automatically moving baffle in microgravity and determine the behavior and possible advantages of liquid encapsulation in microgravity conditions. This low-cost MSG experiment will resolve several key technological questions and lessen the risk and uncertainties of using a baffle and liquid encapsulation in future major materials science facilities. (First flight: UF-1)

Rotating Wall Perfused System (RWPS): The RWPS apparatus will use the microgravity environment to investigate, support, and enhance the formation of three-dimensional functional tissue equivalents in a continuously perfused environment for tissue engineering and cell culture. RWPS will also be used to study models of cellular systems in order to understand cellular processes and investigate cellular adaptation to the space environment. The BTR, BCSS, and GSM will support RWPS research. (First flight: UF-2)

Interferometer for Protein Crystal Growth (IPCG): The IPCG is an apparatus designed to operate in the MSG in order to measure details of how protein molecules move through a fluid and then form crystals. The IPCG comprises three major systems designed to produce images showing density change in fluid as a crystal forms: an interferometer, six fluid assemblies, and a data system. (First flight: UF-2)

Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions (InSPACE): InSPACE hardware is being designed to be accommodated by the MSG. Observations of three-dimensional microscopic structures of magnetorheological fluids in a pulsed magnetic field will be made. (First flight: UF-2)

Coarsening of Solid-Liquid Mixtures-2: This MSG investigation is designed to obtain data on steady-state coarsening behavior of two-phase mixtures in microgravity. For the first time, coarsening data with no adjustable parameters will be collected and then directly compared with theory. This will allow a greater understanding of the factors controlling the morphology of solid-liquid mixtures during coarsening. (First flight: UF-2)

Microencapsulation Electrostatic Processing System (MEPS): Microencapsulation research in space has developed a new drug delivery system consisting of multilayered microcapsules. MEPS

is an automated system that forms multilayered, liquid-filled microcapsules containing pharmaceuticals. The unit will automatically control fluid flow, record video of fluid interfaces as the microcapsules are formed, and harvest the capsules. Electrostatic deposition is used to apply a thin coating on the microcapsules to make them less recognizable by immune cells in the blood stream. MEPS can also be used for select fluid physics experiments. (First flight: UF-1)

Payloads that are planned and/or in development that have not yet been manifested are listed below in alphabetical order.

Colloidal Disorder-Order Transition-2 Apparatus: This hardware fits in a glovebox and is used to photograph samples of dispersions of very fine particles as they form various crystalline or gel structures. This hardware was flown previously on USML-2 and STS-95.

Dynamic Studies of Cellular and Dendritic Interface Pattern Formation: This investigation is designed to provide a fundamental scientific understanding of cellular and dendritic microstructure formation under directional solidification conditions.

Glovebox Laser-Cooled Atomic Clock Experiment (GLACE): The GLACE investigation is designed to develop a laser-cooled cesium atomic space clock using a magneto-optic trap, highly stable lasers, vacuum systems, and a flywheel oscillator. GLACE will also measure the interaction properties of cesium at nanokelvin temperatures.

Laser Microscopy Module (LMM): The capabilities of this complex microscope will include video microscopy, white light illumination, image-analyzing interferometry, confocal microscopy, laser tweezers, and spectrophotometry. The first four experiments to use the LMM will be the Constrained Vapor Bubble experiment, the Physics of Hard Spheres-2 experiment, the Physics of Colloids in Space-2 experiment, and the Low-Volume Fraction Entropically Driven Colloidal Assembly experiment.

Observable Protein Crystal Growth Apparatus (OPCGA): The OPCGA flight investigation hardware comprises three major components: the mechanical system, the optical system, and the video data acquisition and control system. The OPCGA hardware also provides 96 individual experiment cells with the capability to collect optical data on 72 cells.

Primary Atomic Reference Clock in Space (PARCS): The PARCS investigation will measure various predictions of Einstein's Theory of General Relativity, including gravitational frequency shift and the local position invariance on the rate of clocks. PARCS will also achieve a realization of the second (the fundamental unit of time, which is tied to the energy difference between two atomic levels in cesium) at an order of magnitude better than that achievable on Earth.

Rubidium Atomic Clock Experiment (RACE): The RACE investigation will interrogate rubidium (^{87}Rb) atoms one to two orders of magnitude more precisely than Earth-based systems, achieving frequency uncertainties in the 10^{-16} to 10^{-17} range. RACE will

improve clock tests of general relativity, advance clock limitation, and distribute accurate time and frequency from the ISS.

Shear History Extensional Rheology Experiment (SHERE): SHERE hardware is being designed to be accommodated in the MSG. The experiment will measure the viscoelastic tensile shear stresses in monodisperse dilute polymer solutions while they are being rapidly stretched. An instrument called the Microfilament Extensional Rheometer will perform this measurement.

The following international payload is planned to be flown on the ISS.

Facility for the Study of Crystal Growth and of Fluids Near the Critical Point (DECLIC): The DECLIC facility is being developed by the French space agency (CNES) in cooperation with Glenn Research Center to provide an autonomous or teleoperated capability at middeck locker-scale to accommodate research on high-pressure samples of fluids near the critical point, transparent materials systems during solidification, and other fluids experiments that are compatible with available diagnostics. Through cooperative interagency agreements (negotiated but unsigned at the end of 1999), NASA will provide launch, integration, and resources for DECLIC and will share in the utilization of the facility.

Table 12 ISS Flights With Major Significance to Microgravity Science, Chronologically by Launch Date

Launch Date*	Flight	Vehicle	ISS Flight Designation	Milestone
Oct. 2000		S204	2R	Soyuz Vehicle: Three-Person Permanent International Human Presence Capability
Jan. 2001	STS-98	OV 104	5A	U.S. Laboratory Delivery
Feb. 2001	STS-102	OV 103	5A.1	U.S. Laboratory Outfitting — Delivery of International Standard Payload Racks
April 2001	STS-100	OV 105	6A	First Two EXPRESS Racks, Microgravity Capability
May 2001	STS-104	OV 104	7A	Phase 2 Complete — Delivery of Hyperbaric Airlock
June 2001	STS-105	OV 103	7A.1	U.S. Laboratory Outfitting, Two Additional EXPRESS Racks
Aug. 2001	STS-106	OV 105	UF-1	Utilization Flight — Continued U.S. Laboratory Outfitting, MSG Rack
Jan. 2002	STS-110	OV 105	UF-2	Utilization Flight — Continued U.S. Laboratory Outfitting, Fifth EXPRESS Rack
Oct. 2002	STS-118	OV 104	12A.1	Continued U.S. Laboratory Outfitting
Sept. 2003	STS-125	OV 103	1J	Japanese Experiment Module (JEM) Laboratory Delivery
Oct. 2003	STS-127	OV 104	UF-3	Utilization Flight — External Payload Pallet Delivery, Combustion Integrated Rack, and First Materials Science Research Rack (MSRR-1)
Jan. 2004	STS-128	OV 103	UF-4	Utilization Flight — External Payload and Added External Payload Pallet Delivery
Feb. 2004	STS-129	OV 105	2J/A	Delivery of the External Facility of the JEM
June 2004	STS-132	OV 105	UF-5	Utilization Flight — External Payload Pallet Delivery, Fluids Integrated Rack, X-Ray Crystallography Facility, and Sixth EXPRESS Rack
Oct. 2004	STS-135	OV 105	1E	European Space Agency (ESA) Laboratory Delivery
Jan. 2005	STS-136	OV 103	17A	Six-Person Life Support Capability, Seventh EXPRESS Rack
March 2005	STS-138	OV 104	19A	Transition to Six-Person Crew, Eighth and Final EXPRESS Rack

June 2005	STS-140	OV 105	UF-7	Utilization Flight — Centrifuge Accommodations Module Delivery
July 2005	STS-141	OV 104	UF-6	Utilization Flight — Laboratory Outfitting
Sept. 2005	STS-142	OV 103	16A	Delivery of Crew Habitation Module; Seven-Person Permanent Crew Capability; Biotechnology Facility; Fluids and Combustion Facility Shared Accommodations Rack; MSRR-2; MSRR-3

**Dates based on International Space Station Revision E DCN04 Interim Assembly Sequence*

Space Station Facilities for Microgravity Research

The Microgravity Research Program (MRP) continues to develop several multiuser facilities specifically designed for long-duration scientific research aboard the ISS. To obtain an optimal balance between science capabilities, costs, and risks, facility requirements definitions have been aligned with evolving space station capabilities. In total, the MRP has defined requirements for five multiuser facilities for the ISS: the Biotechnology Facility (BTF), the Fluids and Combustion Facility (FCF), the Low-Temperature Microgravity Physics Facility (LTMPF), the Materials Science Research Facility (MSRF), and the Microgravity Science Glovebox (MSG).

BTF

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

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

Biotechnology research during the early phases of the ISS will be conducted using a modular accommodations rack system known as the Expedite Processing of Experiments to Space

Station (EXPRESS) rack. The EXPRESS rack requires individual payloads to develop additional capabilities and involves science implementation trade-offs. The EXPRESS rack will hold currently existing equipment previously flown on the space shuttle and on *Mir*. It will also accommodate the first generation of equipment built specifically to meet space station requirements. The BTF is targeted to be operational in 2005.

FCF

The FCF is a modular, multiuser facility that will be permanently located in the U.S. Laboratory Module of the ISS to accommodate sustained, systematic microgravity experimentation in both the fluid physics and combustion science disciplines. The FCF flight segment consists of three powered racks and up to one rack of on-orbit stowage in the ISS. The powered racks are called the Combustion Integrated Rack (CIR), the Fluids Integrated Rack (FIR), and the Shared Accommodations Rack (SAR). These FCF racks will be incrementally deployed to the ISS, then fully integrated into the FCF system upon the arrival of the SAR. The three racks will operate together with payload experiment equipment, ground-based operations facilities, and the FCF ground segment to perform at least five fluids physics experiments and five combustion science experiments per year with available FCF and ISS resources. Owing to the modularity, capability, and flexibility of the FCF system, experiments from science disciplines outside of fluids and combustion, as well as commercial and international payloads, can also be supported by the FCF.

The FCF is being developed at Glenn Research Center (GRC). GRC in-house definition of the FCF concluded in fiscal year (FY) 1999, culminating in a successful preliminary design review of the CIR (the first FCF rack that will be deployed to the ISS) and a baseline of the science requirements envelope document. A request for industry proposals was released and proposals were evaluated by GRC in FY 1999 for the selection of a prime contractor to develop the FCF and its initial fluids and combustion payloads for the ISS. This Microgravity Research Development and Operations Contract will also support integration, operations, and fluids/combustion payload developments after the deployment of the FCF to the ISS and during steady-state operations.

Common design of CIR, FIR, and SAR subsystems was enhanced in FY 1999 to improve the performance and

cost-effectiveness of the FCF system and to facilitate shared use of facility capabilities by the fluids and combustion science disciplines. FCF science diagnostics were modularized to permit on-orbit reconfiguration, replacement, and shared use of FCF advanced imaging capabilities. These and other innovative solutions implemented in the FCF design resulted in the nomination of the FCF for NASA's Continuous Improvement Award in FY 1999. GRC also received a Federal Laboratories Technology Transfer Award in FY 1999 for successfully transferring to industry the FCF embedded web software, which was recognized as NASA Software of the Year in 1998.

Significant progress was also made in the definition of initial fluids and combustion payloads for the FCF in FY 1999. Payload developments were redirected toward multiuser apparatus that customize the FCF for experimentation in a given fluids or combustion subdiscipline. This approach lowers the cost of experiments and makes more efficient use of ISS resources by facilitating reuse of payload hardware for multiple experiments. A Multiuser Droplet Combustion Apparatus and Light Microscopy Module are currently on parallel development paths with the CIR and FIR, respectively, to accommodate a number of the initial combustion and fluids experiments planned for the FCF.

LTMPF

The LTMPF project saw a very busy year during which the facility's requirements definition review (RDR) was completed successfully and the authority to proceed was granted. The science requirements envelope document, the preliminary project plan, the project implementation plan, and the functional requirements document were all completed as was required to support the RDR. Trade studies have been ongoing in FY 1999 to further define the best facility configuration given cost, mass, and schedule constraints.

The current facility configuration is a single helium dewar with one probe insert that can support two or more experiments during each flight. An engineering model of the probe was developed and characterized. Shake tests of the probe with flight-like components from three candidate experiments have been scheduled for early next year.

A preliminary software requirements document has been completed and a prime candidate single-board computer and Ethernet interface circuit boards have been selected. These components will be radiation tested early next year. To maximize the program-wide benefits, the LTMPF project and the FCF project are jointly performing these radiation tests. This joint effort is resulting in large savings to both projects, greater investment from vendors supplying the test articles, and potential savings to many more ISS payload projects in the future.

A number of modifications to the ISS manifest in FY 1999 have resulted in a proposed launch delay for the first LTMPF mission from July 2003 to June 2004.

MSRF

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

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

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

NASA is currently developing the Quench Module Insert (QMI) and the Diffusion Module Insert (DMI) for the MSL. The QMI is a high-temperature Bridgman-type furnace with an actively cooled cold zone. The QMI is being designed to accommodate a rapid quenching capability. The DMI is a Bridgman-type furnace insert designed to accommodate processing temperatures up to 1,600° C. The requirements for this insert include precise control and the ability to operate in a mode with high isothermality. ESA is currently developing the Low Gradient Furnace (LGF)

and Solidification Quench Furnace (SQF) module inserts. The LGF is a Bridgman-Stockbarger furnace and is primarily intended for crystal growth experiments, providing for directional solidification processing with precise temperature and translation control. The SQF is being optimized for metallurgical experiments requiring large thermal gradients and rapid quenching of samples. Both of the ESA module inserts can accommodate processing temperatures up to 1,600° C. Additional module inserts can be developed and utilized over the lifetime of the MSL.

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

MSG

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

The MSG is being developed through an international agreement between NASA and the European Space Agency (ESA). In exchange for developing the MSG, the agreement provides ESA with early utilization opportunities in the facility without any exchange of funds between the two agencies. ESA's prime contractor for the MSG is Astrium. In FY 1999, the MSG project completed its critical design review. The MSG ground unit was shipped to Marshall Space Flight Center in September 1999. The MSG flight unit is tentatively scheduled to launch to the ISS in October 2001.

Ground-Based Microgravity Research Support Facilities

In FY 1999, NASA continued to maintain very productive ground facilities for reduced-gravity research. These facilities included KC-135 parabolic flight aircraft, a drop tower, the Zero Gravity Facility, a drop tube, and several other facilities. The reduced-gravity facilities at Glenn Research Center (GRC), Johnson Space Center (JSC), and Marshall Space Flight Center (MSFC) have supported numerous investigations addressing various processes and phenomena in several research disciplines. A state of apparent weightlessness, also known as microgravity, can be created in these facilities by executing a freefall or semi-freefall condition where the force of gravity on an object is offset by its linear acceleration during a "fall" (a drop in a tower or a parabolic maneuver by an aircraft). Even though ground-based facilities offer relatively short experiment times of up to 20 seconds, this available test time has been found to be sufficient to advance the scientific understanding of many phenomena. Also, many experiments scheduled to fly on the space shuttle and the International Space Station are tested and validated in the ground facilities prior to testing in space. Experimental studies in a low-gravity environment can enable new discoveries and advance the fundamental understanding of science. Many tests performed in NASA's ground-based microgravity facilities, particularly in the disciplines of combustion science and fluid physics, have resulted in exciting findings that are documented in a large body of literature.

JSC's **KC-135** is the primary aircraft for reduced-gravity research. The KC-135 can accommodate several experiments during a single flight. Low-gravity conditions can be obtained for approximately 20 seconds as the aircraft makes a parabolic trajectory. The trajectory begins with a shallow dive to increase air speed, followed by a rapid climb at up to a 50- to 55-degree angle. The low-gravity period begins with the pushover at the top of the climb and continues until the pullout is initiated when the aircraft reaches a 40-degree downward angle. During the parabola, an altitude change of approximately 6,000 feet is experienced. More than 50 parabolas can be performed in a single flight. In FY 1999, 42 experiments were performed during 2,401 trajectories over 134.2 flight hours.

The GRC **2.2-Second Drop Tower** offers a shorter test time than the KC-135, but its simple mode of operation and capability of performing several tests per day make it an attractive and highly utilized test facility, particularly for performing evaluation and feasibility tests. The drop tower is able to provide gravitational levels that range from 1 percent of Earth's gravitational acceleration to 0.01 percent. More than 18,995 tests have been performed in the drop tower to date. In FY 1999, as in the past several years, the number of drop tests conducted averaged more than 100 per month.

Reduced-gravity conditions in the drop towers are created by dropping an experiment in an enclosure known as a drag shield to isolate the test hardware from aerodynamic drag during a 24-meter freefall in an open environment. Seventeen experiments

were supported during the 1,355 drops performed in FY 1999. As in the past, several of these experiments were in support of the development of research that will be conducted in space. The steady utilization of the drop tower is expected to continue, as many new experiments are in the design and fabrication phases of development for the coming years.

The **Zero Gravity Research Facility** at GRC, a registered U.S. national landmark, provides a quiescent low-gravity environment for a test duration of 5.18 seconds as experiments are dropped in a vacuum chamber that goes 132 meters underground. Aerodynamic drag on the freely falling experiment is nearly eliminated by dropping in a vacuum. This procedure restricts drop tests to two per day, resulting in fewer projects supported in this facility than in the 2.2-Second Drop Tower. However, the relatively long test time and excellent low-gravity conditions more than compensate for the

lower test throughput rate. In FY 1999, five major projects were supported as 137 test drops were executed.

The **Drop Tube Facility**, located at MSFC, consists of sections of a stainless steel pipe with a 26-centimeter diameter vertically assembled into a tube 105 meters long. With air completely evacuated, the tube can produce freefall times of 4.6 seconds. Vacuum levels of less than a billionth of an atmosphere are achievable. The drop tube is especially useful for high-temperature material processing assays and experiments in droplet dynamics and engineering tests, such as the ones designed to yield results for the Tethered Satellite Mission. In FY 1999, two experiments were supported during 300 drops.

Table 13 summarizes activities at ground-based microgravity research facilities in FY 1999.

Table 13 Use of Ground-Based Low-Gravity Facilities in FY 1999

	KC-135	2.2-Second Drop Tower	Zero Gravity Facility	Drop Tube Facility
Number of investigations supported	42	17	5	2
Number of drops or trajectories	2,401	1,355	137	300
Number of flight hours	134.2	N/A	N/A	N/A

Getting the word out about what microgravity researchers do and why they do it is crucial to maintaining the strength and relevance of the science program. The Microgravity Research Program's (MRP's) outreach efforts are aimed at a broad audience that includes researchers who have not yet considered the benefits of conducting experiments in microgravity, industrial engineers and scientists, students in all grade levels, instructors and administrators in a variety of educational settings, and the lay public. Methods for communicating with these groups are also broad. Microgravity researchers and support personnel are involved in a number of outreach activities that include visiting classrooms, staffing exhibits at national conferences, offering tours and open houses at microgravity science facilities, and sponsoring student researchers at NASA research centers. In addition, print and World Wide Web (WWW) publications highlighting specific research projects allow the MRP to reach a worldwide audience.

In fiscal year (FY) 1999, more than 44,700 elementary and secondary school teachers and administrators attended annual meetings of the National Science Teachers Association, the National Council of Teachers of Mathematics, the International Technology Education Association, and the National Association of Biology Teachers, all of which featured booths staffed by MRP personnel. These major national educator conferences give NASA the opportunity to demonstrate new ways to teach students about the importance of microgravity research. Microgravity science and mathematics posters, teacher's guides, mathematics briefs, microgravity demonstrator manuals, microgravity mission and science lithographs, and WWW microgravity site sheets were distributed to teachers at these conferences.

In addition to these efforts, several new microgravity education products were developed and made available to educators in FY 1999. Two new NASA educational briefs were developed: *Microgravity — Fall Into Mathematics* and the *NASA Protein Crystallography Cookbook*. Efforts were increased in FY 1999 to make educators aware of all the microgravity research education products that are available online through MRP WWW pages, NASA Spacelink, and the NASA CORE (Central Operation of Resources for Educators) education distribution system.

The MRP's quarterly newsletter, *Microgravity News*, continues to reach thousands of K–12 teachers, curriculum supervisors, science writers, university faculty, graduate students, scientists, principal investigators, and technology developers. *Microgravity News* features articles on experiment results, flight missions, science and technology developments, research funding opportunities, meetings, collaborations, and microgravity science researchers. Distribution for each newsletter has grown to 10,800 copies, an increase from the 10,300 copies distributed last year. A rise has been seen in the number of individuals requesting to be added to the mailing list via e-mail submission to the address microgravitynews@msfc.nasa.gov. In addition, distribution of *Microgravity News* to public and private associations, corporations, laboratories, and educator resource centers continues to grow. The newsletter can also be accessed on the WWW at <http://mgnews.msfc.nasa.gov/site/>.

The Microgravity Research Program Office's (MRPO's) WWW home page at <http://microgravity.msfc.nasa.gov> provides regular updates on microgravity news highlights, information about upcoming conferences, microgravity-related research announcements, enhanced links to microgravity research centers, educational links, and links to the microgravity image archive. The newly developed Research Results web site at <http://mgnews.msfc.nasa.gov/site/resindex.html> features reviews of several successful benchmark microgravity flight experiments. A list of important microgravity WWW sites is presented in **Table 14**.

The MRP was represented to more than 25,000 attendees at Rensselaer Polytechnic Institute's (RPI's) Space Week activities in Troy, New York, April 5–12, 1999. During the week-long celebration of space, the MRP's exhibit was on display in the Rensselaer field house exhibit area. NASA Administrator Daniel Goldin was the keynote speaker for the event marking the 175th anniversary of RPI, NASA's 40th anniversary, and the 30th anniversary of the *Apollo* moon landing. Other conferences in FY 1999 at which exhibits and materials developed by Microgravity Outreach and Education staff were used include the American Association for the Advancement of Science conference; the National Manufacturer's Association conference; Georgetown University's Lombardi Cancer Center Gala; the American Society for Gravitational and Space Biology meeting; the American Public Health Association's conference; the American Association of Pharmaceutical Scientists conference; the International Space Station Utilization conference; the Biophysical Society's annual meeting; the Minerals, Metals, and Materials Society conference; the NASA Spacelab Forum; the Materials Research Society conference; the Society for Biomaterials conference; the American Crystallographic Association conference; the American Society of Mechanical Engineers conference; and the Experimental Aircraft Association's AirVenture '99 airshow.

Outreach and Education Highlights

Microgravity researchers and support personnel contributed their time and expertise to a number of successful outreach products and activities in FY 1999, including the following notable projects:

Public Outreach

- NASA bioreactor demonstrations and poster presentations of biotechnology cell science research were on display at Johnson Space Center's (JSC's) annual in-house activities. These activities included the Open House, where the public was invited to tour JSC facilities, and Inspection '99, which was aimed at showcasing technologies for educators and for business and industry audiences. JSC also provided exhibits in support of the MRPO and NASA headquarters at the National Association of Biology Teachers' conference, the meeting of the American Association for the Advancement of Science, and the American Institute of Aeronautics and Astronautics conference. Microgravity program research scientists jointly developed presentations for public audiences

on space life sciences in cooperation with Ames Research Center and a network of museums, planetariums, science and technology centers, and academic and commercial organizations. The Life Science Museum Partners Network was inaugurated and will cooperate with the Star Station One Foundation for similar presentations focused on the International Space Station (ISS).

- At the American Association for the Advancement of Science meeting in Anaheim, California, demonstrations of freefall, superconducting levitation, magnetostriction devices, a bioreactor, and atomic clocks highlighted the display representing the Office of Life and Microgravity Sciences and Applications' (OLMSA's) plans for scientific investigation on the ISS. Posters displayed the broad areas of science inquiry being carried out in the OLMSA program.
- Several microgravity scientists from the Jet Propulsion Laboratory (JPL) participated in the "Physics Is Fun Day" at Knott's Berry Farm in Buena Park, California. A drop tower display provided demonstrations on how fluids, flames, and mechanical devices perform differently when placed in freefall, intriguing the many students who visited the JPL display area.
- On October 10–11, 1998, Lewis Research Center (now Glenn Research Center [GRC]) held a public open house with 48,000 visitors in attendance. The MRP was represented in several ways. The Zero Gravity Facility housed a "Mission Specialist" activity for children; the Zero Gravity Facility, KC-135 parabolic aircraft, Telescience Support Center, ISS U.S. Laboratory module mock-up, and ISS Fluids and Combustion Facility racks were each open for tours; and several microgravity-related children's activities were included in DiscoveryFEST (Future Engineers and Scientists in Training) tents.
- The Microgravity Science Division was well-represented at the GRC name change ceremony in May 1999. The ceremony brought more than 200 children to the center. During their visit, the children used a variety of tools to investigate bubbles and soap films. The record "bubble on the table" had a diameter of 27 inches. Microgravity science mission lithographs, activity sheets, and lists of WWW sites (including bubble-related sites) were distributed to the children, teachers, and parents.
- The 1999 JPL Open House drew 55,000 visitors to the laboratory June 5–6, 1999. Volunteers from the microgravity fundamental physics program described the behavior of phenomena in microgravity using a mini drop tower; demonstrated methods used by investigators in the program, such as superconductor levitation, and described the process of developing flight apparatus and experiments for investigations in space.
- The cellular biotechnology program manager spoke to Discovery Channel viewers of the program *Science Live!* about some of the research that is being conducted with the NASA bioreactor. *Science Live!* highlights new developments

in various areas of science including space and spacecraft. The interview was conducted for the episode titled "*Science Live!* on Location at the Johnson Space Center," which aired November 3, 1999.

Reaching Out to Students and Educators

- Fourteen graduate students were selected to receive support for research to be performed during the 1999–2000 academic year through the Graduate Student Research Program (GSRP). The GSRP is a center-wide activity in which students from a national pool of applicants are selected to receive support for ground-based microgravity research. Graduate students also have the opportunity to conduct a portion of their research at a NASA facility. All selections were based on a competitive evaluation of academic qualifications, proposed research plans, and the student's projected use of NASA and/or other research facilities.
- The National Center for Microgravity Research on Fluids and Combustion (NCMRFC) has developed a brochure announcing up to three graduate assistantships per year that would provide full tuition at Case Western Reserve University (CWRU), a stipend for graduate study in the Department of Mechanical and Aerospace Engineering, and the opportunity to conduct research with NCMRFC scientists. Students may apply for an assistantship commencing in either the fall or spring semester. The brochure has been sent to a comprehensive list of engineering deans at universities across the United States and to a list of four-year historically black colleges and universities and other minority universities, and has been announced to Ohio's state-funded universities through a cooperative agreement with the Ohio Aerospace Institute. Three students are currently being supported at CWRU through this program.
- A number of educator workshops were conducted in FY 1999. A key feature of many of these workshops was the use of the Microgravity Demonstrator, a portable mini drop tower, to explain various aspects of microgravity research. The demonstrator has become a staple of the outreach program and continues to be frequently requested by educators. As an example of the effectiveness of the Microgravity Demonstrator as an outreach tool, in December 1998, GRC, in conjunction with NCMRFC, shipped a demonstrator unit to New York for the third annual Garcia Materials Research Science and Engineering Center Open House at Queens College. The demonstrator was seen by more than 300 students (mostly in grades 10 and 11) and 20 teachers during the open house. In addition, the demonstrator was used in several local high schools while out on loan. Proving that you're never too old to learn, GRC also used the Microgravity Demonstrator to explain microgravity research to residents of a local nursing home. Many high school physics teachers are using the Microgravity Demonstrator manual and videotape to build their own drop towers. The PDF version of the Microgravity Demonstrator manual, available through the NASA

Education Program's Spacelink web page at <http://spacelink.nasa.gov>, was downloaded by almost 1,000 users in FY 1999.

- Another key product of the MRP's K–12 education initiative is the *Microgravity Teacher's Guide*. This popular NASA educator's guide was downloaded from the Spacelink web site by over 159,000 users in FY 1999.
- Work was begun on a collaborative project between the NASA Microgravity Research Program and the International Technology Education Association (ITEA) to develop a microgravity technology curriculum guide. Representatives from ITEA and curriculum developers visited NASA's MRP field centers to gather ideas for the guide and to receive technical input on potential curriculum content. This effort represents NASA's first cooperative activity with ITEA and serves as a benchmark for other NASA Enterprise/ITEA cooperative activities. The curriculum guide is scheduled for completion in early FY 2000 and will be presented at the ITEA annual conference.
- Biotechnology research scientists volunteered their time to bring hands-on science activities to seven- to twelve-year-old children in JSC's "Sizzling Summer Camp" pilot program and at the annual "Bring Our Children to Work Day." Scientists also presented flight experiment photos and video to high school students and mentored NASA summer intern and co-op students. Two other scientists taught organic chemistry and space cell biology classes at local universities.
- A draft plan has been created for leveraging the resources of the Educator Resource Center (ERC) at JPL to train K–5 teachers in basic physics principles. That focus fills a critical need, as supplements for elementary-level curriculum and training support in physics and related mathematics are scarce.
- During the past year, JPL hosted three graduate students and 12 undergraduate students pursuing work in fundamental physics. JPL also contributed fundamental physics content to two NASA microgravity CD-ROMS.
- Through the California Institute of Technology Precollege Science Initiative (CAPSI), an inquiry-based curriculum unit on matter was developed for eighth-grade students. This curriculum unit is being tested in classrooms in Pasadena, California, to refine the subject matter and the teaching techniques. JPL is also beginning to work actively with the ERC and its Classroom of the Future.
- Especially popular with younger visitors to JPL in FY 1999 was a demonstration of a superconducting instrument called Mr. SQUID, in which a small hidden magnet swinging on a string was detected. Students, with the help of Mr. SQUID, were asked to guess which hand held the magnet.
- Student activities at JPL have resulted in numerous useful instructional devices, including a new stroboscopic apparatus to study drop collisions and a computer-interfaced compound pendulum for demonstrating deterministic chaos and showing the sensitivity of pendulum motions to initial conditions.
- A fall 1998 NCMRFC microgravity workshop for 19 middle school science and math teachers from Lakewood, Ohio, led to continuing involvement with several teachers. In May 1999, an NCMRFC K–12 representative visited Emerson Middle School and used the Microgravity Demonstrator and other tools to prepare teachers for their upcoming class trip to Cedar Point amusement park. NCMRFC staff then accompanied Emerson students on their field trip to the park to test microgravity amusement park physics materials. Lessons learned during the trip and pre-trip activities will be incorporated into the draft microgravity amusement park science guide.
- On November 21, 1998, 150 seventh- and eighth-grade girls and two teachers in the Stark County "EQUALS" workshop saw demonstrations that helped explain microgravity research. This event was designed to encourage middle school girls to stick with math and science by showing them positive role models.
- During National Chemistry Week in November 1998, representatives of the GRC Microgravity Science Division and NCMRFC provided demonstrations to high school students and members of the general public during a special weekend event at the Great Lakes Science Center. A variety of exhibits, including the Microgravity Demonstrator, were located in the atrium area of the science center so that visitors could participate in the demonstrations without having to pay museum admission. A presentation was made in the "Situation Room" about the STS-95 space shuttle mission following its landing earlier that day.
- Forty-five children toured the 2.2 Second Drop Tower during the 1999 "Bring Our Children to Work Day" at GRC. The children saw microgravity demonstrations and actual drops in the tower.
- A workshop to create a program for student involvement in a research flight experiment was conducted in February 1999 at the University of Alabama, Huntsville. Educators from across the United States, business representatives, and Marshall Space Flight Center representatives were in attendance. As a result of the meeting, science kits for growing the best possible crystals in space are being developed. Once the pilot program successfully demonstrates feasibility and incorporation of classroom lessons, it will be expanded to include all 50 states and other corporate sponsors. Twelve teacher workshops have been conducted to instruct educators on how to prepare and perform experiments in the classroom. Thirteen student/school visitations were conducted in which students prepared ground samples to be compared with future flight samples. The flight and ground samples will utilize the same crystallization conditions for a one-to-one comparison. Workshops were conducted in which high school students were certified to load flight samples using the flash-freezing technique of sample preparation. These students then prepared 123 flight samples.

- In March 1999, a set of seminars was presented to students at Andrews High School, a college preparatory school for girls in Willoughby, Ohio. Two teachers and 40 advanced placement physics and chemistry students from Andrews participated in a tour of GRC. At two of the four stops, the students were given a tour of the Zero Gravity Facility and learned about microgravity research while seeing the Microgravity Demonstrator in use.
- Three great minds of science — Galileo, Newton, and Einstein — are the subjects of a new NASA educational brief titled *Microgravity: Fall Into Mathematics*. This publication, developed by the NCMRFC K–12 Educational Program, provides mathematical challenges and has descriptions of different types of microgravity research platforms. The brief was developed to coincide with the debut of a new microgravity educational exhibit conceived by the NCMRFC and created by MRPO support personnel. Artwork from the educational brief was used for the first time at the April 1999 National Council of Teachers of Mathematics convention. The exhibit artwork and educational brief text are being modified to fit a poster format and will be available in spring 2000 under document number EW-2000-01-001-GRC.
- In summer 1999, the GRC Office of Educational Programs sponsored two NASA education workshops for teachers. During each of the two-week-long workshops, 25 teachers were treated to a “Microgravity Day,” which featured a gravity song, hands-on activities, and tours of facilities. NCMRFC summer teacher and student interns helped with Microgravity Day sessions and an associated egg drop competition. During the workshops, several teachers were mentored by microgravity personnel through day-long shadowing opportunities and full two-week guidance of urban school teams.
- NCMRFC received 27 applications to its Summer Internship Program. Twenty-one applicants were from Ohio, and the remainder were from Mississippi, New Jersey, New York, Puerto Rico, and West Virginia. NCMRFC also received 13 teacher applications: two from California, two from Indiana, one from Kansas, seven from Ohio, and one from South Carolina. The teacher applicants indicated their grade levels as follows: five high school teachers, six middle school teachers, one elementary school teacher, and one teacher doing post-graduate work. Selection of two students and one teacher was completed in April 1999. The two students spent half their time working in microgravity laboratories at GRC and the other half developing educational material that is available on the NCMRFC WWW site.
- In July 1999, six teachers from California, Maryland, Ohio, and South Carolina spent a week at the NCMRFC brainstorming ideas for a new K–4 microgravity activity guide. The teachers heard presentations about gravity and microgravity, crystal growth, fluids, combustion science, and sounding rockets. They participated in a live video tour of the ISS mock-up at JSC, toured and saw drops at the 2.2

Second Drop Tower and Zero Gravity Facility, saw the engineering model of the Combustion Integrated Rack, and participated in a number of hands-on activities. The teacher focus group developed a plethora of ideas for activities dealing with how microgravity conditions are created, density studies, crystal growth, how candles burn, buoyancy-driven convection, and other related topics. Some of the activities will be incorporated into elementary-level products under development at NCMRFC.

- On September 7, 1999, Kathy Higgins, of the Hudson, Ohio, school system, joined NCMRFC as the first teacher on sabbatical sponsored by the K–12 Educational Program. Higgins is an elementary school teacher who has taught first, second, and fifth grades. During her tenure at GRC, she will develop an early primary activity guide and help with educator workshops.

Outreach to the Science Community

- Almost 9,000 people visited NASA’s biotechnology program exhibit at the following seven conferences in FY 1999: the meeting of the American Association of Pharmaceutical Scientists, the American Crystallographic Association meeting, the American Society for Biochemistry and Molecular Biology meeting, the meeting of the Society for Biomaterials, the Biophysical Society conference, the INTERPHEX conference, and the meeting of the Protein Society.
- Cell science research in the NASA bioreactor was presented to officials of the Republic of Costa Rica during their visit to JSC. Throughout the year, representatives from Congress and other visitors to JSC were given laboratory tours, hardware demonstrations, and research highlights from both space- and ground-based research using the NASA bioreactor.
- JPL scientists supported JSC in staffing a NASA outreach booth at the Centennial American Physical Society meeting in Atlanta, Georgia. Displays highlighted research planned for the ISS. More than 11,000 physicists attended the meeting, and those visiting the booth were provided information about NASA-sponsored research opportunities in all of the microgravity disciplines.
- From November 1998 to June 1999, GRC and NCMRFC presented nine talks on fluid physics and transport phenomena delivered by eminent lecturers from universities across the country. The series was marketed to the microgravity fluid physics research community and to area industries through a brochure and mailing campaign. A significant accomplishment of the lecture series was 14.8 percent participation by industry and organizations external to GRC.

Industrial Outreach

- NCMRFC identified and surveyed principal investigators within the fluids and combustion research programs regarding current interactions with industry. Within the fluids research

program, interactions with 52 companies were identified, including five companies represented by current principal investigators (PIs) or co-investigators. Within the combustion research program, interactions with 56 companies were identified, including 11 companies represented by current PIs or co-investigators. The surveys helped identify promising applications areas for the program.

- NCMRFC formed an Industry Liaison Board as part of a major endeavor in its fundamental role of adding value to NASA's Microgravity Research Program in fluids and combustion. NCMRFC successfully recruited a 10-member board of key individuals (vice presidents of research and technology or their equivalents) across a broad spectrum of aerospace and nonaerospace organizations. The board is chaired by William Ballhaus Jr., vice president of science and engineering at Lockheed Martin Corporation. Companies represented on the board in FY 1999 were TRW, Inc.; the Eaton Corporation; the Cleveland Clinic Foundation; GE;

AlliedSignal, Inc.; Sandia National Laboratory; Sherwin Williams Company; Teledyne Continental Motors; and Ford Motor Company. The board is chartered to identify industry applications where microgravity fluids and combustion research is potentially relevant; evaluate current research for relevance to applications; and provide recommendations to enhance the program's value to industry.

- Ann Heyward, industrial outreach manager for NCMRFC, attended the American Society of Mechanical Engineers' (ASME's) Fluids Engineering Division Meeting July 19–22, 1999, in San Francisco, California, to participate in the meeting's Industry Exchange Program and the formation of the Coordinating Group for Industrial Technology (CGIT). This group is charged with developing ASME's Fluids Engineering Division's Industry Exchange Program for future meetings. Participation in the CGIT affords NASA the opportunity for additional industry contacts and exposure to industrial applications priorities in the fluids engineering arena.

Table 14 Important Microgravity WWW Sites

NASA Home Page

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

Microgravity Research Division Home Page

NASA headquarters' Microgravity Research Division and microgravity sites with links to news, other programs, and NASA Research Announcements.
<http://microgravity.hq.nasa.gov/>

Microgravity Research Program Home Page

Information about microgravity research activities with links to image archives and related science and technology web sites.
<http://microgravity.msfc.nasa.gov/>

Microgravity News Home Page

Online issues of *Microgravity News*, a quarterly newsletter about the field of microgravity science.
<http://mgnews.msfc.nasa.gov/site/newsindex.html>

Marshall Space Flight Center (MSFC) Home Page

Links to information about MSFC, the International Space Station, and research at MSFC's laboratories.
<http://www1.msfc.nasa.gov/>

Glenn Research Center (GRC) Home Page

Information on GRC and links to descriptions of special facilities, such as the Wind Tunnel Complex, the Propulsion System Laboratory, and drop towers.
<http://www.grc.nasa.gov/>

Jet Propulsion Laboratory (JPL) Homepage

Links to the latest news, status reports, and images from JPL's missions, as well as information about the laboratory at JPL.
<http://www.jpl.nasa.gov/>

Microgravity Combustion and Fluids Database

Information on microgravity combustion science, fluid physics, and acceleration measurement experiments and publications.
<http://microgravity.grc.nasa.gov/fcarchive/index.html>

Microgravity International Distributed Experiment Archives (IDEA) Database

Information on microgravity science experiments.
<http://mgravity.itsc.uah.edu/microgravity/idea/idea.stm>

European Space Agency (ESA) Microgravity Database

Experiment descriptions, results, diagrams, and video sequences.
<http://www.esrin.esa.it/htdocs/mgdb/mgdbhome.html>

Zero Gravity Research Facility

Description and images of one of the GRC drop towers.
<http://zeta.grc.nasa.gov/facility/zero.htm>

NASA Human Spaceflight

A comprehensive source for information on NASA's spaceflight programs that support the Human Exploration and Development of Space Enterprise.
<http://spaceflight.nasa.gov/index-n.html>

Shuttle Flights

Information on the most recent mission with links to all shuttle flights to date.
<http://spaceflight.nasa.gov/shuttle/index.html>

International Space Station

General and detailed information about the development of the International Space Station, including links to recent news, details of assembly, and images.
<http://spaceflight.nasa.gov/station/index.html>

Understanding Gravity and Microgravity

The definition of microgravity and how it is achieved, with links to microgravity science disciplines.

<http://microgravity.msfc.nasa.gov/wimg.html>

NASA Spacelink: A Resource for Educators

NASA education information, materials, and services.

<http://spacelink.nasa.gov/>

Spacelink: Microgravity Teacher's Guide

Microgravity Teacher's Guide with physical science activities for grades 6–12.

<http://spacelink.nasa.gov/Instructional.Materials/NASA.Educational.Products/Microgravity/>

Spacelink: Mathematics of Microgravity

Mathematics of Microgravity Guide identifying the underlying mathematics and physics principles that apply to microgravity.

<http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Physical.Science/Microgravity/Mathematics.of.Microgravity/index.html>

Spacelink: Microgravity-Fall Into Mathematics

The great minds of microgravity — Galileo, Newton, and Einstein — are the subjects of this NASA Educational Brief.

<http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/>

[Physical.Science/Microgravity/Microgravity-Fall.Into.Mathematics/index.html](http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Physical.Science/Microgravity/Microgravity-Fall.Into.Mathematics/index.html)

Spacelink: Microgravity Demonstrator

The Microgravity Demonstrator is a tool designed by NASA engineers to demonstrate and teach principles of microgravity science and relationships to science and math. The manual provides instructions for building a microgravity demonstrator and includes classroom activities.

<http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Physical.Science/Microgravity/Microgravity.Demonstrator/index.html>

Spacelink: Microgravity Video Resource Guide

This video resource guide contains background material and classroom activities dealing with the five scientific disciplines in NASA's microgravity research program.

<http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Physical.Science/Microgravity/Microgravity.Video.Resource.Guide/index.html>

Microgravity Meetings and Symposia

Bulletin board of meetings, conferences, and symposia and a list of societies and web sites of interest to the microgravity science community.

<http://zeta.grc.nasa.gov/ugml/ugml.htm>

8 For More Information

NASA's goal is to improve the quality of life on Earth by using ground- and space-based research to promote new scientific and technological discoveries. The Microgravity Research Program plays a vital role in our nation's economic and general health by carefully selecting, funding, and supporting scientists across the country. It also serves as an important link in the international endeavors that are the hallmark of America's space program, which is conducting business better, cheaper, and faster through cooperative ventures and other streamlined practices.

By disseminating knowledge and transferring technology among private industries, universities, and other government agencies, NASA's Microgravity Research Program continues to build on a foundation of professional success, evidenced by the number of publications and conferences attended, while reaching out to encompass the populace at large. Educational outreach and technology transfer are among the program's top goals, making the benefits of NASA's research available to the American public. Space shuttle and *Mir* research missions, as well as experiments performed in short-duration microgravity facilities, are yielding new understanding about our world and the universe around us, while paving the way for long-duration microgravity science on the International Space Station.

For more information about NASA's Microgravity Research Program, use the following contact information:

Microgravity Research Division

NASA Headquarters

300 E Street, S.W.

Washington, D.C. 20546-0001

Fax: (202) 358-3091

Phone: (202) 358-1490

World Wide Web address:

<http://microgravity.hq.nasa.gov/>

<http://microgravity.msfc.nasa.gov/>

Funding for the Microgravity Research Program in fiscal year (FY) 1999 totaled \$183.9 million. This figure includes the Microgravity Research Program budget of \$113.7 million and \$70.2 million of the Office of Space Flight's budget, which is allocated for International Space Station (ISS) utilization and facilities. These funds supported a variety of activities across the microgravity science disciplines of biotechnology, combustion science, fluid physics, fundamental physics, and materials science, including an extensive ground-based research and analysis program; development and flight of microgravity space shuttle and sounding rocket missions; planning and 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 1999 Microgravity Funding Distribution by Science Discipline

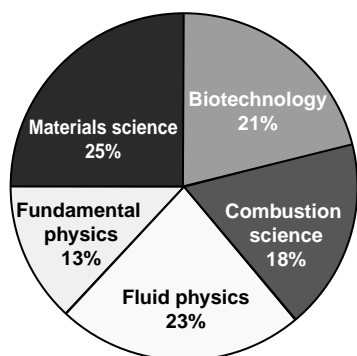
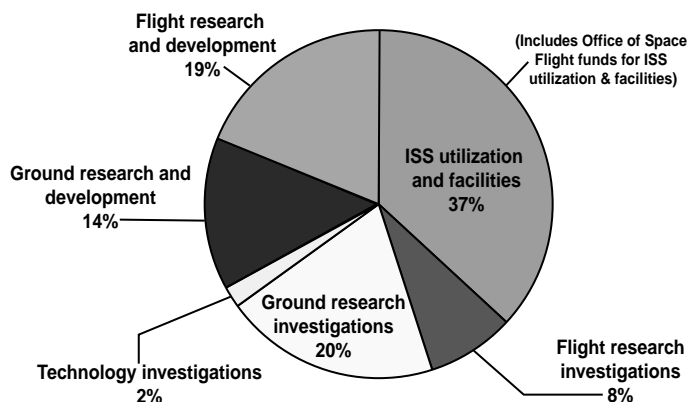


Figure 2 presents funding in support of ISS mission planning, development of ISS technology and hardware, development of flight- and ground-based research projects, execution of flight and ground investigations, and development of technology to support those investigations.

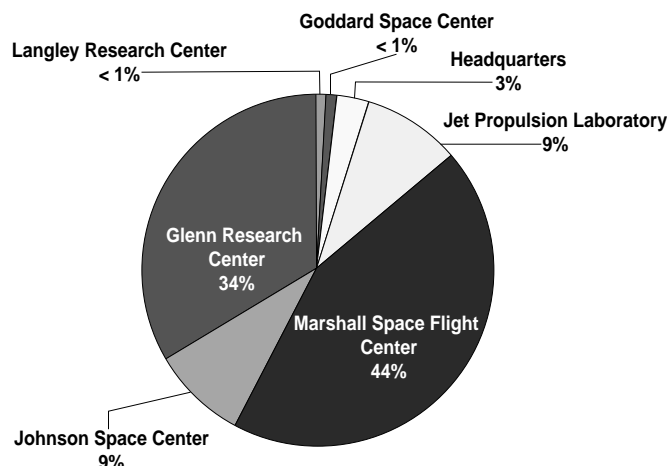
Figure 2 — FY 1999 Microgravity Funding by Mission Function



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

- Glenn Research Center — combustion science, fluid physics, and microgravity measurement and analysis.
- Jet Propulsion Laboratory — fundamental physics and advanced technology development.
- 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 glove-box program.

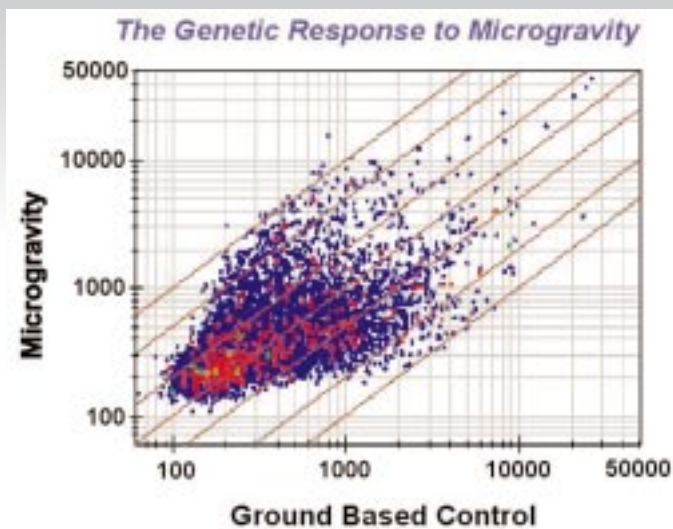
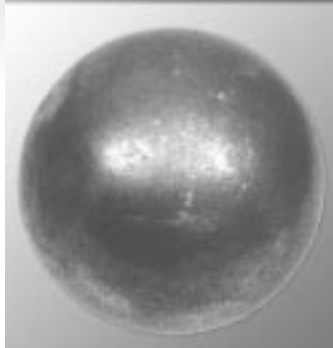
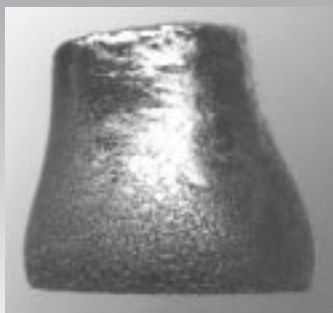
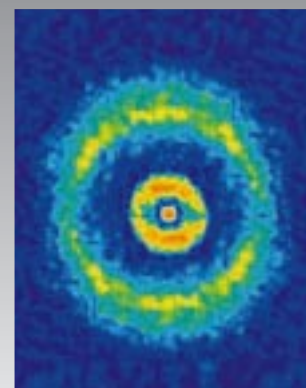
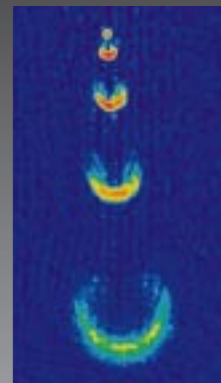
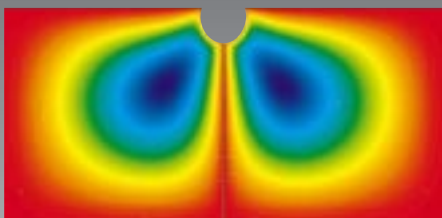
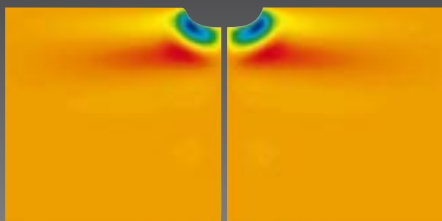
Figure 3 — FY 1999 Microgravity Funding Distribution by NASA Field Centers



10 Acronyms and Abbreviations

ACA	American Crystallographic Association	ERC	Educator Resource Center
APS	American Physical Society	ERE	Extensional Rheology Experiment
ASM	American Society for Metals	ESA	European Space Agency
ASME	American Society of Mechanical Engineers	ESL	Electrostatic Levitator
ATD	Advanced Technology Development	EXPRESS	Expedite Processing of Experiments to Space Station
atm	atmosphere	FCF	Fluids and Combustion Facility
BCDCE	Bi-Component Droplet Combustion Experiment	FEANICS	Flow Enclosure Accommodating Novel Investigations in Combustion of Solids
BCSS	Biotechnology Cell Science Stowage	FIR	Fluids Integrated Rack
BRS	Bioproduct Recovery System	FIST	Flammability Diagrams of Combustible Materials in Microgravity
BSTC	Biotechnology Specimen Temperature Controller	FY	fiscal year
BTF	Biotechnology Facility	GAS	Get Away Special
BTR	Biotechnology Refrigerator	GLACE	Glovebox Laser-Cooled Atomic Clock Experiment
BTS	Biotechnology System	g-LIMIT	Glovebox Integrated Microgravity Isolation Technology
BUNDLE	Bridgman Unidirectional Dendrite in a Liquid Experiment	GMSF	Growth and Morphology of Supercritical Fluids
CAPSI	Caltech Precollege Science Initiative	GN₂	Gaseous Nitrogen
CEA	Carcinoembryonic antigen	GRC	Glenn Research Center
CGH	Coupled Growth in Hypermonotectics	GSFC	Goddard Space Flight Center
CGIT	Coordinating Group for Industrial Technology	GSM	Gas Supply Module
ChEx	Confined Helium Experiment	GSRP	Graduate Student Research Program
CIR	Combustion Integrated Rack	HOST	Hubble Space Telescope Orbital Systems Test
CNES	French space agency	HRT	high-resolution thermometer
COLLIDE	Collisions Into Dust Experiment	ICR	investigation continuation review
CORE	Central Operation of Resources for Educators	ICU	Interim Control Unit
COSPAR	Committee on Space Research of the International Council of Scientific Unions	IDEA	International Distributed Experiment Archives
CSA	Canadian Space Agency	IEEE	Institute of Electrical and Electronics Engineers
CSLM	Coarsening in Solid-Liquid Mixtures	IFFD	Internal Flows in a Free Drop
CVX	Critical Viscosity of Xenon	IML	International Microgravity Laboratory
CWRU	Case Western Reserve University	InSPACE	Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions
DCAM	Diffusion-Controlled Crystallization Apparatus for Microgravity	IPCG	Interferometer for Protein Crystal Growth
DCE	Droplet Combustion Experiment	ISRU	In-Situ Resource Utilization
DCPCG	Dynamically Controlled Protein Crystal Growth	ISS	International Space Station
DDCE	Dynamics of Droplet Combustion and Extinction Experiment	ITEA	International Technology Education Association
DECLIC	Facility for the Study of Crystal Growth and of Fluids Near the Critical Point	JPL	Jet Propulsion Laboratory
DLR	German Aerospace Research Establishment	JSC	Johnson Space Center
DMI	Diffusion Module Insert	KSC	Kennedy Space Center
ECC	Experiment Control Computer	LGF	Low Gradient Furnace
EDU	Engineering Development Unit		
ELF	Enclosed Laminar Flames		

LMM	Laser Microscopy Module	PCS	Physics of Colloids in Space
LMS	Life and Microgravity Spacelab	PECASE	Presidential Early Career Award for Scientists and Engineers
LTMPF	Low-Temperature Microgravity Physics Facility	PEP	Particle Engulfment and Pushing by a Solid/Liquid Interface
MAMS	Microgravity Acceleration Measurement System	PI	principal investigator
MDCA	Multiuser Droplet Combustion Apparatus	PIMS	Principal Investigator Microgravity Services
MEPS	Microencapsulation Electrostatic Processing System	QMI	Quench Module Insert
MGM	Mechanics of Granular Materials	RACE	Rubidium Atomic Clock Experiment
MISTE	Microgravity Scaling Theory Experiment	RDR	requirements definition review
MIT	Massachusetts Institute of Technology	REEFS	Radiative Enhancement Effects on Flame Spread
MRD	Microgravity Research Division	RPI	Rensselaer Polytechnic Institute
MRP	Microgravity Research Program	RTS	Remote Triaxial Sensor
MRPO	Microgravity Research Program Office	RWPS	Rotating Wall Perfused System
MRS	media reclamation system	SAMS	Space Acceleration Measurement System
MSFC	Marshall Space Flight Center	SAMS-FF	Space Acceleration Measurement System for Free Flyers
MSG	Microgravity Science Glovebox	SAR	Shared Accommodations Rack
MSL	Microgravity Science Laboratory	SCR	science concept review
MSRF	Materials Science Research Facility	SHERE	Shear History Extensional Rheology Experiment
MSRR	Materials Science Research Rack	SIBAL	Solid Inflammability Boundary at Low Speed
MTH	metallothionein	SL	Spacelab
NAE	National Academy of Engineering	SQF	Solidification Quench Furnace
NASDA	Japanese space agency	SSPF	Space Station Processing Facility
NCMRFC	National Center for Microgravity Research on Fluids and Combustion	STEP	Satellite Test of the Equivalence Principle
NIH	National Institutes of Health	STES	Single-Locker Thermal Enclosure System
NRA	NASA Research Announcement	STS	Space Transportation System
NRC	National Research Council	SUE	Superfluid Universality Experiment
NIST	National Institute of Standards and Technology	TIGER-3D	Transition From Ignition to Flame Growth Under External Radiation in Three Dimensions
NMR	nuclear magnetic resonance	TMS	Minerals, Metals, and Materials Society
OARE	Orbital Acceleration Research Experiment	UAB	University of Alabama, Birmingham
OLMSA	Office of Life and Microgravity Sciences and Applications	UCI	University of California, Irvine
OPCGA	Observable Protein Crystal Growth Apparatus	UF	Utilization Flight
PARCS	Primary Atomic Reference Clock in Space	USML	United States Microgravity Laboratory
PCAM	Protein Crystallization Apparatus for Microgravity	USMP	United States Microgravity Payload
PCG-BAG	Protein Crystal Growth — Biotechnology Ambient Generic	USRA	Universities Space Research Association
PCG-STES	Protein Crystal Growth — Single Thermal Enclosure System	VDA	Vapor-Diffusion Apparatus
		WWW	World Wide Web



In the microgravity environment of space, the effects of Earth's gravity are dramatically reduced, allowing scientists to pursue research not possible in ground-based laboratories.

NASA'S MICROGRAVITY RESEARCH PROGRAM



National Aeronautics
and Space Administration

Microgravity Research Division

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