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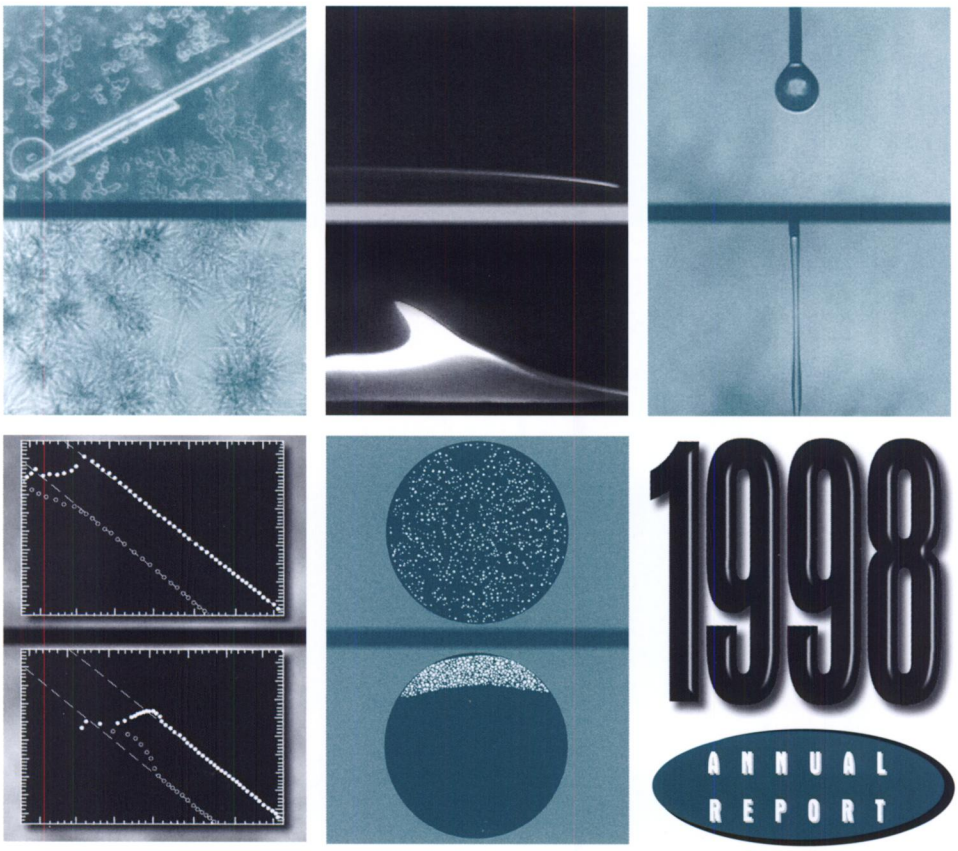
NASA'S MICROGRAVITY RESEARCH PROGRAM



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

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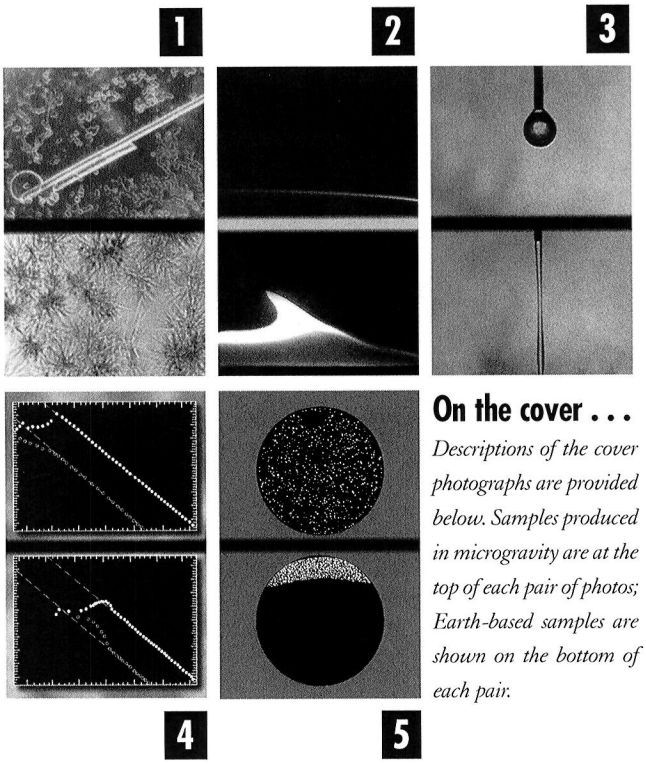
NASA'S MICROGRAVITY RESEARCH PROGRAM

1998 ANNUAL REPORT

NASA/TM–1999-209757

National Aeronautics and
Space Administration

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



On the cover . . .

Descriptions of the cover photographs are provided below. Samples produced in microgravity are at the top of each pair of photos; Earth-based samples are shown on the bottom of each pair.

1 Biotechnology

Understanding the structure of the protein raf kinase is important for cancer research. When grown in microgravity (top), the protein forms long, thin crystals that are approximately an order of magnitude larger than the small, needle-like crystals grown on Earth (bottom). Large, uniform crystals generally yield better structural information when analyzed through X-ray diffraction, which in turn can lead to a better understanding of how the structure of a protein is related to its function in the human body.

2 Combustion Science

Research on flame spread across pools of liquid fuel reveals numerous differences in flame spread behavior in microgravity when compared with ground-based experiments. In microgravity (top), flame spread is much slower and steadier than in Earth's gravity, and much of the flame is dimmer with no apparent soot or plume. In Earth's gravity (bottom), the flame spread has a pulsating character, and the flame advances in a fast/slow periodic motion. The effect of buoyancy in the gas phase of the normal-gravity sample can be seen in the soot-filled plume that develops in the trailing portion of the flame.

3 Fluid Physics

In Earth's gravity, when a stream of liquid emitted from a downward pointing nozzle is perturbed at a given frequency, the stream begins to waver, creating wave-like undulations at the surface. The 1 g photo (bottom) shows the undulations in a stream of silicon oil. Generally, this process occurs in microgravity as well; however, for low enough flow rates in microgravity, an absolute instability occurs in which streaming ceases altogether. This absolute instability is shown by the growing drop of liquid in the microgravity sample (top). The liquids in both photos are flowing at the same low rate. A theory has been developed to predict when this absolute instability will occur for any given fluid; the theory can be used for jet stream applications in space.

4 Fundamental Physics

Making a substance thinner and thinner will eventually change the properties of the material. This is called the finite size effect and is an important area of study for physicists. This effect is best studied in microgravity using liquid helium. Data obtained in ground-based studies (bottom) show a helium sample's ability to retain heat and suggest that the level of heat retention is much lower than it actually is. This is because gravity makes it impossible to reach the region dominated by finite size effects. Measurements made in microgravity (top), show a much higher level of heat retention. The filled circles in the graphs represent measurements above the superfluid transition in helium. The open circles represent measurements below the transition. The superfluid transition in helium is analogous to the superconducting transition in other materials.

5 Materials Science

Theories of coarsening in solid-liquid mixtures dictate that the larger particles in such a mixture will grow at the expense of the smaller particles, which decrease in size, while the total number of particles in the mixture decreases. This phenomenon occurs in metallurgical systems, such as the high-temperature materials used in turbine blades, and degrades the strength of alloys. Researchers studying coarsening behavior in microgravity are able to greatly reduce the effects of gravity, which causes sedimentation to occur in ground-based studies. In the cross section photos of samples containing tin particles, sedimentation is evident in the ground-based study (bottom), where all of the tin particles have risen to the top of the sample; in the microgravity sample (top), the particles are evenly dispersed.

Executive Summary

Program Goals for FY 1998

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 other 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 oversees investigations in fundamental physics and is responsible for microgravity advanced technology development and transfer activities; Johnson Space Center in Houston, Texas, which manages the cell and tissue culture portion of the biotechnology discipline; Glenn Research Center in Cleveland, Ohio, which supervises 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 studies in the biotechnology and materials science disciplines and is responsible for the microgravity glovebox program. The MRP's goals for fiscal year (FY) 1998 are listed below:

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 the 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 measures, allowing more 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 missions and goals statements. In FY 1998, the MRP initiated the task of developing performance goals that support the MRP's mission statement. The mission statement is as follows:

- 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.
- 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's performance goals were finalized in FY 1998 in fulfillment of Congress' mandate and will be used in FY 1999 and FY 2000 to assess the program's progress. The MRP annual report for FY 1999 will include information about that assessment.

Program Approach

To meet these goals, the MRP focused in FY 1998 on providing its researchers with opportunities to perform their experiments in microgravity facilities on Earth and in space. The fourth United States Microgravity Payload mission (USMP–4), the last scheduled dedicated microgravity science mission to be carried on the space shuttle, flew in FY 1998 carrying microgravity combustion science, fundamental physics, and materials science experiments onboard. Work was also completed in preparation for STS-95, a multidisciplinary research mission launched in late October 1998 with astronaut John Glenn aboard. Microgravity experiments in biotechnology and fluid physics were selected to fly on this mission. FY 1998 also marked the completion of the last stay of an American astronaut aboard the Russian Space Station *Mir* as part of Phase I of the International Space Station (ISS). Phase I provided NASA with invaluable experience in living and working for long periods in a microgravity environment and with the opportunity to gain experience in carrying out microgravity experiments in a space station laboratory.

In anticipation of the close of the NASA/*Mir* program and the last scheduled opportunities for dedicated microgravity missions on the space shuttle for some time to come, the MRP shifted its emphasis in FY 1998 to the use of short-duration microgravity facilities (sounding rockets, KC-135 aircraft, drop towers and tube). This shift was made in an effort to maintain the access to microgravity environments needed by researchers while the space shuttle, which has been the primary vehicle for performing experiments in microgravity, is engaged in assembly flights for the ISS. The MRP also worked to prepare for the deployment of microgravity facilities to the ISS by developing utilization plans and a schedule for the first Microgravity Research Division–funded research that will be conducted on the station. The first utilization of the ISS for microgravity experiments is scheduled for early 2000.

Program Highlights in FY 1998

In FY 1998, the MRP continued to solicit and select new research proposals as well as support ongoing research projects. Proposals from the 1997 biotechnology and combustion science NASA Research Announcements (NRAs) were selected for funding, and NRAs soliciting proposals in fluid physics and materials science were prepared and released. Research chosen from these NRAs will form the core of the program at the beginning of the ISS era. The approximately $100.4 million FY 1998 research budget supported ongoing research projects headed by 377 principal investigators. Results from these projects were published in 683 journal articles and addressed in 823 technical presentations. (Refer to the "Introduction" section of this report for more details.)

The release of the National Research Council's review of microgravity research in support of NASA's Human Exploration and Development of Space (HEDS) Enterprise confirmed that microgravity research has an important role to play in the success of future exploration missions. Research focused on developing technologies to support exploration missions to the Moon and Mars continues to be a priority of the program. Projects are underway in this area, and proposals addressing these issues are encouraged in recent and upcoming NRAs.

Eight microgravity investigations were conducted during the flight of USMP–4, which was launched on November 19, 1997. This 16-day mission hosted microgravity experiments in combustion science, fundamental physics, and materials science. The mission produced groundbreaking results concerning the effects of confinement on the properties of materials and the first video images of dendrites forming in microgravity. For more details about these results, please see the Confined Helium Experiment in the "Fundamental Physics" section of this report and the Isothermal Dendritic Growth Experiment in the "Materials Science" section.

Five microgravity experiments in biotechnology, fluid physics, and acceleration measurement were prepared for flight on the multidisciplinary mission STS-95, which launched in early

FY 1999. Two experiments investigating the behavior of colloidal systems (suspensions of solid particles in a fluid) were part of the mission. The second Colloidal Disorder-Order Transition (CDOT-2) experiment revealed new information about the physics of crystallization, and the second Colloidal Gelation (CGEL-2) experiment investigated three different kinds of colloidal systems to compare their behaviors in microgravity. For more details about CDOT-2 and CGEL-2, see the "Fluid Physics" section of this report.

The NASA/*Mir* program hosted eight experiments in biotechnology in FY 1998. A single instrument known as the Diffusion-Controlled Apparatus for Microgravity accommodated 324 protein samples for crystallization during flight. On the cell science side of the biotechnology discipline, an experiment in which rat renal cells were cultured helped to verify the function of two new equipment units, a cell incubator and a refrigerator, and helped researchers to better understand the mechanisms behind the expression of hormones important in the treatment of kidney diseases. For more details on these and other experiments flown on *Mir*, see the "Biotechnology" section of this report.

In January 1998, 15 of the international partners in the development of the ISS signed new intergovernmental agreements establishing a framework for the assembly of the ISS over the next five years. Meetings of international collaborators in the microgravity programs of several of the participating nations were aimed at continuing the work of establishing joint development and utilization plans for microgravity facilities on the station. The group of participants, known as the International Microgravity Strategic Planning Group, will help to ensure that the right capabilities will be available for performing the widest range of experiments on the space station with a minimum of overlap in facility development by the individual partner nations.

The MRP continued its cooperation in FY 1998 with other federal agencies including the National Institutes of Health (NIH) and the Food and Drug Administration (FDA). In cooperation with the NIH, NASA has produced the first *in-vitro* culture system that permits the study of the disease cycle of HIV in human lymphoid tissue. Work with the FDA through an interagency agreement is enabling the use of NASA-developed novel fiber-optic probe technology to study the ocular effects of diabetes. Researchers hope to develop techniques for early detection of the disease and methods for combating its adverse effects on human eyesight. For more details on these activities, see the "Biotechnology" and "Fluid Physics" portions of this report.

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 1998:

- *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 over 10,300 copies in calendar year 1998.
- Through NASA's Graduate Student Research Program, 13 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 39,000 elementary and secondary school teachers and administrators in attendance at annual meetings of science, technology, and mathematics teachers' associations.

For details on these and other education and outreach activities, refer to the "Education and Outreach" portion of this report.

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Introduction 1

This fiscal year (FY) 1998 annual 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 1998 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 1998, plans for utilization of the research potential of the International Space Station, technology development, and various educational/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 1 summarizes information from the *Microgravity Science and Applications Program Tasks and Bibliography for FY 1998* that may be of particular interest to the reader. Data for FY 1994–1997 are shown for comparison with FY 1998 statistics.

Table 1 FY 1994–1998 Research Task Summary: Overview Information and Statistics
(includes some continuing projects at no additional cost)

	FY 1994	FY 1995	FY 1996	FY 1997	FY 1998
Number of principal investigators	243	290	358	329	377
Number of co-investigators	252	287	396	375	446
Number of research tasks	316	347	508	414	465
Total number of bibliographic listings	944	1,200	1,573	1,428	1,868
■ Proceeding papers	145	140	237	177	305
■ Journal articles	371	526	600	576	683
■ NASA technical briefs	13	11	14	10	31
■ Science/technical presentations	391	509	706	647	823
■ Books/chapters	24	14	16	18	26
Number of patents applied for or awarded	1	1	2	4	8
Number of students funded	434	534	780	748	853
Number of degrees granted based on MRD-funded research	125	178	247	243	277
Number of states with funded research (including District of Columbia)	36	34	35	36	36
FY MRD Budget ($ in millions)	188	163.5	159	105.3	100.4

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 1998*, available online at *http://peer1.idi.usra.edu/peer_review/taskbook/micro/mg98/mtb.CFM*. Detailed information on the research tasks funded by the MRD during FY 1998 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 2 lists the number of research tasks and types performed at each NASA center for FY 1994–1998.

Table 2 Microgravity Research Tasks and Types by Fiscal Year
(responsibilities by center)

Center	Ground					Flight					ATD*					Center Totals				
	94	95	96	97	98	94	95	96	97	98	94	95	96	97	98	94	95	96	97	98
Jet Propulsion Laboratory	27	28	45	23	42	7	5	7	5	9	3	3	3	3	3	37	36	55	31	54
Johnson Space Center	10	34	32	42	37	0	1	1	1	1	0	0	1	1	1	10	35	34	44	39
Lewis Research Center	131	125	203	137	152	35	32	46	40	44	5	6	6	7	6	171	163	255	184	202
Marshall Space Flight Center	62	76	124	117	127	25	25	32	31	39	4	6	4	5	3	91	107	160	153	169
Research Task Totals	233	266	406	319	358	69	65	87	78	93	13	16	15	17	13	315	347	508	414	464

*Advanced Technology Development

2 Microgravity Research Conducted in FY 1998

In fiscal year (FY) 1998, 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 1998 are presented below.

Biotechnology *Overview*

Biotechnology research manipulates biological molecules, tissues, and living organisms to obtain products or perform specific functions. Research conducted in microgravity allows scientists to greatly reduce the effects of gravity, which can adversely impact experiment results. NASA's microgravity biotechnology program addresses major areas that support NASA's exploration goals, the application of NASA technology to terrestrial commercial and biomedical entities, investigation of the adaptation of terrestrial life to the space environment, and research aimed at understanding the effects of microgravity on biological processes. The microgravity biotechnology program investigates the use of low gravity in protein crystal growth (PCG) and in cell science as it relates to tissue engineering. PCG researchers grow protein crystals and other biological molecules and assemblies, such as DNA, RNA, and viruses, to provide materials for high-resolution structural analysis by X-ray diffraction and to understand the basis for crystal formation in low-gravity environments. Cell science investigators study and evaluate the benefit of low gravity, which promotes three-dimensional growth of mammalian cells for tissue engineering. Marshall Space Flight Center (MSFC) in Huntsville, Alabama, is the microgravity biotechnology managing center and directly supports research in protein crystal growth. Cell science and tissue engineering are conducted at Johnson Space Center (JSC) in Houston, Texas.

A NASA Research Announcement in biotechnology, released in December 1997, garnered 164 research proposals. The proposals were reviewed in July 1998, resulting in the selection of 48 new investigations for funding.

Academic, industrial, and federal government researchers, armed with space-grown protein crystals that provide improved resolution of the structure of key protein molecules, are creating a new generation of rationally designed drugs. Researchers use the structural data to aid in the design of drugs that will interact with specific regions of the proteins and thereby treat specific diseases. A critical stage in drug design is identification and characterization of the target structure so that the proper "key" can be designed to unlock — or lock — a protein's function. High-quality crystals yield the best resolution of protein molecular structures through X-ray analysis. Microgravity often substantially improves the quality of crystals and increases structural resolution. During this past year, the program's success in acquiring such critical data continued. Macromolecular crystals grown in space revealed new information about the three-dimensional structure of important proteins. Results from recent experiments aboard the space shuttle and the Russian space station, *Mir*, are the basis for developing techniques and equipment for experiments on the International Space Station (ISS). For example, the Diffusion-Controlled Apparatus for Microgravity on *Mir* yielded novel insights into the role of microgravity in producing larger, higher-quality crystals.

Crystallographic research in microgravity augments the development of superior drugs for treatment of a wide range of clinical conditions, thus minimizing the trial-and-error approach to drug development. BioCryst Pharmaceuticals, Inc. (Alabama), Bristol-Myers Squibb (New Jersey), DuPont Merck (Delaware), Eastman Kodak (New York), Eli Lilly (New Jersey), Schering Plough (New Jersey), Smith Kline Beecham (Pennsylvania), Upjohn (Michigan), and Vertex (Massachusetts) partner with NASA and NASA-funded researchers to produce high-quality protein crystals for new drug development. The first set of drugs from NASA-sponsored research is in Phase III clinical trials, the last series of trials prior to approval for general use. Although not all drugs successfully complete clinical trials, progression to Phase III emphasizes the important contributions of NASA research to general public health issues. Treatment for a deadly cutaneous T-cell lymphoma is the result of the joint research efforts of MSFC; the Center for Macromolecular Crystallography in Birmingham, Alabama; and BioCryst Pharmaceuticals, Inc. The new skin cancer treatment is currently in Food and Drug Administration human clinical trials.

NASA PCG success is underscored in the structural analysis of an antibody to fight respiratory syncytial virus (RSV). RSV attacks the respiratory airways and lungs. According to the National Academy of Sciences' Institute of Medicine in Washington, D.C., every year nearly 4,000,000 children ages one to five are infected by the virus in the United States. Approximately 100,000 of these children require hospitalization and 4,000 die annually from the infection. No vaccine is available, and physicians considered the virus the most serious infectious disease for infants in the United States. Daniel Carter, president of New Century Pharmaceuticals in Huntsville, Alabama, determined the three-dimensional molecular structure of the RSV antibody using protein crystals grown aboard the space shuttle. This research will help scientists understand key interactions between the antibody and virus, facilitating development of treatments for the disease.

Protein crystal growth highlights in fiscal year (FY) 1998 included:

- Improved structural analysis of Factor D protein crystals for anti-inflammatory drug therapy for open heart surgery patients. Human clinical testing is set to begin in late 1998.
- Successful crystal growth of Human Antithrombin III, a protein that controls blood coagulation.
- Improved resolution of the structure of HIV protease/inhibitor complex. Results may have applications for designing new drugs for AIDS therapies.
- Development of several protein inhibitors of viral influenza (types A and B). Phase II human clinical trials of the inhibitors will begin in late 1998.
- Early analysis of detailed structural data on Chagas' disease, a debilitating and deadly disease that afflicts more than 20,000,000 people in Latin America and parts of the United States, offers potential for the development of treatment for the disease.

Cell science, the other major area of research in NASA's microgravity biotechnology program, uses the low-gravity environment of space and NASA ground-based facilities to grow three-dimensional human tissues and organ-like structures. Standard cell culture in 1 g on Earth does not allow extensive three-dimensional growth of tissue. Microgravity and NASA's ground-based bioreactor facilitate the growth of cells into functional tissue units. Researchers use tissues grown outside the body as an improved test bed for drug development. This research will also enable better understanding of tissue growth and development. Early results have been encouraging. Tissue culturing in microgravity has yielded larger, more uniform cell assemblies than have been obtained in ground-based laboratories. The experience gained by performing cellular research aboard the space shuttle and *Mir* will allow cell science investigators to start using the ISS immediately rather than spending time learning how to use it.

Using NASA's Biotechnology Specimen Temperature Controller, Timothy Hammond and colleagues, at Tulane University and its Environmental Astrobiology Center, cultured rat renal tubular cells for four months in the Biotechnology System facility on *Mir*, from September 1997 to January 1998. The experiment, Biotechnology of Three-Dimensional Tissue Engineering, was designed to help verify the function of two new equipment units of the BTS: the cell incubator module and refrigerator. Tissues grew well on *Mir*, assembling and propagating larger aggregates than the control experiments on the ground. The cells in these aggregates also expressed receptor sites that enable assessment of the potential for drug toxicity, an important step in developing a nonanimal, nonclinical test for renal toxicity. In early 1998, Hammond cultured a sample of human renal cortical cells in the Bioreactor Demonstration System on the STS-90 mission. Based on the results from automated gene array analysis of the expression of 10,000 genes in the kidney tissue, a select but substantial group of 1,632 genes were changed (upregulated or downregulated) in microgravity. These exciting results from Hammond's investigation raise the possibility of a select group of gravity-dependent genes that are independent of known genes associated with the shear stress of heat shock responses. Six specific transcription factors underwent large changes in microgravity, including the Wilms tumor, zinc finger protein, and the vitamin D3 receptor. Hammond eventually wants to use these findings to make kidney implants for hormonal therapy. Renal cortical cells produce hormones needed by patients with kidney disease or AIDS, and others who are undergoing cancer chemotherapy.

During the Biotechnology Coculture experiment conducted aboard *Mir* in the spring of 1998, breast carcinoma cells and endothelial cells were grown together in the Bioreactor Demonstration Unit. Principal investigators (PIs) Elliot Levine, of Wistar Institute, and Thomas Goodwin, of JSC, wanted to produce tumor tissue with blood vessel precursors. Attempts *in vitro* on the ground have been difficult, but microgravity may afford two advantages: 1) spatial arrangement of the two cells, blood vessel, and tumor; and 2) induction of the first stages of blood vessel formation.

In addition to research in space, ground-based cell science research from an extramural scientific community of more than 70 scientists from throughout the country is also producing new insights and discoveries. For example, Jeanne Becker, of the University of South Florida, has successfully cultured ovarian and breast cancer cells into masses that resemble the original tumor. By studying how these tissue masses grow, she hopes to further our understanding of the factors important in the growth and spread of tumors. This is extremely important work for women's health, because the current survival rate for ovarian cancer is nearly the same as it was over 30 years ago. A major new research effort was initiated by Robert Richmond at MSFC to study the development of breast cells from healthy women who are at significant risk for breast cancer. This research will allow extended studies of the growth of healthy tissues, followed by rigorous normal-versus-tumor comparisons. NASA bioreactor technology is also being used to investigate a potential new cardiac treatment by Charles Hartzell and Robert Akins, both of the Alfred I. DuPont Hospital for Children. In this approach, cells taken from a damaged heart or cells donated from another individual are recombined in the NASA bioreactor into an organized, functional tissue that can be surgically reimplanted.

Researchers at the NASA/National Institutes of Health (NIH) Center for Three-Dimensional Tissue Culture have already produced the first *in-vitro* culture system that permits the study of HIV pathogenesis inside human lymphoid tissue. In addition, there are currently 15 ongoing projects at the center addressing a spectrum of biomedical research issues that the NIH identified as having the potential to benefit from NASA tissue culture technology.

Cell science highlights in FY 1998 included:

- Enhanced expression of renal drug toxicity receptors in space, an important step in developing tests for renal drug toxicity.
- Successful identification of a number of genes in human renal cortical cells that experienced an alteration in activity in space.
- Use of NASA bioreactors to produce the first *in-vitro* system to permit the study of HIV in human lymphoid tissue on Earth in 1 g.
- Establishment of on-orbit cell culture capability for the continuous operation of the Biotechnology Facility (BTF) for the ISS.
- Validation of the Data Acquisition and Control System for the BTF during long-duration operation in space.

Meetings, Awards, and Publications

At the annual Biophysical Society Meeting in Kansas City, Missouri, February 23–25, 1998, a NASA representative discussed how the space agency works as a partner with private industries and universities in space-based research to help the pharmaceutical and health care industries develop tools for commercial research.

Astronaut David Wolf addressed the meeting of the 1998 biotechnology cell science program investigator working group, held February 26–28 at JSC. Wolf, who played a major role in the development of the NASA bioreactor, reviewed aspects of his stay on *Mir* and answered questions from the nearly 100 participants.

A biotechnology discipline working group meeting was held March 2 at JSC. Discussions at the meeting focused on the performance of biotechnology research on the ISS and the formation of a working group to define requirements for the BTF for the space station. Meeting participants also viewed some of the hardware being developed for the ISS.

Space research advances in biotechnology were featured at a session titled "Pharmacy in Space" during the 145th annual meeting of the American Pharmaceutical Association in Miami Beach, Florida, March 22–24. The presentation focused on microgravity biotechnology research leading toward drug development for the treatment of disease. Special media briefings were given by Robert Richmond (Laboratory for Structural Biology, MSFC), Lawrence DeLucas (Center for Macromolecular Crystallography), Ewa Ciszak (Laboratory for Structural Biology, MSFC), Dennis Morrison (JSC), and David Bourne (College of Pharmacy, University of Oklahoma).

One of the most important meetings in FY 1998 was the annual review meeting of the NASA-NIH Advisory Subcommittee on Biomedical and Behavioral Research, which was held April 2–3 in Yulee, Florida. In its review of the PCG program, the subcommittee concluded that "despite limited experimental opportunities, the program has generated considerable new, useful, and important data." The subcommittee was "convinced by the evidence that larger crystalline specimens are obtainable in microgravity than on Earth" and that this method is important for determining protein structures. The subcommittee also sees great promise in new PCG techniques being developed by NASA. It recommended that NASA actively seek areas of mutual interest with the NIH and that research in these areas be stimulated by joint funding.

The annual conference of the Society for Biomaterials, held April 23–25 in San Diego, California, featured an exhibit highlighting NASA's biotechnology research, including PCG.

More than 250 scientists, many conducting NASA-sponsored research, attended the Seventh International Conference on the Crystallization of Biological Macromolecules held May 3–8 in Granada, Spain.

The 1998 Congress on *In Vitro* Biology, held May 30–June 4 in Las Vegas, Nevada, featured a session titled "Microgravity and Biotechnology: Bringing Space Home to Earth," chaired by J. Milburn Jessup (University of Pittsburgh Medical Center) and Neal Pellis (JSC), with papers by Donald Durzan (University of California, Davis), Arthur Sytkowski (Beth Israel Deaconess Medical Center), Jessup, and Pellis.

More than 200 participants representing Canada, China, France, Germany, Japan, the Netherlands, Russia, and the United States took part in the First Pan-Pacific Basin Workshop in Microgravity Sciences, held July 8–11 at Waseda University in Tokyo, Japan. The workshop promoted cooperation among researchers in the microgravity community by encouraging discussions and fostering teamwork.

The American Crystallographic Association conference, held July 19–22 in Arlington, Virginia, featured an exhibit highlighting NASA's efforts in PCG.

Preliminary results from two flights of the first Microgravity Sciences Laboratory (MSL–1) mission were reviewed August 25–26 at MSFC. Experiments carried by MSL–1 included the Protein Crystallization Apparatus for Microgravity (PCAM), the Handheld Diffusion Test Cells, and the Second-Generation Vapor Diffusion Apparatus (VDA-2). Carter presented PCAM results, which represent an important step toward developing a treatment for RSV.

Significant results from the research conducted in the bioreactor aboard *Mir* were published in the December 1997 issue of the *Proceedings of the National Academy of Sciences*. Lisa Freed, of the Massachusetts Institute of Technology, and her colleagues reported that initially disc-like specimens of cartilage tissue, when cultured for four months in microgravity, tend to become spherical in space, demonstrating that tissues can grow and develop into distinct structures in microgravity. Freed's *Mir* tissue samples were smaller, more spherical, and mechanically weaker than Earth-grown control samples. These results demonstrate the feasibility of microgravity tissue engineering for longer durations than a shuttle mission and may have implications for long human

space voyages and for treating musculoskeletal disorders on Earth. A separate commentary in the proceedings notes that NASA bioreactor research in space "offers an unprecedented opportunity for studying complex fluid assemblies."

DeLucas was an invited panelist on the "Open for Business" International Space Station video conference, held by NASA and PBS on February 26.

Media coverage in FY 1998 included articles in *Popular Mechanics*, *Infectious Diseases in Children*, *Frontiers of Medicine*, and *Design News*, as well as stories featured on Fox TV and NBC. For CNN, astronaut Andrew Thomas, during his second week aboard *Mir*, described work with experiments in a NASA bioreactor.

FY 1998 Flight Investigations—Protein Crystal Growth

***Mir*-6/ STS-86**	**Diffusion-Controlled Apparatus for Microgravity** Daniel Carter
***Mir*-6/ STS-86**	**Gaseous Nitrogen Dewar** Alexander McPherson
***Mir*-6/ STS-86**	**Interferometry for Protein Crystal Growth** Alexander McPherson
***Mir*-8/ STS-89**	**Diffusion-Controlled Apparatus for Microgravity** Daniel Carter
***Mir*-8/ STS-89**	**Gaseous Nitrogen Dewar** Alexander McPherson
STS-90	**Protein Crystallization Apparatus for Microgravity** Daniel Carter
STS-90	**Second Generation Vapor Diffusion Apparatus** Lawrence DeLucas

Flight Experiments

The flight phase of the **Gaseous Nitrogen (GN_2) Dewar** project aboard *Mir* was completed with the flights of its last two dewars, one during *Mir* Increment 6 and the other during Increment 8. The dewars returned 257 samples of 21 different proteins. Early results show a marked improvement in X-ray diffraction properties over earlier *Mir* flights. Exceptional crystals of catalase, thaumatin, cellulase, lysozyme, and concanavalin B were grown. The program has demonstrated the ability of a new technique to screen large quantities of crystals grown at low cost. Analysis of these samples continues.

The **Interferometry of Protein Crystal Growth (IPCG)** experiment was placed aboard *Mir* in September 1997 and operated by astronaut Andrew Thomas in the *Mir* Glovebox. It was returned to Earth in January 1998 on STS-89. Significant operational data were obtained, and the system is being modified for possible future flights. PCG experiments usually involve a small, simple apparatus; however, IPCG employed a sophisticated optical system to observe crystal growth.

Flights on *Mir* and the space shuttle in FY 1998 facilitated the growth of protein crystals in three different apparatus in microgravity: the **Diffusion-Controlled Apparatus for Microgravity (DCAM)**, the **Protein Crystallization Apparatus for Microgravity (PCAM)**, and the **Second Generation Vapor Diffusion Apparatus (VDA-2)**. A total of 324 cells containing protein crystals grown in the DCAM were returned to Earth during the past year, 162 each on *Mir* Increments 6 and 8. Six cylinders containing 378 protein samples in the PCAM and three trays of syringes for growing protein crystals in the VDA-2 were all flown on the STS-90 shuttle flight in October 1998.

The Microgravity Research Division continues to work to identify the scientific experiments that will be conducted on the first three ISS utilization flights (UF–1, UF–2, and UF–3). Already identified is the **Dynamically Controlled Protein Crystal Growth Apparatus (DC/PCG)**, which will allow the investigator to control the evaporation rate or the temperature profile in order to control protein crystal growth. Methods to date have allowed no variations beyond conditions set before flight. DC/PCG uses a humidity sensor to control the evaporation rate and thermoelectric heating and cooling units to control the temperature profile. Both systems employ a laser scattering sensor to detect the onset of aggregation, and a computer to adjust conditions. Due to schedule and budgetary constraints, work focused on the vapor diffusion system in 1998. Work will resume on the thermal systems in 1999. Also scheduled for an ISS utilization flight are the **Enhanced GN_2 Dewar and the Observable Protein Crystal Growth (OPCG) Apparatus.** The Enhanced GN_2 Dewar is based on the GN_2 Dewar flown on *Mir* with added electronic monitoring. The OPCG will use interferometry to reveal flow patterns and density differences in fluids around protein crystals as they nucleate and grow. A prototype was completed and tested in January 1998, and lysozyme crystals were used in test runs. Engineering improvements were made to enhance operation and reduce crew setup time. About 35 percent of the design drawings were completed. A flight test is planned on STS-107 in 2000 in preparation for deployment aboard the ISS.

Two cell science experiments were conducted using the Bioreactor Demonstration Unit (BDU) aboard *Mir*. One experiment also used equipment carried aboard the Neurolab (STS-90) mission. Specimens for the **Biotechnology of Three-Dimensional Tissue Engineering (BIO3D)** experiment were cultured in the new Biotechnology Specimen Temperature Controller (BSTC) delivered to *Mir* by STS-86 and retrieved by STS-89. The BSTC incubated rat renal cells to test the cell

FY 1998 Flight Investigations — Cell Science

***Mir*-6/ STS-86**	**Biotechnology of Three-Dimensional Tissue Engineering** Peter Lelkes, Neal Pellis,Timothy Hammond
***Mir*-8/ STS-89**	**Biotechnology System Coculture of Endothelial Cells and Human Breast Carcinoma** Elliot Levine, Thomas Goodwin
***Mir*-8/ STS-89**	**Biotechnology System Data Acquisition and Control System** Steve Gonda
STS-90	**Human Renal Tubular Cells** Timothy Hammond
STS-90	**Microgravity-Induced Differentiation of HL-60** Neal Pellis, Thomas Goodwin
STS-95	**Microgravity Microencapsulation of Drugs** Dennis Morrison, Benjamin Mosier

repository and refrigeration units. A bioreactor and associated support gear known as the Bioreactor Demonstration System were flown on STS-90 to culture human renal tubular cells. The BDU for coculturing breast carcinoma cells and endothelial cells in the **Biotechnology Coculture (COCULT)** experiment was delivered to *Mir* by STS-89 and retrieved by STS-91.

Successful on-orbit serial culture from on-orbit cell repositories was accomplished at 14-day intervals over a 70-day period on *Mir* Increment 6 using rat renal tubular cells. Cell repositories and serial passage are critical to enabling capabilities needed to support planned continuous operation of the BTF and biotechnology cell science applications for NASA's Human Exploration and Development of Space Enterprise.

The BTF's Data Acquisition and Control System (DACS) was successfully designed and validated for long-duration operation in a space environment. PI Steve Gonda, of JSC, conducted a risk mitigation investigation on the DACS in the Biotechnology System facility aboard *Mir*. Flash PC cards and radiation recovery software were incorporated in the DACS to overcome space radiation–induced Single Event Upsets and to allow continuous long-duration operation.

The FY 1998 ground and flight tasks for biotechnology are listed in **Table 3**. Further details regarding these tasks may be found in the complementary document *Microgravity Research Division Program Tasks and Bibliography for FY 1998*, available online at *http://peer1.idi.usra.edu/peer_review/taskbook/micro/mg98/mtb.CFM*.

Table 3 Biotechnology Tasks Funded by the Microgravity Research Division in FY 1998

(includes some continuing projects at no additional cost)

Flight Experiments

Protein Crystal Growth Vapor-Diffusion Flight Hardware and Facility
Daniel C. Carter
New Century Pharmaceuticals, Inc., Huntsville, AL

Protein Crystal Growth in Microgravity
Lawrence J. DeLucas
University of Alabama, Birmingham, AL

Growth, Metabolism, and Differentiation of MIP-101 Carcinoma Cells
J. Milburn Jessup
University of Pittsburgh Medical Center, Pittsburgh, PA

Membrane Transport Phenomena
Larry W. Mason
Lockheed Martin Astronautics, Denver, CO

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

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

Investigation of Protein Crystal Growth Mechanisms in Microgravity
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, Fort 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 Arnold
University of Iowa, Iowa City, IA

The Use of Bioactive Glass Particles as Microcarriers in Microgravity Environments
Portonovo S. Ayyaswamy
University of Pennsylvania, Philadelphia, PA

Protein Crystal–Based Nanomaterials
Jeffrey A. Bell
Rensselaer Polytechnic Institute, Troy, NY

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

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

Quantitative, Statistical Methods for Preflight Optimization and Postflight Evaluation of Macromolecular Crystal Growth
Charles W. Carter
University of North Carolina, 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, AL

Microgravity-Simulated Prostate Cell Culture
Leland W. Chung
University of Virginia, Charlottesville, VA

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, AL

Development of Robotic Techniques for Microgravity Protein Crystal Growth
Lawrence J. DeLucas
University of Alabama, 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, CA

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

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 Analysis and Countermeasure 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

Self-Assembly of Hepatocyte Spheroids in Microgravity
Wei-Shou Hu
University of Minnesota, Minneapolis, MN

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 Pittsburgh Medical Center, Pittsburgh, PA

Use of Rotating Wall Vessel to Facilitate Culture of Norwalk Virus
Philip Johnson
University of Texas Medical School, Houston, TX

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

Fibril Formation by Alzheimer's Disease Amyloid in Microgravity
Daniel A. Kirschner
Boston College, Chestnut Hill, MA

Applications of Atomic Force Microscopy to Investigate Mechanisms of Protein Crystal Growth
John H. Konnert
Naval Research Laboratory, Washington, DC

Regulation of Skeletal Muscle Development and Differentiation *In Vitro* by Mechanical and Chemical Factors
William E. Kraus
Duke University Medical Center, Durham, NC

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

Ground-Based Program for the Physical Analysis of Macromolecular Crystal Growth
Alexander J. Malkin
University of California, Riverside, CA

Thyroid Follicle Formation in Microgravity: Three-Dimensional Organoid Construction in a Low-Shear Environment
Andreas Martin
Mount Sinai Medical Center, New York, NY

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

Diffusion, Viscosity, and Crystal Growth of Proteins in Microgravity
Allan S. Myerson
Polytechnic University, Brooklyn, NY

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

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

Isolation of the Flow, Growth and Nucleation Rate, and Microgravity Effects on Protein Crystal Growth
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

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

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

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

Robotic Acquisition and Cryogenic Preservation of Single Crystals of Macromolecules for X-Ray Diffraction
Craig D. Smith
University of Alabama, Birmingham, AL

Gastric Mucosal Cell Culture in Simulated Microgravity
Adam J. Smolka
Medical University of South Carolina, Charleston, SC

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

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

Experimental Studies of Protein Crystal Growth Under Simulated Low-Gravity Conditions
Eugene H. Trinh
Jet Propulsion Laboratory, Pasadena, CA

Nucleation and Convection Effects in Protein Crystal Growth
Peter G. Vekilov
University of Alabama, Huntsville, AL

Protein Precipitant–Specific Criteria for the Impact of Reduced Gravity on Crystal Perfection
Peter G. Vekilov
University of Alabama, 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

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

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

Search for a Dilute Solution Property to Predict Protein Crystallization
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* Hemopoieses in a Three-Dimensional Human Bone Marrow Culture Under Simulated Microgravity**
J. H. David Wu
University of Rochester, Rochester, NY

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 *Overview*

Combustion and the results of combustion processes affect each of us every day. The majority of the world's electric power production, home heating, and ground and air transportation are made possible by combustion. 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. Being able to control 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 to the extent that measurements can be made. 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 — Virtually all practical combustion devices, except gas stoves, 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 accelerated flows 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 — Technological improvements in measurement are mandated due to historic and valid criticism of the qualitative nature of early microgravity experiments and, more importantly, due to benefits for active control of combustors.

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 like butane lighters and gas stoves, although highly turbulent, operate in the "laminar flamelet" regime; that is, their flames are typically smooth and steady. Improvements in understanding laminar flame structure and associated characteristics will have a direct impact on 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, titanium oxides), coatings (e.g., diamonds), and monolithic solids (e.g., boron carbide, 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 improving the products.

Surface flame spread — Large-scale fires and fire spread on Earth are complicated by buoyancy-fed turbulent processes and thermal radioactive 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.

Partial-gravity combustion — Combustion issues on the surfaces of the Moon and Mars will include habitat fire safety, waste incineration, roving vehicle power, and propellant storage safety.

In response to the 1997 NASA Research Announcement for combustion science, 155 proposals were received. Funding for 41 ground-based projects, 8 flight definition investigations, and 2 international research collaborations was awarded.

Meetings, Awards, and Publications

Merrill King, of NASA headquarters, and Kurt Sacksteder, of Lewis Research Center, chaired the microgravity combustion session of the 36th Aerospace Sciences Meeting in Reno, Nevada, held January 12–15, 1998.

A paper titled "Effects of Unsteady Stretch on the Strength of a Freely Propagating Flame Wrinkled by a Vortex," by C. J. Mueller and J. F. Driscoll, both of the University of Michigan, and D. L. Reuss and M. C. Drake, both of General Motors Research and Development, received the Combustion Institute's Silver Medal Award at the 26th International Symposium on Combustion, held August 3–7, 1998, in Boulder, Colorado. The award is the most prestigious given for a single paper in combustion science. The paper was generated from work partially sponsored by the microgravity combustion program.

Flight Experiments

In fiscal year (FY) 1998, three investigations completed their flight tests: Enclosed Laminar Flames, Turbulent Gas-Jet Diffusion Flames, and the Solid Surface Combustion Experiment. Descriptions of results obtained in FY 1998 are given below.

The **Enclosed Laminar Flames (ELF)** glovebox investigation flew on the fourth United States Microgravity Payload (USMP–4) mission in November 1997. The primary objective of the ELF investigation was to determine the mechanisms controlling the stability of round laminar gas-jet diffusion flames in a co-flow air duct. The study was specifically focused on the effect of buoyancy on the flame characteristics and velocities at liftoff, reattachment, and blowout of the flame. When the fuel or air velocity is increased to a critical value, the flame base abruptly jumps downstream, and the flame is said to have reached its liftoff condition. Flow conditions are such that the flame cannot be maintained at the burner rim despite the presence of both fuel and oxygen. When the velocity is further increased, the flame will eventually extinguish at its blowout condition. In contrast, if the velocity is reduced, the flame base eventually returns to anchor at the burner rim, at a velocity lower than that of liftoff, indicating a hysteresis effect. Approximately 50 tests were conducted during the mission, using a 50-50 mixture (by volume) of methane and nitrogen as the fuel. Stable lifted flames were observed in microgravity, except at high fuel flows where the microgravity flames blew out immediately after liftoff. The experimental results verify the hypothesis that substantially greater velocities are required to destabilize the flame in microgravity due to the absence of buoyant acceleration in the flow. Preliminary results reveal that the increase in air velocity required to induce liftoff in microgravity (compared to that required in normal gravity) was nearly equal to the increase required to induce blowout.

Turbulent Gas-Jet Diffusion Flames (TGDF) flew as a Get Away Special investigation on the STS-87 mission. TGDF was a study of vortex interactions in a gas-jet flame. In the experiment, toroidal flow vortices were generated by sinusoidally varying the open diameter of an iris around the base of a propane gas-jet flame, thereby causing large-scale fluctuations in the entrained air flow. The experiment's key variable was the iris frequency, which was varied between 1.5, 3.0, and 5.0 hertz. TGDF's primary objective was to gain an understanding of the dynamic behavior of the vortex/flame interaction, including possible vortex breakup or merging, and the interaction's effect on the time-averaged values of flame temperature, radiation, and shape. In addition, the experiment has provided insights into the development and extinction of microgravity flames. Analysis of the results has revealed that the microgravity flame possesses three axially spaced zones of vortex interaction, defined by the energy transfer between the oscillation and the mean field, which varies among these zones. These experimental results have been compared with a comprehensive numerical model of the pulsed flame in order to validate the accuracy of the model and verify our understanding of the flame behavior.

The **Solid Surface Combustion Experiment (SSCE)** flew for its 10th and last time on STS-91 in May 1998. SSCE, the first combustion experiment flown on the shuttle, originally flew on STS-41 in 1992. SSCE was designed to obtain benchmark flame spread data in quiescent test atmospheres, the least likely conditions to encourage flame spread. The SSCE hardware included a sealed chamber module containing the test samples; ashless filter paper or polymethyl methacrylate (PMMA), also known as acrylic plastic; and a test atmosphere of 35–70 percent oxygen mixed with nitrogen. The samples were instrumented with thermocouples. A second module contained cameras, a computer, and a battery. SSCE flames were recorded on film and video; thermocouple temperatures were recorded digitally. Several scientifically significant observations have emerged from the SSCE tests: (1) steady flame spread occurs over thin samples, even in quiescent atmospheres; and (2) thicker PMMA samples burn unsteadily and finally self-extinguish, but they require as much as 9 minutes to quench. Comparisons of flight data with numerical simulations indicate that unlike in normal-gravity results, radiative heat transfer is a dominating influence in flame spread in quiescent atmospheres. In summary, these experiments demonstrate that the controlling mechanisms for material flammability and flame spread are quite different in microgravity and normal Earth gravity.

The FY 1998 ground and flight tasks for combustion science are listed in **Table 4**. Further details regarding these tasks may be found in the complementary document *Microgravity Research Division Program Tasks and Bibliography for FY 1998*, available online at *http://peer1.idi.usra.edu/peer_review/taskbook/micro/mg98/mtb.CFM*.

Table 4 Combustion Science Tasks Funded by the Microgravity Research Division in FY 1998

(includes some continuing projects at no additional cost)

Flight Experiments

Low-Velocity, Opposed-Flow Flame Spread in a Transport-Controlled, Microgravity Environment
Robert A. Altenkirch
Mississippi State University, Mississippi State, MS

Reflight of the Solid Surface Combustion Experiment With Emphasis on Flame Radiation Near Extinction
Robert A. Altenkirch
Mississippi State University, Mississippi State, MS

Gravitational Effects On Laminar, Transitional, and Turbulent Gas-Jet Diffusion Flames
M. Y. Bahadori
Science and Technology Development Corporation, Los Angeles, CA

Candle Flames in Microgravity
Daniel L. Dietrich
Lewis 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

Unsteady Diffusion Flames: Ignition, Travel, and Burnout
Frank Fendell
TRW Space and Electronics Group, Redondo Beach, CA

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

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

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

The High–Lewis Number Diffusive-Thermal Instability in Premixed Gas Combustion and Low-Temperature Hydrocarbon Oxidation and Cool Flames
Howard G. Pearlman
Lewis Research Center, Cleveland, OH

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

Ignition and Flame Spread of Liquid Fuel Pools
Howard D. Ross
Lewis Research Center, Cleveland, OH

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

Combustion of Solid Fuel in Very Low Speed Oxygen Streams
James S. T'ien
Case Western Reserve University, Cleveland, OH

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

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

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

Ignition and Combustion of Bulk Metals in Microgravity
Melvyn C. Branch
University of Colorado, Boulder, CO

Modeling of Microgravity Combustion Experiments — Phase II
John D. Buckmaster
University of Illinois, Urbana-Champaign, Urbana, IL

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

Buoyancy Effects on the Structure and Stability of Burke-Schumann Diffusion Flames
L.- D. Chen
University of Iowa, Iowa City, IA

Gravitational Effects on Premixed Turbulent Flames: Microgravity Flame Structures
Robert K. Cheng
Lawrence Berkeley Laboratory, Berkeley, CA

Sooting and Radiation Effects in Droplet Combustion
Mun Y. Choi
University of Illinois, Chicago, IL

Combustion of Interacting Droplet Arrays in a Microgravity Environment
Daniel L. Dietrich
Lewis Research Center, Cleveland, OH

Interaction of Burning Metal Particles
Edward L. Dreizin
The Titan Corporation, Princeton, NJ

Internal and Surface Phenomena in Heterogeneous Metal Combustion
Edward L. Dreizin
The Titan Corporation, Princeton, NJ

Flame-Vortex Interactions Imaged in Microgravity
James F. Driscoll
University of Michigan, Ann Arbor, MI

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

Effects of Gravity on Sheared and Nonsheared Turbulent, Non-Premixed Flames
Said E. Elghobashi
University of California, Irvine, CA

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

Combustion of Electrostatic Sprays of Liquid Fuels in Laminar and Turbulent Regimes
Alessandro Gomez
Yale University, New Haven, CT

Characteristics of Non-Premixed Turbulent Flames in Microgravity
Uday Hegde
National Center for Microgravity Research on Fluids and Combustion, Cleveland, OH

Three-Dimensional Flow in a Microgravity Diffusion Flame
Jean R. Hertzberg
University of Colorado, Boulder, CO

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

Unsteady Numerical Simulations of the Stability and Dynamics of Flames in Microgravity
K. Kailasanath
Naval Research Laboratory, Washington, DC

Real-Time, Quantitative, Three-Dimensional Imaging of Diffusion Flame Species
Daniel J. Kane
Southwest Sciences Inc., Santa Fe, NM

Soot and Radiation Measurements in Microgravity Turbulent Jet Diffusion Flames
Jerry C. Ku
Wayne State University, Detroit, MI

Studies of Flame Structure in Microgravity
Chung K. Law
Princeton University, Princeton, NJ

Chemical Inhibitor Effects on Diffusion Flames in Microgravity
Gregory T. Linteris
National Institute of Standards and Technology, Gaithersburg , MD

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

Structure and Dynamics of Diffusion Flames in Microgravity
Moshe Matalon
Northwestern University, Evanston, IL

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

Combustion of PTFE: The Effect of Gravity on Ultrafine Particle Generation
J. T. McKinnon
Colorado School of Mines, Golden, CO

Premixed Turbulent Flame Propagation in Microgravity
Suresh Menon
Georgia Institute of Technology, Atlanta, GA

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 Syntheses of Ceramic-Metal Composite Materials Under Microgravity Conditions — Phase II
John J. Moore
Colorado School of Mines, Golden, CO

Stretched Diffusion Flames in Von Karman Swirling Flows
Vedha Nayagam
National Center for Microgravity Research on Fluids and Combustion, Cleveland, OH

Flow and Ambient Atmosphere Effects on Flame Spread at Microgravity
Paul D. Ronney
University of Southern California, Los Angeles, CA

Combustion of Unconfined Droplet Clusters in Microgravity
Gary A. Ruff
Drexel University, Philadelphia, PA

Quantitative Measurement of Molecular Oxygen in Microgravity Combustion
Joel A. Silver
Southwest Sciences Inc., Santa Fe, NM

Numerical Modeling of Flame Balls in Fuel-Air Mixtures
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

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

Interactions Between Flames on Parallel Solid Surfaces
David L. Urban
Lewis Research Center, Cleveland, OH

Studies of Wind-Aided Flame Spread Over Thin Cellulosic Fuels in Microgravity
Indrek S. Wichman
Michigan State University, East Lansing, MI

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

Laser Diagnostics for Fundamental Microgravity Droplet Combustion Studies
Michael Winter
United Technologies Research Center, East Hartford, CT

Combustion of a Polymer (PMMA) Sphere in Microgravity
Jiann C. Yang
National Institute of Standards and Technology, Gaithersburg, MD

Fluid Physics *Overview*

Fluid physics is the study of the motion of fluids and the effects of such motion. Since three of the four states of matter (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, as well as natural, processes and phenomena. Fluid motions are responsible for most 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. Fluid motion in most situations is strongly influenced by gravity. The low-gravity environment of Earth orbit 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 106 ground-based and 20 flight and flight definition principal investigators (PIs) conducting research as well as developing the theoretical framework for understanding the effects of gravity on processes involving fluids. Work in complex fluids covers research involving colloids, foams, granular media, rheology of non-Newtonian fluids, and emulsions and suspensions. Researchers studying interfacial phenomena are interested in liquid-vapor interface configurations, contact line dynamics, capillary-driven flows, and the shape stability and breakup of liquid bridges and drops. Studies of dynamics and instabilities include research on thermocapillary and thermosolutal flows, biofluid mechanics, geological fluid flows, pattern formation, and electrokinetics and electrochemistry. Work in multiphase flows and phase change includes studies of 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.

Through a rigorous peer review process, 39 researchers were selected to receive grants from a total of 228 who submitted proposals in response to the NASA Research Announcement for microgravity fluid physics that was released in December 1996. These grants total more than $13 million over a four-year period and include 6 flight definition and 33 ground-based investigations. A listing of all of the fluid physics grants, along with their PIs, is provided in **Table 5**.

Some highlights of the microgravity fluid physics program activities during fiscal year (FY) 1998 are included below.

- An interagency agreement between NASA and the Food and Drug Administration (FDA) was signed for the use of a NASA-developed novel fiber-optic probe technology to study ocular effects of diabetes with the dual objectives of early detection of the disease and combating its adverse effects on human eyesight. Prior to study on humans, the fiber-optic eye probe will be used to collect measurements on sand rats, a proven model for diabetes in humans. An agreement to collaborate on joint research projects focused on diabetes, especially concerning its effects on ocular tissue, was reached between NASA's Microgravity Research Division, NASA's Office of Life and Microgravity Sciences and Applications, the Electro-Optics Branch of the FDA's Center for Devices and Radiological Health, and the FDA's Office of Science and Technology. These projects will use laser light scattering technology developed by NASA. NASA and the FDA will share research data from these joint projects and publish related data in open scientific literature.
- Noel Clark, of the University of Colorado, reported the first observation of macroscopic chiral domains (areas of asymmetry) in a fluid phase of achiral, or symmetric, molecules, a major discovery in condensed matter science. This observation follows studies of the relationship between macroscopic and molecular chirality that were begun by Louis Pasteur in 1848. Pasteur found that crystals of a molecularly chiral salt of "racemic acid" existed in left- and right-handed forms. The left- and right-handed molecules spontaneously segregate into macroscopically chiral crystals. Subsequently, there have been many observations of coexisting domains of opposite handedness crystallized from molecules that are chiral as well as from achiral isotropic solutions (achiral molecules). In the latter cases, the molecules adopt chiral conformations, which pack more effectively than achiral conformations. However, in the 150 years since Pasteur's research, all observations of such spontaneous chiral segregation have been made in crystal phases. Clark's is the first observation in a fluid. Researchers are interested in chirality because of its influence on the phase behavior and macroscopic structure of liquid crystals.
- G. Paul Neitzel, of the Georgia Institute of Technology, co-authored the cover story "When Liquids Stay Dry," which appeared in the January 1998 issue of *Physics Today*. In the article, Neitzel describes how under certain conditions, two drops of a single liquid can be pressed against one another in air and held in place indefinitely, without coalescing, like two balloons deformed under pressure. This surprising behavior of liquids has been explained only recently, and its technological implications are still being explored.
- The dynamics of a fluid surface filled with high-amplitude ripples were studied by Seth Putterman, of the University of California, Los Angeles, using diffusing light photography, which resolves the height of the ripples at all locations instantaneously. Even when nonlinearities are strong enough to generate Kolmogorov cascades (encountered in turbulent flows) from long wavelength (where energy is input) to

shorter wavelength, the resulting turbulent state contains large coherent spatial structures. The appearance of these structures in a thermal equilibrium state (with the same average energy) would be highly improbable. This work provides new insight into the structure and properties of turbulence, which are considered to be the last major unsolved problems in theoretical physics.

- John Tarbell, of Pennsylvania State University, reported a major breakthrough in understanding the function of endothelial cells (cells that line internal body cavities) in regulating transport in the cardiovascular exchange system. His research helps to explain how alterations in blood flow in microgravity can affect transvascular exchange and consequent fluid volume shifts that affect astronauts and suggests a variety of possible approaches for pharmacologic intervention to regulate endothelial hydraulic conductivity in microgravity.
- Philip Marston, of Washington State University, and his research team members have confirmed that single bubble sonoluminescence (SBSL) produced by an ultrasonic standing wave in a spherical flask of water is not quenched by the transition from hypergravity to reduced gravity produced by NASA's KC-135 aircraft. Sonoluminescence ("light from sound"), first discovered in 1990, is the result of extremely nonlinear pulsations of gas/vapor bubbles in liquids when subject to sufficiently high-amplitude acoustic pressures. In a single collapse, a bubble's volume can be compressed more than a thousandfold in less than a microsecond. Even the simplest consideration of the thermodynamics yields pressures on the order of 10,000 atmospheres and temperatures of at least 10,000 K. It is not surprising that light should be emitted from such an extreme process. Acoustically induced light emission from SBSL has proven to be one of the most exciting and perplexing problems in physics in the last decade.
- The National Center for Microgravity Research on Fluids and Combustion (NCMRfc) was invited to participate in the University of Minnesota's Center for Interfacial Engineering (CIE) annual Fall Meeting, held in Minneapolis, Minnesota, September 14–16, 1998. The CIE is a National Science Foundation (NSF) Engineering Research Center founded in 1988 and supported by the University of Minnesota, NSF, and member companies. In a special poster session, NCMRfc presented an overview of NASA-sponsored work in microgravity fluid physics with particular relevance to thin films and coatings. A number of promising industrial contacts were made with senior management and research representatives from companies including Xerox, Kodak, and Goodyear. Fluid physics discipline working group member Matthew Tirrell, of the University of Minnesota, was instrumental in establishing many of these contacts. A potential future collaboration between the NCMRfc and the CIE will be explored.

Meetings, Awards, and Publications

The second Heat Transfer Gallery was held at the International Mechanical Engineering Congress and Exhibition in Dallas, Texas, in November 1997. At the session, photographs were displayed depicting various processes that occur in the presence of temperature gradients. Eight of the highest-rated displays were selected for publication in the special section of the *ASME* [American Society of Mechanical Engineers] *Journal of Heat Transfer*, vol. 130, August 1998. Of the eight selections, three were from fluid physics PIs.

A video, "Water Balloon Rupture in Low Gravity," by Mark Weislogel, of Lewis Research Center (LeRC), and Seth Lichter, of Northwestern University, was submitted to the Gallery of Fluid Motion and displayed at the November American Physical Society meeting in San Francisco, California. The video was selected to appear in the *Physics of Fluids* Gallery of Fluid Motion edition. The video shows normal- and slow-motion clips of large water balloons ruptured in the low-gravity environment of LeRC's DC-9 aircraft.

The Fourth Microgravity Fluid Physics and Transport Phenomena Conference, held in Cleveland, Ohio, on August 12–14, 1998, was attended by 364 scientists and engineers from around the world. The International Space Station (ISS) was the theme for this highly successful conference at which the scientific community was apprised of the research opportunities planned for the station. The conference was organized by the NCMRfc, a newly established organization whose charter includes promoting research in microgravity fluid physics and combustion science by exploring and developing various types of programs that will enhance the interplay among scientists from a variety of disciplines.

The following meetings and conferences of note also took place during FY 1998:

Meeting/Conference	***Date***
Nuclear Reactor Thermohydraulics	October 1997
American Physical Society's Division of Fluid Dynamics Meeting	November 1997
The American Institute of Chemical Engineers' Annual Meeting	November 1997
The American Society of Mechanical Engineers' International Mechanical Engineering Congress and Exposition	November 1997
Third India Society of Heat and Mass Transfer/ American Society of Mechanical Engineers' Heat and Mass Transfer Conference	December 1997
The American Institute of Aeronautics and Astronautics' 12th Annual Microgravity Science and Space Processing Symposium	January 1998

International Forum — Second Conference on Application of Thermophysics in Microgravity	January 1998
Institute for Multifluid Science and Technology	February 1998
The American Physical Society's March Meeting	March 1998
Space '98 and Robotics '98 Presentations	April 1998
Lasers and Electro-Optics, International Quantum Electronics Conference	May 1998
Summer School on Soft Condensed Matter Physics	May 1998-June 1998
The American Society of Mechanical Engineers' Fluids Engineering Conference	June1998
Third International Conference on Multiphase Flow	June 1998
The 13th International Congress on Eye Research	July 1998
Third Annual Microfabrication and Microfluidic Technologies Conference	August 1998
11th International Heat Transfer Conference	August 1998

Dudley Saville, of Princeton University, won the prestigious 1997 American Institute of Chemical Engineers' (AIChE's) Alpha Chi Sigma Award. This award is given annually by AIChE in recognition of "outstanding accomplishments in fundamental or applied chemical engineering research."

Amir Faghri, dean of engineering at the University of Connecticut, received the 1998 Thermophysics Award for "significant and substantial contributions in developing both simple and advanced thermophysical models — notably in evaporation, solidification and melting, free surface flows, and phase change."

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*, *Optics Letters*, and the *Journal of Colloids and Interface Science*.

The Optical Society of America's (OSA's) journal, *Applied Optics*, published photographs of the Physics of Hard Spheres Experiment hardware and colloidal crystals grown in space on the front cover of its special issue titled "Lasers, Photonics, and Environmental Optics." This feature issue of *Applied Optics* contains a selection of papers on photon correlation and scattering presented at the OSA Topical Meeting August 21–24, 1996, in Capri, Italy.

Flight Experiments

The second flight of the **Mechanics of Granular Materials (MGM)** experiment was conducted during the STS-89 mission in January 1998. MGM had flown previously on STS-79 in September 1996. The PI for the experiment is Stein Sture, of the University of Colorado, Boulder. Six displacement-controlled, drained, triaxial compression soil specimen experiments were performed at very low effective confining stresses of 0.05, 0.52, and 1.30 kilopascals. Three experiments were subjected to monotonic loading and unloading cycles, while the other three experiments were subjected to cyclic loading. The results show very high peak strength friction angles in the range of 47.6 to 70.0 degrees, which are mainly due to overconsolidation and grain-interlocking effects. It was observed that the residual strength levels in the monotonic loading experiments were in the same range as those observed at higher confining stress levels. The dilatancy angles were unusually high, in the range of 30 to 31 degrees. All specimens displayed substantial initial stiffness and elastic moduli during unloading and reloading events, which are nearly an order of magnitude higher than conventional theories predict. A periodic instability phenomenon, which appears to result from the buckling of multiple internal arches and columnar systems augmented by stick-slips, was observed in the experiments. Computed tomography measurements revealed valuable data about the internal fabric of the specimens and the specimens' deformation patterns. Uniform diffuse bifurcation with multiple radial shear bands was observed in the specimens tested in a microgravity environment. In the axial direction, two major conical surfaces were developed. Spatial nonsymmetrical deformations were observed in specimens tested in a terrestrial laboratory.

The **Collisions Into Dust Experiment (COLLIDE)** was the first microgravity experiment to study the effects of collisions in planetary rings and protoplanetary disks. This Get Away Special experiment, which flew on STS-90 in April 1998, was designed and built with strong student involvement at the Laboratory for Atmospheric and Space Physics at the University of Colorado, Boulder. The PI is Joshua Colwell, of the University of Colorado, Boulder. Unique low-energy impact experiments were performed on simulated planetary regolith, the fine powder coating the surfaces of most bodies in the Solar System, such as asteroids, ring particles, and the Moon. The goal of COLLIDE was to understand the partitioning of energy in collisions at less than 1 meter/second impact velocity — speeds characteristic in the early protoplanetary nebula and planetary ring systems. Results from COLLIDE showed that surface forces in the regolith prevent the release of any significant amount of dust ejecta in low-energy impacts. Production of dust in some planetary rings is therefore primarily a result of micrometeoroid bombardment. This unexpected result poses new questions about the high abundance of dust observed in Neptune's ring arcs, for example. The absence of ejecta and the low-rebound velocities of the impactors (2–3 percent of impact velocity) confirm ground-based studies suggesting that the presence of regolith aids the process of binary accretion in early planet formation. The absence of dust ejecta in the COLLIDE impacts points to a sensitive transition region in impact parameter space between collisions that produce significant quantities of ejecta (seen in ground-based studies at higher energies) and those that produce no ejecta. Mapping this parameter space will provide sensitive constraints on models of ring evolution and planetesimal formation.

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 will be installed and run in the French ALICE-II facility on the Russian space station, *Mir*. 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 distinguishes 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 will examine 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 will 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 will be conducted over a 40-day period.

The goal of the **Capillary-Pumped Heat Transfer (CHT)** investigation, designed by Kevin Hallinan, of the University of Dayton, and conducted on the first Microgravity Science Laboratory (MSL–1) mission in July 1997, was to investigate instabilities and failures in capillary-pumped loops (CPLs) in microgravity. CPLs require no power and can be used in satellites to transfer heat with high efficiency from electrical components to space radiators. CPLs have proven to be unreliable in space operations, and while explanation has been elusive, CHT answered many questions. The glovebox investigator did observe the instabilities in the evaporator meniscus, as expected, for a capillary heat transfer device in microgravity. For heat input from the vapor side of the meniscus, the instabilities, though present, had little impact on the operation of the device. For heat input on the liquid side of the meniscus, the instabilities produced much more violent oscillations. In some instances, these oscillations caused some of the liquid in the condenser to be ejected, ultimately collecting and bridging in the bend section of the vapor return line, thereby disrupting the device operation. Evaporator dryout followed. The latter type of instability is not observed on Earth due to the restoring effect of gravity. One of the more striking observations of this experiment, however, was that even if the evaporator meniscus was stable, the operation of both test devices was disrupted by the formation of a liquid slug in the vapor return line. This underscores the importance of interfacial phenomena in determining the equilibrium or low-energy liquid-vapor interface configurations in microgravity environments. These effects, if not properly accounted for, can easily lead to failure or undesirable operation of capillary-driven devices.

The **Physics of Colloids in Space (PCS)** experiment, designed by David Weitz, of the University of Pennsylvania, and Peter Pusey, of the University of Edinburgh, is slated to become the first fluid physics experiment to be carried out on the ISS. This experiment will be conducted in the Expedite Processing of Experiments to Space Station (EXPRESS) rack, located in the U.S. laboratory module of the station. 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 properties of new materials and their precursors. Weitz and Pusey plan to conduct tests on seven samples of selected binary colloidal crystals, emulsions, colloid/polymer mixtures, and fractal colloid gels. The design of flight hardware has been completed and all of the flight hardware is on hand for assembly. The Phase 0/1 safety review was completed with Johnson Space Center's Safety Board. The PI team has successfully tested the low-angle light scattering technique, which is being implemented in the flight hardware. Most of the colloidal samples for flight have been delivered by the PI. PCS is now scheduled to be launched in July 2000.

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 (MW) monodisperse polystyrene (MW = 2 million) dissolved in oligomeric 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 oligomeric polystyrene only. The experiments will be conducted on a Terrier Black-Brant sounding rocket with an MK70 booster. The sounding rocket provides 300 seconds of microgravity time. A total of five flights are needed to complete the 10-test matrix (2 tests/flight). The first flight is scheduled for the mid-1999 time frame. The authority-to-proceed review was conducted by the Microgravity Research Program Office and approval was granted. Several key development milestones were completed, including the critical design review, payload design review, and completion of the flight hardware design. The test fluid was formulated by the PI and delivered to LeRC. All the flight hardware components are on hand and assembly has started.

The **Colloidal Gelation (CGEL)** experiment is a glovebox investigation that will further colloid research through the study of three kinds of colloids: binary alloy colloids, which are colloids possessing particles of different sizes; colloid polymers, which are colloids that in addition to having spherical particles, also have long, chain-like molecules; and fractal colloid aggregates, which are colloids with repeating structural patterns or networks. CGEL was conducted on STS-95 in October 1998. Prior to launch, PIs Weitz and Pusey carefully formulated the colloidal samples for flight and turned them over to LeRC for loading into the flight cells. Flight hardware was delivered and the colloidal sample cells were prepared. The samples were delivered a few days prior to the launch to prevent settling and formation of undesirable structures.

The **Colloidal Disorder-Order Transition (CDOT)** glovebox investigation was designed to test fundamental theories that describe atomic behavior. First conducted on the second United States Microgravity Laboratory (USML–2) in 1995, CDOT showed some totally unexpected behavior of colloids in microgravity. To learn and expand on the knowledge gained from the first flight, Paul Chaikin, of Princeton University, and William Russel, of Princeton University, developed new test samples, and the flight hardware was improved to provide better light scattering data during its second flight on STS-95. Prior to launch, the flight hardware was delivered and the colloidal samples were prepared and sent to LeRC for loading into the flight cells. The samples were delivered a few days prior to the launch to prevent settling and formation of undesirable structures.

The **Internal Flows in Free Drops (IFFD)** glovebox investigation, designed by PIs Satwindar Sadhal, of the University of Southern California, and Eugene Trinh, of the Jet Propulsion Laboratory, was conducted on MSL–1. The first accurate data for drop deformation as a function of acoustic pressure were obtained for a sample located at the pressure minimum plane in the ultrasonic standing wave. IFFD was repeated on the STS-95 mission with the addition of a stinger heater to introduce differential heating of the drop so that thermocapillary flows could be observed.

The FY 1998 ground and flight tasks for fluid physics are listed in **Table 5**. Further details regarding these tasks may be found in the complementary document *Microgravity Research Division Program Tasks and Bibliography for FY 1998*, available online at *http://peer1.idi.usra.edu/peer_review/taskbook/micro/mg98/mtb.CFM.*

Table 5 Fluid Physics Tasks Funded by the Microgravity Research Division in FY 1998

(includes some continuing projects at no additional cost)

Flight Experiments

Two-Phase Gas-Liquid Flows in Microgravity: Experimental and Theoretical Investigation of the Annular Flow
Vemuri Balakotaiah
University of Houston, Houston, TX

The Dynamics of Disorder-Order Transitions in Hard Sphere Colloidal Dispersions
Paul M. Chaikin
Princeton University, Princeton, NJ

Collisions Into Dust Experiment
Joshua E. Colwell
University of Colorado, Boulder, CO

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

The Melting of Aqueous Foams (Foam Optics and Mechanics)
Douglas J. Durian
University of California, 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 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, AZ

Microgravity Segregation in Binary Mixtures of Inelastic Spheres Driven by Velocity Fluctuation Gradients
James T. Jenkins
Cornell University, Ithaca, NY

Bubble Dynamics on a Heated Surface
Mohammad Kassemi
National Center for Microgravity Research on Fluids and Combustion, Cleveland, OH

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

Study of Two-Phase Gas-Liquid Flow Behavior at Reduced-Gravity Conditions
John McQuillen
Lewis Research Center, Cleveland, OH

Pool Boiling Experiment
Herman Merte Jr.
University of Michigan, Ann Arbor, MI

Industrial Processes Influenced by Gravity
Simon Ostrach
Case Western Reserve University, Cleveland, OH

Surface Tension–Driven Convection Experiment (STDCE-1, STDCE-2)
Simon Ostrach
Case Western Reserve University, Cleveland, OH

Diffusing Light Photography of Containerless Ripple Turbulence
Seth J. Putterman
University of California, 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, CO

Thermocapillary Migration and Interactions of Bubbles and Drops
R. S. Subramanian
Clarkson University, Potsdam, NY

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
University of Pennsylvania, Philadelphia, PA

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
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

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

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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, CA

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S. H. Chan
University of Wisconsin, Milwaukee, WI

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

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Joshua E. Colwell
University of Colorado, Boulder, CO

Fluid Interface Behavior Under Low- and Zero-Gravity Conditions
Paul Concus
University of California, Berkeley, CA

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

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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, CO

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

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Stephen H. Davis
Northwestern University, Evanston, IL

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Anil Deane
University of Maryland, College Park, MD

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John K. Eaton
Stanford University, Stanford, CA

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Boyd F. Edwards
West Virginia University, Morgantown, WV

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Said E. Elghobashi
University of California, Irvine, CA

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Amir Faghri
University of Connecticut, Storrs, CT

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Alice P. Gast
Stanford University, Stanford, CA

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Frank J. Giovane
Naval Research Laboratory, Washington, DC

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

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Ashok Gopinath
Naval Postgraduate School, Monterey, CA

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

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

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Nail A. Gumerov
Dynatherm Inc., Fulton, MD

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Hossein Haj-Hariri
University of Virginia, Charlottesville, VA

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Kevin P. Hallinan
University of Dayton, Dayton, OH

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Daniel A. Hammer
University of Pennsylvania, Philadelphia, PA

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John Hegseth
University of New Orleans, New Orleans, LA

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Cila Herman
Johns Hopkins University, Baltimore, MD

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R. G. Holt
Boston University, Boston, MA

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R. G. Holt
Boston University, Boston, MA

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George M. Homsy
Stanford University, Stanford, CA

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Eric W. Kaler
University of Delaware, Newark, DE

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Yasuhiro Kamotani
Case Western Reserve University, Cleveland, OH

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

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Edward G. Keshock
Cleveland State University, Cleveland, OH

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Jungho Kim
University of Denver, Denver, CO

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Edgar Knobloch
University of California, Berkeley, CA

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

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Sindo Kou
University of Wisconsin, Madison, WI

Electric Field–Induced Interfacial Instabilities
Robert E. Kusner
Lewis Research Center, Cleveland, OH

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

The Breakup and Coalescence of Gas Bubbles Driven by the Velocity Gradients of a Nonuniform Flow
L. G. Leal
University of California, Santa Barbara, CA

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

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Seth Lichter
Northwestern University, Evanston, IL

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Sung P. Lin
Clarkson University, Potsdam, NY

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Michael Loewenberg
Yale University, New Haven, CT

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Daniel W. Mackowski
Auburn University, Auburn, AL

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James V. Maher
University of Pittsburgh, Pittsburgh, PA

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Philip L. Marston
Washington State University, Pullman, WA

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Philip L. Marston
Washington State University, Pullman, WA

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

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

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Constantine M. Megaridis
University of Illinois, Chicago, IL

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Herman Merte Jr.
University of Michigan, Ann Arbor, MI

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Ali Nadim
Boston University, Boston, MA

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Masami Nakagawa
Colorado School of Mines, Golden, CO

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

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Hasan N. Oguz
Johns Hopkins University, Baltimore, MD

Production of Gas Bubbles in Reduced-Gravity Environments
Hasan N. Oguz
Johns Hopkins University, Baltimore, MD

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Daniel R. Ohlsen
University of Colorado, Boulder, CO

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Marc Perlin
University of Michigan, Ann Arbor, MI

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Robert L. Powell
University of California, Davis, CA

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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, CA

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

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Chris B. Rogers
Tufts University, Medford, MA

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Daniel E. Rosner
Yale University, New Haven, CT

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

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

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Leonard W. Schwartz
University of Delaware, Newark, DE

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Eric S. Shaqfeh
Stanford University, Stanford, CA

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Paul J. Sides
Carnegie Mellon University, Pittsburgh, PA

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Bhim Singh
Lewis Research Center, Cleveland, OH

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Gregory T. Smedley
California Institute of Technology, Pasadena, CA

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

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

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

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Kathleen J. Stebe
Johns Hopkins University, Baltimore, MD

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Paul H. Steen
Cornell University, Ithaca, NY

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Harry L. Swinney
University of Texas, Austin, TX

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Saleh Tanveer
Ohio State University, Columbus, OH

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

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

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Penger Tong
Oklahoma State University, Stillwater, OK

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Eugene H. Trinh
Jet Propulsion Laboratory, Pasadena, CA

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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 *Overview*

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 burning 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 understand better 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 instruments, and these instrumentation advances in turn provide the foundation for tomorrow's breakthrough technologies. These advances contribute to the competitiveness of American industry and further support and enhance human presence 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 these phenomena depends strongly on the details of our understanding of fundamental forces such as gravity.

A significant accomplishment in fiscal year (FY) 1998 was the development of the Road Map for Fundamental Physics in Space. This road map spells out an aggressive research program from which NASA's future research and technology development activities in fundamental physics can be established. More than 100 scientists, technologists, and educators under the leadership of the fundamental physics discipline working group participated in the development of the road map document. The road map identifies two long-term goals of the research program (the quests described above) and three research areas: gravitational and relativistic physics (GRP), laser cooling and atomic physics (LCAP), and low-temperature and condensed matter physics (LTCMP). There is significant synergy across the three research areas both in terms of scientific overlap and overlap in experimental techniques. The goals and research areas laid out in the road map promise a scientifically rewarding, technologically challenging, flexible, and exciting program of fundamental physics research in space.

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 it is the most dominant, as it can act over very great distances. In fact, 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 equivalently to all bodies, regardless of their makeup. 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 also very subtle and difficult to measure accurately. Yet they are large enough that they must be taken into account even in 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 measurement 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 smallest pieces of matter and the complex behavior of large systems. Furthermore, 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 completely under the experimenter's control promises novel results and new insights previously hidden from view in Earth-bound laboratories. The NASA 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 measurements of higher precision and longer observation times. These techniques are also

being employed to develop improved clocks, both for testing basic theories of nature and for 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 condensed matter as it nears critical points, or conditions of pressure and temperature at which the properties of two different phases of matter 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 the 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, groups of fundamental particles, and even 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. Gravity causes pressure differences in a sample, so the critical phenomena can only be observed in a very small region. If an experiment is conducted in space, the pressure can be uniform across the sample, and much more comprehensive measurements can be made. Furthermore, in microgravity, a drop of the sample 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 the behavior of mixtures and confined media and test the universality of critical phase transitions and the scaling laws at such points. In addition, the dynamic behavior 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 are being performed of large-scale quantum systems to learn the hydrodynamics of such systems and of the melting and freezing of quantum crystals.

Of the 86 proposals received in response to the 1996 fundamental physics NASA Research Announcement (NRA), 26 grants were awarded. Three of these new grants are in GRP; 9 are in LCAP; and 14 are in LTCMP. Six of the new grants are for flight definition tasks. Eighteen of the principal investigators (PIs) selected are new to the NASA community of researchers, and two, William Phillips, of the National Institute of Standards and Technology (NIST), and David Lee, of Cornell University, are Nobel laureates in physics. The 1996 NRA grants bring the total number of investigations in microgravity fundamental physics to 54 — 10 flight or flight definition projects and 44 ground-based studies.

Some notable scientific achievements during FY 1998 are listed below:

- Robert Chave and his team at the Jet Propulsion Laboratory (JPL) and the California Institute of Technology (Caltech) have received one patent and contributed 10 NASA New Technology Reports describing applications of the magnetostrictive materials being developed under their Advanced Technology Development task. The devices described range from a magnetostrictive valve for the regulation of temperature in cryosurgical probes to a liquid helium valve, and include magnetostrictive inertial reaction motors and heat switches.
- Robert Duncan, of the University of New Mexico, and the Critical Dynamics in Microgravity team have obtained measurements of the thermal conductivity in liquid helium very near the superfluid/normal fluid interface that demonstrate the nonlinearity in this property, which has been predicted by theorists but has never previously been observed.
- Kurt Gibble, of Yale University, made the first measurements of p-wave scattering cross sections in cesium at low temperatures.
- Daniel Heinzen, of the University of Texas, made the first observation of Feshbach resonances in laser-cooled atoms.
- Mark Kasevich, of Yale University, achieved Bose-Einstein condensation (BEC) in his laboratory.
- Wolfgang Ketterle, of the Massachusetts Institute of Technology (MIT), demonstrated BEC confinement using laser light and also demonstrated the excitation of two different spin states in a single condensate.
- Richard Packard, of the University of California, Berkeley, has discovered that superfluid ^{4}He passing through a small aperture emits acoustic noise, which can be explained in a model analogous to shot noise in a conductor. This experiment is a preliminary step toward observing acoustic radiation at the Josephson frequency in ^{4}He, a result of fundamental significance to the understanding of this macroscopic quantum system. In addition, the Berkeley group recently described a superfluid ^{3}He phenomenon where DC currents are created when the Josephson frequency of a superfluid weak link matches the frequency of an external perturbation. The effect may be used to develop a future superfluid quantum interference device, a potential sensitive rotation sensor. Recently, Packard's group has discovered the phenomenon of third sound in superfluid ^{3}He.
- Results from the ground-based investigations have been published in 26 presentations, 58 proceedings papers, and 91 articles in refereed journals, adding up to a total of 192 bibliographic listings.
- The investigations have supported 38 students who are working toward their doctoral degrees, 5 master's students, and 16 undergraduate students. Eight graduate students received their doctoral degrees in FY 1998.

Meetings, Awards, and Publications

Participation by fundamental physics researchers in technology conferences is important to promote the cross-discipline aspects of the field's advanced technologies and make them available for other space- and ground-based applications. Fundamental physics researchers participated in the Space Technology & Applications International Forum, held January 25–29, 1998, and in the Sixth International Conference and Exposition on Engineering, Construction, and Operations in Space, held April 26–30, 1998. Both meetings were held in Albuquerque, New Mexico.

Many LTCMP investigators participated in the annual March Meeting of the American Physical Society (APS), held in Los Angeles, California, March 16–20, 1998. This forum provides a unique opportunity to share results with a very broad cross section of the physics community and served again this year to stimulate awareness of the microgravity program in fundamental physics and its accomplishments.

The APS' Division of Atomic, Molecular, and Optical Physics held their annual meeting in Santa Fe, New Mexico, May 27–30, 1998. All LCAP fundamental physics PIs participated in the meeting. The meeting also included a panel discussion exploring potential collaborations between NASA and the National Science Foundation in areas of scientific overlap. The science community was generally in favor of the ideas brought forward at this meeting.

The 1998 Institute of Electrical and Electronics Engineers' International Frequency Control Symposium was held in Pasadena, California, May 26–29, 1998. All clock investigators were represented at this annual meeting, which focuses on timekeeping and frequency-control technologies.

Lute Maleki, of JPL, represented the microgravity fundamental physics program at the European Space Agency (ESA) workshop on the Atomic Clock Ensemble in Space (ACES) project held in Neuchâtel, Switzerland, June 12, 1998. Collaborations, including ideas for sharing technology, were discussed for the ACES project, which will involve flying a laser-cooled cesium clock and a hydrogen maser aboard the International Space Station.

The Symposium on Quantum Fluids and Solids was held June 9–14, 1998, at the University of Massachusetts in Amherst, Massachusetts. The symposium was partially sponsored by NASA and included oral and poster sessions on fundamental physics in microgravity. The oral sessions included talks by Guenter Ahlers, of the University of California, Santa Barbara; Duncan; Ketterle; John Lipa, of Stanford University; Humphrey Maris, of Brown University; and Packard. The poster sessions included many contributions by PIs in the fundamental physics program. Following peer review, the proceedings will be published in the *Journal of Low Temperature Physics*.

The 1998 NASA/JPL workshop titled Fundamental Physics in Microgravity, took place June 23–25, 1998, in Oxnard, California. The 78 attendees heard reports of new experimental data and theoretical results relating to these data, plus plans for new investigations. International participants were from China, England, Germany, Japan, and Russia. The program included 38 scientific presentations, a discussion about the Road Map for Fundamental Physics in Space, and discussions of flight hardware options for the different research areas.

The First Pan-Pacific Basin Workshop on Microgravity Sciences was held at Waseda University in Tokyo, Japan, July 8–11, 1998. More than 200 microgravity researchers attended the conference. There were three sessions in fundamental physics with presentations by Chinese, European, Japanese, Russian, and U.S. researchers. Enterprise Scientist Mark C. Lee gave a spirited talk on NASA's overall vision for the next few decades and demonstrated how fundamental physics is well-poised to support this vision.

The Committee on Space Research of the International Council of Scientific Unions' Symposium on Fundamental Physics in Space was held July 12–19, 1998, in Nagoya, Japan. The symposium featured seven sessions, including two on testing the equivalence principle and one on using advanced clocks in space. The JPL Road Map for Fundamental Physics in Space was presented.

The official kickoff meeting of the multinational Satellite Test of the Equivalence Principle study was held at the University of Bremen in Bremen, Germany, September 9–11, 1998. This meeting resulted in some significant progress, including an agreement with ESA's science director to review a new baseline that expands ESA's contribution to the study. Representatives of the British and German national funding agencies were also present, which resulted in establishing funding for participation in the study by some of the national laboratory personnel.

More than 50 nations were represented at the 49th International Astronautical Congress held September 28–October 2, in Melbourne, Australia. Mark C. Lee presented a talk titled "The NASA Microgravity Fundamental Physics Program" at a plenary session of the meeting. A symposium focusing on the latest developments in microgravity sciences and processes featured a fundamental physics session titled "Gravity and Fundamental Physics."

A workshop on Precision Time Transfer in Space was held in Boulder, Colorado, October 15–16, 1998. It was organized by the NIST group to support the needs of their cesium clock flight definition experiment. Potential time transfer techniques were identified and trade studies are under way to evaluate their relative merits before a baseline selection is made.

Fundamental physics investigators garnered several awards this past year:

- David Ceperley, of the University of Illinois, was presented the Daniel Heineman Award for Computational Physics at the March Meeting of the APS in Los Angeles, California.

- David Goodstein, of Caltech, won the 1998 Oersted Medal of the American Association of Physics Teachers, the highest honor bestowed on a physics educator.
- Wolfgang Ketterle was presented the 1998 Discover Award for Emerging Technology by *Discover Magazine* for his atom laser development.
- William Phillips 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. Phillips was also selected as chair of the Division of Laser Science of the APS.
- Daniel Stamper-Kurn, a graduate student working on a fundamental physics BEC experiment at MIT, was one of the winners of the 1998 New Focus Student Award of the Optical Society of America.
- Nai-Chang Yeh, of Caltech, received the 1998 Outstanding Young Researcher Award, given by the Overseas Chinese Physics Association.

Flight Experiments

The **Confined Helium Experiment (CHeX)** had a successful flight as part of the fourth United States Microgravity Payload (USMP–4) mission, launched November 19, 1997. All components of the experiment performed very well during the flight. The helium in the cryostat lasted for over 12 days on orbit, which represents a large improvement over the previous flight of the Lambda Point Experiment (LPE) in 1992. The high-resolution thermometers performed better than expected, achieving a resolution of about 90 picokelvins in 1 second. This is comparable to performance on the ground, demonstrating that the design implemented for CHeX solved the cosmic ray heating issue experienced during the LPE flight. The instrument thermal control system performed well, limited primarily by heat input from external sources. Heat input was detected from the South Atlantic Anomaly, the cosmic ray background, crew activity, the primary thruster systems, the KU-band antenna, and the Space Accelerations Measurement System experiment. These heating effects did not significantly degrade the fidelity of the science data collected. A total of 2,450 heat capacity measurements were gathered. Fifty-nine total scans across the innermost region of the finite-size heat capacity peak and five high-temperature scans out to the wings of the peak were performed. The collected data are currently being analyzed to determine in detail the heat capacity curve near the finite-size peak, the shift of the peak from the bulk helium value, and the specific heat behavior above and below the transition. Overall, the curve appears as expected, but there are some interesting features that appear not to agree with current theories. Once the data analysis phase is completed, it is clear that the goals of the experiment will be achieved. The results will significantly extend our understanding of the length scaling of finite-size effects. By combining the flight data with ground measurements at smaller confinement dimensions, we can determine how the finite-size effect can be extrapolated to any length scale of interest.

Critical Viscosity of Xenon (CVX) was conducted on the STS-85 mission, launched August 7, 1997. The raw data from this very successful experiment have now been converted to values of viscosity. The final data set is internally consistent and is also consistent with ground-based measurements in the temperature range where gravity's effects are negligible. As expected, the observed divergence of viscosity is a factor of two larger than the best ground-based measurements. The exponent characterizing the divergence is in excellent agreement with the value from a recent theory. Close to the critical temperature (within about 3 millikelvins), viscoelasticity caused a rounding of the divergence and the appearance of an imaginary component of viscosity. CVX provided an accurate test of viscoelasticity theory, and a paper, titled "Viscoelasticity of Xenon Near the Critical Point," is being submitted to the journal *Physical Review Letters*. The principal investigator has proposed a follow-up flight investigation to measure the shear thinning predicted to occur near the critical point of a pure fluid. By increasing the amplitude of the oscillating screen by a factor of 30, it should be possible to measure shear thinning within a few millikelvins of the critical point. Following an investigation continuation review, NASA granted CVX-2 the authority to proceed to develop a flight experiment. The project team at Lewis Research Center is modifying the CVX-1 hardware to meet the new CVX-2 requirements. Flight hardware availability is scheduled for June 1999, with the possibility of a flight investigation in late 1999.

The Critical Fluid Light Scattering Experiment (Zeno) is officially completed. Zeno was carried out on two separate missions — USMP–2 and USMP–3. The PI, Robert Gammon, is from the University of Maryland. The final NASA project reports have been submitted. The central archival journal publication is still pending further discussion by the peer community of the interpretation of the measured density fluctuation relaxation times. High-precision measurements of the relaxation times were obtained. The PI has used analysis techniques to avoid bias of the results from the non-equilibrium density in the fluid sample that was seen unexpectedly during data collection. The main remaining difficulty is in correlating the data with independent measurements of other thermophysical properties of xenon using current theory.

The FY 1998 ground and flight tasks for fundamental physics are listed in **Table 6**. Further details concerning these tasks may be found in the complementary document *Microgravity Research Division Program Tasks and Bibliography for FY 1998*, available online at *http://peer1.idi.usra.edu/peer_review/taskbook/micro/mg98/mtb.CFM*.

Table 6 Fundamental Physics Tasks Funded by the Microgravity Research Division in FY 1998

(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 ^{4}He
Guenter Ahlers
University of California, Santa Barbara, CA

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

Critical Viscosity of Xenon
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

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

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

Develop a Laser-Cooled Cesium Clock for Scientific and Technical Applications in Space
Donald Sullivan
National Institute of Standards and Technology, Boulder, CO

Ground-Based Experiments

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

New Phenomena in Strongly Counterflowing He-II near T_λ
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 ^{3}He-^{4}He 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, MD

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

Precision Measurements With Trapped, Laser-Cooled Atoms in a Microgravity Environment
Daniel J. Heinzen
University of Texas, Austin, TX

Gravitational Effects in Bose-Einstein Condensate of Atomic Gases
Tin-Lun Ho
Ohio State University, Columbus, OH

Collisional Frequency Shifts Near Zero-Energy Resonance
Randall G. Hulet
Rice University, Houston, TX

A Quantum Degenerate Fermi Gas of ^{6}Li 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

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

Red-Shift Test of General Relativity on Space Station Using Superconducting Cavity Oscillators
John A. Lipa
Stanford University, Stanford, CA

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

Theoretical Studies of Liquid ^4He Near the Superfluid Transition
Efstratios 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, CA

Search for Spin-Mass Interaction With a Superconducting Differential Angular Accelerometer
Ho J. Paik
University of Maryland, 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

Superfluid Density of Confined ^4He near T_l
David Pearson
Jet Propulsion Laboratory, Pasadena, CA

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, CA

Research and Analysis in Support of Project SEE (Satellite Energy Exchange): Test of the Equivalence Principle and Measurement of Gravitational Interaction Parameters in an Ultraprecise 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 Cesiated Containers
Peter Taborek
University of California, Irvine, CA

Ground-Based Investigations With the Cryogenic Hydrogen Maser and the Double-Bulb Rubidium Maser
Ronald L. Walsworth
Smithsonian Institution, Cambridge, MA

Materials Science *Overview*

The goal of the microgravity materials science program is to establish and improve the quantitative and predictive relationships in 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 new metal alloys, semiconductors, ceramics, glasses, and polymers. These new materials can be used to improve the performance of a wide range of products, including complex computers, and stronger, more durable metal alloys may be manufactured.

Several important events took place during fiscal year (FY) 1998, including the flight of the fourth United States Microgravity Payload (USMP–4) mission in November 1997. The mission carried four microgravity materials science experiments and two materials science glovebox investigations onboard. To ensure that experiments get to orbit, the materials science program emphasizes supporting principal investigators (PIs) in the flight definition phase by providing NASA resources to help the investigators through the science concept review (SCR) and requirements definition review (RDR) processes in a timely manner. Multiple science and engineering teams were established to assist the PI teams in developing experiment concepts, identifying technology, modeling, testing for feasibility, and prototyping hardware.

In FY 1998, the materials science program continued work on projects in support of the Human Exploration and Development of Space (HEDS) Enterprise Strategic Plan. The plan outlines enterprise goals, performance measurements, and metrics. An assessment of the progress made by the microgravity materials science program toward fulfilling HEDS goals was presented to the associate administrator for life and microgravity sciences and applications.

The development of the Materials Science Research Facility (MSRF) concept was completed. The MSRF is designed to accommodate a diverse group of microgravity materials science experiments on the International Space Station (ISS). The facility includes three independent Materials Science Research Racks (MSRRs) containing insert modules that can be interchanged and replaced on orbit. Refinement of the configuration options was completed, and a budget plan was baselined with early emphasis on defining the concept for the first MSRR. Formulation of a science requirements envelope for initial investigators was established and reviewed during the year. A systems requirements review for the first rack was held in July, thus successfully completing the first major milestone for this important materials science capability. Work with the European Space Agency (ESA) on negotiating the scope of a joint NASA/ESA module for the facility was a significant step in establishing requirements with our international partner engineering team. Currently, launch of the first rack is planned for the third Utilization Flight (UF-3) to the ISS.

The Electrostatic Containerless Processing System Facility, donated to Marshall Space Flight Center (MSFC) by Space Systems/Loral, is now operational for flight definition and ground-based investigators. The official handover of the facility to MSFC took place in July. With this new capability, MSFC can provide critical resources to the microgravity materials science research community to continue and enhance ground-based research in support of the development of experiments during the transition to flight. Processing levitated materials represents an important area of research in microgravity materials science. This method provides access to the metastable state of an undercooled (supercooled) melt. By levitating materials so that they are free from contact with the walls of a container, a high-purity environment can be obtained for the study of reactive, high-temperature materials and for investigations of refractory solids and melts. These capabilities are critical to the research of several PIs in the microgravity materials science program.

The development of dendritic growth hardware in FY 1998 aided current flight definition researchers by providing data and feasibility tests for low-temperature, isothermal systems and PI-defined test chambers. The equipment and supporting capabilities for dendritic growth were moved into the ground support area of the newly opened Microgravity Development Lab last fall. The hardware development is important for a number of investigations, including studies using the model material succinonitrile, which researchers hope will advance the predictability of metal casting methods. Other activities in the dendritic growth area involved the design of a robust test chamber, stinger tips to produce a single crystal within a controlled emergence angle, and a high-resolution digital optics system. All of this development work will provide the basis for designing and developing a flexible isothermal facility to support many current and future microgravity researchers.

The 1998 NASA Research Announcement (NRA) for materials science was issued in December 1998, and proposals are due in early 1999. Four SCRs were completed for projects selected in the 1994 NRA. SCRs for the remaining projects selected in 1994 and those selected in 1996 will be held in 1999. It is anticipated that a number of materials science RDRs will be completed in FY 1999.

Meetings, Awards, and Publications

Ames Research Center hosted the Second Phase 1 Research Program Interim Results Symposium March 30–April 1, 1998, in Moffett Field, California. The conference emphasized science

results from shuttle/*Mir* Increments 4 and 5. Initial results for NASA's Liquid Metal Diffusion experiment and the Canadian Space Agency's (CSA's) Queen's University Experiment in Liquid Diffusion were presented.

The First Pan-Pacific Basin Workshop on Microgravity Sciences took place in Tokyo, Japan, July 8–11, 1998. As a member of the organizing committee, N. Ramachandran, of the Universities Space Research Association, coordinated the abstract submissions from the United States and Canada. Approximately 160 papers, including 25 by PIs in the microgravity materials science program, were presented in 38 sessions over three-and-a-half days. Presentations covered all aspects of microgravity research — biotechnology, combustion, fluids, fundamental physics, life sciences, materials, and experimental technology. More than 250 people attended the meeting. Keynote addresses on the opening day were given by A. B. Sawaoka (representing Japan), Arnauld Nicogossian (NASA headquarters), Yuri Ossipyan (Russia), and Wen-Rui Hu (China). Nicogossian's talk focused on salient findings from space shuttle and *Mir* missions and offered a perspective on future science activities on the ISS.

The 1998 Microgravity Materials Science Conference was held July 14–16 at the Von Braun Center in Huntsville, Alabama. There were over 300 attendees at the conference, which was organized by the microgravity materials science discipline working group. This biennial conference brings together all NASA-sponsored materials scientists who received funding through the NRA process. Altogether, 87 scientists made oral presentations, and 36 new award recipients presented posters. The plenary address was given by Ivan Egry, of the German Space Agency (DLR), who described results from last year's successful flight of TEMPUS, an electromagnetic containerless processing facility, on the first Microgravity Science Laboratory (MSL–1) mission. Donald Gillies, of MSFC, also gave a plenary talk titled "The Current Microgravity Materials Science Program." Roger Crouch, payload specialist on the MSL–1 mission and its reflight, also spoke at the banquet. In conjunction with the conference, the discipline working group hosted the Materials Science/Radiation Shielding Review. This workshop was chaired by Thomas Parnell, of MSFC, and is the first of several planned workshops in materials science that will focus on the exploration aspects of the HEDS Enterprise.

MSFC sponsored the Third Phase 1 Research Program Interim Results Symposium, held in Huntsville, Alabama, November 3–5, 1998. The symposium included presentations of the preliminary science results for shuttle/*Mir* flights, with emphasis on Increments 6 and 7. Opening remarks were made by John Uri (co-chair from Johnson Space Center), Oleg Lebedev (co-chair from Russian Spacecraft Corporation Energia), Joel Kearns (director of the Microgravity Research Program Office), and by the conference organizer and host, Roger Kroes (MSFC). Approximately 100 scientists attended all or part of the symposium. Sessions were held on human and life sciences, space biology, vehicle dynamics, external environment, Earth science, environmental monitoring, biotechnology, combustion science, materials science, and radiation. A total of 56 papers were presented, of which 16 were microgravity presentations. Michael Banish, a PI in the microgravity materials science program, presented results from the Liquid Metal Diffusion experiment. The symposium also had international participation with ten presentations by Russians and two by Canadians.

Reza Abbaschian, professor and chair of the Department of Materials Science and Engineering at the University of Florida, received the Minerals, Metals, and Materials Society's (TMS') 1998 Educator Award. The award honors Abbaschian as an outstanding educator, leader, researcher, and inventor who provides a standard for today's academician. In addition to this award, TMS also chose Abbaschian for the 1999 Leadership Award, which honors an individual who has demonstrated outstanding leadership in the fields of metallurgy and materials.

Martin Glicksman, of Rensselaer Polytechnic Institute, was awarded the 1998 Space Processing Award by the American Institute of Aeronautics and Astronautics (AIAA) at the 36th Aerospace Sciences Meeting. This prestigious award, which is conferred by the AIAA biennially, was presented to Glicksman for "premier contributions to the fields of low-gravity fluid physics, materials science, and microgravity processing, and for outstanding leadership in guiding the nation's Microgravity Science Program."

William Johnson, Ruben and Donna Mettler Professor of Materials Science, Engineering, and Applied Science at the California Institute of Technology, was awarded the Materials Research Society Medal. The medal is awarded each year for an outstanding recent discovery or advancement that has a major impact on the progress of a materials-related field. Johnson was recognized for the development of bulk metallic glass-forming alloys, the fundamental understanding of the thermodynamics and kinetics of glass formation and crystallization of glass-forming liquids, and the application of glass-forming liquids in engineering.

Flight Experiments

The purpose of the experiments conducted in the **Advanced Automated Directional Solidification Furnace (AADSF)** on USMP–4 was to determine how gravity-driven convection affects the composition and properties of alloys (mixtures of two or more materials, usually metal). The AADSF solidified crystals of two different alloys that are used to make infrared detectors and lasers. Lead-tin-telluride and mercury-cadmium-telluride are alloys of compound semiconductor materials that were used as experiment samples. Although both these materials are used in detectors and lasers, their properties and compositional uniformity are affected differently during the solidification process. Information gained by studying these alloys will make it possible to determine the effect of the microgravity environment on their optical and semiconducting behaviors. The results will help in devising ground processing methods and achieving absolute theoretical performance limits.

Experiments in the **MEPHISTO** furnace facility on USMP–4 were designed to investigate fundamentals of directional solidification in metals and semiconductors, which have a strong tendency to facet or grow undesirable faces. The experiments were a joint effort involving researchers from NASA, the French space agency (CNES), and Australia. The sophisticated technique employed in the MEPHISTO apparatus enabled extremely sensitive measurements to be made on the effect of growth rate and small alloying elements on a bismuth alloy with a small addition of tin. This alloy is very anisotropic, and a knowledge of the fundamentals of faceting in this alloy, under the controlled conditions of microgravity, will provide an important data bank for the production of similar metals and semiconductors in ground-based laboratories.

The **Isothermal Dendritic Growth Experiment (IDGE)** was designed to study the dendritic solidification of molten materials. Because virtually all industrially important alloys solidify from a molten state by a dendritic process, a fundamental understanding of dendritic solidification is necessary to correct mathematical models to provide a basis for improved industrial production techniques. The sample material for the IDGE experiment on USMP–4 was pivalic acid.

The purpose of the **Liquid Phase Sintering** experiment was to test theories of liquid-phase sintering and to examine coalescence and pore behavior during liquid-phase sintering in the microgravity environment. To comprehensively understand the gravitational effects on the evolution of both microstructure and macrostructure during liquid-phase sintering, tungsten-nickel-iron alloys with tungsten content varying from 35 to 98 weight percent were sintered in the Large Isothermal Furnace (LIF), built by the Japanese space agency (NASDA). In FY 1998, researchers worked on analyzing the data gathered from the flight of the experiment on MSL–1.

The **Diffusion Processes in Molten Semiconductors (DPIMS)** experiment conducted on MSL–1 was designed to provide a definitive measurement of the diffusion coefficients of trace impurities such as gallium, silicon, and antimony in molten germanium and to investigate the dependence of diffusion on temperature, impurity type, and sample diameter. The experiments were performed in the LIF. DPIMS activities for FY 1998 included a problem investigation of an anomaly experienced during the MSL–1 mission and postflight ground tests in the flight furnace.

The primary objective of the **Coarsening in Solid-Liquid Mixtures** experiment was to measure the temporal evolution of solid particles during coarsening. On MSL–1, the particles were coarsened for times from 1 second to 24 hours after a 9-minute period in which the particles were heated to 185° C. A better understanding of coarsening will benefit many products because a large number of commercially important alloys undergo coarsening. Many of them coarsen in the solid state, such as high-temperature superalloys and low-temperature aluminum alloys. In FY 1998, data were analyzed and found to be sufficient for determining the kinetics and particle size distribution with unprecedented accuracy. Several new evaluation techniques have been developed, and numerous research papers have been published from this study.

The **Wetting Characteristics of Immiscibles (WCI)** experiment is an advanced study of the way immiscible liquids (liquids that do not mix) behave, with the goal of producing combinations in which the two liquids are uniformly distributed. WCI was designed to study ways to control wetting behavior (the tendency of one of the liquids to adhere to the walls of the container in microgravity). Twelve samples of succinonitrile/glycerine were processed in the Middeck Glovebox during the USMP–4 mission. Sample compositions spanned the miscibility gap and ranged from 15 to 70 weight percent glycerine.

The **Particle Engulfment and Pushing by a Solid/Liquid Interface (PEP)** experiment examined the solidification of liquid metal alloys on USMP–4. Findings from this investigation may lead to improved techniques for processing metal alloys on Earth, resulting in stronger, lighter materials for use in the auto and aerospace industries. PEP may also provide an understanding of how and why potholes form on road surfaces and how to prevent them.

The FY 1998 ground and flight tasks for materials science 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 1998*, available online at *http://peer1.idi.usra.edu/peer_review/taskbook/micro/mg98/mtb.CFM.*

Table 7 Materials Science Tasks Funded by the Microgravity Research Division in FY 1998
(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, 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, AL

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

Experiments on Nucleation in Different Flow Regimes
Robert J. Bayuzick
Vanderbilt University, Nashville, TN

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

Alloy Undercooling Experiments in Microgravity Environment
Merton C. Flemings
Massachusetts Institute of Technology, Cambridge, MA

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

Evolution of Local Microstructures: Spatial Instabilities of Coarsening Clusters
Martin E. Glicksman
Rensselaer Polytechnic Institute, Troy, NY

Isothermal Dendritic Growth Experiment
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

Orbital Processing of High-Quality Cadmium Telluride
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 Western Reserve University, Cleveland, OH

Space- and Ground-Based Crystal Growth Using Magnetically Coupled Baffle
Aleksandar G. Ostrogorsky
Rensselaer Polytechnic Institute, Troy, NY

Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments
David R. Poirier
University of Arizona, 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, 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, Huntvsille, AL

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

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

Coarsening in Solid-Liquid Mixtures
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 ($Bi_{12}SiO_{20}$), 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, 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

Ostwald Ripening of Liquid and Solid Droplets in Liquid Metal Matrices
Alan J. Ardell
University of California, Los Angeles, CA

Temperature Dependence of Diffusivities in Liquid Metals
R. M. Banish
University of Alabama, Huntsville, AL

Molecularly Tailored Surfaces via Self-Assembly Processes: Synthesis, Characterization, and Modeling
Mark A. Barteau
University of Delaware, Newark, DE

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

Evolution of Crystal and Amorphous Phase Structure During Processing of Thermoplastic Polymers
Peggy Cebe
Tufts University, Medford, MA

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

Thermophysical Properties of High-Temperature Liquid Metals and Alloys
Ared Cezairliyan
National Institute of Standards and Technology, Gaithersburg, MD

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, CA

Theoretical and Experimental Investigation of Vibrational Control of the Bridgman Crystal Growth Technique
Alexandre I. Fedoseyev
University of Alabama, 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
Adrienne C. Friedli
Middle Tennessee University, Murfreesboro, TN

Melt Stabilization of PbSnTe in a Magnetic Field
Archibald L. Fripp
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, CO

Novel Directional Solidification Processing of Hypermonotectic Alloys
Richard N. Grugel
Universities Space Research Association, 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
Universities Space Research Association, 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 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 Laboratory, Berkeley, CA

Nonequilibrium Phase Transformations
Kenneth A. Jackson
University of Arizona, Tucson, AZ

Dislocation Formation During Growth of Semiconductor Crystals
Monica L. Kaforey
Case Western Reserve University, Cleveland, OH

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

Influence of Natural Convection and Thermal Radiation on Multicomponent Transport and Chemistry in MOCVD Reactors
Anantha Krishnan
CFD Research Corporation, Huntsville, AL

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

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, AL

Investigation of "Contactless" Crystal Growth by Physical Vapor Transport
Witold Palosz
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

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, Pittsburgh, PA

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, 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
Jet Propulsion Laboratory, Pasadena, CA

A Proposal to Further 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

Models of Magnetic Damping for 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

Thin Film-Mediated Phase Change Phenomena: Crystallization, Evaporation, and Wetting
John S. Wettlaufer
University of Washington, Seattle, WA

Defect Generation in CVT-Grown $Hg_{1-x}Cd_xTe$ Epitaxial Layers Under Normal- and Reduced-Gravity Conditions
Heribert Wiedemeier
Rensselaer Polytechnic Institute, Troy, NY

Use of Microgravity to Control the Microstructure of Eutectics
William R. Wilcox
Clarkson University, Potsdam, NY

Improved Spacecraft Materials for Radiation Shielding
John Wilson
Langley Research Center, Hampton, VA

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

3 Acceleration Measurement

Overview

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 that researchers experimenting in microgravity conditions wish to avoid, information about accelerations is critical to the interpretation of science experiment results.

Most experiments are conducted in microgravity to avoid fluid flow; however, fluid motion is strongly influenced by accelerations. 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. Since measuring the microgravity conditions of a microgravity science experiment is as crucial as measuring the temperature of a thermodynamics experiment, for example, 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 aircraft, and the International Space Station (ISS).

The device most frequently used to measure the quality of a microgravity environment is the Space Acceleration Measurement System (SAMS), which has flown on 20 missions since its first flight on STS-40 in June 1991. The seven SAMS units record 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, one SAMS unit 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. 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 acceleration measurement program 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 in mission summary reports, data files on CD-ROM and Internet file servers, and specialized analysis reports for scientists. Some of the highlights of the fiscal year (FY) 1998 acceleration measurement program are discussed below.

USMP–4

SAMS units F and G successfully supported the Isothermal Dendritic Growth Experiment, the Confined Helium Experiment, and experiments conducted in the Advanced Automated Directional Solidification Furnace and the French furnace, MEPHISTO, during the fourth United States Microgravity Payload (USMP–4) mission in November 1997. The SAMS units provided both real-time and recorded data to support these experiments. At the request of the USMP–4 crew, SAMS also provided software for an onboard display of SAMS data, which the crew used frequently during the mission to monitor the effects of their activities on the microgravity environment.

The OARE provided low-frequency acceleration measurements during the USMP–4 mission. Numerous effects similar to those seen on previous missions were observed, and one unique characteristic was attributed to cabin and airlock depressurization prior to astronaut space walks during the mission. This is the first time such shuttle activity has been analyzed using microgravity acceleration data. The characteristic is similar to effects experienced during a water dump, but results in a higher acceleration level.

The Principal Investigator Microgravity Services (PIMS) project supported the USMP–4 mission with premission environment analyses for some PI teams and real-time support during the mission. In addition to these activities, PIMS supported operations at Lewis Research Center's (LeRC's) Telescience Support Center and Marshall Space Flight Center's (MSFC's) Payload Operations Control Center during the mission by monitoring SAMS and OARE instrument operations as well as communications between mission participants. PIMS project members also prepared responses to nearly 100 requests for analysis from PI teams and mission personnel.

Improvements to the way SAMS units operate and collect data have been the focus of two efforts in FY 1998; the first of these is the use of hard disk drives in all SAMS units. Over the years, the optical disk drives used in SAMS units have experienced multiple failures during equipment testing and occasionally during mission operations. While no significant on-orbit data have been lost, the SAMS optical disk drives were replaced with hard disk drives for the USMP–4 mission. This change has resulted in improved mission operations for SAMS and has greatly reduced the postmission data processing time.

A second improvement for SAMS, a neural network system, was operated in real time during USMP–4 to test the feasibility of using neural networks to automatically analyze the microgravity environment. The neural network system was developed at Pennsylvania State University with support from PIMS to classify microgravity disturbances into groups with similar characteristics, as recorded by SAMS units. This system uses multilayer neural networks to establish cause-and-effect relationships between the observed acceleration environment and the source of a disturbance. The ability of the system's established knowledge base to accurately name acceleration environment events and add new events to the knowledge base was tested during the mission. A knowledge base was first established using SAMS data from the USMP–3 mission flown in February 1996. The same experiment carrier was used for both the USMP–3 and USMP–4 missions with a similar complement of experiments. Tests conducted during USMP–4 demonstrated the successful clustering of acceleration data, the characterization of similar acceleration events, and the use of the system to simplify the interpretation of data. This work will aid in the further development of an expert system for microgravity environment analysis for ISS operations.

KC-135

During FY 1998, 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 feedback to the flight crew and science teams. A new unit, called the SAMS for Free Flyers (SAMS-FF), provided payload-specific support on the KC-135 aircraft. SAMS-FF is a compact acceleration system consisting of a small triaxial sensor head connected to a portable computer. Presently, software is being developed 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.

STS-89

SAMS unit D successfully supported the Mechanics of Granular Materials experiment during the eighth shuttle mission to *Mir* in January 1998. The SAMS unit was modified to include downlink and command capabilities through the SPACEHAB Experiment Data System Main Unit. Operation of the modified unit served as a demonstration of new capabilities to support the second Microgravity Science Laboratory (MSL–2) mission planned for the year 2000.

STS-95

A hermetically sealed SAMS-FF system was delivered, installed, and successfully integrated with the Hubble Space Telescope Orbital Systems Test (HOST) payload for the launch of the STS-95 shuttle flight in October 1998. HOST is a spaceflight demonstration of components scheduled for the third Hubble Space Telescope servicing mission. At the request of Goddard Space Flight Center, SAMS-FF supported this mission by measuring the vibrations produced by a new cryocooler. The cryocooler is designed to cool sensitive electronic components on the Hubble Space Telescope Near Infrared Camera and Multi-Object Spectrometer. The small size and flexible architecture of SAMS-FF allowed the specific mission requirements to be met in a very short time. Data collected by SAMS-FF will be analyzed and a report prepared after the mission. PIMS project personnel worked with HOST investigators to arrange data processing and analysis support for SAMS-FF data that were acquired during STS-95.

Mir

SAMS unit E, which has been aboard the Russian space station since 1994, successfully completed long-duration on-orbit operations in June 1998 and was returned to Earth on STS-91. Data disks from SAMS unit E were processed and put on a server for analysis by PIMS. After traveling approximately 532 million miles while in orbit for 3 years and 10 months, the SAMS unit was examined and found to be operational but in need of a cleaning. Biological matter, notes written in Russian, and grime were present on and inside the unit. The failure of one sensor head was traced to one wire within one internal cable of the SAMS main unit. Originally designed for 14-day shuttle flights, the success of SAMS for nearly four years of on-orbit operations amazed its engineers.

ISS

Development of SAMS-II, a system for conducting acceleration measurements on the ISS, continued this year. The instrument's Remote Triaxial Sensor system proceeded from qualification hardware buildup through environmental and performance verification testing. The first flight sensor hardware was fabricated and acceptance testing was initiated. Shipment of the first flight sensor hardware to the hardware integration team will occur in early FY 1999.

During FY 1998, the SAMS-II design was modified to incorporate an interim control unit to support microgravity science experiments in Expedite Processing of Experiments to Space Station (EXPRESS) Racks and in the Microgravity Science Glovebox during the early utilization phase of the ISS. The interim control unit will be replaced with a full-featured control unit when the microgravity science facility racks are installed on the station.

Operational activities continued for interfacing SAMS-II with the ISS. Plans for data handling were developed by the SAMS-II project team and the Telescience Support Center. Plans for data analysis were also developed with the PIMS project.

An agreement was reached with the SAMS-II project to provide measurement support for the upcoming on-orbit test of the Active Rack Isolation System (ARIS) on the ISS. The test will evaluate design modifications implemented from ARIS' previous risk-mitigation activities. Two additional Remote Triaxial Sensor Electronics Enclosures will be deployed within International Subrack Interface Standard drawers, allowing triaxial measurement at three locations to support the ARIS test objectives.

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 is being developed by LeRC under a Technical Task Agreement with Johnson Space Center (JSC). During FY 1998, the MAMS engineering unit was developed and demonstrated, and MAMS flight hardware subsystems were also completed. In addition, Phase I of MAMS flight software development was completed. The MAMS team also developed detailed operations plans. MAMS is scheduled to be deployed in 2000 for ISS environmental verification.

The MAMS and SAMS-II projects developed a consolidation plan to reduce future on-orbit resources consumed by all acceleration measurement systems and to eliminate duplication of hardware development. One low-frequency sensor will now be flown on the ISS instead of two. The data from this single sensor will be provided to both the ISS vehicle designers and to science investigators. The consolidation of the two systems will result in faster, better, and cheaper implementation of the quasi-steady measurement requirements for the ISS. In addition, consolidation of the two systems allowed the MAMS project to incorporate SAMS-II-specific requirements into the initial development of MAMS. Although no present work was eliminated on SAMS-II, future work to further develop SAMS-II will be reduced, since an additional low-frequency subsystem will not be needed in SAMS-II.

Meetings and Conferences

The inaugural Microgravity Environment Interpretation Tutorial was presented at MSFC in October 1997 to a select group of scientists and microgravity personnel. Most of the attendees were associated with the USMP–4 mission, which launched shortly after the tutorial. The response from the participants was very positive. Excellent suggestions were also received for the second tutorial, which was conducted in September 1998. Discipline project scientists from LeRC, MSFC, and the Jet Propulsion Laboratory (JPL), 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.

Acceleration measurement program representatives coordinated and chaired a session of the American Institute of Aeronautics and Astronautics' 36th Aerospace Sciences Meeting and Exhibit in Reno, Nevada, in January 1998. The "Acceleration Measurement and Control in Reduced-Gravity Environments" session included the following papers:

- Low-Gravity Flight Director for Free-Floating Experiments: DC-9 Testing.
- Space Acceleration Measurement System for Free Flyers (SAMS-FF) — Initial Test Results.
- The Quasi-Steady Acceleration Environment on STS-78 (LMS) [Life and Microgravity Spacelab mission].
- MMA [Microgravity Measurement Assembly] on the LMS and MSL–1 Spacelab Missions.
- An Assessment of the Quality of the Space Station Microgravity Environment for the Directional Solidification of Semiconductors.
- A High-Fidelity Dynamic Model for the Active Rack Isolation System.
- International Space Station Microgravity Acceleration Measurement System.

Informal briefings were also presented on the ISS microgravity requirements and the concept of the Microgravity Environment Interpretation Tutorials. Session coordination was completed in preparation for the 37th meeting, which was scheduled for January 1999.

The 17th Microgravity Measurements Group (MGMG) meeting was conducted in March 1998 at the Ohio Aerospace Institute in Brook Park, Ohio. Approximately 80 attendees from various disciplines within the international microgravity community heard talks on the transition of microgravity science research from the shuttle, *Mir*, and free flyers to the ISS. 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 science experiment PIs, project scientists, numerical modelers, instrumentation developers, and acceleration data analysts, participated. The attendees included representatives from NASA headquarters, JPL, JSC, Kennedy Space Center, LeRC, and MSFC; Daimler-Benz Aerospace; universities in Germany, Italy, Russia, and the United States; and commercial companies in Russia and the United States.

Representatives of several other national agencies presented summaries of the measurement, analysis, and characterization of the microgravity environment of the shuttle, *Mir*, and sounding rockets over the past 15 years. This extensive effort to characterize these environments has laid a foundation for pursuing a similar course during future microgravity experiment operations on the ISS.

The MGMG, which has a long history of serving as a mechanism for cooperation between the international space agencies participating in microgravity science research, coordinated with

the International Microgravity Strategic Planning Group (IMSPG), which held a meeting that same week at LeRC. The 17th MGMG meeting served as a formal setting for the IMSPG to address their concerns about the microgravity environment on the ISS. IMSPG members representing the Canadian Space Agency (CSA), the European Space Agency (ESA), the French space agency (CNES), the German space agency (DLR), and the Japanese space agency (NASDA) attended the Wednesday morning MGMG session as a joint meeting of the MGMG and the IMSPG. Considerable discussion took place concerning the expected microgravity levels on the ISS and how the predicted microgravity environment on the ISS compares with what has been experienced on the shuttle and *Mir*.

The results of SAMS operations on *Mir* for NASA/*Mir* Increments 3, 4, and 5 were presented at the Second Phase 1 Research Program Results Symposium held at Ames Research Center in March 1998.

A paper titled "Effects of Exercise Equipment on the Microgravity Environment" was presented in the Application, Methods, Measurement Technology session of the Gravitational Effects in Materials and Fluid Sciences Symposium at the 32nd COSPAR Scientific Assembly, held July 12–19, 1998. COSPAR is the Committee on Space Research of the International Council of Scientific Unions.

An overview of PIMS plans for retrieval, storage, and distribution of data from the ISS was presented to representatives of ESA at ESTEC, the European Space Research and Technology Center, September 23–29, 1998. A representative of the acceleration measurement program attended the final data review for the Microgravity Measurement Assembly (MMA) flown onboard the MSL–1 mission and its reflight. Discussions were also conducted with the MMA project team for a conference paper on quasi-steady acceleration measurements on MSL–1 with OARE and MMA data.

4 Technology

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 address scientific concerns, both focused and broadly based. Focused development projects ensure the availability of technologies to satisfy the science requirements of specific microgravity flight- or ground-based programs. Broadly based development projects encompass a long-term, proactive approach to meeting the needs of future projects and missions related to the Human Exploration and Development of Space Enterprise.

Scope of Projects

Historically, ATD projects have encompassed a broad range of activities. Funded projects include 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 fiscal year (FY) 1998, four NASA centers were involved in the Microgravity Research Program-sponsored ATD Program: the Jet Propulsion Laboratory (JPL), Johnson Space Center (JSC), Lewis Research Center (LeRC), and Marshall Space Flight Center (MSFC). The FY 1998 projects, listed in **Table 8**, illustrate the breadth of technologies covered by the ATD Program. Further details on these projects and the ATD Program can be found in the *Advanced Technology Development Program Annual Update*, NP-1998-01-02-MSFC.

Solicitation

The Microgravity Research Division (MRD) solicited the 1998 ATD projects from NASA centers through a two-step process and selected the very best for funding. First, concept papers were solicited from each NASA center involved in microgravity research. Next, the MRD director and ATD program manager formed an ATD review panel consisting of microgravity science representatives from each NASA center and from the MRD at NASA headquarters. The panel reviewed concept papers for their technical merit and significance to the microgravity field, and selected candidates for further consideration. These successful candidates submitted fully detailed ATD proposals. Proposals were peer-reviewed by experts, selected from non-NASA organizations, in corresponding technology areas. Final selections were made based on the panel's recommendations. In making its recommendations, the panel considered the proposal's relevance to the anticipated technology needs of the Microgravity Research Program, potential for success, and potential for the project to enable new types of microgravity investigations.

Table 8 FY 1998 ATD Projects

Magnetostrictive Low-Temperature Actuators
Robert Chave, JPL, Pasadena, California

The objective of this ATD project is to further the development of low-temperature magnetostrictive materials. Reducing the cost and increasing the uniformity of magnetostrictive crystals will enhance potential applications, which could include acoustic pumps for microgravity cryogen transfer or magnetometers that use magnetostrictive crystals as the primary sensor element and fiber optics for readout.

Development of an Electrostrictive Valve
Talso Chui, JPL, Pasadena, California

The objectives of this ATD project are to develop a miniature cold valve with no moving parts for use as an active phase separator for liquid helium and to study the ability of a submicron aperture to act as a tunable Josephson junction in ^{4}He.

Quantitative Computed Tomography for Materials Science
Donald Gillies, MSFC, Huntsville, Alabama

This ATD project focuses on using computed tomography (CT) to relate density to chemical composition of a sample. It will also examine the use of CT as a technique for obtaining at least some three-dimensional information prior to sectioning a sample.

Space Bioreactor Bioproduct Recovery System
Steve Gonda, JSC, Houston, Texas

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 designed to operate in microgravity.

Advanced Diagnostics for Combustion
Paul Greenberg, LeRC, Cleveland, Ohio

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, Pasadena, California

Smaller and lighter high-resolution thermometers (HRTs) will be 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; therefore, the new, smaller HRTs, developed under this ATD project, will benefit these experiments.

Manufacturing of Refractory Containment Cartridges

Dick Holmes, MSFC, Huntsville, Alabama

This ATD project focuses on using plasma spray in a low-pressure, inert environment to form containment cartridges to be used for growing crystals of metals, alloys, and semiconductors in microgravity.

Passive Free-Vortex Separator

John McQuillen, LeRC, Cleveland, Ohio

The objective of this ATD project is to develop an effective, low-power, two-phase separation system. The system will enable the separation of two-phase flows for reuse during long-term spaceflight.

Space Qualifiable Magneto-Optical Trap

Lute Maleki, JPL, Pasadena, California

The objectives of this ATD project are the development and demonstration of a space qualifiable magneto-optical trap as a building block module for laser cooling and atomic physics experiments in space. This task will enable the transition of NASA-funded research in the laser cooling area from ground-based activities to space experiments.

Laser Light Scattering With Multiple Scattering Suppression

William Meyer, National Center for Microgravity Research on Fluids and Combustion (NCMRfc), LeRC, Cleveland, Ohio
Maryjo Meyer, LeRC, Cleveland, Ohio

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.

Surface Light Scattering

William Meyer, NCMRfc, LeRC, Cleveland, Ohio
Maryjo Meyer, LeRC, Cleveland, Ohio

This ATD project enables a new way of addressing surface sloshing that will allow the measurement of both surface tension and viscosity for transparent and optically accessible opaque media.

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

Ben Ovryn, Department of Mechanical and Aerospace Engineering, Case Western Reserve University (CWRU), Cleveland, Ohio; NCMRfc, LeRC, Cleveland, Ohio

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.

The Laser-Feedback Interferometer: A New, Robust, and Versatile Tool for Measurements of Fluid Physics Phenomena

Ben Ovryn, Department of Mechanical and Aerospace Engineering, CWRU, Cleveland, Ohio; NCMRfc, LeRC, Cleveland, Ohio

The objectives of this ATD project are to evaluate, adapt, and deliver a novel form of interferometry, based upon laser-feedback techniques, that will provide a robust, versatile, state-of-the-art diagnostic instrument applicable to a wide variety of investigations in microgravity fluid physics and transport phenomena. The instrument can be used to measure both temporal and spatial change in optical path length and object reflectivity.

Solid-Liquid Interface Characterization Hardware

Palmer Peters, MSFC, Huntsville, Alabama

This ATD project focuses on the real-time characterization of temperature distributions within samples during directional solidification. Present technologies are limited by the size of the thermocouples, when discrete thermocouples are used, and by interpretation of the Seebeck signal for many applications, especially those having nonplanar interfaces. 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, Huntsville, Alabama

The primary objective of this ATD project is to develop the 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, Pasadena, California

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, Huntsville, Alabama

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, which can induce controllable fluid flows in the melt.

A Pulsed Tunable Laser System for Combustion

Randall Vander Wal, NCMRfc, LeRC, Cleveland, Ohio
Howard Ross, LeRC, Cleveland, Ohio

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, Huntsville, Alabama

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, Huntsville, Alabama

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 based on a tapered-fiber probe in a near-field scanning optical microscope.

Additional Information

For additional information on the ATD program and the new microgravity instrumentation technology development and transfer program activities, please contact Isabella Kierk, program manager, Instrumentation Technology Development and Transfer, Jet Propulsion Laboratory, Mail Stop 233-200, 4800 Oak Grove Dr., Pasadena, CA 91109; phone: (818) 354-1879; fax: (818) 393-5273; e-mail: *Isabella.Kierk@jpl.nasa.gov*.

5 Hardware

Experiment Hardware for the Space Shuttle and *Mir* Flights

Significant efforts continued in fiscal year 1998 in preparation of multiuser and experiment-unique apparatus for missions using the space shuttle and the Russian space station, *Mir*. Listed in **Table 9** are shuttle missions with significant microgravity experiments, followed by short descriptions of the U.S.-developed flight experimental apparatus that have been in use and are under development in the Microgravity Research Program to support those missions. A list of flight experiment hardware being developed by international partners that will be used by U.S. investigators appears in **Table 10**.

Table 9 Shuttle Missions With Major Microgravity Experiments on Board, Chronologically by Launch Date

Launch Date	Flight	Mission	Full Name
April 1985	STS-51B	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	*Mir*–1	Shuttle/*Mir*–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	International Microgravity Laboratory–2
Nov. 1995	STS-74	*Mir*–2	Shuttle/*Mir*–2
Feb. 1996	STS-75	USMP–3	United States Microgravity Payload–3
March 1996	STS-76	*Mir*–3	Shuttle/*Mir*–3
June 1996	STS-78	LMS	Life and Microgravity Spacelab
Sept. 1996	STS-79	*Mir*–4	Shuttle/*Mir*–4
Jan. 1997	STS-81	*Mir*–5	Shuttle/*Mir*–5
April 1997	STS-83	MSL–1	Microgravity Science Laboratory–1
May 1997	STS-84	*Mir*–6	Shuttle/*Mir*–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	*Mir*–7	Shuttle/*Mir*–7
Nov. 1997	STS-87	USMP–4	United States Microgravity Payload–4
Jan. 1998	STS-89	*Mir*–8	Shuttle/*Mir*–8
March 1998	STS-90		Neurolab
Oct. 1998	STS-95		Shuttle
Dec. 2000**	STS-107		Shuttle
Feb. 2001	STS-113	MSP–1	Microgravity Science Payload–1

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

** Tentative date

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

Bioreactor Demonstration Unit (BDU): The BDU is a rotating cylinder bioreactor that is supported by subsystems that provide media perfusion and exchange, continuous measurement and control of nutrient media, pH, glucose, oxygen, and carbon dioxide; incubator temperature control, and data storage. It is useful for the investigation of cell science and tissue engineering. (STS-70, Shuttle/*Mir*–4, STS-85, Shuttle/*Mir*–8)

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

Biotechnology Specimen Temperature Controller (BSTC): BSTC is a thermally controlled, single-locker module designed to incubate multiple small cell cultures. It has a single chamber capable of maintaining an internal temperatue within the range of 36° C to 40° C and the capability of monitoring CO_2 concentrations within the chamber in the range of 0 to 20 percent. BSTC can deliver custom blended air/CO_2 gas mixtures, is programmable, and may operate either independently or in conjunction with facility computers. (Shuttle/*Mir*–6 and Neurolab)

Biotechnology System: This instrument is 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 is being developed to perform multiple combustion experiments in orbit; the first two experiments were the Laminar Soot Processes experiment and the Structure of Flameballs at Low Lewis Number experiment. (MSL–1, MSL–1R)

Confined Helium Experiment Apparatus: This apparatus provides 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 provides 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 provides 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 is a modified Bridgman-Stockbarger furnace for crystal growth from a melt or vapor. (USML–1, USML–2)

Data Acquisition and Control System (DACS): DACS is designed to provide systems to monitor, operate, and control experiment-specific systems and facility-based systems in the Biotechnology Facility on the ISS. (*Mir* 2–7)

Diffusion-Controlled Protein Crystallization Apparatus for Microgravity (DCAM): The DCAM hardware, which was designed for long-duration protein crystal growth on *Mir*, combines liquid-liquid diffusion and dialysis methods to effect protein crystal growth. Each DCAM tray assembly consists of 27 DCAM experiment chambers containing precipitant solutions and protein sample solutions. (Shuttle/*Mir*–4, Shuttle/*Mir*–5, Shuttle/*Mir*–6)

Drop Physics Module: This apparatus is 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)

Droplet Combustion Experiment Apparatus: This apparatus is designed to study droplet behavior during combustion by measuring burning rates, extinction phenomena, disruptive burning, and soot production. (MSL–1, MSL–1R)

Gas Supply Module (GSM): The GSM provides a mixture of highly purified pressurized gases required for long-duration, on-orbit cell culture and tissue engineering investigations. (Shuttle/*Mir*–4, Shuttle/*Mir*–8)

Gaseous Nitrogen (GN_2) Dewar Protein Crystal Growth Experiment Apparatus: The GN_2 dewar is a device that can maintain samples at cryogenic temperatures for about 13 days. Frozen liquid-liquid diffusion and batch protein crystal growth experiments are launched in a GN_2 dewar and then allowed to

thaw to initiate the crystallization process in a microgravity environment. The GN2 dewar houses a protein crystal growth insert that typically holds approximately 200 protein samples. (Shuttle/*Mir*–4, Shuttle/*Mir*–5, Shuttle/*Mir*–6)

Geophysical Fluid Flow Cell: This instrument uses electrostatic forces to simulate gravity in a radially symmetric vector field, centrally directed toward the center of the cell. This allows investigators 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 is an apparatus designed to operate in the *Mir* glovebox to measure details of how protein molecules move through a fluid and then form crystals. IPCG comprises 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 is being 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 provides 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)

Low-Temperature Microgravity Physics Cryogenic Dewar: This apparatus supports different experiments, including the Lambda Point Experiment, the Confined Helium Experiment, and the Critical Dynamics in Microgravity experiment. (USMP–4, MSP–1)

Low-Temperature Platform: This apparatus provides a 2 K environment for fundamental physics experiments for up to 12 days on the shuttle. It also provides the mechanical and data interfaces between the experiment and the shuttle carrier. The apparatus supported the Lamba Point Experiment and the Confined Helium Experiment. (USMP–1, USMP–4)

Mechanics of Granular Materials Experiment Apparatus: This instrument uses 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)

Microgravity Glovebox: This is a modified middeck glovebox designed for *Mir* that will enable 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 is used to determine the smoldering characteristics of combustible materials in microgravity environments. (STS-69)

Middeck Glovebox: The glovebox is a multidisciplinary facility used for small scientific and technological investigations. (USMP–3, USMP–4, STS–95, MSP–1)

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

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

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

Protein Crystallization Apparatus for Microgravity (PCAM): The PCAM is used to evaluate the effects of gravity on vapor diffusion protein crystal growth and to produce improved protein crystals in microgravity for determination of molecular structures. Each PCAM cylinder contains 9 crystallization plates, each having 7 sample chambers, for a total of 63 chambers per cylinder. The total number of samples that can be flown in a Single-Locker Thermal Enclosure System unit is 378. (MSL–1, MSL–1R, STS–85, STS–95)

Second-Generation Vapor Diffusion Apparatus (VDA-2): The VDA-2 trays are 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) has been added to the original double-barreled VDA syringes to improve mixing during activation of vapor diffusion protein crystal growth flight experiments. A Single-Locker Thermal Enclosure System (STES) can accommodate four VDA-2 trays. Each VDA-2 tray has 20 sample chambers, for a total of 80 samples per STES. (MSL–1, MSL–1R, Shuttle/*Mir*–6, STS-95)

Single-Locker Thermal Enclosure System (STES): The STES replaces a single middeck locker and provides a controlled temperature environment within plus or minus 0.5° C of a set point

in the range from 4° C to 40° C. The STES houses a variety of protein crystal growth experiment apparatus, including the PCAM and VDA-2. (MSL–1, MSL–1R, Shuttle/*Mir*–6, STS-95)

Solid Surface Combustion Experiment Apparatus: This instrument is 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 (SAMS): SAMS measures and records the acceleration environment in the space shuttle middeck and cargo bay, in the Spacelab, SPACEHAB, and on *Mir*. (Multiple missions)

Space Acceleration Measurement System for Free-Flyers (SAMS-FF): SAMS-FF measures and records the acceleration environment on KC-135 parabolic aircraft, on suborbital rockets, and on the space shuttle. (Multiple missions)

Surface Tension-Driven Convection Experiment Apparatus: This apparatus is 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 is used to study the role of large-scale flame structures in microgravity transitional gas jet flames. (Get Away Special Experiment)

Table 10 Flight Experiment Hardware Developed by International Partners and Used by NASA's Microgravity Research Program

Advanced Gradient Heating Furnace	European Space Agency (ESA)
Advanced Protein Crystallization Facility	ESA
Applied Research on Separation Methods Using Space Electrophoresis	French National Center for Space Studies (CNES)
Biolab	German Space Agency (DARA)
Bubble, Drop, and Particle Unit	ESA
Critical Point Facility	ESA
Cryostat	German Aerospace Research Establishment (DLR)
Electromagnetic Containerless Processing Facility (TEMPUS)	DARA
Electromagnetic Furnace	DARA
Free Flow Electrophoresis Unit	National Space Development Agency of Japan (NASDA)
Gradient Freezing Furnace	ESA
Large Isothermal Furnace	NASDA
Material for Study of Interesting Solidification Phenomena on Earth and in Space (MEPHISTO)	CNES
Microgravity Isolation Mount	Canadian Space Agency (CSA)
Microgravity Measurement Assembly	ESA
Mirror Furnace	NASDA
Quasi-Steady Acceleration Measurement	DLR
Queens University Experiment in Liquid Diffusion	CSA
Satellite Test of the Equivalence Principle	ESA/NASA

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 International Space Station (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:

- Biotechnology Facility (BTF).
- Fluids and Combustion Facility (FCF).
- Low-Temperature Microgravity Physics Facility (LTMPF).
- Materials Science Research Facility (MSRF).
- Microgravity Science Glovebox (MSG).

BTF

The BTF will accommodate systems to support cell growth, tissue engineering, protein crystal growth, and fundamental biotechnology research using the microgravity environment and the extended mission time of the space station. In addition, this facility will house the hardware for new areas of biotechnology research that are being explored. Due to funding limitations, the Expedite Processing of Experiments to Space Station (EXPRESS) Rack facility will be used to accommodate the needs of biotechnology research during the early phases of the space station. The development of the BTF as a facility dedicated to meet the comprehensive needs of biotechnology researchers has been delayed to a later phase in the space station's operational life. Development of the BTF is taking place at Johnson Space Center.

In fiscal year (FY) 1998, the two-year, on-orbit operation of the Biotechnology System (BTS) facility onboard Russian Space Station *Mir* was successfully completed. Operation of the BTS served as an important risk mitigation effort for the BTF. Validation of BTF concepts and operations through long-duration operations, demonstration of technology and systems to support biotechnology investigations, verification of BTF operational and training procedures, and fundamental science investigations were included in the risk mitigation activities. Final analysis of risk mitigation investigations will be completed by 2000.

FCF

The FCF will be a permanent on-orbit facility located in the U.S. Laboratory Module of the ISS. The FCF will support NASA's Human Exploration and Development of Space microgravity program objectives. In particular, the FCF will accommodate and facilitate sustained, systematic microgravity fluid physics and combustion science experiments for the lifetime of the ISS, defined as 10 years with an option to extend to 15 years. The FCF is being developed by Lewis Research Center, which is responsible for managing NASA's microgravity fluid physics and combustion science programs. The capabilities and development schedule for the facility have been tightly integrated with the scientific needs and schedules of these programs. As a consequence, the most promising principal investigators (PIs) currently funded by NASA have been scheduled to FCF availability beyond the year 2004. A PI's actual flight date will be determined later, based on merit. This integrated approach assures the maximum scientific relevancy and return at the lowest cost.

Since its concept design review in December 1994, the projected development cost of the FCF has been cut in half, while the projected scientific productivity has been more than doubled. Compared to NASA-funded microgravity fluids and combustion experiments flown on the space shuttle, ISS FCF experiments will cost about one-fifth to one-third as much to build. The FCF will use three on-orbit racks working together to achieve the necessary economies — one rack for combustion research, one for investigations in fluid physics, and one shared accommodations rack, which will provide power and diagnostics to both of the science racks. In 1997, the hardware concept was substantially revised to allow the three FCF racks to be launched at intervals of approximately one year and operate independently until the last rack arrives.

In FY 1998, the first rack scheduled for launch, the Combustion Integrated Rack (CIR), was further developed. The revised FCF system concept, and the CIR in particular, was reviewed by a nonadvocate committee at the hardware concept review in June. Two pieces of FCF-developed advanced technology received special recognition: the FCF Embedded Web Software Technology won the NASA "Software of the Year" award, and the ISS TRANSHAB considered using the FCF-developed Electrical Power Control Unit in place of the standard ISS power controllers.

The CIR will be launched in 2002, followed by the Fluids Integrated Rack in 2003, and the Shared Accommodations Rack (SAR) in 2004. When the SAR is on orbit, equipment will be moved among the three racks to create the originally envisioned three-rack system, which will perform the full range of fluids and combustion experiments. The FCF project operated with minimal staff in FY 1998. Staff will increase slightly in FY 1999, but full staffing is not planned before FY 2000.

LTMPF

The LTMPF is being designed at the Jet Propulsion Laboratory to accommodate a diverse group of long-duration microgravity experiments in low-temperature physics. In FY 1998, the LTMPF project continued its Phase A activities. The project team worked to develop a conceptual design and a science requirements envelope document (SRED), which establishes key interface descriptions. The SRED development focuses on meeting the detailed requirements of the current flight definition experiments, while at the same time not precluding the future flight of any of the current ground experiments. Based on the results of trade studies, it was decided to change the baseline concept from a dual-instrument dewar to two single-instrument dewars. This baseline change will significantly reduce the complexity of the instrument integration and test tasks, thereby reducing risk to the program. The design work culminated at the end of the year in a

nonadvocate concept design review. Significant progress was also made in developing the instrument concept that will be used by the investigator teams to achieve experiment objectives in the facility. The Fast Alternative Cryogenic Testbed (FACET) flight definition task for the LTMPF made good progress toward its technology demonstration milestone. To achieve maximum synergy, the LTMPF industrial partner is developing the electronics for FACET. Three additional flight definition investigations for the LTMPF were selected from the 1996 NASA Research Announcement for fundamental physics. Two of the selected projects are in low-temperature physics, and one is in gravitational physics. A slightly earlier first launch planning date for the LTMPF was negotiated with Johnson Space Center and the Microgravity Research Program Office, although this flight has not yet been manifested.

MSRF

The MSRF is being designed to meet the near-term and long-range goals of the microgravity materials science program and its evolving group of peer-reviewed science investigations. The facility is expected to fulfill the science requirements of increasingly sophisticated microgravity investigations and to permit the development of experiment equipment for research throughout the life of the ISS. Development of the MSRF is taking place at Marshall Space Flight Center (MSFC).

The initial concept for the MSRF consists of three Materials Science Research Racks (MSRR-1, MSRR-2, and MSRR-3), which will be developed for phased deployment beginning on the third Utilization Flight (UF-3). The MSRRs will accommodate investigations in basic materials research and applications in the fields of solidification of metals and alloys, thermophysical properties, polymers, crystal growth of semiconductor materials, ceramics, and glasses. Each MSRR is a stand-alone, autonomous rack and will be composed of on-orbit replaceable experiment modules; module inserts; investigation unique apparatus; and/or multiuser, generic processing apparatus. Development of the first MSRR configuration is being coordinated with the development of the NASA/European Space Agency (ESA) experiment module, which will be deployed on MSRR-1. Additional experiment modules for MSRR-2 and MSRR-3 will be developed in the future. The experiment modules for each rack will be designed to be "smart" furnaces, including avionics packages designed to support each unique investigation. The experiment modules for MSRR-2 and MSRR-3 will be consistent with the developing rack architecture studies conducted at MSFC and will have optimum flexibility to support on-orbit maintenance and change-out of key components.

In FY 1998, significant progress was made on the MSRF. Science requirements were coordinated with the various materials science investigators who will utilize the facility, and a draft of the SRED for MSRR-1 was developed and is nearing release. In addition, work began on the SREDs for MSRR-2 and MSRR-3. An overall payload accommodation study was completed for all approved materials science flight and flight definition investigations, along with preliminary experiment module concepts for the MSRF and a rack architecture study for the follow-on racks.

Initial project concept definition and budget development in support of flight opportunities were completed along with experiment module traffic models, which project the potential long-term accommodation of the various materials science flight investigations. A system requirements review for the MSRR-1 in-house activity was completed in August 1998, as scheduled. Development of the MSRF project plan is well under way. This plan describes the top-level overall approach to be utilized by MSFC in the implementation of the MSRF project on the space station. In addition, appropriate implementation plans have been initiated. These plans delineate the agreements between the ESA cooperative effort and the Space Product Development commercial experiment module accommodation on MSRR-1. Development of the preliminary MSRF integration requirements document was completed and is in review. This document identifies the responsibilities of the various experiment module developers during payload integration into each MSRF rack.

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 space station crewmembers, the environment of the space station, and investigations on potentially hazardous materials. NASA's previous successes with gloveboxes flown on the space shuttle and on *Mir* provided valuable experience in determining the requirements for the MSG.

The MSG is being developed through an international agreement between NASA and ESA. In exchange for developing the MSG, the agreement provides ESA with early utilization opportunities in the facility without any exchange of funds between the two agencies. ESA's prime contractor for the MSG is Daimler-Benz Aerospace. In FY 1998, the MSG project entered the critical design review phase. The MSG is tentatively scheduled to launch to the ISS in November 2000.

Ground-Based Microgravity Research Support Facilities

In FY 1998, NASA continued to maintain very productive ground facilities for reduced-gravity research that include KC-135 parabolic flight aircraft, a drop tower, the Zero-Gravity Facility, a drop tube, and several other facilities. The reduced-gravity facilities at Johnson Space Center (JSC), LeRC, and 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 a few 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 provide 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.

In FY 1998, JSC's KC-135 became the primary aircraft for reduced-gravity research. Like its predecessor, the DC-9, the KC-135 can accommodate several experiments during a single flight. Low-gravity conditions of approximately 20 seconds can be obtained 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 50-55 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. Over 50 parabolas can be performed on a single flight. In FY 1998, 68 experiments were performed during 3,925 trajectories over 159 flight hours.

The LeRC 2.2-Second Drop Tower obviously 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 0.01 of Earth's gravitational acceleration to 0.0001. Over 17,000 tests have been performed in the drop tower to date. In FY 1998, as in the past several years, drop tests averaged about 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-m freefall in the open environment. Some 32 experiments were supported during the 1,417 drops performed in FY 1998. As in the past, several of these experiments were in support of the development of experiments 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 LeRC, 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 m 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 1998, seven major projects were supported as 154 test drops were executed.

The Drop Tube Facility, located at Marshall Space Flight Center, consists of sections of a 26-cm diameter stainless steel pipe vertically assembled into a tube of 105 m in length. Completely evacuated of air, 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, as well as experiments in droplet dynamics and engineering tests such as the ones designed to yield results for the Tethered Satellite Mission. In FY 1998, three experiments were supported during 334 drops.

Table 11 summarizes activities at ground-based microgravity research facilities in FY 1998.

Table 11 Use of Ground-Based Low-Gravity Facilities in FY 1998

	KC-135	2.2-Second Drop Tower	Zero Gravity Facility	Drop Tube Facility
Number of investigations supported	68	32	7	3
Number of drops or trajectories	3,925	1,417	154	334
Number of flight hours	159	N/A	N/A	N/A

6 Education and Outreach

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 at other institutions who have not yet considered the benefits of conducting their 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 reaching out to 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. Print and World Wide Web (WWW) publications highlighting specific research projects allow the MRP to reach a worldwide audience.

In fiscal year (FY) 1998, more than 39,000 elementary and secondary school teachers and administrators attended annual meetings of the National Science Teachers Association, the National Council of Teachers of Mathematics, and the International Technology Education Association. These conferences give NASA the opportunity to demonstrate new ways to teach students about the importance of microgravity research. Microgravity science 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 1998. Four new grade level–specific microgravity mathematics posters were developed and over 5,000 were distributed at national education conferences. A new video describing the microgravity demonstrator was developed and submitted to the NASA CORE educational product catalog for distribution. "Microgravity — A Teacher's Guide With Activities in Science, Mathematics, and Technology" was revised as a NASA Educational Guide. Efforts were increased in FY 1998 to make educators aware of all the microgravity research education products that are available online through microgravity research program WWW pages, NASA Spacelink, and the NASA CORE 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 and principal investigators, and technology developers. *Microgravity News* features articles on experiment results, shuttle missions, science and technology developments, research funding opportunities, meetings, collaborations, and microgravity science researchers. Distribution for each newsletter has grown to 10,300 copies, an increase from the 9,082 copies distributed last year. A marked rise has been seen in the number of individuals requesting to be added to the mailing list via e-mail submission to the new address *microgravitynews@msfc.nasa.gov*. In addition, distribution of *Microgravity News* to public and private associations, corporations, laboratories, and education 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 WWW home page at *http://microgravity.msfc.nasa.gov* continues to provide regular updates on upcoming conferences, microgravity-related research announcements, enhanced links to microgravity research centers, educational links, and links to the newly developed microgravity image archive. A list of important microgravity WWW sites is presented in **Table 12.**

The MRP was represented to more than 25,000 attendees at the biennial conference of the American Association of Retired Persons in Minneapolis, Minnesota, the week of June 1–5. During the conference, the Human Exploration and Development of Space exhibit was on display in the NASA exhibit area. A bioreactor was also on display and operating at the booth, generating particular interest among conference-goers. Other conferences at which exhibits and materials developed by the Microgravity Outreach and Education staff in FY 1998 were used include the American Association for the Advancement of Science conference, the NASA University Research Centers Conference, the National Manufacturer's Association conference, and the biennial Space '98 conference.

Research Center Activities

The MRP was very active in education and outreach in FY 1998. One center-wide activity is the Graduate Student Research Program (GSRP). From a national pool of 67 applicants who submitted research proposals to NASA to perform microgravity research, 13 graduate students were selected to receive support for ground-based microgravity research during 1998–99, under the GSRP. Graduate students who will conduct a portion of their research at a NASA facility were also selected. 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. A list of the graduate students selected to perform research in 1998–99 may be found at *http://microgravity.nasa.gov/gsrp.html.*

Jet Propulsion Laboratory

JPL hosted 10 college students as summer interns in FY 1998. The students, many from colleges without substantial budgets for research, were expected to make significant contributions to the research projects they worked on during their summer tenure. The students wrote computer programs, helped design hardware for magnetostrictive devices, and processed and tested superconducting materials being applied to low-temperature devices. JPL continues its involvement in the educational activity begun last year in cooperation with the California Institute of Technology Pre-College Science Initiative. JPL scientists are working with middle school teachers to develop materials with an emphasis on gravity effects on fluid behavior. These materials

will be used by middle school students in an inquiry-based learning environment. JPL scientists are also actively engaged in outreach to the community. Several have taken kits displaying low-temperature phenomena to grade schools and high schools. At the JPL Open House in June 1998, JPL scientists interacted with more than 10,000 visitors in the Cryogenics Laboratory, where demonstrations on topics ranging from levitating magnets to the behavior of superfluid helium were conducted.

Johnson Space Center

Members of the biotechnology cell science program at JSC also participated in numerous educational and outreach programs throughout FY 1998. These events included presentations and exhibits on the bioreactor at the Defense Orientation Conference Association meeting, Texas Children's Hospital, a conference at the University of Texas Medical Branch at Galveston, and the Greater Houston Partnership state legislators' visit. A bioreactor demonstration was presented at the JSC Open House, and biotechnology cell science program personnel volunteered to support exhibit displays. In addition to these activities, several biotechnology personnel served as judges for the 1998 Houston-area high school science fair, held at the George R. Brown Convention Center, and during Engineering Week, biotechnology personnel visited schools in Clear Lake, Texas, to promote engineering studies.

Langley Research Center

"Connect — Microgravity: Doing More in Less," one of four live educational programs produced this year by the LaRC Education Office, was aired April 23, 1998, on PBS stations in Alabama, Kentucky, Ohio, South Carolina, and Virginia and to other viewers in the United States via the StarNET system. The program was selected for the 1998 Aurora Gold Award, under the category of instructional and science education. The Aurora Awards are designed to recognize independent excellence in the film and video industries. The program focused on microgravity research and was hosted by Shelley Canright, LaRC pre-college officer. Senator John Glenn and NASA researchers from MSFC (Felecia Ewing) and LeRC (Nancy Rabel Hall) were featured. Pre-viewing activities for grades K–4 and 5–8, which were included in the 50-page print material for the show, were developed in part by LeRC Microgravity Science Division (MSD) staff. The "Connect" video series is typically replayed on NASA TV several times throughout the year as part of the standard NASA TV Education File.

Lewis Research Center

The 11th Summer Session Program of the International Space University (ISU) brought 88 students and more than 187 faculty, staff, research assistants, and distinguished lecturers from 32 countries to Cleveland, Ohio, this summer. The session was hosted by Cleveland State University (CSU) and the Ohio Aerospace Institute (OAI) and sponsored by LeRC, OAI, CSU, and a group of northern Ohio businesses. Among the invited presenters were several LeRC personnel. Howard Ross, Robert Friedman, and Sandra Olson gave presentations on combustion science. Ross gave a talk titled "Burning to Go: Combustion on Orbit and Mars;" Friedman spoke on "Spacecraft Fire Safety;" and Olson lectured on "Out of This World Fire Science: How Solids Burn in Microgravity." Representing fluid physics, Francis Chiaramonte gave a presentation on "Pool Boiling in Microgravity" as a topic of interest relative to the ISU Microgravity Activities for Generating International Cooperation (MAGIC) design project. Henry Nahra, project scientist for the Behavior of Rapidly Sheared Bubbling Suspension project, presented a lecture on aspects of his work in a discussion with the MAGIC project design teams. Dennis Stocker organized tours of microgravity exhibits in LeRC's Visitor's Center and Zero-Gravity Facility. Stocker and Eric Baumann used a microgravity demonstrator to explain the principle of freefall and led a tour that watched a drop in the 2.2-Second Drop Tower. David Francisco presented the Combustion Integrated Rack, which will be placed on the International Space Station.

LeRC also hosted over 40 summer students and high school and college faculty under the sponsorship of a number of summer programs. These summer employees were able to contribute their talents and skills to the microgravity research program and interact with NASA scientists and engineers in both office and laboratory settings. The programs offered the students and faculty opportunities to acquire new skills and firsthand experience using NASA's unique facilities. Most of the students and teachers were introduced to the program through the Lewis Educational and Research Collaborative Internship Program, the Lewis Summer High School Apprenticeship Research Program, or the National Center for Microgravity Research Summer Internship Program.

Exhibits describing microgravity fluids and combustion research, the future of microgravity research on the International Space Station, and educational outreach performed by the MRP were provided at a number of events, including the installation of a drop tower in the Lewis Visitor's Center; displays and demonstrations at the National Science Olympiad; the 34th Joint Propulsion Conference sponsored by the American Institute of Aeronautics and Astronautics, the American Society of Mechanical Engineers, the Society of Automotive Engineers, and the American Society for Engineering Education; and a Space Station Celebration event at LeRC in which 1,000 people learned more about NASA, the International Space Station, and microgravity research. In addition, LeRC MSD representatives used the microgravity demonstrator and other devices at the Cedar Point and Geauga Lake amusement parks during their annual Physics Days to explain microgravity to middle and high school students and teachers. The MRP was also represented in the NASA exhibit at AirVenture '98. AirVenture '98 was the 44th annual fly-in at Oshkosh, Wisconsin. The event was sponsored by the Experimental Aircraft Association and drew a record 855,000 visitors.

Microgravity research media events coordinated by LeRC included the following highlights:

- Howard Ross, a senior researcher in the microgravity combustion science program, was a key participant in the February 1998 PBS video conference titled "ISS — Open for Business."
- A 15-minute segment on the History Channel's program "Fire Fighting — Extreme Conditions: Fire in the Sky," was broadcast March 17, 1998.
- *Popular Science* included microgravity fire and fluids photos as part of an article on the International Space Station in its spring 1998 issue.
- A sidebar piece by Ross on candle and solid combustion was included in an article by Shannon Lucid in the May 1998 issue of *Scientific American*.

LeRC MSD representatives arranged more than 40 school visits and tours at LeRC. In addition, MSD representatives arranged classroom visits by astronauts Donald Thomas and Roger Crouch and by Russian Academy of Science member Vadim Polezhaev.

Marshall Space Flight Center

MSFC's Microgravity Outreach and Education Office hosted several tours and workshops. Among these events was a tour for 50 U.S. and 30 international teachers selected by their respective state or country as Teacher of the Year. Their teaching disciplines included not only science and technology but also English, special education, math, music, geography, and foreign languages. The Outreach and Education Office provided four separate groups of teachers with an overview of microgravity and the benefits of conducting research in space. Microgravity educational products were made available to all teachers, and those teachers not in the science or math disciplines were encouraged to share them with their math and science colleagues.

A display providing an overview of each of the five microgravity science disciplines and a description of how microgravity is achieved was developed and installed in the new Microgravity Development Laboratory building at MSFC. The graphics developed for this display will serve as the foundation for future exhibits and brochures.

An updated version of the MSFC biotechnology program exhibit made its rounds to national conferences and meetings for the first time in 1998 and exposed many in the scientific community to the program. Approximately 4,500 scientists and professionals affiliated with the Biophysical Society, the American Pharmaceutical Association, the Biomaterials Society, and the American Crystallographic Association received information at conferences and through mailings about NASA's role in the field of biotechnology. In addition, 134 names were added to the biotechnology database that will be used to inform scientists of future NASA Research Announcements. The program shared its exciting protein crystal growth story with the American Pharmaceutical Association membership through a NASA session titled "Pharmacy in Space."

Microgravity Data Archiving

The Microgravity Research Program Office at MSFC manages the Microgravity Flight Data Archive (MFDA), which houses descriptions of experiment procedures and results, lists of publications, and points of contact for flight-based microgravity investigations. The archive has elements that reside at MSFC (biotechnology and materials science investigations) and LeRC (investigations in combustion science and fluid physics). In FY 1998, the MSFC portion of the MFDA became interoperable with the European Space Agency's (ESA's) online Microgravity Database. This cooperative work led to the design of the International Distributed Experiment Archives (IDEA), which allows a single access point for searching and browsing information on microgravity experiments from both archives. IDEA is available at *http://mgravity.itsc.uah.edu/microgravity/idea/idea.stm*. FY 1999 plans for IDEA include developing access to the Japanese space agency's (NASDA's) online microgravity database.

Also in FY 1998, the local web pages and underlying database for the MSFC biotechnology and materials science elements of the MFDA were updated. The IDEA web site now provides an integrated interface for searching local and international records. Records from recent experiments were added, and duplicate ESA records were purged. Plans for FY 1999 are to begin redesigning the archive database for integration of information from multiple sources, enhance reporting capabilities, as well as to provide interactive tools to allow experiment investigators to directly enter information into the archive database.

LeRC has been actively building its archive collection in the areas of combustion science and fluid physics. There are over 715 combustion science papers and over 446 fluid physics papers in the archive; a listing of the papers by author, along with abstracts from the papers, is being made available on the WWW. The experiments database currently consists of information on a number of recent experiments, along with information on a few experiments from earlier missions. This information, contained in Experiment Data Management Plan (EDMP) databases, includes such items as experiment descriptions; lists of publications associated with the experiment; summaries of experiment results and data; and listings of videos, photos, and digital data. In FY 1998, archivists continued gathering data on fluids and combustion experiments from all missions previously flown. The EDMPs are being formatted for the WWW and will be available online in FY 1999. Photographs from the experiments will also be added to the database in late FY 1999 and early FY 2000.

Table 12 Important Microgravity WWW Sites

NASA Home Page
Information and links to all NASA centers
http://www.nasa.gov/

Microgravity Research Division Home Page
NASA headquarters' Microgravity Research Division and microgravity sites with links to other news and 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/

Marshall Space Flight Center (MSFC) Home Page
Information about MSFC, current shuttle missions, the International Space Station, and research at MSFC's labs
http://www1.msfc.nasa.gov/

Lewis Research Center (LeRC) Home Page
Information on LeRC, including the work of its Microgravity Science Division and descriptions of special facilities, such as the Wind Tunnel Complex, the Propulsion System Laboratory, and drop towers
http://www.lerc.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 and fluid physics experiments
http://www.lerc.nasa.gov/WWW/MCFEP/

Microgravity Research Experiments (MICREX) Database
Information on microgravity experiments with a link to the European Space Agency (ESA) Microgravity Database
http://mgravity.itsc.uah.edu/microgravity/micrex/micrex.stm

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 LeRC drop towers
http://zeta.lerc.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

What Is Microgravity?
The definition of microgravity and how it is achieved
http://microgravity.msfc.nasa.gov/wimg.html

LeRC Microgravity Science Division Educational Information
LeRC microgravity educational activities and links to other NASA educational sites
http://zeta.lerc.nasa.gov/new/school.htm

NASA Spacelink: A Resource for Educators
NASA education information, materials, and services, including NASA Educator Resource Centers
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/

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.lerc.nasa.gov/ugml/ugml.htm

Funding for the Microgravity Research Program in fiscal year (FY) 1998 totaled $139.6 million. This budget supported a variety of activities across the microgravity science disciplines of biotechnology, combustion science, fluid physics, fundamental physics, and materials science (the Advanced Technology Development Program is also shown in this depiction), including an extensive ground-based research and analysis program; development and flight of microgravity shuttle and sounding rocket missions; ISS planning, technology, and hardware development; and educational outreach. The funding distribution for combined flight and ground efforts in the various microgravity research disciplines is illustrated in **Figure 1.**

Figure 1 — FY 1998 microgravity funding distribution by science discipline

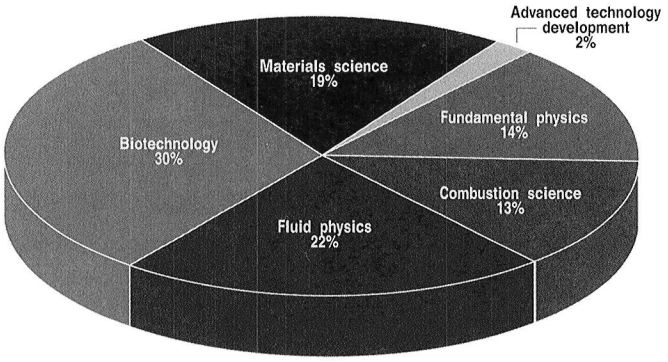
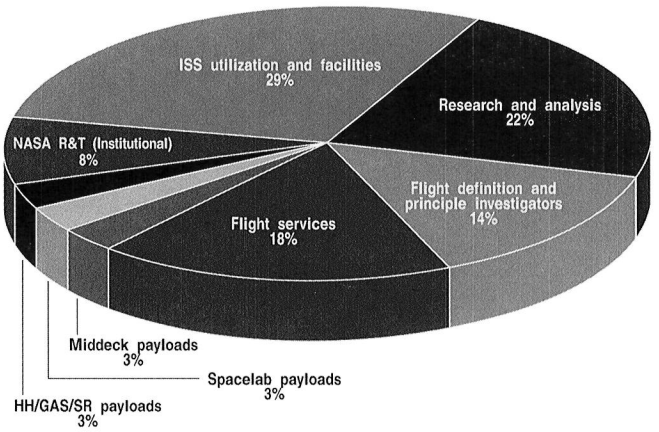


Figure 2 presents the funding distribution by microgravity mission function. Included in this representation is the research and analysis element that supports the ground-based microgravity principal investigators (PIs) not covered in a mission-specific budget. PI funding associated with flight investigations and flight services (including science, engineering, and management support and parabolic aircraft and suborbital rocket fees) is identified. Middeck payloads; Spacelab payloads; and Hitch-Hiker (HH), Get-Away Specials (GAS), and Suborbital Rocket (SR) payloads are separately identified. The NASA Research and Technology (R&T) institutional portion covers elements such as Program Mission Support and Headquarters-Incurred Costs. The International Space Station (ISS) element represents funding for experiments for the ISS and *Mir* programs.

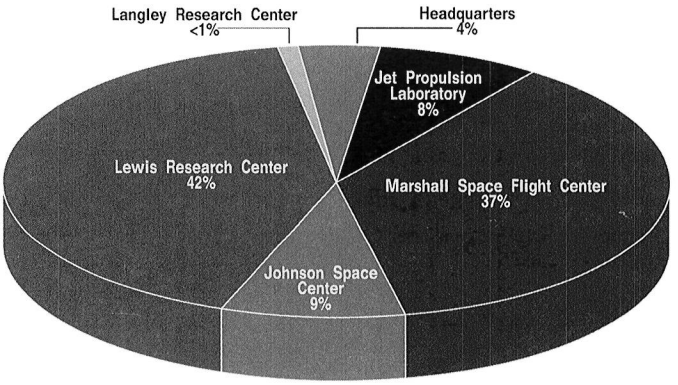
Figure 2 — FY 1998 microgravity funding distribution by mission function



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:

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

Figure 3 — FY 1998 microgravity funding distribution by NASA field centers



For More Information 8

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/

9 Acronyms and Abbreviations

AADSF ..... Advanced Automated Directional Solidification Furnace
ACES ..... Atomic Clock Ensemble in Space
AIAA ..... American Institute of Aeronautics and Astronautics
AIChE ..... American Institute of Chemical Engineers
AIDS ..... acquired immunodeficiency syndrome
APS ..... American Physical Society
ARIS ..... Active Rack Isolation System
ASME ..... American Society of Mechanical Engineers
ATD ..... Advanced Technology Development
atm ..... atmosphere
BDU ..... Bioreactor Demonstration Unit
BEC ..... Bose-Einstein condensation
BIO3D ..... Biotechnology of Three-Dimensional Tissue Engineering
BRS ..... Bioproduct Recovery System
BSTC ..... Biotechnology Specimen Temperature Controller
BTF ..... Biotechnology Facility
BTR ..... Biotechnolgy Refrigerator
Caltech ..... California Institute of Technology
CDOT ..... Colloid Disorder-Order Transition
CGEL ..... Colloid Gelation Experiment
CHeX ..... Confined Helium Experiment
CHT ..... Capillary-Pumped Heat Transfer
CIE ..... Center for Interfacial Engineering
CIR ..... Combustion Integrated Rack
CNES ..... French space agency
COCULT ..... Biotechnology Coculture
COLLIDE ..... Collision Into Dust Experiment
COSPAR ..... Committee on Space Research of the International Council on Scientific Unions
CPL ..... capillary-pumped loop
CSA ..... Canadian Space Agency
CSU ..... Cleveland State University
CT ..... computed tomography
CVX ..... Critical Viscosity of Xenon
CWRU ..... Case Western Reserve University
DACS ..... Data Acquisition and Control System
DARA ..... German space agency
DCAM ..... Diffusion-Controlled Protein Crystallization Apparatus for Microgravity
DC/PCG ..... Dynamically Controlled Protein Crystal Growth Apparatus
DLR ..... German Aerospace Research Establishment
DPIMS ..... Diffusion Processes in Molten Semiconductors
EDMP ..... Experiment Data Management Plan
ELF ..... Enclosed Laminar Flames
ERE ..... Extensional Reology Experiment
ESA ..... European Space Agency
ESTEC ..... European Space Research and Technology Center
EXPRESS ..... Expedite Processing of Experiments to Space Station
FACET ..... Fast Alternative Cryogenic Testbed
FCF ..... Fluids and Combustion Facility
FDA ..... Food and Drug Administration
FY ..... fiscal year
GAS ..... Get Away Special
GMSF ..... Growth and Morphology of Supercritical Fluids
GN_2 ..... gaseous nitrogen
GRP ..... gravitational and relativistic physics
GSM ..... Gas Supply Module
GSRP ..... Graduate Student Research Project
HEDS ..... Human Exploration and Development of Space
HH ..... Hitch-Hiker
HIV ..... human immunodeficiency virus
HOST ..... Hubble Space Telescope Orbital Systems Test
HRT ..... high-resolution thermometer
IDEA ..... International Distributed Experiment Archive
IDGE ..... Isothermal Dendritic Growth Experiment
IFFD ..... Internal Flows in a Free Drop
IML ..... International Microgravity Laboratory
IMSPG ..... International Microgravity Strategic Planning Group
IPCG ..... Interferometry of Protein Crystal Growth
ISS ..... International Space Station
ISU ..... International Space University
JPL ..... Jet Propulsion Laboratory

JSC ..... Johnson Space Center
LCAP ..... laser cooling and atomic physics
LeRC ..... Lewis Research Center
LIF ..... Large Isothermal Furnace
LMS ..... Life and Microgravity Spacelab
LPE ..... Lambda Point Experiment
LTCMP ..... low-temperature condensed matter physics
LTMPF ..... Low-Temperature Microgravity Physics Facility
MAGIC ..... Microgravity Activities for Generating International Cooperation
MAMS ..... Microgravity Acceleration Measurement System
MEPHISTO ..... Material for the Study of Interesting Solidification Phenomena on Earth and in Space
MFDA ..... Microgravity Flight Data Archive
MGM ..... Mechanics of Granular Materials
MGMG ..... Microgravity Measurements Group
MICREX ..... Microgravity Research Experiments
MIT ..... Massachusetts Institute of Technology
MMA ..... Microgravity Measurement Assembly
MRD ..... Microgravity Research Division
MRP ..... Microgravity Research Program
MRPO ..... Microgravity Research Program Office
MSD ..... Microgravity Science Division
MSFC ..... Marshall Space Flight Center
MSG ..... Microgravity Science Glovebox
MSL ..... Microgravity Science Laboratory
MSRF ..... Materials Science Research Facility
MSRR ..... Materials Science Research Rack
MW ..... molecular weight
NASDA ..... Japanese space agency
NCMRfc ..... National Center for Microgravity Research on Fluids and Combustion
NIH ..... National Institutes of Health
NIST ..... National Institute of Standards and Technology
NMR ..... nuclear magnetic resonance
NRA ..... NASA Research Announcement
NSF ..... National Science Foundation
OAI ..... Ohio Aerospace Institute
OARE ..... Orbital Acceleration Research Experiment
OPCG ..... Observable Protein Crystal Growth Apparatus
OSA ..... Optical Society of America
PCAM ..... Protein Crystallization Apparatus for Microgravity
PCG ..... protein crystal growth
PEP ..... Particle Engulfment and Pushing by a Solid/Liquid Interface
PI ..... principal investigator
PIMS ..... Principal Investigator Microgravity Services
PMMA ..... polymethyl methacrylate
RDR ..... requirements definition review
RSV ..... Respiratory Synctial Virus
R&T ..... Research and Technology
SAMS ..... Space Acceleration Measurement System
SAMS-FF ..... Space Acceleration Measurement System for Free Flyers
SAR ..... Shared Accommodations Rack
SBSL ..... single bubble sonoluminescence
SCR ..... science concept review
SL ..... Spacelab
SR ..... Suborbital Rocket
SRED ..... science requirements envelope document
SSCE ..... Solid Surface Combustion Experiment
STES ..... Single-Locker Thermal Enclosure System
STS ..... Space Transportation System
TEMPUS ..... Electromagnetic Containerless Processing Facility
TGDF ..... Turbulent Gas-Jet Diffusion Flames
TMS ..... Minerals, Metals, and Materials Society
UF ..... Utilization Flight
USML ..... United States Microgravity Laboratory
USMP ..... United States Microgravity Payload
VDA ..... Vapor Diffusion Apparatus
WCI ..... Wetting Characteristics of Immiscibles
WWW ..... World Wide Web
Zeno ..... Critical Fluid Light Scattering Experiment

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