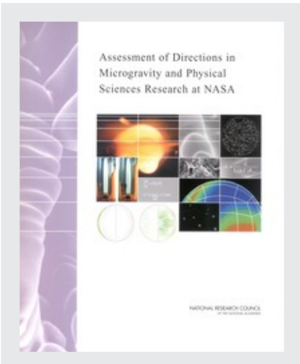

Assessment of Directions in Microgravity and Physical Sciences Research at NASA

DETAILS

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Committee on Microgravity Research; Space Studies Board; Division on Engineering and Physical Sciences; National Research Council

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Space Studies Board
Division on Engineering and Physical Sciences

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Preface

In October of 2000 NASA's Microgravity Research Division was reorganized as part of the reorganization of the Office of Life and Microgravity Sciences and Applications. As a result, the microgravity division—now known as the Physical Sciences Division—took on the responsibility for a broader range of research for NASA. As part of these responsibilities the division was expected to extend its programs in biotechnology and the physical and engineering sciences beyond the current focus on experiments for the International Space Station and to establish interdisciplinary research efforts in the areas of nanoscience, biomolecular physics and chemistry, and exploration research. The division was also tasked to contribute to the understanding of gravity-related physical phenomena in biological systems, working in concert with the Fundamental Space Biology Division and the Biomedical and Human Support Research Division. In general, the new division was expected to carry out (1) fundamental microgravity research, (2) microgravity research to support the development of exploration technologies, and (3) research across a range of other physical science disciplines to address specific NASA needs. Research in this third category might or might not be gravity related but was intended to draw on the unique knowledge base already available in the microgravity program.

Although the former microgravity division's role had been expanded beyond the scientific examination of gravity-related phenomena, its new role within NASA was not yet fully defined, and the additional resources available for new investigations were expected to be limited. There was a need, therefore, for a new charter to provide focus for the division's efforts, as well as a careful targeting of topics within the newly added research areas. NASA, therefore, requested that the Committee on Microgravity Research carry out a two-phase study containing the following elements:

- *Phase I.* As part of a preliminary study the committee was asked to develop an overall unifying theme, or "mission statement," for NASA's program in microgravity and physical sciences. This theme would encompass the expanded range of research that the program will undertake and would provide

NASA with broad scientific guidelines for determining whether specific research questions fall within the new program's purview. As part of this effort the committee would consider the appropriate role of the microgravity and physical sciences program with respect to other programs within NASA, such as the Human Exploration and Development of Space enterprise. The committee would also identify, in general terms, the research opportunities in the newly added discipline areas that could appropriately be pursued by the program.

- *Phase II*. During the second phase of the study the committee would identify more specific topics within the new discipline areas on which the division could most profitably focus. In doing this the committee would consider what special capabilities and knowledge exist in the current program that could be applied to the new disciplines being added to the program. The committee would also assess the current status of the division's research program and attempt to prioritize future research directions, including both current and new disciplines.

The phase I report was published in December of 2001. The results of the phase II study were released in prepublication form in November of 2002. This, the final edited text, supersedes all previous versions of this report.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Jerry Bernholc, North Carolina State University,
Carol A. Handwerker, National Institute of Standards and Technology,
Donald Ingber, Children's Hospital, Boston,
Daniel D. Joseph, University of Minnesota,
Robert Langer, Massachusetts Institute of Technology,
Carlo D. Montemagno, University of California, Los Angeles, and
William A. Sirignano, University of California, Irvine.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Rainer Weiss, Massachusetts Institute of Technology. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

CHARGE TO THE COMMITTEE AND BACKGROUND

Performing experiments in low Earth orbit has been the focus of much of the research funded by NASA's Physical Sciences Division (PSD) and its predecessors for over 30 years. This microgravity research can be divided into five broad areas, all of which focus primarily on phenomena that are strongly perturbed by gravity: biotechnology, combustion, fluid physics, fundamental physics, and materials science. To these disciplines, the Physical Sciences Division is considering adding research in such emerging areas as biomolecular physics and chemistry, nanotechnology, and research in support of the human exploration and development of space (HEDS). In response to a request from NASA, the Committee on Microgravity Research produced a phase I report (NRC, 2001), in which it proposed criteria for selecting additional research in these new areas and set forth a mission statement for the PSD.

The present report is the phase II report. In it, the committee identifies more specific topics within the emerging areas on which the PSD can most profitably focus. The committee also assesses the past impact and current status of the PSD's research programs in combustion, fluid physics, fundamental physics, and materials science and gives recommendations for promising avenues of future research. At NASA's request the committee did not address work in the biotechnology area, as that area had been the subject of a recent review (NRC, 2000a). In assessing the impact of the work, the committee considered the following points:

- The contribution of important knowledge from microgravity research on a given topic to the larger field of which the research is a part;
- The progress made by microgravity research in answering the questions posed on each topic; and
- The potential for further progress in each area of microgravity research.

Areas of future research in the existing disciplines are recommended, and guidance is given for setting priorities across these areas and within the emerging areas. The scientific impact of the existing disciplines, which was assessed by addressing the three indicators listed above, was a particularly important consideration when establishing priorities across the existing microgravity programs.

The microgravity program has evolved considerably since its inception as the materials processing in space program of the Skylab era. With the exception of the biotechnology program (NRC, 2000a), in the early 1990s a major emphasis was placed on outreach to the science communities of which the microgravity disciplines were a part. This outreach took the form of biannual conferences in each of the disciplines prior to the release of a NASA Research Announcement (NRA) and an extensive canvasing of the community with notification of the opportunity to apply for support. The result was much greater visibility for NASA's combustion, fluid physics, fundamental physics, and materials science programs within the larger fields of which they are a part, and an increase in the number of proposals submitted. The impact of this outreach became clear as the committee assessed the quality of the investigators and research in the NASA program. The early 1990s also saw the establishment of the fluid physics and combustion programs in their current forms and then, in the past 5 years, an expansion of the fundamental physics program. More recently, the PSD has begun to expand beyond the traditional microgravity-related disciplines to include research in which gravity may have no role, such as biomolecular physics and nanotechnology.

The recent financial problems of the International Space Station (ISS) have brought a major uncertainty to the future of the microgravity program. Many of the facilities that were destined for the ISS have been delayed, and the crew time available for science has been drastically curtailed (NRC, 2003). This financial crisis has also affected the ground-based research program. Whether this is a temporary setback or the beginning of the end of the microgravity program remains to be seen. Given the uncertainty, the committee did not consider what ISS resources would or would not be available when it formulated its findings and recommendations.

IMPACT OF MICROGRAVITY PROGRAM

In assessing the impact of the PSD-funded work in each of the existing microgravity disciplines (except, as mentioned, biotechnology), the committee employed a number of metrics. These included analysis of the citations received by papers, the citation rates for publications of research results, the prominence of the journals in which results were published, the changes to standard textbooks that resulted from research findings, documented influence on industry or NASA applications, and the fraction of principal investigators selected as fellows of various societies, elected as members of the National Academies of Engineering or Science, or chosen for other recognition such as awards in their field.

Below is a partial listing of the research topics that have had an impact on their respective field:

- The fluid physics research program has produced a large body of significant research in areas ranging from flows due to surface tension gradients to the dynamics of complex liquids—with important applications to industrial processes such as oil recovery and to NASA flight technologies. The unique access to space provided by NASA has led to the development of ground-based and flight research programs that have enabled growth and advancement of research in such fields as thermocapillary flow, and it has attracted leading investigators to the program, including members of both the National Academy of Sciences and the National Academy of Engineering, as well as numerous fellows of professional societies.
- The combustion research program has made important contributions to the fundamental understanding of such combustion behavior as the chemical kinetics of flames and flame length variation,

resulting in the correction of both basic theory and college textbooks. The results of studies on smoldering, flame spread, radiative transfer, and soot production not only have led to changes in spacecraft fire safety procedures, but also have advanced knowledge about some of the most important practical problems in combustion on Earth. Some of these results are already being incorporated into industry applications such as aircraft combustor design. The NASA combustion program currently supports some of the most distinguished combustion scientists in the world, including members of the National Academy of Engineering and numerous fellows of professional societies.

- The fundamental physics research program has made important contributions to both basic theory and the practice of research in such areas as critical point physics and optical frequency measurement, and the work of its investigators is published frequently in the leading scientific journals. Access to the space environment enabled a definitive test of the widely applicable renormalization group theory,[1] while ground-based research sponsored by the program led to an orders-of-magnitude reduction in the labor, physical infrastructure, and time needed for scientists around the world to perform optical frequency measurements. The program has attracted high-caliber talent, including six Nobel laureates and over two dozen investigators who are either members of the National Academy of Sciences or fellows of professional societies.
- Research in NASA's materials program has led to major theoretical insights into solidification and the crystal growth process and has resulted in both the verification and refutation of classical theories predicting materials solidification behavior and microstructural development. Much of this work also has direct relevance to important commercial processes such as casting and semiconductor production, and research results have been utilized by such diverse industries as metal-cutting tool production (to improve a production process responsible for hundreds of millions of dollars in annual costs) and jet engine manufacturing. Investigators have received numerous prestigious awards for their work in this program, and a high percentage of them are professional society fellows and members of the National Academy of Engineering and National Academy of Sciences.

HIGH-PRIORITY MICROGRAVITY RESEARCH

Listed below are the areas of research judged by the committee to have a high priority within each microgravity discipline. It should be kept in mind that there are numerous additional areas of promising research in each of the fields that were not given the highest priority at this time and thus were not explicitly recommended. Some of these areas might achieve a higher priority in the future. In addition, the committee expects that in future years the communities will generate new research topics that will be as promising as those recommended here.

Fluid Physics

Fluid physics should continue to play a dual role in NASA's physical sciences research program. For scientists in general, the program provides access to a unique laboratory that permits the isolation and study of the effects of nongravitational forces on fluid behavior. For NASA, the program provides the basis for acquiring knowledge necessary for the development of the next generation of mission-enabling technologies essential to NASA's human exploration and development of space. The recommended areas of research are these:

[1] For which the Nobel Prize in physics had previously been awarded.

- *Multiphase flow and heat-transfer technology.* This is a critical technology area for space exploration and a sustained human presence in space (NRC, 2000b) and is relevant to numerous terrestrial technologies.
- *Self-assembly and crystallization.* Such research is expected to advance fundamental knowledge of phase transitions and lead to innovation in terrestrial technologies—for example, the fabrication of novel materials such as photonic crystals.
- *Complex fluid rheologies.* The behavior of complex fluids, such as the particle dynamics and segregation flows of dry granular materials or magnetorheological fluids, is important to technologies needed for NASA's HEDS efforts as well as to numerous industrial applications.
- *Interfacial processes.* Surface-tension-related phenomena are important for a number of mission-related technologies, and the microgravity environment offers experimentalists expanded length scales on which to observe interfacial phenomena compared to Earth.
- *Wetting and spreading dynamics.* Experimental and theoretical research in these areas is necessary for improved understanding of thin-film dynamics in a variety of applications from coating flows to boiling heat transfer.
- *Capillary-driven flows and equilibria.* Capillary-driven flows and transport regimes associated with evaporation and condensation are important for both terrestrial and space-based applications.
- *Coalescence and aggregation.* Research on the effects of gravity (and its absence) on coalescence and aggregation is necessary for HEDS since these processes are important to power and life support systems.
- *Cellular biotechnology.* Improved understanding of transport processes in bioreactors is important for HEDS medical applications and could lead to significant advances in the biological sciences and the biotechnology industry by improving the ability to control tissue and cell growth.
- *Physiological flows.* Fluids research in connection with biomedical applications (both terrestrial and space-related) will be necessary, for example, to better define paths to effective countermeasures for bone loss in microgravity and to explore the behavior of red blood cells in suspension.

Combustion

The microgravity combustion research program has been driven by two objectives: (1) a need to understand those physical phenomena thought to be relevant for spacecraft fire safety and (2) a desire to deepen knowledge of fundamental combustion processes on Earth. Both of these objectives are addressed by the following high-priority research:

- *Development of computer simulations of fire dynamics on spacecraft.* Earth-based fire protection techniques have evolved through thousands of years of fire-fighting experience. Since there is no such experience base for space fires, physics-based computer simulations are the only alternative. Such simulations have also proved to be of great value in assessing fire safety and control strategies for fires on Earth.
- *Research on ignition, flame spread, and screening techniques for engineering materials in a microgravity environment.* The goal of the research is the development of a science-based method for determining the fire performance of materials that are candidates for use in space. The results would also be directly usable in the space fire computer simulation codes referred to above. The two programs taken together would provide a major advance in the understanding of fires in space and in the ability to mitigate their consequences.
- *Safety of oxygen systems.* One of the critical systems on the ISS and other space, lunar, and

planetary habitats is the oxygen generation and handling system. Thus an understanding of the dynamics and extinguishment of fires involving oxygen is necessary.

- *Smoldering combustion.* Smoldering and transition to flaming combustion are significantly different in microgravity than on Earth and thus require additional studies.
- *Soot and radiation.* Basic processes that lead to the formation and emission of small carbon particles in high-temperature combustors remain to be understood, and radiation heat transfer has many critical implications for fire safety.
- *Turbulent combustion.* Turbulence in general and turbulence in the presence of combustion are exceedingly difficult phenomena to model and understand. Nevertheless, most industrial combustion devices and natural fires involve turbulent combustion, and thus the potential impact of this work is large.
- *Chemical kinetics.* The chemical kinetics and reaction mechanisms of practical fuels and fuel blends of interest to industry remain unknown.
- *Nanomaterial synthesis in flames.* Flames provide an inexpensive means of producing nanoparticles for mass use. The work to date has generally been empirical, and opportunities exist for understanding the chemical composition and thermal structure of the flow that is conducive to synthesis of the desired forms of materials.

Fundamental Physics

In fundamental physics, the committee gave high priority to the successful execution of the specific experiments that have already been selected for flight on the ISS. These experiments will test important fundamental principles in physics, and in most cases an experiment's success would end any further need for space experimentation in that area. These already-selected experiments, along with new areas that have been given high priority, are as follows:

- *Currently Selected ISS Experiments*

—*Low-temperature experiments.* The results of the four planned experiments, along with the results of experiments that have already flown, are expected to provide a full picture of the equilibrium behavior of systems near critical points, including the role of boundaries and the dynamical response to perturbations.

—*Relativity and precision clock experiments.* The results of these experiments are expected to substantially improve the precision and stability of atomic clocks.

—*Other NASA clock application experiments.* By flying other types of clocks simultaneously with the atomic clock experiments, such fundamental ideas as the Einstein weak equivalence principle can be tested.

- *New Areas*

—*Antimatter search and measurements.* A positive identification of heavy antimatter would be highly significant for astrophysics and cosmology.

—*Elemental composition survey.* Measurement of the cosmic-ray elemental composition up to and beyond the "knee" in the cosmic-ray spectrum should provide the best clues to the origin of cosmic rays.

Materials Science

Materials science has played a central role in many of the discoveries that have shaped our world, from integrated circuits to low-loss optical fibers and high-performance composite materials. These research areas, which also contain many subdiscplines, will continue this tradition of science-driven discoveries of great importance to both the nation and NASA:

- *Nucleation process within, and properties of, undercooled liquids.* The nucleation process plays a prominent role in setting materials properties. Currently the conditions governing the nucleation of stable and metastable phases are not well understood.
- *Dynamics of microstructural development during solidification.* The ability to directly link processing conditions to the resulting materials properties is still not at hand because the mechanisms governing the development of microstructure during solidification are not well understood.
- *Morphological evolution of multiphase systems.* The properties of a material are linked to the size, shape, and spatial distribution of the component phases. Understanding the morphological evolution of these systems will allow prediction of the manner in which the properties of a material evolve.
- *Computational materials science.* It is now possible to design a material using simulations to obtain a desired set of properties. This capability will create a new paradigm for designing industrially relevant materials because the materials will be created with a minimum of costly, time-consuming experiments. This approach can have a significant impact on NASA as it ensures that the desired materials properties of interest to NASA will be attained, and in a greatly reduced time and at lower cost.
- *Thermophysical data of the liquid state in microgravity.* Accurate thermophysical data for the liquid state is required for computational modeling of materials processing.
- *Nanomaterials and biomimetic materials.* There are many promising avenues for materials research at the nanoscale and at the interface between the biological and materials sciences. These new directions are discussed in Chapter 7, "Emerging Areas," and are listed below.

HIGH-PRIORITY RESEARCH IN THE EMERGING AREAS

Emerging technologies, particularly at the confluence of the biological, physical, and engineering sciences at the nanoscale, offer NASA an ideal opportunity to address its own technology needs by leveraging knowledge gained from the worldwide investments in these fields. NASA should stay in a position to capitalize rapidly on anticipated advances in nanotechnology. This includes building and maintaining sufficient in-house expertise and ensuring that the PSD reaches out to new communities since many disciplines are involved, including physics, chemistry, biology, materials science, medical science, and engineering. Important technologies for fabricating new materials and devices will originate from novel approaches to molecular assembly, combined with nano- and microfabrication tools and the exploitation of design principles inspired by nature. The following topics were identified by the committee as the most promising areas of future research relevant to NASA's needs and PSD capabilities:

- *Methods for long-term stabilization of proteins in vitro.* Long-term preservation of protein function is essential to the utilization of proteins in space in sensors, for diagnostics, and in bioreactors on extended flight missions.
- *Cellular responses to gravity-mediated tissue stresses.* Developing a mechanistic understanding of how applied loads and stresses affect cellular processes and the underlying molecular processes will lead to a better understanding of the impact of low-gravity conditions on human health.
- *Technologies to produce nanoengineered hybrid materials with multiple functions.* Investments in nanoengineered materials consisting of diverse molecular species or phases, or hybrid materials,

could provide NASA with new materials that can sense, respond, self-repair, and/or communicate with the user.

- *Integrated nanodevices*. Emerging technologies for engineering micro- and nanodevices able to sense, process acquired data, and take action based on sensory inputs could contribute significantly to achieving NASA's goals.
- *Power generation and energy conversion*. Nanotechnology promises to increase the efficiency of energy conversion, decrease weight, and increase the overall energy density for energy storage.
- *Knowledge base for stabilizing cell function in vitro*. Efforts to stabilize cells may represent an effective strategy for producing needed cell types to meet emergencies on demand while eliminating the need to keep an extensive inventory of cell types available in space.

RESEARCH PRIORITIES AND PROGRAM DIRECTIONS

In order to assess and compare research across the microgravity disciplines, the committee critically examined the potential impact of the research on the scientific field of which it is a part, on NASA's technology needs, and on industry or other terrestrial applications. The committee's evaluation of research in each of these categories is expected to assist NASA program planners by providing the insight into likely risks and potential rewards of the research necessary to create a vibrant microgravity research program that has an impact in all of these areas.

Because of the brief history and rapid development of the fields of research in the emerging areas, it was not possible to evaluate research in those areas using the same criteria applied to the research in combustion science, fluid physics, fundamental physics, and materials science. While the likelihood that PSD-funded research in emerging areas will have significant impacts on NASA capabilities cannot be evaluated at this time, the magnitude of the impact of successful research is potentially very high. Therefore the committee ranked the research topics in the emerging areas only relative to each other and suggests that the PSD utilize this prioritization to help allocate funds that have been set aside for these emerging areas.

Prioritizing Microgravity Sciences Research

When comparing research *across* disciplines, the committee considered only those areas already identified above as having a high priority for one of the disciplines. To evaluate the recommended research areas, the committee separately judged the likelihood that the research would have a significant impact in (1) the scientific field of which it is part, (2) industry or terrestrial applications, and (3) NASA technology needs. Within each of these categories the committee looked specifically at both the magnitude of the potential impact that the research would have on that category, and the likelihood that the research would be successful in achieving that impact. The impact and probability of success were assessed independently of each other since it was possible for areas with a potential for high impact to have a low probability of success and vice versa. The results of the committee's assessment are plotted in Figures ES.1, ES.2, and ES.3. Note that the setting of actual research priorities must depend on NASA's programmatic goals and that those goals determine both the desired end result, such as scientific discovery, and the level of acceptable risk. The purpose of these plots, then, is to provide NASA with tools that it can use to rationally select the best research, regardless of which combination of scientific discovery (Figure ES.1), terrestrial applications (Figure ES.2), or NASA technology needs (Figure ES.3) NASA chooses to emphasize or what trade-offs between research risk and reward it is willing to accept.

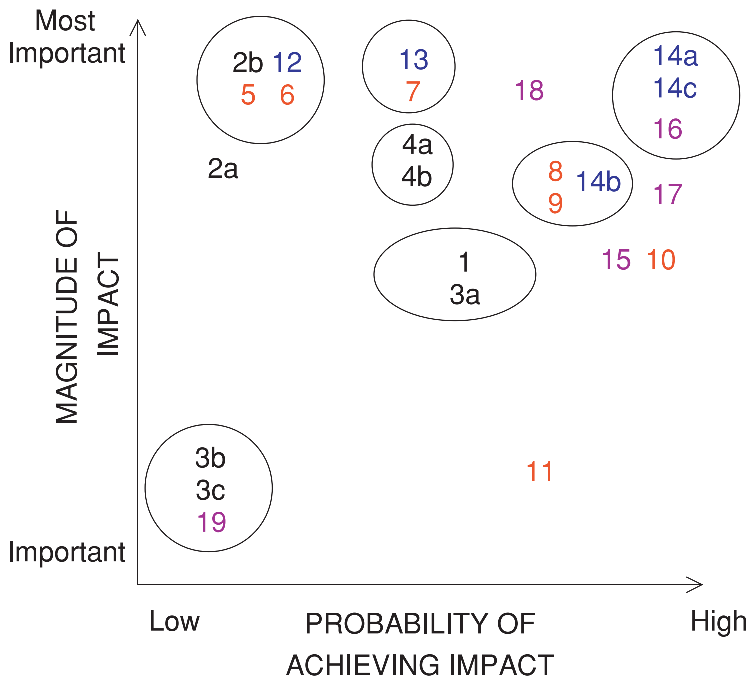

FIGURE ES.1 Assessment of research topics in terms of their likely impact on scientific knowledge and understanding.

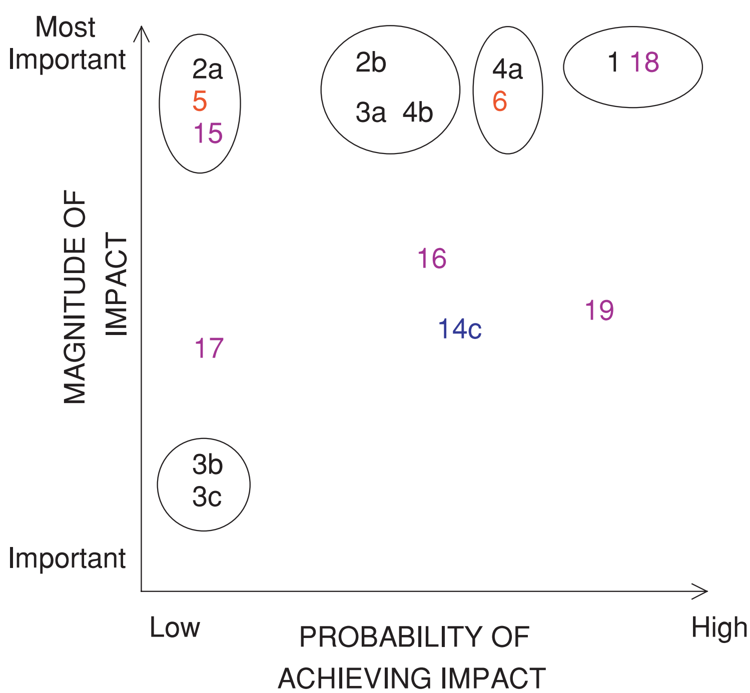

FIGURE ES.2 Assessment of research topics in terms of their likely impact on terrestrial applications such as industry's technology needs.

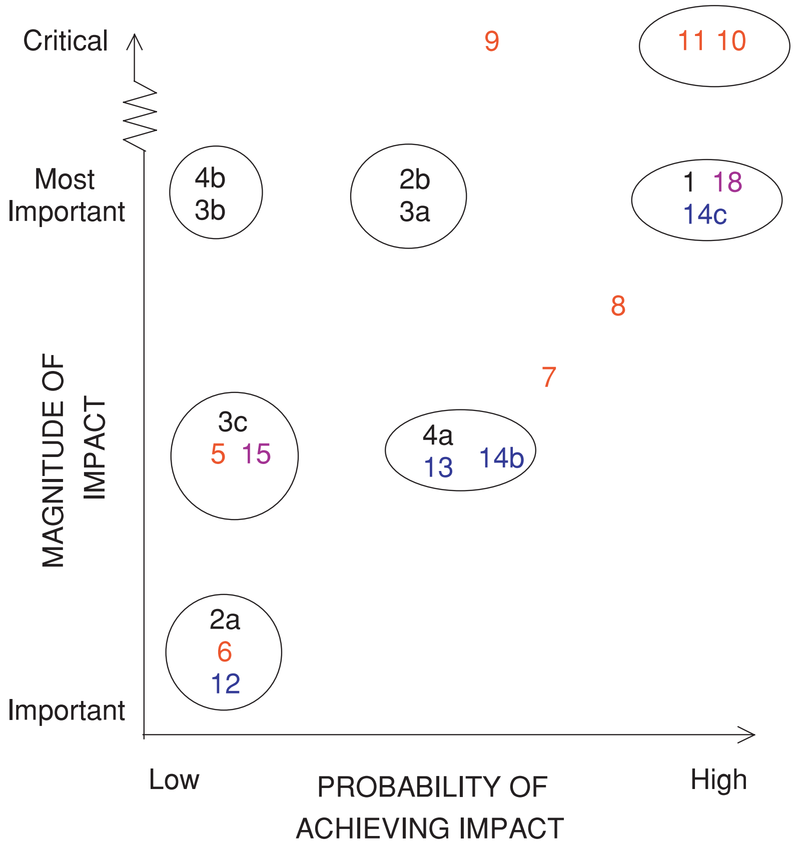

FIGURE ES.3 Assessment of research topics in terms of their likely impact on NASA's technology needs.

FIGURES ES.1, ES.2, and ES.3:

Only subjects already considered by the committee to be of high priority in at least one discipline are included in this analysis, and therefore the magnitude scale ranges only from important to very important (or critical). A subject may not have a high impact in every category and therefore may not appear in every figure. Numbers inside the same circle should be considered to occupy approximately the same position in the figure. The numbers in the figures represent the research topics as follows:

1. Multiphase flow and heat transfer;
2. Complex fluids: (a) self-assembly and crystallization, (b) complex fluid rheologies;
3. Interfacial processes: (a) wetting and spreading, (b) capillary-driven flows and equilibria, (c) coalescence and aggregation (liquid phase);
4. Biofluid dynamics: (a) cellular biotechnology, (b) physiological flows;
5. Turbulent combustion;
6. Chemical kinetics;
7. Soot and radiation;
8. Smoldering combustion;
9. Development of computer simulations of fire dynamics on spacecraft;
10. Oxygen systems fire safety;
11. Ignition, flame spread, and screening techniques for engineering materials;
12. Antimatter search/measurements;
13. Elemental composition survey;
14. Complete the current set of fundamental physics ISS experiments: (a) low-temperature experiments, (b) relativity and precision clock experiments, (c) other NASA clock application experiments;
15. Nucleation process within, and the properties of, undercooled liquids;
16. Dynamics of microstructural development during solidification;
17. Morphological evolution of multiphase systems;
18. Computational materials science;
19. Collection of thermophysical data of liquid state in microgravity.

Priorities in the Emerging Areas

All of the areas recommended below satisfy the criteria identified in the phase I report for choosing research in the emerging areas (NRC, 2001). The development of methods for the long-term stabilization of proteins in vitro and research on cellular responses to gravity-mediated tissue stresses are of higher priority than the others, because these areas are not typically supported by other agencies. The research on exploiting nanotechnology for power generation and energy conversion is also ranked "most important" because of the great importance of power generation and energy conversion in NASA's spaceflight program and the major impact these technologies may have on this program. The remaining areas, ranked as important, are heavily supported by agencies such as the Defense Advanced Research Projects Agency, the Department of Energy, the National Science Foundation, and the Department of Defense as well as by other divisions within NASA. Thus the PSD should partner with these agencies or other divisions within NASA to pursue such research. In the past, the PSD has successfully partnered with other agencies, such as the National Cancer Institute. The recommended topics are given below. Note that these are not rank-ordered within each category.

Most Important

- Develop methods for the long-term stabilization of proteins in vitro.
- Work on understanding cellular responses to gravity-mediated tissue stresses.
- Exploit nanotechnology for power generation and energy conversion.

Important

- Develop enabling technologies to produce nanoengineered hybrid materials with multiple functions.
- Develop integrated nanodevices.
- Develop methods for stabilization of cellular function in vitro.

Program Balance

When considering the question of the overall balance within the PSD between microgravity research and research in the emerging areas, the committee looked at several factors. These included the degree of support received by topics in emerging areas from other government agencies and other divisions within NASA, the considerable potential of the microgravity research disciplines to yield important new results, the potentially high impact of successful research in emerging areas, and the ability of the PSD to provide unique resources or knowledge. These and other factors argued for a balanced PSD program of research that retains the unique potential for studying the effects of gravity on phenomena in combustion, fluid physics, materials, fundamental physics, and biotechnology topics such as tissue culturing. The committee concluded that the proportion of the physical sciences program devoted to the emerging areas should remain relatively modest, perhaps 15 percent of the program, until such time as a clear justification arises for increasing its size. This fraction of the program should allow NASA to have an impact on a limited number of highly focused topics within the broad emerging areas while leveraging the research of other agencies. It would also permit the majority of the research in the microgravity areas to continue to produce the high-impact results described in the discipline chapters.

Peer Review

The committee has commented numerous times in past studies on the role that rigorous peer review has had in greatly improving the quality of the research funded by the Physical Sciences Division, and strongly recommended its continued use in future funding selections (NRC, 1994, 1997, 2000b). As the program moves into new areas of research it is worth emphasizing again that any research proposal submitted to the program—no matter how relevant to an area considered highly desirable for inclusion in the program—should be funded only if it has undergone a rigorous peer review and has received both high marks for scientific merit and a high ranking compared with competing proposals.

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1

Introduction and Overview

Performing experiments in low Earth orbit has been the primary focus of much of the research funded by NASA's Physical Sciences Division (PSD) and its predecessors for over 30 years. That research examined phenomena in which the physical processes under investigation are significantly affected by gravity. Along with experiments destined for flight, in the past 10 years the division has made a concerted effort to develop an extensive ground-based research effort. The ground-based program includes research in which gravity plays a major role and that, in addition, (1) requires further experimentation to demonstrate conclusively both the need for a microgravity experiment and the importance of the results that could be obtained from a spaceflight experiment or (2) involves only theoretical investigations. More recently, the PSD has begun to expand beyond the traditional microgravity-related disciplines to include research in which gravity may have no role, such as biomolecular physics and chemistry and research in support of the human exploration and development of space (HEDS).

The traditional program can be divided into five broad areas, all of which focus primarily on phenomena that are strongly perturbed by gravity. These areas are biotechnology, combustion, fluid physics, fundamental physics, and materials science. The biotechnology program focuses primarily on two fields—protein crystal growth and the effects of gravity on cell and tissue formation. The combustion program encompasses efforts ranging from research in support of fire safety in space to studies of basic combustion phenomena. The research in fluids involves projects on topics as diverse as colloidal crystallization and pattern formation during convection. Fundamental physics had its genesis as a low-temperature physics program but more recently has been expanded to include topics such as laser cooling, cosmic rays, and atomic clocks. The materials science program has funded research in a wide variety of areas, from solidification and crystal growth to the thermophysical properties of liquids cooled far below their melting points.

To these existing disciplines the PSD is considering adding research in biomolecular physics and chemistry and in nanotechnology, as well as research in support of HEDS. In its phase I report (NRC, 2001), the Committee on Microgravity Research proposed two criteria for adding research in these new areas:

1. Directly address challenges at the interface between the physical sciences, engineering, and biology in support of NASA's mission, preferentially capitalizing on existing expertise or infrastructure in the Physical Sciences Division, and
2. Support research either not typically funded by other agencies or to be conducted in close partnership with other agencies.

The phase I report also identified broad areas of promising research into which the division might expand: nanoscale materials and processes, biomolecular physics and chemistry, cellular biophysics and chemistry, and integrated systems for HEDS. Detailed descriptions of research in these areas are provided in this report.

Establishing priorities between the existing microgravity programs and research in the new areas requires assessing the impact of the research and the quality of the investigators in the existing microgravity program. Clearly, it is not in the best interest of NASA or the nation to deemphasize a vibrant, productive program simply to move into a new research area, while it is equally clear that poorly performing programs should not be continued. Accordingly, in this report the Committee on Microgravity Research assesses the research in the existing microgravity program, paying attention to the following:

1. The degree to which knowledge gained from microgravity research on a given topic has contributed to the larger field of which the research is a part;
2. Progress in understanding the microgravity research questions posed on each topic; and
3. The potential for further progress in each area of microgravity research.

To assess quantitatively the impact of the NASA-funded work, the committee employed a number of metrics. While any of these metrics taken alone can be misleading, a synthesis of more than one provides a reasonable measure of the success of a program. Literature citations of the research were one of the possible metrics used by the committee. A given paper cited in this report as an example of strong impact was generally selected because it either was known to have been highly cited in the literature (the number of citations needed to qualify varies with subfield) or because it had a high citation rate (in the case of a recent publication). Other metrics used by the committee to judge the importance of an investigation were the prestige of the journal in which the results were published, whether the results caused textbooks to be altered, and whether there is any documented influence on industry or NASA.

At NASA's request the committee did not examine the NASA biotechnology effort as this program was recently reviewed (NRC, 2000); however, in the interests of completeness the findings and conclusions of that study have been encapsulated in this report.

The microgravity program has evolved considerably since its inception as the materials processing in space program of the Skylab era. With the exception of the biotechnology program, in the early 1990s a major emphasis was given to outreach to the science communities of which the microgravity disciplines were a part. This outreach took the form of biannual conferences in each of the disciplines prior to the release of a NASA Research Announcement (NRA) and extensive canvasing of the community with notification of the opportunities to apply for support. The result was a large increase in the visibility of the combustion, fluid physics, materials, and fundamental physics programs and in the number of proposals submitted. The impact of this outreach became clear as the committee assessed the quality of the investigators and of the research in the program. That time frame also saw the establishment of the fluids and combustion programs in their current forms, and in the past 5 years, there has been an expansion of the fundamental physics program.

In addressing these issues in the traditional microgravity disciplines, it is necessary to remember that there are drawbacks to performing microgravity experiments that do not exist for ground-based experimentation. This problem is a basic dilemma that must be considered in any evaluation of the microgravity program. Aside from the obvious financial costs, which are not addressed further in this report, the difficulty of extracting large amounts of data from the microgravity environment cannot be ignored. An earthbound laboratory can in principle bring to bear a large array of diagnostic equipment and accommodate the often sizable space requirements of the experiment. Moreover, if long run times are needed to collect data, the ground-based laboratory routine can be adjusted to accommodate such a requirement. These advantages are difficult to achieve in microgravity. Thus, the limited data set acquired in microgravity will only be of value in instances where it is nearly impossible to extract the same information under normal laboratory conditions. Moreover, performing experiments in space frequently requires the development of instrumentation that is unique to a particular experiment. This can require a significant lead time, often on the order of a decade or more, which takes up a significant portion of an investigator's career. When combined with limited flight opportunities, these drawbacks explain the relative scarcity of flight experiments in many disciplines over the past decade.

The recent financial problems of the International Space Station (ISS) have brought a major uncertainty to the future of the microgravity program. Many of the facilities that were destined for the ISS have been delayed, and the crew time available for science has been drastically curtailed. Although additional funding for a few of the facilities has been secured, their final status remains uncertain. The original 2002 operational date for the ISS has slipped by several years. Moreover, as the report of the International Space Station Management and Cost Evaluation Task Force noted, "The existing ISS Program Plan for executing the FY 02-06 budget is *not credible*" (IMCE, 2001). An analysis of the effects of the ISS cutbacks on the science that can be performed on the ISS is given in *Factors Affecting the Utilization of the International Space Station for Research* by the NRC Task Group on Research on International Space Station (NRC, 2003). The financial crisis has also affected the ground-based program. For example, a current NRA explicitly states the following: "[D]ue to severe resource limitations, we do not plan to make flight definition awards in the combustion area from this NRA" (NASA, 2001). Whether this is a temporary setback or the beginning of the end of the microgravity program remains to be seen. Given the uncertainty in the future, the committee did not consider the availability of ISS resources in formulating its findings and recommendations.

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2

Fluid Physics Research Program

INTRODUCTION AND BACKGROUND

Fluid physics, while having an identity entirely its own, also serves as the underpinning of a large portion of the physical sciences research program of NASA's Office of Biological and Physical Research (OBPR). Indeed, it is the absence of buoyancy-driven fluid (liquid or gas) convection (that on Earth is caused by density variations coupled with gravitational acceleration) that gives rise to the curious phenomena observed in weightless environments. Hence, in microgravity, observations of spherical flame fronts, symmetric dendrite formation during solidification processes, unusual colloidal structures, and the growth of some living tissues and macromolecular protein crystals that differ from their terrestrial counterparts are all attributable to the lack of buoyant convection. Thus, the Physical Sciences Division's programs in combustion, materials, fundamental physics, and biotechnology all share an intersection with fluid physics.

The motivation for investigating fluid behavior under the unique conditions afforded by NASA's microgravity facilities is the desire to further the understanding of the complex behavior of fluids by taking advantage of near-weightless conditions to make measurements and observations that are not possible in terrestrial laboratories and, thereby, study physical phenomena typically overwhelmed by buoyant convection. Many problems that occur due to the effects of buoyancy, sedimentation, hydrostatic pressure gradients, or limitations due to the small length scales of interfacial processes under normal gravity conditions can be avoided in microgravity. Indeed, some of the earliest problems associated with spaceflight that required solutions also are of a fluid-physics origin. For example, the problem of liquid management in space is exacerbated by the absence of gravity that on Earth keeps the liquid at the container "bottom." Solutions suitable for short-duration missions or longer missions with resupply capability will need to be rethought for future long-duration manned missions to Mars owing to more stringent mass limitations. Likewise, both life-support and heat-transfer systems rely on the transport of multiphase flows, knowledge of which is far from complete.

The fluid physics program of NASA's OBPR supports both flight- and ground-based research. Since 1992 five major research thrust areas have emerged: (1) dynamics and instabilities, (2) complex fluids, (3) multiphase flow and heat transfer, (4) interfacial phenomena, and (5) biofluid dynamics. Some of these areas (for example, areas 1, 3, and 4) have a richer history in terms of program support than others (for example, areas 2 and 5) and have therefore yielded longer "threads" of related research. A few of these threads are highlighted in the following section to provide a picture (rather than an extensive program review) of the program, and their impact is then discussed.

FLUID PHYSICS RESEARCH: SELECTED EXAMPLES

Thermocapillary Phenomena

Thermocapillarity is the variation of a liquid's surface tension (or of the interfacial tension between two immiscible liquids) with temperature. Thus, the existence of an interfacial-temperature gradient produces a force that drives interfacial, and hence bulk, fluid motion. (Surface tension-driven flows can also occur when there are surface gradients in composition.) When the OBPR's physical sciences research program was known as the materials processing in space program, one early endeavor focused on the use of the containerless float-zone crystal-growth process to improve the size and quality of crystals of semiconductor materials in space, in the absence of the apparently detrimental effects of weight and buoyant convection. However, it was found that thermocapillary convection, which normally plays a secondary role to buoyant convection on Earth, becomes dominant in microgravity environments, and the detrimental "striations" observed in Earth-grown material were also observed in some space-grown crystals. Eyer et al. (1984) demonstrated that surface-temperature fluctuations (due to unstable themocapillary convection) at free melt surfaces cause these striations. Smith and Davis (1983a,b), in their related theoretical studies, discovered a new type of instability, the hydrothermal wave, that is relevant for some range of the liquid's Prandtl number. The Smith and Davis theory was later conclusively confirmed in the laboratory (Riley and Neitzel, 1998). Other research has been aimed at eliminating or suppressing the instability, for example, by using open-loop, feed-forward control. Terrestrial and spaceflight experiments (Kamotani et al., 2000) have also examined transitions to oscillatory flow in geometries other than liquid bridges (captive drops held between solid supports) and thin layers.

In addition to studying the instability of thermocapillary convection, considerable research has been done that utilizes thermocapillary convection to control the position and motion of liquids and gases in microgravity. In addition to their utility in microgravity, thermocapillary processes are useful in removing air bubbles from glasses during their manufacture. Recent extensions of these ideas are finding applications to problems encountered in moving liquids or gases through small channels in microelectromechanical systems (MEMS) devices.

Other NASA-sponsored work dealing with thermocapillarity has either developed independently of the above research or been spawned by it. For example, recent studies (Dell'Aversana and Neitzel, 1998) showed that noncoalescence can be sustained by thermocapillary-driven flow in a thin region separating two drops of the same liquid phase. Current work on this subject is investigating the possibility of using noncoalescing nonwetting systems as nearly frictionless bearings for low-load applications.

Capillary Phenomena

Interfacial or capillary phenomena are those features of liquid-gas or liquid-liquid interfaces other than the thermocapillary phenomena discussed above. These phenomena are of particular interest to

NASA because of the need to manage liquids in weightless environments, but they also pertain to problems encountered in terrestrial environments. Capillary effects such as wicking in heat pipes (Faghri, 1995; Peterson et al., 1998), capillary pumped loops (Westbye et al., 1995), and vane structures in cryogenic storage (Dodge, 1990) can be used to manage the disposition and transport of liquids under weightless conditions. The dynamics of moving contact lines is an important but poorly understood aspect of wetting that is the subject of investigation in ground and flight experiments (Decker and Garoff, 1997; Weislogel and Lichter, 1998) and is associated with thin films, coating flows, and drying processes such as the removal of rinse water from the surface of a silicon wafer during wet processing. Contact-line dynamics affects the behavior of vapor bubbles in boiling, where to adequately model nucleation of bubbles on the heater surface requires knowledge of the dynamic contact angle behavior.

The study of capillary surface equilibrium shapes and their stability is a well-established area of research. Configurations of interest to NASA researchers have ranged from liquids partly contained in angular (Concus and Finn, 1990) and smooth-walled containers (Slobozhanin and Alexander, 2001) to captive drop or liquid bridges (Lowry and Steen, 1995). Interest in the latter was motivated by materials-processing techniques such as float-zone crystallization and zone refining. In addition to analyzing the stability of such configurations, recent research has focused on using forced flow (Lowry and Steen, 1997) and acoustic (Morse et al., 1996) and electric fields (Burcham and Saville, 2000; Marr-Lyon et al., 2000) to stabilize liquid bridge configurations that would otherwise be unstable. The oscillations, dynamics, and break-up of drops, jets, and other free surfaces have been and continue to be studied (e.g., Agrawal et al., 2000; Eggleton et al., 2001; McKinley and Tripathi, 2000). While there is a great deal of classical and current literature on capillary dynamics, many problems remain unsolved, for example, those of sloshing or other motions that require knowledge of contact-line behavior and await improvements in our understanding of contact-line dynamics.

Complex Fluids

Research on the rheology and thermodynamical behavior of complex fluids (colloids, granular materials, plasmas, and foams) has emerged as a prominent part of the ground-based and flight programs following the 1991 NASA Research Announcement. That there are similarities between these apparently different systems was illustrated recently (Trappe et al., 2001). For example, a number of systems—including colloids, granular media, foams, and molecular systems—can undergo nonequilibrium transitions between different fluidlike states and from fluidlike states to solidlike states. Colloids, granular media, and molecular systems can exhibit “jamming,” where crowding of the component particles prevents them from further exploration of the phase space. Recent results suggest that attractive interactions in colloidal systems may have the same jamming effect as confining pressure in granular media and that a jamming phase diagram for attractive colloidal particles provides a unifying link between the glass transition, gelation, and aggregation.

Microgravity research on colloids is focused on disorder-order transitions in hard-sphere colloidal dispersions (Cheng et al., 1999; Zhu et al., 1997) and on binary colloidal structures (Hiddessen et al., 2000). Microgravity experiments on colloids were motivated by the emerging field of colloid engineering and directed self-assembly of mesoscopic structures. Colloidal phase diagrams, growth kinetics, and physical properties obtained from flight experiments and supporting ground-based research will yield information that will facilitate the use of colloidal precursors to fabricate novel materials. Flight experiments flown between 1996 and 1998 involved monodisperse hard-sphere colloids, binary colloidal alloys, and colloid-polymer mixtures; they have produced rich and in some cases unexpected results, such as coarsening during crystallization (Cheng et al., 2002). Ground-based research has included the examination of fractal colloidal aggregation and the behavior of colloid polymer gels. This research has been productive, yielding the first detailed information about the consequences of scale-invariant structure on the properties of colloids (Cipelletti et al., 2000).

The entropically driven growth of colloids in low volume-fraction systems has also been investigated (Crocker et al., 1999). Crystallization in low volume-fraction suspensions is driven by attractive particle interactions caused by the entropic depletion. Entropic depletion creates a condition not unlike supersaturation. This drives the ordered aggregation of the particles. These interactions create growth conditions similar to those associated with atoms and molecules; this is in direct contrast to the "space-filling" mode of colloidal crystal growth that is driven by packing constraints. In the low volume-fraction limit, nucleation of colloidal crystals can occur on a surface in the absence of bulk phase separation. The use of surface templates offers further options for controlling the growing structures (Crocker et al., 1999).

Aspects of crystallization are being investigated through experiments on plasma dust crystallization. In these experiments, spheres interact through a shielded Coulomb potential, causing them to arrange in liquidlike structures or solidlike structures. The "condensed" (liquid and crystalline) states of colloidal plasma systems were studied under microgravity conditions (Morfill et al., 1999). The observed states represented new forms of matter: quasi-neutral, self-organized plasmas. In contrast to states observed in terrestrial measurements, the systems under microgravity are three-dimensional and exhibit stable vortex flows, sometimes adjacent to crystalline regions, and a central "void" free of microspheres. Related ground-based research on plasma dusts has also yielded fruitful results—for example, Pieper and Goree (1996) examined the applicability of fluid-based dispersion relations to strongly coupled dusty plasmas. They measured real and imaginary parts of the complex wave number for low-frequency compressional waves in dusty krypton plasma. Their results agreed with a theoretical model of damped dust acoustic waves, ignoring strong coupling, but not with a strongly coupled dust-lattice wave model.

Complex fluid rheology is an emerging research area that promises to take advantage of low-gravity conditions to isolate particular aspects of fluid rheology. Magnetorheological fluids are composed of magnetically soft particles dispersed in liquids. Applied magnetic fields can then be used to alter their properties rapidly and reversibly. Ground-based experiments by Furst and Gast (1999) on magnetorheological fluids have made some advances. They investigated the micromechanical properties of dipolar chains and columns in a magnetorheological suspension. Using optical tweezers, they directly measured the deformation of dipolar chains parallel and perpendicular to the applied magnetic field and observed the field dependence of mechanical properties such as resistance to deformation, chain reorganization, and rupturing of the chains. These forms of energy dissipation are important for understanding and tuning the yield stress and the rheological behavior of magnetorheological suspensions.

Foams have unique rheological properties that, depending on the stress-strain conditions, range from solidlike to fluidlike. For example, at small-amplitude strains, foams can deform and recover their shape elastically; at larger strains, viscoelastic behavior occurs (manifested by a hysteretic strain-energy curve), and if the strain exceeds a critical value, the foam flows. Foam rheology has thus far been studied only on the ground (Gopal and Durian, 1999).

Granular dynamics has emerged as a new area in the fluid physics program. Results to date are ground-based. For example, Howell et al. (1999) carried out experiments on a slowly sheared two-dimensional granular material and found a continuous transition as the packing fraction (the ratio of solid [granular] and total volumes) passed through a value equal to 0.776. As the critical packing fraction is approached from above, the compressibility becomes large, the mean velocity slows, the force distributions change, and the network of stress chains changes from a tangled dense network to intermittent long radial chains near the critical value. Other planned space experiments involve the influence of inertia on segregation in granular systems with two particle sizes (Louge et al., 2001), and flight experiments are planned for the ISS.

Multiphase Flow and Heat Transfer

Although it has been of interest to the microgravity program for some time, microgravity research in multiphase flow has not been pursued vigorously within the fluid physics program (however, multiphase flow research is pursued outside the program by other NASA divisions). As discussed in previous NRC reports (NRC, 1995, 2000), NASA is well aware that designers of future space systems must face a number of issues and concerns related to multiphase flow and heat-transfer processes in weightless and reduced-gravity environments. Applications involving such processes include gas-liquid and liquid-liquid systems for advanced life support operations (evaporators, condensers, thermal buses, and electrolysis units) and particulate-fluid systems that are encountered in association with planetary exploration (dust control in human habitats, in situ processing of planetary materials for power, and so on). Preliminary low-gravity experimentation (mostly on KC-135 aircraft) has identified low-gravity flow regimes and phase distribution in isothermal gas-liquid flows.

Boiling heat transfer has been studied extensively outside NASA's program over the last 50 years, and there has been some interest in determining boiling heat-transfer regimes under low-gravity conditions. However, results obtained in low-gravity drop facilities and aircraft have been contradictory, with some data showing that pool boiling heat fluxes were insensitive to changes in gravity level, and other data suggesting that heat-transfer rates are enhanced in low-gravity conditions. A significant unknown in the prediction and application of flow boiling heat transfer in microgravity is the upper limit of the heat flux for the onset of dryout (or critical heat flux) for given conditions at fluid-heater surfaces, including geometry, system pressure, and bulk liquid subcooling. Furthermore, the dependence of the critical heat flux on gravity has yet to be fully explained. As a result, there is still no rational basis for predicting pool boiling heat transfer under microgravity conditions (NRC, 1995, 2000). Current research in the program is focused on these and related issues, but future progress requires access to longer-duration low-gravity conditions than can be provided by drop facilities or aircraft.

Biofluid Dynamics

Although fluids clearly play a role in many biological processes, biofluid dynamics has only recently emerged as a thrust area within the fluid physics program. To date, ground-based studies in this area have focused on two themes: microgravity effects on transport across endothelial cell membranes (Chang et al., 2000a,b) and capillary-elastic instabilities in the closure and reopening of small airways in lungs in microgravity (Howell et al., 2000).

IMPACT OF THE FLUID PHYSICS RESEARCH PROGRAM

The need to understand the behavior of liquid propellants under weightless conditions was recognized in the early days of NASA's space program, and it can be argued that the roots of microgravity fluids research extend back to early experimental and theoretical work in this area. The fluid physics program became established in its own right following the 1991 NASA Research Announcement (NRA). Until then, fluids research had played only a secondary role in that most of it was motivated by or directly related to materials research.

Research in thermocapillarity, however, has been dominated by NASA-sponsored investigations for the last couple of decades. For example, a simple search in the Institute for Scientific Information (ISI) science citation index for 1980, 1985, 1990, and 1995 yielded 9, 7, 38, and 80 articles, respectively, showing the expansion of the field in just over 15 years. NASA-sponsored investigators were and continue to be leaders in thermocapillary flow research. The importance of thermocapillary flows in low gravity was discussed by Ostrach (1982). Early work that established the foundations for subsequent thermocapillary flow research was performed by Sen and Davis (1982), who obtained the first solutions for thermocapillary-driven convection in bounded geometries. Smith and Davis (1983a,b) proposed the existence of a hydrothermal wave mechanism for thermocapillary flow instability. Oscillatory thermocapillary flows were later discussed by Ostrach et al. (1985). VanHook et al. (1997) recently resolved a long-standing disagreement between theory and experiment in the formation of hexagonal patterns during Marangoni instability of a thin liquid layer heated from below. (Marangoni instability of a static fluid state occurs when flow arises due to surface tension gradients caused when an initially flat isothermal surface deforms to a non-planar non-isothermal surface.)

Thermocapillary flow research, originally motivated by problems in crystal growth techniques, has been undertaken outside NASA's program and adapted to other technologies. For example, recent innovations involving thermocapillarity include liquid positioning in MEMS devices (APS, 2000; Gwynne, 2000; Mazouchi and Homsy, 2001) and microchip thermocapillary pumps for DNA analysis (Sammarco and Burns, 2000; Kataoka and Troian, 1999).

Some research themes (complex fluids, multiphase flow, biofluids) are still developing. Nevertheless, ground-based research has already yielded new results. For example, the work of Furst and Gast (1999) involving magnetorheological fluids is an important step in the understanding of the effect of magnetic fields on fluid behavior. Such fluids are used in advanced vibration technology (ranging from loudspeakers to automobile-braking systems) and as cooling fluids in transformers and are an attractive option for controlling fluids in weightless environments.

As noted previously, the colloid experiments flown between 1996 and 1998 have produced rich and in some cases unexpected results, such as coarsening during crystallization (Cheng et al., 1999). Work by Crocker et al. (1999) established surface templates as another option for controlling the growing structures. These preliminary results from experiments on colloids show every indication that future work in complex fluids will produce significant results. Indeed, a recent article (Anderson and Lekkerkerker, 2002) on the insights into phase-transition kinetics that can be obtained from colloid science attests to this.

Other work on complex fluids has also begun to have an impact. Experiments by Howell et al. (1999) on granular flow have established a continuous order-disorder transition in stress distribution as a function of the granular-packing fraction. In addition to its scientific value, this work is an important step toward understanding the flow dynamics of granular media. The processing of granular media is important in industries ranging from food storage and packaging to pharmaceuticals. Approximately 50 percent of the chemical industry products and at least 75 percent of the raw materials are in granular form (Nedderman, 1992) amounting to $61 billion annually. It is estimated (Jaeger et al., 1996) that 60 percent of the capacity of many U.S. industrial plants is wasted because of problems related to the transport of granular materials. Thus, the impact on industry of even small gains in understanding the dynamics of granular media should be profound.

Flight investigations into the liquid and crystalline states of colloidal or "dusty" plasma systems (Morfill et al., 1999; Thomas et al., 1994) revealed new forms of matter: quasi-neutral, self-organized plasmas. Pieper and Goree (1996) resolved a long-standing controversy over the applicability of fluid-based dispersion relations to strongly coupled dusty plasmas. The pioneering work of these investigators has resulted in a rapid increase in published research on dusty plasmas over the last 10 years.

While NASA-supported (through the fluid physics program) multiphase-flow research has produced some significant advances (for example Dukler et al., 1988), this work is cited infrequently, possibly because it is mostly relevant to secondary and tertiary oil recovery in the petroleum industry and to NASA fluid system designers.[1] In a more general context, interest in the link between small-scale fluids processes and larger-scale continuum hydrodynamics led to significant work by Koplick and Banavar (1995) that clearly demonstrated the link between specific fluid processes at the molecular scale and the large continuum scale. This work is significant because it quantifies the extent to which continuum models can be expected to give reliable predictions at very small length-scales.

Aside from fundamental contributions to specific topic areas, the overall impact of the fluid physics research program can be put into perspective by considering the following: In 2001 there were 110 PIs in the program. Between 1998 and 2000, the research sponsored by the program produced several hundred papers that were published in internationally recognized journals (NASA, 1998-2000). Of these papers, over 120 were published in the *Journal of Fluid Mechanics* and *Physics of Fluids*, two prominent journals for fluid dynamics; 44 in *Physical Review Letters*, a leading physics journal; 8 in *Nature*; and 7 in *Science*. (The last two are recognized as the two premier journals covering all of science.) Furthermore, 4 of the fluid physics program's investigators are members of the National Academy of Sciences, 8 are National Academy of Engineering members, and there were 37 fellows of the American Physical Society, 5 fellows of the American Society of Mechanical Engineers, and 12 fellows of the American Institute of Aeronautics and Astronautics.

FUTURE DIRECTIONS IN FLUID PHYSICS RESEARCH

Fluid physics should continue to serve a dual purpose in NASA's physical sciences research program. For scientists in general, it provides access to a unique laboratory that permits the isolation and study of the effects of nongravitational forces on fluid behavior. For NASA, the program facilitates the acquisition of knowledge necessary for the next generation of mission-enabling technologies essential to NASA's human exploration and development of space. Indeed, the need for improvements in the understanding and application of fluid phenomena (e.g., multiphase-flow processes) has already been recognized as one of the primary opportunities for future fluids research (NRC, 2000). In what follows, the committee outlines areas of research that should be pursued, their significance, and the expected benefits of the results. In some cases, these recommendations are similar to those of an earlier NRC report on the role of microgravity research in support of technologies for the human exploration and development of space (NRC, 2000), and more details can be found in that report. In other instances, the recommendations are based on the promise of advances in fundamental knowledge or innovation in terrestrial technologies.

Research motivated entirely by NASA's mission must be made visible across all organizations within NASA. This is essential if the work is to enter into the conceptual stages of mission and mission systems design. Furthermore, it is essential that OBPR personnel keep the research community (outside and inside NASA) apprised of design issues that could be resolved through research within the OBPR. Research that is solely related to NASA's space exploration mission can be assigned a high priority only if OBPR meets this obligation.

[1] J. Sherwood, principal research scientist, Schlumberger, letter dated December 10, 2001.

Multiphase Flow and Heat Transfer

Multiphase-flow and heat-transfer technology is a critical technology for space exploration and a sustained human presence in space (NRC, 2000) and has relevance to numerous terrestrial technologies. NASA has often avoided using multiphase systems and processes in spacecraft because their behavior under low-gravity conditions is not well understood. Without a quantitative understanding of such systems, the design of revolutionary mission-enabling technology will be either severely impeded or forestalled altogether.

Research on multiphase flow and interfacial processes is essential to providing a knowledge base for the development of mission-enabling technologies with the potential to bring about revolutionary changes in spacecraft hardware (NRC, 2000). Phase-change systems for power, propulsion, and life support will be required for reliable long-term operation and improved efficiency. For example, two-phase liquid-vapor heat rejection systems lead to significant reductions in vehicle size, volume, and weight. The dynamics of miscible and immiscible interfaces in two-phase flows has relevance to advanced life support systems and to terrestrial applications such as secondary oil recovery. Droplet dynamics and liquid atomization (in, for example, sprays) occur in power and propulsion systems and in thermal control systems. Bubbly flows, such as those that occur in thermohydraulic loops, also need improved understanding so that problems anticipated under microgravity conditions can be addressed. Under terrestrial conditions, gravity usually dominates the behavior of many of these multiphase systems, affecting such important parameters as heat transfer, pressure drop, interfacial area in multiphase liquids, flow stability, and transitions. There is much to be learned about the behavior of these systems under low-gravity conditions.

Specific examples of research topics that should be pursued are (1) the identification of low-gravity flow regimes, the mechanisms that govern the effects of gravity, and interfacial and bulk constitutive laws for specific flow regimes through experiments and the synergistic development of computer-modeling capabilities; (2) assessment of the effects of gravity on forced convective boiling, two-phase forced convective heat transfer, and convective condensation heat-transfer; (3) investigation of schemes for active and passive single- and two-phase heat transfer and pressure drop reduction; and (4) assessment of the effects of gravity on flow regimes and the stability of adiabatic and two-phase boiling flows in porous media, and on flows in porous media used for plant or crop growth for food sources.

The results of this research will have significant impact on NASA's space exploration program, and the increased knowledge of constitutive laws for multiphase-flow systems will undoubtedly impact industry here on Earth (e.g., thermal systems, power generation, waste treament, and mineral separations technology).

Complex Fluids

Self-assembly and Crystallization

Recent advances using new imaging techniques that allow direct observation of individual colloidal particles undergoing phase transitions have elucidated some of the details underlying transitions between gas, liquid, solid, and liquid crystalline phases. These transitions, while ubiquitous in nature, are not always accessible to experiment. Preliminary microgravity experiments have demonstrated the value of conducting such experiments in a weightless environment and have already produced surprising results. Colloidal research planned for the ISS and in complementary ground-based programs will provide a knowledge base for self-assembly in the fluid phase. Self-assembly of colloids offers a direct route to the fabrication of micro- and nanoscale devices with controllable structure and properties. Such research is also expected to advance fundamental knowledge and lead to innovation in terrestrial technologies—for example, the fabrication of novel materials such as photonic crystals.

Complex Fluid Rheology

The fluid physics program has already initiated research on the rheological behavior of other complex fluids, such as the particle dynamics and segregation flows of dry granular materials, or magnetorheological fluids. Preliminary results are promising, and these studies should be continued. Improved understanding of granular flows will also be beneficial to in situ resource utilization (ISRU) (on planetary exploration missions) and to the industrial processing and packaging of granular materials (pharmaceuticals, food, building materials, and so on). The ability to tailor rheological response to rapidly changing conditions using magnetorheological fluids has already led to their incorporation into active damping control systems and braking systems and into cooling systems for electrical transformers. Their use in weightlessness has additional appeal since they could replace buoyancy as a means of controlling fluid motion. Furthermore, the manipulation of a small volume of liquid at microscales has clear overlap with research areas recommended in the emerging technology areas in Chapter 7.

Interfacial Processes

In low gravity, surface-tension-related phenomena can dominate liquid behavior. At small length scales, gravity is often not a controlling factor in determining the disposition of small liquid volumes, and surface forces predominate. Thus, research on interfacial processes will be important for mission-related technologies and for terrestrial applications. The microgravity environment of a low-Earth-orbit laboratory allows for the isolation of interfacial effects such as surface tension and offers experimentalists expanded length scales on which to observe interfacial phenomena and compare them with the same phenomena on Earth.

Wetting and Spreading Dynamics

Experimental and theoretical research in these areas is necessary for improved understanding of thin-film dynamics in a variety of applications that range from coating flows to boiling heat transfer. Contact-line dynamics can control the coating of solid surfaces, the cooling of hot surfaces, and the behavior of vapor bubbles in boiling. On a macroscopic scale, contact angles depend on contact-line speeds and, hence, on flow driven by gravity. Ultrathin liquid films can rupture, i.e., form dry spots, as a consequence of intermolecular attractions, creating new contact lines. Such considerations are important in the design of, for example, micro heat pipes. There is also overlap with research issues in microfluidics and nanotechnology, discussed in the next chapter.

Capillary-Driven Flows and Equilibria

Surface tension depends on the temperature of the interface and the concentration of impurities, regardless of whether they are intentional or accidental. When temperature and/or concentration vary along a fluid-fluid interface, stresses are created that drive motions in the fluid that enhance the transport of heat and mass. Steady motions can become unstable and lead to time-oscillatory behavior. Such variable surface-tension effects can control the migration of suspended droplets or the motion of droplets on solid surfaces and can be exploited to control droplet placement in low-gravity environments.

Capillary-driven flows and transport regimes associated with evaporation and condensation are important for both terrestrial and space-based applications. Such flows occur in chip-based chemical assays, micro heat pipes, and larger-scale space-based systems, and they merit further investigation.

Capillary equilibria associated with filling and maintaining liquid volumes are important for small-scale applications on Earth and for both small- and large-scale space applications. Under low-gravity conditions, surface tension can control the shapes and stability of liquid bodies. Small disturbances can dramatically shift the position of a liquid from one portion of the container volume to another, leading to configurational changes that can be important for the drainage of fuel tanks, fluids handling, and the storage of cryogenic fluids. While much work has already been done in this area, research on capillary equilibria needs to be extended to meet specific problems posed by spacecraft fluid system geometries and to applications involving microfluidic devices (see also Chapter 7).

Coalescence and Aggregation

Phase separation involves the isolation of a solid, liquid, or gas or all three from the liquid or gas in which it or they are dispersed. Numerous fluid-fluid phase-separation processes rely on the coalescence or aggregation of dispersed phases to form continuous phases, for example, droplet condensation, boiling, condensation, and foam drainage. Relative motions caused by gravity, thermocapillary forces (due to the temperature dependence of surface tension), and intermolecular forces all contribute to foam drainage and film rupture, which can be either advantageous or disadvantageous, depending on the application. Research on the effects of gravity or its absence on coalescence and aggregation is necessary for the human exploration and development of space (HEDS). These processes are important to power and life support systems for HEDS (e.g., the separation of liquid phases or the removal of bubbles or solid particles from a liquid in waste management systems) and to many related terrestrial applications.

Biofluid Dynamics and Related Interdisciplinary Research

New synergies gained from using the insight and techniques of fluid physics and transport phenomena in the world of biological sciences hold considerable promise. Future research directions that can evolve out of preexisting research themes in the fluid physics program are outlined below. New research directions in biofluids, such as microfluidic systems for drug delivery, are discussed in Chapter 7.

Cellular Biotechnology

Growth of tissues and cells in bioreactors has been motivated by the engineering of human tissues for a variety of transplantation purposes from articular cartilage in the knees to pancreatic cells for the treatment of diabetes. Studies of tissues and cell cultures grown in terrestrial bioreactors and microgravity bioreactors have shown striking differences in morphology and structural properties. These differences are attributed to the presence or absence of gravity and the resulting differences in flow patterns within the bioreactor. The flow within the bioreactor is known to influence growth, morphology, and structure, by virtue of shear stress exerted on the tissue or cell and mass transfer. To design and operate bioreactors more effectively and efficiently requires a better understanding of these effects. Advances in the understanding of transport processes in bioreactors will be of interest to NASA from the viewpoint of HEDS medical applications and will lead to significant advances in the biological sciences and the biotechnology industry by enabling better control of tissue and cell growth.

Physiologic Flows

The elimination of gravity is known to affect the human body through the modification of stresses and transport processes. In the lungs, air-liquid interface problems occur in relation to airway closure and reopening, and particle deposition and clearance are particularly important where dusty planetary environments are expected. Bone loss and regeneration experienced during long-term spaceflight are influenced by transport processes, as are other intercellular and intracellular functions. Fluids research in connection with biomedical applications (both terrestrial and space-related) will be necessary to better define paths to effective countermeasures.

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3

Combustion Research Program

A major fire in space resulting in any type of loss of mission will not be excused by the public and will lead to decades of setback for all kinds of space research and space applications. (p. 34)

INTRODUCTION

The NASA microgravity combustion research program has always been driven by two objectives: a desire to understand the physical phenomena thought to be relevant for spacecraft fire safety and a wish to deepen our knowledge of fundamental combustion processes on Earth (Sacksteder, 1990; Ross, 1993; Urban and King, 1999; Faeth, 2001). The absence of any safe refuge in space makes the prevention or containment of small fires a subject of critical importance to NASA, and fire safety will remain critical as long as a human presence in space remains part of NASA's activities. Two of the three requirements needed to initiate a fire—an oxygen-containing environment and an energy source for ignition—are basic elements of any life support system. Elimination of the third element, a combustible fuel, has been a focus of both microgravity research and space vehicle design for decades. However, it remains an elusive goal, because almost all materials are combustible in the presence of oxygen at sufficiently high temperatures (for example, an aluminum storage canister burning with pure oxygen initiated the Mir fire). Moreover, all manned spaceflights have embarked with large amounts of even more readily ignitable materials.

Microgravity is useful for the study of fundamental combustion processes on Earth because the most basic combustion phenomenon is the release of heat. The resulting density changes induced in the reacting gases on Earth generate buoyancy forces that strongly influence the mixing and transport of the reactants at all but the smallest scales of motion. Much of what one wants to understand about combustion takes place precisely at these small scales, which are often inaccessible to measurements on Earth. Moreover, buoyancy makes combustion phenomena extremely complex. The study of buoyancy-driven flows is an important field in its own right. Fluid convection induced by mechanically controlled pressure differences and buoyancy forces introduced by the thermal energy released by combustion together with radiative transport of part of that energy dominate the transport of mass, momentum, and energy in most earthbound combustion scenarios (e.g., power generation, furnaces, fires). The chemical reactions usually occur at the smallest length scales. These length scales are typically set by a balance between the rate at which chemical reactions liberate energy and transform mass, and the molecular diffusion that transports the reactants into and energy away from the thin flame zones where combustion chemistry occurs. This transport is highly localized and is only effective if the larger-scale processes have provided the immediate vicinity of the flame with an adequate supply of reactants and an appropriate thermal environment. The large density changes in flames induced by the release of chemical energy cause significant buoyancy-induced motion, impeding studies of combustion phenomena on Earth (Faeth, 2001). As a result, much of the basic theory in this field has been developed under the assumption that the effects of gravity can be ignored at the smallest scales relevant to combustion, even though most earthbound experiments do involve effects of larger-scale, buoyancy-induced motions. This has made the inevitable conflict between simplified theories and earthbound experiments extremely difficult to resolve.

The most important feature of the current NASA combustion program, then, is access to a microgravity environment. The negligible buoyancy in such an environment means that many small-scale effects, which are often masked on Earth (Sacksteder, 1990), can be probed in space. In addition, there are many practical situations that occur on a scale too small for buoyancy to normally be a factor. However, when these are simulated on a larger scale on Earth, buoyancy then becomes important, thereby modifying the physics. The microgravity environment allows this scale-up without introducing buoyancy, so that similitude is maintained and the measurement and resolution are improved. If the microgravity time requirements are not too demanding, the NASA 2-second and 5-second drop towers are also available. Special-purpose aircraft flying trajectories designed to provide a reduced gravity environment can also be used if the level and the steadiness of the microgravity required for the experiment are not too demanding. A useful description of how these facilities achieve microgravity is given by Ross (2001).

Many of the combustion processes have been found to require long times to reach a steady state from the time of ignition under microgravity conditions (Ross, 2001). Flames that are ignited in normal gravity and then subjected to microgravity behave very differently from those ignited under microgravity. The sooting tendency of flames in limited-duration microgravity experiments was found to be vastly different from that of flames stabilized in extended-duration microgravity on the space shuttle (Faeth, 2001). Many of the combustion processes, such as flame balls, are extremely sensitive to fluctuations in the microgravity levels, termed *g*-jitter. For example, the flame balls observed in space shuttle experiments became unstable when low-power steering rockets fired and changed acceleration levels from 10^{-4} to 10^{-3} times Earth gravity (Ronney, 1998). Finally, studies of turbulent combustion phenomena require that the experiment be repeated often enough to draw statistical inferences (Cheng et al., 1999). The time required for accumulation of these data is simply not available in any Earth-based microgravity facilities. For all these reasons, progress in combustion studies critically depends on the availability of the Combustion Integrated Rack facilities on the ISS.

History and Current Program

The first microgravity experiments were conducted by Kumagai and coworkers (Kumagai and Isoda, 1957) in Japan; they were interested in experimentally confirming the theoretical burning rates predicted for the combustion of small spherical droplets. NASA conducted its first combustion experiments in space on Skylab in 1974 (Kimzey, 1974); the experiments focused on the flammability of solid materials commonly used in spacecraft (Urban and King, 1999). By 1990, enough progress had been made to warrant an invited minireview of the emerging field of microgravity research by the Combustion Institute, the international scientific organization devoted to the entire field of combustion science (Sacksteder, 1990). There had been no follow-up to the early Skylab experiments, and virtually all of the 42 citations in this paper were to ground-based experiments, theoretical analyses, or plans for future experiments in space. However, enough progress had been made to identify several distinct categories of microgravity research—premixed gases, diffusion flames, droplet combustion, flame spread over liquid and solid fuels, and smoldering combustion—that have persisted to the present day.

By 1992 the situation had changed dramatically. The first NASA Research Announcement (NRA) had been issued in 1989, resulting in 13 definition study awards (ground- and aircraft-based experiments and analyses intended to establish the need for and viability of space-based experimentation) and 6 flight experiment candidacy awards (Ross, 1993). Moreover, 4 space experiments had been completed, and a total of 24 microgravity combustion and spacecraft fire safety projects were being supported. The visibility of microgravity combustion research had advanced by 1994 to the point that an entire session of the Twenty-Fifth International Symposium on Combustion was devoted to this subject (Combustion Institute, 1994). The expansion of the NASA program was quite rapid over the next few years. At the time of the Fourth International Microgravity Combustion Workshop, in 1997, the Microgravity Combustion Science Program supported 48 ground-based studies, 7 flight definition studies, and 11 spaceflight experiments, among the total of 73 supported programs (King, 1997).

Since the late 1990s, combustion in microgravity has been accepted as an important component of basic research in most branches of combustion science. The Twenty-Seventh International Symposium on Combustion, held in 1998, provided three distinct measures of the impact this research has had on the field. First, the invited Plenary Lecture (Ronney, 1998), the most prestigious forum offered to the international combustion community, was devoted to microgravity research. The growth of the field in less than a decade is evident from the 115 references in the written version of that plenary lecture, which covered the topics considered in the earlier review (Sacksteder, 1990), including several experiments performed on the space shuttle. Second, the sessions on microgravity combustion contained 23 of the 367 papers accepted for presentation at the symposium (Olson et al., 1998). Such presentations are very competitive; fewer than half the papers submitted are published in the proceedings. Third, a special presentation by G. Linteris, "Fire in Space," recounted his experience as the combustion science payload specialist on space missions STS-83 and STS-94. A summary of that talk (Linteris et al., 1999) can be found in the special issue of *Combustion and Flame* (1999) devoted to microgravity combustion research supported by NASA.

The years 1998-2000 probably represent a high-water mark for the program. The Twenty-Eighth Symposium, held in 2000 (Combustion Institute, 2000), did not break out microgravity combustion as a separate entity but integrated papers on the topic into their appropriate technical sessions. The total number of papers involving microgravity research was similar to that in the previous symposium. *Microgravity Combustion: Fire in Free Fall* (Ross, 2001) represents the first attempt to produce a volume that could serve as an advanced textbook devoted to microgravity research. It is current through 1999, with occasional citations to later work. It is interesting to note that nearly 80 percent of the book is concerned with the topics discussed by Sacksteder in his 1990 review (Sacksteder, 1990). The Fifth International Microgravity Workshop, held in 1999, was marked by optimism about the immediate future. The National Center for Microgravity Research in Fluids and Combustion had recently been opened, a record number of new microgravity combustion experiments had been funded following the most recent NRA, and 120 papers were presented either orally or as posters. NASA was focused on the forthcoming ISS and the Combustion Integrated Rack (CIR). "The CIR is scheduled for launch on UF-3 in October, 2002 and will begin its scientific work immediately" (King, 1999).

The year 2001 brought major uncertainty to the future of the ISS in general and the microgravity combustion research program in particular. The Sixth International Microgravity Workshop took place "at a time when the role of combustion research supporting NASA's future missions and our ongoing contributions to fundamental science are being re-examined'' (Sacksteder, 2001). The workshop proceedings describe 117 investigations, demonstrating again the vitality of the research program. Unfortunately, the workshop took place at a time when the future of the CIR, intended as the laboratory for future microgravity combustion experiments, was in doubt. Although some additional funding for the CIR has been secured, its final status remains uncertain. The original 2002 operational date has slipped by several years. Moreover, as the report of the International Space Station Management and Cost Evaluation Task Force noted, " The existing ISS Program Plan for executing the FY 02-06 budget is not credible'' (Young, 2001). While the final consequences of this report are unclear, the current NRA explicitly states: "Due to severe resource limitations, we do not plan to make flight definition awards in the combustion area from this NRA" (NASA, 2001). Whether this is a temporary setback or the beginning of the end of the microgravity combustion program remains to be seen.

IMPACT OF NASA COMBUSTION RESEARCH

The topics that have received extensive coverage in NASA's microgravity combustion research program include the following:

- Flame spread on thin and thick solids,
- Smoldering combustion,
- Jet flame lengths and shapes,
- Turbulent flames,
- Soot and radiation,
- Flame balls, and
- Droplet combustion and chemical kinetics.

The NASA microgravity combustion research program supported approximately 70 investigators in FY 2001. Of these NASA investigators, 5 are members of the National Academy of Engineering, 10 are fellows of the American Institute of Aeronautics and Astronautics, 5 are fellows of the American Physical Society, and 4 are fellows of the American Society of Mechanical Engineers. Two of the NASA combustion principal investigators (PIs) have received the distinction of being among the 100 most cited engineers in the world.

The microgravity combustion research conducted over the last 10 to 12 years has contributed to our fundamental knowledge of some of the most basic combustion phenomena, to the improvement of fire safety on present and future space missions, and to the advancement of knowledge about some of the most important practical problems in combustion on Earth. Substantial progress has been made in spite of the very challenging environment, the limited time available for experimentation, and the serious limits on the types of measurements that can be made.

Flame spread over thick and thin solids is a fundamental problem in combustion and is very relevant to fire safety in space and on Earth. Experiments conducted in microgravity facilities on Earth and particularly in space provided very-high-quality data for flame spread rates because there were no significant buoyancy-induced fluctuations. These data have led to the validation of computer models of the ignition and flame spread processes (Mell and Kashiwagi, 2000; Mell et al., 2000). Such validation is helping researchers to advance with renewed confidence these models for flame spread in accidental fires on Earth.

Experiments on the flammability of thin and thick solids and also of hydrocarbon fuel droplets at varying oxygen concentrations in microgravity and normal gravity showed that microgravity flames are stable at lower oxygen concentrations. For example, the flammability for a vertical thin cellulosic tissue increased under microgravity, and combustion was possible at 13 to 14 percent oxygen concentration instead of the 15.6 percent oxygen concentration required at normal gravity. Recent studies of flame spread over thermally thick solids (those for which the thermal penetration depth is much less than the thickness of the material for the duration of the experiment) in microgravity have shown that such flames are unstable and eventually extinguish themselves because of the excessive heat loss away from the combustion zone (Altenkirch et al., 1998). If this finding can be verified for a large range of materials and if the damage that occurs during the unstable combustion portion is minimal, then use of thermally thick solids may turn out to be a part of the fire safety strategy. However, additional work is necessary before the practical benefits of this research can be realized.

More recent work in flame spread over solids is considering the effects of sample widths and edge effects. Such work is necessary from the point of view of practical design as well as for assessing the generality of the findings achieved with finite-width samples with edges. Work has also been initiated on fire spread on more general shapes such as cylinders (as opposed to flat plates and paperlike objects).

Experiments on smoldering in microgravity, on the other hand, show that the process is slower than in normal gravity. In addition, the microgravity smolder is even less bright and less detectable than that on Earth. This makes the fire safety problem in space even more challenging because the slow-growing smolder can go undetected for a longer time and when it breaks into a fire, the fire will propagate faster. Experiments on hot surface ignition in microgravity show shorter ignition delays, reinforcing the need for improved fire safety.

In experiments of very practical significance to spacecraft fire safety, it was found that flames over electric wire insulations spread 30 to 50 percent faster in microgravity than in normal gravity (Kikuchi et al., 1998). Overheated electric wire insulation is one of the more common sources of accidental fires on Earth and will continue to be one in space. This hazard arises when the loss of energy from the flame region to the ambient is reduced by the lack of natural convection. An understanding of this effect is critical to maintaining spacecraft fire safety. The experimental finding from the research program concerning enhanced spread rates needs to be accommodated in material screening and approval tests. Such test apparatus should mimic a microgravity environment in Earth-based material-testing facilities.

The microgravity combustion research program has already had a significant impact on space shuttle and ISS fire safety and fire-fighting procedures (Pedley, 2001). Based on the microgravity combustion research finding that even weak ventilation flows lead to rapid fire spread in microgravity, it has now become standard practice to shut off ventilation flows if a fire starts in a module, rather than to deploy an extinguisher. The findings on the effects of oxygen enrichment on flammability limits have led to the minimization of the enrichment levels as much as possible. The engineers responsible for fire safety on the space shuttle and the ISS at the Johnson Space Center recognize that the microgravity combustion research program has shown many counterintuitive fire behaviors. They also recognize that the margin of safety based on normal gravity material testing is significantly greater than that in microgravity. However, significant further work is necessary to develop a real understanding of fire and fire suppression in space habitats, as discussed in the next section.

Experiments with both nonluminous and luminous jet flames have shown that flame lengths increase significantly in microgravity. Significant improvements in the models were needed to achieve agreement with the experimental data for a range of fuels. The Froude number (the ratio of buoyancy to pressure forces) was established as the correct parameter for correlating the lengths of buoyant flames. This is an interesting development, particularly because of the seminal contribution of Burke and Schumann, who were able to predict flame lengths with an analytical expression derived by ignoring buoyancy that coincidentally provided good agreement with limited data. In fundamental science, correction of a theory that seems to have been accepted for a few decades is challenging and is a particularly significant accomplishment of the microgravity program.

The results of the NASA microgravity research program concerning flame length variation with flow rate have been incorporated into newer undergraduate-level textbooks (Turns, 2000). The older textbooks erroneously stated that the flame length increased with increasing flow rates and then became constant for high Reynolds number (ratio of inertial to viscous forces) turbulent flames. The data and discussion presented in Turns (2000) clearly show that the reality is more complicated. Flame lengths increase at different rates in microgravity and normal gravity, and the microgravity flames are much longer than the normal gravity flames at low and intermediate Reynolds numbers. However, the surprising feature of the data is that even at the highest Reynolds numbers at which extinction is observed, the flame length in microgravity continues to be much larger than that for flames in normal gravity. Furthermore, this holds for all known fuels. Theoretically, the two flame lengths should reach a common asymptotic value, but conditions appropriate for this asymptote have never been realized experimentally.

Soot production and emission by combustors continues to be a major environmental problem for Earth-based applications such as diesel engines. Soot consists of primary 20- to 100-nanometer-diameter, mostly carbon particles that generally agglomerate into larger fractal structures. Soot production and oxidation mechanisms have been developed and validated using microgravity combustion data. Soot contains carbon particles that are a significant health risk to many urban populations in the United States and the world. Methods of controlling soot emissions developed based on a knowledge of their kinetics would be of significant value to human health here on Earth.

The microgravity studies of sooty flames provided many surprises. The primary carbon particles grown in microgravity are much larger than those grown in normal gravity under similar conditions. Further, the microgravity agglomerates were also larger than those in normal gravity, possibly because of the longer residence times resulting from the long flame lengths. The agglomeration process is enhanced in microgravity, leading to very large blobs of soot. This result provided data on sooting tendencies that are being used to improve understanding of chemical kinetic mechanisms. The soot behavior in microgravity suggested numerous strategies for soot control (for example, retarded fuel velocity) and also improved experimental design for soot studies. For example, a flat flame premixed burner with a stabilization disk and interrogation along the axis is providing data for formation and oxidation rates of soot in very controlled environments, leading to significant improvements in the chemical kinetic rate models (Sunderland and Faeth, 2001; Sunderland et al., 1995).

Many of the microgravity studies have shown the significant role of radiation heat transfer in combustion phenomena (Bedir et al., 1997; Ju et al., 1998). This role was usually ignored in the past in applications other than fire research. An improved awareness of the radiation coupling with chemistry and fluid mechanics in many combustion applications is a significant outcome of the microgravity combustion program.

Other fundamental contributions have been made as a result of experimental studies involving the first-ever stabilization of flame balls, which are relatively stable spherical surfaces across which reactants become products (Ronney, 1998). This phenomenon, which was only theoretically predicted before the microgravity experiments, is novel in that unlike propagating spherical flames, the flame ball surface remains stationary, separating reactants and products for as long as the experiment could be conducted on the space shuttle. This work was the highlight of Ronney's plenary lecture (Ronney, 1998). This confirmation of simple and elegant theories by experiment is something NASA strives for. The existence of such a confirmation from a practical science such as combustion is very satisfying.

Modern combustion equipment is designed using computational methods that require chemical kinetics information for liquid hydrocarbons. The industries that design aircraft combustors, such as General Electric Aircraft Engines (Mongia, 2002), are utilizing the chemical kinetics mechanisms developed by NASA microgravity combustion PIs like Dryer and coworkers (Marchese et al., 1999; Manzello et al., 2000). These mechanisms are also being used by diesel engine manufacturers working in collaboration with the Department of Energy in a Cooperative Research and Development Agreement (CRADA) team. The chemical kinetics mechanisms being continuously upgraded using the NASA microgravity combustion data are used in the latest combustion textbooks (Turns, 2000).

The high-quality droplet combustion data not only contributed to the evaluation of the d^2 law (the regression rate of the burning droplet surface area is constant) but also led to the validation of detailed chemistry mechanisms for practical hydrocarbon fuels. The lack of understanding of the detailed chemistry mechanisms for practical fuels is one of the critical problems hampering the computer-aided optimization of combustion devices on Earth. The chemical mechanisms validated in the microgravity program by Dryer and coworkers (Marchese et al., 1999; Manzello et al., 2000) are of significant value in this effort. More recent work in droplet combustion is looking at fuel mixtures and the resulting partial distillation and its effects on vaporization and combustion. This topic is important for the use of alternative fuels in automobile engines, which could enhance cold start capabilities and reduce hydrocarbon pollutant emissions.

FUTURE DIRECTIONS IN COMBUSTION RESEARCH

Fire Safety

Clearly, combustion research aimed at answering the very practical questions for which NASA engineers are currently seeking answers is needed soon. To remedy the paucity of knowledge about fire safety on the ISS, the combustion research necessary for completing the risk assessment project to satisfaction must receive the highest priority at all levels. A major fire in space resulting in any type of loss of mission will not be excused by the public and will lead to decades of setback for all kinds of space research and space applications. The fire danger and research need are very real based on the cited communications (Pedley, 2001) between engineers responsible for fire safety of the ISS.

Fire safety onboard the ISS needs to be and will be one of the most important cornerstones of the future combustion program. It is important because fires in space are different in many respects from fires on Earth. The first difference is that they can be more challenging to extinguish and harder to detect, as revealed by the ongoing combustion research experiments discussed above. The second difference is that they can be disastrous to a very-high-value, high-visibility project. The third and most important difference is that there are almost no escape routes. Therefore, fire safety should be the highest priority in the short-term (perhaps 3 to 5 years) future. The program should strive for establishing special screening procedures and tests for space materials, and should account for the differences in detection, fire spread, and oxygen environments. Further, it should recognize that all the catastrophic and near-catastrophic fire events in the history of the U.S. and international space programs (Apollo 1, Apollo 13, and Mir) involved oxygen-supported fires. Finally, a physics-based computer simulation of fire development and suppression in space should form a backbone for future fire-safety-related research and design.

Much of current spacecraft fire safety design is based on risk assessment methodologies developed by the insurance industry over many decades of experience in successfully protecting and occasionally paying for high-value real estate. Data on expected fire hazards, fire behavior, and fire safety equipment function and effectiveness in space are, however, unavailable. Further, Earth-based fire protection techniques have evolved using thousands of years of fire-fighting experience. *Obviously, there is no such experience base for space fires. Physics-based computer simulations are the only alternative.* Indeed, even for Earth-based fires, such simulations have been of great value in assessing fire safety and control strategies.

The recommended directions for fire safety research for the ISS and other space habitats are summarized below.

Development of Computer Simulation of Fire Dynamics on Spacecraft

The development of fire simulation computer codes based on computational fluid dynamics (CFD) techniques has been a milestone for fire safety research on Earth. In addition to documenting the progress made in understanding fire phenomena, such codes have been used to investigate specific fires (Madryzkowski and Vettori, 2000; Simcox et al., 1992). They are also routinely used to evaluate smoke movement in buildings and are beginning to be used to evaluate the performance of fire protection systems (McGrattan et al., 2000). One measure of the impact of these codes on fire research on Earth is the fact that the latest version of the Fire Dynamics Simulator (FDS), developed at the National Institute of Standards and Technology (McGrattan et al., 2001), has been downloaded over 4,000 times since its release and, together with its predecessor, is currently in worldwide use. The success of FDS is based on years of submodel development and validation with a variety of Earth-based basic experiments and applications to fire scenarios. The submodels involve processes that are affected significantly by gravity.

Neither FDS nor any other CFD-based computer program written for fire research can currently be used to simulate fire scenarios on the ISS or any other vehicle designed to operate in a microgravity environment. The effects of buoyancy on combustion and convective transport on Earth so dominate fire spread, smoke transport, and suppression techniques that a research and development effort on modeling microgravity fires is needed. Experience with CFD code development in general and FDS development in particular has demonstrated that the creation of a code that simulates microgravity fire will involve many researchers for several years. Given that NASA is not soliciting flight experiments in combustion in its latest NRA, a modeling initiative would be the primary way to advance our knowledge of fire safety in space. A simulation code would also guide the choice of the most effective future space experiments.

Research on Ignition, Flame Spread, and Screening Techniques for Engineering Materials in a Microgravity Environment

The goal of research on ignition, flame spread, and screening techniques for engineering materials in a microgravity environment is to develop a science-based method for determining the fire performance of materials that are candidates for use in space. At present, NASA is supporting studies aimed at the development of screening tests in both Earth gravity (Olson et al., 2001) and microgravity (Fernandez-Pello et al., 2001). However, this research needs to be supplemented with further studies that consider nonplanar material configurations and a wider variety of test materials. The results of an enhanced research program would also be directly usable in the space fire simulation codes described above. Since the flame spread phenomena take place on length scales much smaller than those associated with the spacecraft geometry, having a body of knowledge that relates mass generation rates of combustible materials to the history of the heat flux incident upon the material and the local oxygen environment is a necessary ingredient of a macroscopic fire spread model. This information must be obtained as a function of the material studied and its local shape. The two programs, taken together, would provide a major advance in the understanding of fires in space and in the ability to ameliorate their consequences.

Oxygen Systems Fire Safety

One of the critical systems on the ISS and other space, lunar, and planetary habitats is the oxygen generation and handling system. Combustion with pure oxygen reaches temperatures capable of turning most materials into fuels, with the aluminum canister consumed in the Mir fire being a case in point. A systematic study of ignition and spreading of fires involving an oxygen source such as a jet formed by a leak or initiation of an internal reaction involving failure of an inert coating needs to be undertaken to better protect against such disasters. Ignition of an initial oxygen fire, flame spread by radiation from the ultrahigh-temperature initial ignition source, and special considerations for the extinguishment of fires involving oxygen are research topics requiring experimental and computational attention.

Smoldering Combustion

In many accident scenarios, such as chaffed electric wire insulation, combustible materials are heated to the point of generating toxic and combustible vapors. The generation of these vapors at temperatures too low for flaming combustion is called smoldering. Smoldering often occurs in areas hidden from view, making detection more difficult. The availability of oxygen and an ignition source can often force a transition of smoldering into flaming. Smoldering in Earth's gravity involves removal of the fuel vapors and the energy released during their generation by buoyancy. This means that smoldering and transition to flaming combustion in microgravity will be significantly different and must be studied further.

Basic Combustion Research

Soot and Radiation

While combustion has been studied for hundreds of years, the limits of clean combustion technology are illustrated by large black billows of carbon particles leaving smokestacks and rigs pulling out of truck stops. The inhalation of such particles has been shown to significantly increase levels of morbidity in polluted areas. The basic processes that lead to the formation and emission of small carbon particles in high-temperature combustors remain to be understood. For example, although the transformation of small hydrocarbon molecules into larger polyaromatic hydrocarbons (PAHs) has recently been formulated, the detailed mechanisms of the phase change of such PAHs into nascent solid particles are unknown. Similarly, why the solid particles once formed are not fully burnt by the available oxygen remains an unanswered question.

Microgravity flames were found to produce significantly larger quantities of soot particles than Earth-based flames with the same operating conditions. This is because of the longer residence times available for the inception and growth processes (which, incidentally, also provide an opportunity for more detailed studies of the processes).

Soot particles in flames radiate energy to the surroundings, dominating the heat transfer from large fires and in furnaces. The formation and oxidation processes of soot particles are intimately tied to their temperature, which is affected by the radiation. This means that studies of radiation cannot be decoupled from those of soot formation and oxidation. Radiation heat fluxes from microgravity flames have been measured to be many times higher than those from Earth-based flames of the same power. In short, radiation studies in space environments are critical.

Radiation heat transfer has many implications for the fire safety problem discussed above, including the effects of a highly absorbing carbon dioxide fire suppressant deployed on the ISS, flame spread by preheating, and transition from smoldering to flaming.

Turbulent Combustion

Most industrial combustion devices and natural fires involve turbulent combustion. Turbulent flows generally involve a balance between high inertial forces, pressure gradients, and gravity forces. In most propulsion devices, the pressure gradient forces are much larger than the gravity forces. However, in power plants, material processing, and home heating furnaces and in natural fires, the pressure gradients and gravity forces are comparable. In this regime of turbulent combustion, a large number of applications are affected by gravity and deserve consideration in the program. Some of these applications, such as furnaces and fires, involve turbulent non-premixed flames while others, such as low-emission, lean-burning furnaces, involve turbulent premixed combustion.

Turbulence in general and turbulence in the presence of combustion are exceedingly difficult phenomena that have defied generations of researchers. However, even incremental progress in these difficult areas could have a significant impact on industry, NASA, and the basic sciences. As noted above, the expected similarity between earthbound and microgravity turbulent non-premixed jet flames at high Reynolds numbers was not observed. The reasons for this discrepancy are unknown. The importance of flame size to many earthbound applications underscores the need for improved understanding.

Some recent studies on premixed turbulent flames indicate that the length scales that are affected by the instabilities are significantly different for normal flames and microgravity flames. Length scales in turbulent premixed flames determine the burning rate enhancement, so their improved characterization, including that of the effect of buoyancy, is necessary.

Chemical Kinetics

Chemical kinetics and reaction mechanisms for practical fuels and fuel blends of interest to industry remain unknown. The chemical rates are determined by basic molecular collision rates, velocities, and stearic effects (orientations of the molecules at the time of collision). In normal gravity these processes are often studied in a complex flow environment. Microgravity allows the design of a reacting system (for example, the droplet flame) to be probed in a simpler, one-dimensional flow. Accordingly, microgravity studies of chemical kinetics using droplet flames helped to establish a chemical mechanism for the oxidation of simple hydrocarbon fuels, as discussed earlier. However, similar progress for realistic fuels and fuel blends is necessary.

Nanomaterial Synthesis in Flames

Flames provide an inexpensive means of producing nanoparticles for mass use. Indeed, the soot particles discussed above are carbon nanoparticles. More recent experiments have shown the possibilities for manufacturing more exotic forms of carbon, such as diamonds, buckey balls, and nanotubes, as well as other nanomaterials. The work to date has generally been empirical, and opportunities exist for understanding the chemical composition and thermal structure of the flow that is conducive to synthesis of the desired forms of materials. This is discussed further in Chapter 7.

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4

Fundamental Physics Research Program

INTRODUCTION

Through its Microgravity Research Division—recently renamed the Physical Sciences Division (PSD)—NASA has supported research in fundamental physics for over two decades. Initially the program focused on low-temperature and condensed-matter physics, particularly on critical phenomena and phase transition studies, as these fields stood to benefit from access to the weightlessness of space. Over the last decade, the program was broadened to include research in the fields of laser cooling and atomic physics, gravitational and relativistic physics, and biological physics. The Fundamental Physics Disciplinary Working Group[1] recently published a report outlining and advocating the current and future programs of fundamental physics, *Fundamental Physics in Space, a Roadmap to Unlock Mysteries of the Universe by Exploring the Frontiers of Physics in Space* (Bigelow, 2001). This brochure refers to the two goals that have guided funding selections by the fundamental physics program: To discover and explore fundamental physical laws governing matter, space and time; and to discover and understand organizing principles of nature from which structure and complexity emerge. The fundamental physics branch of the PSD now stands as a key funding agency for scientists whose research would be clarified in the absence of Earth's gravity, many of whom work in the areas of low-temperature and phase-transition physics, cold atom physics, and gravitational physics. Thus the unique portfolio of NASA complements the broader physics research programs that exist within NSF, DOE, and other federal agencies.

Review of the Current Program

Because of the complexity of the experiments, the long lead time for flight preparation, and the limited number of space shuttle flights, only four flight experiments, all in the area of low-temperature

[1]Discipline working groups are internal advisory committees to NASA; they are composed of academic and industrial scientists who represent the interests of the research communities that utilize NASA's microgravity research platforms.

and condensed-matter physics, have been completed. For this reason, the program is reviewed here by experiment rather than by subdiscipline, as is done in the other chapters. Currently about half a dozen flight experiments, in low-temperature and condensed-matter physics, in laser cooling and atomic physics, and in gravitational and relativistic physics, are being prepared for flight onboard the ISS. In addition, the fundamental physics program also provides support for ground-based projects that complement flight projects or have the potential to become flight projects. The duration of the ground-based projects is typically 4 years. Currently approximately 42 ground-based projects are supported by NASA/fundamental physics.

The committee first identifies the flight experiments that have taken place, with consideration of their scientific and technical impact being deferred to the next section. Since there are approximately 40 scientifically distinct ground-based experiments, it would be impractical to discuss each one. The committee therefore comments on just a representative few. While some of the impacts of these projects extend well beyond NASA, others set the stage for the flight experiments that should go onboard the ISS.

Completed Flight Experiments

Four flight experiments sponsored by the fundamental physics program have flown on space shuttles: the lambda point experiment (LPE), the critical fluid light scattering experiment (ZENO), the critical viscosity experiment (CVX), and the confined helium experiment (CHeX). These experiments aimed to provide stringent tests for the current understanding of the nature of a continuous phase transition. The smearing effect due to gravitationally induced density stratification is greatly reduced by carrying out these measurements in space rather than on Earth, allowing the critical point or the precise transition temperature to be approached much more closely. For example, because of Earth's gravity, the singular heat capacity related to the superfluid transition becomes rounded when the temperature of the laboratory sample cell approaches to within 1 microkelvin of the transition temperature, the Lambda point. The results of these highly successful experiments are presented in the section below entitled "Low-Temperature and Critical-Point Physics."

The ZENO and CVX experiments were concerned with how a fluid system (especially xenon) extremely close to its critical point responds to perturbations. By removing the smearing effect of gravity, CVX was able to cleanly demonstrate viscoelasticity in Xenon near its critical point, where such effects are magnified by collective behavior. CHeX made use of much of the hardware recovered from LPE and studied the effect of two-dimensional planar boundaries on the singular heat capacity near the Lambda point to confirm the prediction of the effect of finite sample size.

Flight Experiments Being Prepared for the ISS

While the completed flight experiments in fundamental physics are exclusively in the area of low-temperature and condensed-matter physics, fundamental physics projects designated for flight onboard the ISS also include experiments in laser cooling and atomic physics and in gravitational and relativistic physics. Approximately 35 experiments are scheduled for flight on the ISS or are being designed and prepared for future flight on the ISS or another carrier. Among the flight-approved experiments are the following:

- Critical dynamics in microgravity (DYNAMX),
- Heat capacity at constant heat current (CQ),

- Boundary effect near the superfluid transition (BEST),
- Microgravity scaling theory experiment (MISTE),
- Superconducting microwave oscillator (SUMO),
- Rubidium atomic clock experiment (RACE),
- Primary atomic reference clock in space (PARCS),
- Gravity Probe B, and
- Satellite test of equivalence principle (STEP) (tentative).

The first four of these experiments have been chosen and already passed flight definition through rigorous and multilayer peer review processes. SUMO has passed science concept review and is an approved ISS experiment. RACE and PARCS have been designated as future flight experiments and are currently supported as preflight ground-based research. The first five of these experiments will make use of the low-temperature microgravity physics facility on the ISS. Having passed flight definition review, the first four are basically ready for launch in the next 2 years. SUMO is scheduled for requirements definition review in early 2004. DYNAMX and BEST measure thermal conductivity very near the superfluid transition point to understand the dynamical response near a critical point both for a bulk sample (DYNAMX) and for a finite size sample (BEST). MISTE seeks to critically examine current understanding of the renormalization group theory as it is applied to the liquid-vapor critical point. This will nicely complement the findings of the LPE. Interestingly, DYNAMX and CQ can be accomplished with the same apparatus. Results of the first four experiments, taken together with those of the LPE and CheX experiments, are expected to provide a full picture of the equilibrium behavior of systems near critical points, including the role of boundaries and the dynamical response to perturbations.

Ground-Based Experiments

Ground-based experiments are chosen to complement the flight projects, and some may evolve as potential flight projects in the future. As noted earlier, NASA/fundamental physics currently supports about 42 ground-based experiments on very diverse topics. This chapter comments on just a few of them:

- The measurement of Casimir-like effects near the superfluid transition and the ^{3}He/^{4}He tricritical point showed a direct analogy between forces due to the cutting off of long-wavelength excitation modes associated with thermal rather than quantum electrodynamic fluctuations.
- A second experiment demonstrated the possibility of operating in space a superfluid gyroscope that makes use of superfluid helium's ability to detect absolute rotational motion.
- Nucleation and growth of helium crystals from superfluid helium: Since superfluid helium carries no entropy and is a perfect heat conductor, the dynamics of crystal growth in such a system are not hindered by latent heat effects. In fact melting/freezing waves have been seen. Using microgravity to suppress gravitationally induced gradients, such a system is ideal for addressing a number of fundamental questions about crystal growth.
- A paramagnetic material can be levitated in an inhomogeneous magnetic field (i.e., with a magnetic field gradient). At least two such facilities are supported by the fundamental physics program, one at NASA's Jet Propulsion Laboratory and the other at Brown University, and are being built to simulate a zero-gravity environment. Because of the small region that is available and the presence of a strong magnetic field and field gradient, such an experimental configuration will not replace the

microgravity environment that is available on the ISS or other spacecraft. However, such facilities should be useful for testing components of some of the flight projects or the ideas behind them.

- Currently the low-temperature microgravity physics facility, to be installed on the ISS, can achieve a temperature of 1.5 K. This facility makes it possible and convenient to carry out a number of the scheduled flight experiments such as DYNAMX, BEST, CQ, MISTE, and SUMO. However, many other experiments, for example astrophysical experiments that require sensitive microwave and far-infrared detectors and bolometers, will require lower temperatures. One ground-based project is devoted to the building of a He^3 and He^4 dilution refrigerator that can reach a temperature below 0.1 K.
- Another ground-based program focuses on laser frequency stabilization and development of active antivibration techniques that will ensure optimum performance in the ISS environment. Unexpected advances have broadened this program to include absolute optical frequency measurement via a new and powerful method, as described in the section below entitled “Optical Frequency Measurement.”

Some of the other notable ground-based projects that may lead to future flight studies include the search for an electron electric dipole moment with laser-cooled atoms in space, the demonstration of atom interferometry for detecting acceleration and rotation, study of the feasibility of forming and using Bose-Einstein condensates in space, study of the feasibility of space-based lunar laser ranging, and development of ultrastable laser sources for space science experiments and deep-space communication.

Biological Physics Initiatives

Fundamental physics has taken a leading role in initiating a biological physics effort within the Physical Sciences Division. In the 2000 NRA exercise, six ground-based projects in biological physics were selected for support. Projects in this area include a microscale mixer for protein folding, biomimetic self-assembly of mesostructures in microgravity, and microfabrication of a cell-based estrogen sensor. Support of these projects seems likely to increase the awareness on the part of the biological physics community of NASA’s interest in biological physics.

IMPACT OF NASA’S RESEARCH IN FUNDAMENTAL PHYSICS

One way to discuss the significance of NASA’s funding in fundamental physics is to consider the field’s publication record. In 1998, NASA/fundamental physics is credited partly or exclusively with sponsoring work resulting in the publication of 4 papers in *Nature*, 2 papers in *Science*, and 12 papers in *Physical Review Letters*. In 1999, the numbers were 2 in *Science*, 3 in *Nature*, and 18 in *Physical Review Letters*. In 2000, the numbers were 1 in *Nature*, 2 in *Science*, and 16 in *Physical Review Letters*. It should be noted that *Nature* and *Science* are generally acknowledged as the two premier journals that cover all areas of science, while *Physical Review Letters* is one of the leading journals in physics. This record of publications in these premier journals speaks well for the impact and quality of science supported by NASA/fundamental physics. Another indication of the success of the fundamental physics program’s competitive selection process is the scientific stature of the people involved. Currently six Nobel laureates are supported by and actively involved in the research activities of the fundamental physics program in both flight and ground-based projects. At least nine principal investigators are members of the National Academy of Sciences, and 25 are fellows of the American Physical Society. For the purpose of comparison, the entire fundamental physics program at the time of its expansion consisted of 64 principal investigators.

To give an indication of the significant advances in ground-based fundamental science supported (usually only in part) by NASA's fundamental physics program, the committee now looks at just a few examples of the remarkable success evident over the last half-dozen years or so.

Low-Temperature and Critical-Point Physics

Near a critical point, a homogeneous fluid sample is predicted to show an infinitely sharp peak in a plot of some physical quantity such as specific heat as a function of temperature. In the laboratory, because of Earth's gravity, a fluid sample is inhomogeneously loaded by the weight of the overhead material. This obscures the specific heat or density fluctuation measurement and produces an important broadening when the temperature of the laboratory sample cell closely approaches the transition temperature to within 1 microkelvin. Four experiments utilizing a microgravity environment were sponsored by the fundamental physics program and flown on space shuttles: the LPE, ZENO, CVX, and CHeX. These experiments aimed to provide stringent tests of the current understanding of the nature of a continuous phase transition. In orbit, the heat capacity measured in the LPE was found to remain sharp to within 1 nanokelvin (1 billionth of 1 K) of the lambda point. The shape of the peak was found to be in exact agreement with the prediction of the renormalization group theory of the critical point for temperature intervals from 1 K to 1 billionth of 1 K around the critical point (Lipa et al., 1996). Renormalization group theory, as elucidated by Nobel laureate Kenneth Wilson, is applicable to all physical systems undergoing a continuous phase transformation. The LPE succeeded in making the renormalization group theory one of the most stringently tested theories in physics and brings confidence in our approach and in our ability to understand the organizing principles of seemingly complex systems.

A valuable additional result of the LPE and CHeX was the development and refinement of very-high-resolution magnetic thermometry, which now reaches a resolution near 10^{-11} K in a 1-Hz bandwidth. This result has led to the adoption of this technology for a number of other experiments, including both flight[2] and ground-based NASA projects. In addition to refining and deepening our understanding of phase transition phenomena, this set of flight experiments also demonstrated that it is possible to build highly sophisticated experiments that can survive launch and operate for extended intervals at cryogenic temperatures in space. The success in recycling much of the hardware of the LPE for CHeX provided the impetus for and confidence in establishing the low-temperature microgravity physics facility on the ISS as a platform for accommodating future flight experiments requiring cryogenic temperatures.

Optical Frequency Measurement

One of the unanticipated successes achieved under NASA sponsorship was the recent and rapid development of revolutionary techniques for the measurement of optical frequencies. As recently as 7 years ago a top-rated German team had made the most accurate measurement of an optical frequency, that of a laser stabilized to a particularly suitable resonance line in atomic calcium vapor (Schnatz et al., 1996). Their method was the traditional frequency-multiplier method, which employs repeating multiplier stages to span the huge factor of ~5,000,000 between the microwave standard frequency and the

[2]The flight experiments, as planned for the ISS, are the DYNAMX, MISTE, BEST, and SUMO.

optical frequency system of interest. Altogether some 17 stabilized frequency sources were used as intermediaries, with more than a dozen frequency-stabilizing and frequency-counting systems. This tour de force produced the most accurate measurement of an optical frequency up to that time, with an uncertainty of less than 1×10^{-12}. (It should perhaps be mentioned that the five authors of this report [Schnatz et al., 1996] were adding onto a facility that had been under development and evolving since the early 1970s.) Considering that such national frequency measurement teams are maintained by the United States, Canada, the United Kingdom, Germany, France, Japan, and Russia, one sees that this standards work actually represents a serious scale of effort. However, in 2000 and due in part to NASA funding, it became possible to measure optical frequencies with even greater accuracy using a transparent and simple new approach based on femtosecond lasers, disciplined with high-precision optical phase control systems (these were the subject of the NASA funding). It seems a very unlikely linkup of technologies from the physics domains of the most slowly varying and the most rapidly varying: ultrastable lasers and ultrafast pulse lasers. This unexpected convergence and mutual relevance now has dramatically reduced the physical scale required for successful optical frequency measurement. Another important attribute is that the time between the decision to measure a completely fresh laser and the first results is now measured not in years but in hours, and there is a total generality for the new laser's frequency, across a full octave of wavelengths. This new capability comes from the joint efforts of contributors around the world (Reichert et al., 1999). Indeed, the announcement paper (Diddams et al., 2000) carried the names of authors at several contributing laboratories, but in fact this published work came from a U.S. laboratory where NASA was sponsoring the development of laser frequency stabilization and measurement techniques for continuous lasers. The applicability of these techniques to pulsed lasers was completely unanticipated.

In thinking about the impact of NASA's research, it is important to recognize that this revolutionary development came about in the United States mainly because of the NASA connection, and built on the support for and on the intellectual excitement about the vastly higher sensitivities that would be available for future missions if stable lasers and frequency metrology tools could be developed. Indeed, a number of proposed new space experiments in the fundamental physics area are based on these developments and related techniques; they are discussed in the second half of the next section.

Several future missions will use space-based interferometers. For example, LISA—the multinational Laser Interferometer (gravitational wave) Space Antenna—will use 5 million-km baselines. The Space Interferometry Mission (SIM) will use various specialized interferometers designed to detect any possible local curvature of our space. Space Technology 3 (ST3) and Terrestrial Planet Finder (TPF) are missions to be carried out with separated-spacecraft interferometry, which will require improved control and stability. The needed laser frequency stability (better than 1×10^{-13} at 1 second) has become available due to current NASA-funded ground-based research. NASA's research is also enabling better distance metrology in space. For example, in the gravity recovery and climate experiment (GRACE), the along-track separation between two spacecraft is being measured using microwave techniques to map Earth's gravity field. A follow-on program, EX-5, will use a drag-free spacecraft and laser-based distance tracking to improve by 10-fold the sensitivity to changes in Earth's gravity field (compared with GRACE).

Even people outside the scientific and technical community have heard about the breakthrough known as the Bose-Einstein condensation (BEC). While BEC surely was not one of NASA's highest priorities, the selection process for deciding on which investigators will be supported is a good one: It is competitive, unbiased, and open to a certain degree of scientific risk-taking. Investigators in BEC are now contributing to the microgravity program, having received partial NASA funding. Each has a unique vision for important low-temperature experiments, which in the case of BEC-related research may take place in the temperature range near 10 nanokelvins. One NASA investigator is using cold atom physics to produce molecules (Wynar et al., 2000) that are born basically at rest, without thermal motion. It is expected that the revolutionary insights and capabilities provided by BEC for the larger scientific community will lead to very important follow-on breakthroughs.

FUTURE DIRECTIONS IN FUNDAMENTAL PHYSICS

Any snapshot of a program likely to last a decade or more will show some overlap of future and present. Before it presents completely new directions, the committee repeats its list of flight experiments being prepared for the ISS or another carrier—i.e., approved flight experiments:

- Critical dynamics in microgravity (DYNAMX),
- Heat capacity at constant heat current (CQ),
- Boundary effect near the superfluid transition (BEST),
- Microgravity scaling theory experiment (MISTE),
- Superconducting microwave oscillator (SUMO),
- Rubidium atomic clock experiment (RACE),
- Primary atomic reference clock in space (PARCS),
- Gravity Probe B, and
- Satellite Test of Equivalence Principle (STEP) (tentative).

These choices have been repeatedly evaluated and are heartily endorsed by the committee. The first four, which have already passed the flight definition peer review processes, are discussed earlier in this chapter. SUMO, RACE, and PARCS have been designated as flight experiments. Gravity Probe B may be the most difficult of these experiments, and ground research has been under way for many years. While STEP has been funded by NASA/fundamental physics, the Medium-Size Explorer (MIDEX) competition will soon decide whether it will be approved for flight. The first four experiments will make use of the low-temperature microgravity physics facility on the ISS and, having passed flight definition review, are basically ready for launch in the next 2 to 3 years. DYNAMX and BEST measure the thermal conductivity very near the superfluid transition point to understand the dynamical response near a critical point for a bulk sample (DYNAMX) and a finite-size sample (BEST). MISTE seeks to critically examine the renormalization group theory as it is applied to the liquid-vapor critical point. These will complement nicely the findings of the LPE. Interestingly, the DYNAMX and CQ can be accomplished with the same apparatus. The completion of these four experiments, taken together with the LPE and CheX experiments, is expected to provide a full picture of the equilibrium behavior of systems near critical points, including the role of boundaries and the dynamical response to perturbations. The committee believes the series of scheduled flight experiments will elucidate (1) the nature of the dynamical response and fluctuation for bulk and finite-size samples (DYNAMX, BEST, CQ) and (2) the concept of universality classes (MISTE) near a critical point. One can make a strong case that with the successful completion of these flight projects, critical phenomena in the microgravity environment will be a mature subject. Thus, barring unexpected developments, if these follow-on experiments continue the great success of the already-flown program, they paradoxically may form a natural conclusion to this highly successful line of spaceborne measurements.

The frequency of SUMO is fixed by means of a resonance of an electromagnetic wave in a low-loss microwave superconducting cavity. The frequency of this system, thus depending on material dimensions and the speed of light, has its stability enhanced in a low-gravity, low-vibration environment. It will make use of the low-temperature microgravity physics facility, as did the previous four experiments. Special bidirectional links to ground stations can provide accurate Doppler cancellation and thus enable high-precision frequency measurements relative to ground-based atomic frequency standards. Making measurements also with the onboard atomic clock ensemble will lead to an enhanced test of the general relativistic red shift (see below).

By contrast, RACE and PARCS are two flight experiments that will make use of space to substantially improve the precision and stability of atomic clocks relative to those on Earth. These clocks are based on hyperfine transitions of electrons in atoms such as cesium and rubidium and have been developed to a high degree of performance over the past 35 years. In recent years the performance limitations set by the atoms' thermal motion have been greatly reduced by the use of laser atom-cooling techniques. Now the limit for such an atomic fountain clock becomes the finite time available before the atoms fall back down because of Earth's gravitational pull. These cold-atom fountain clocks, the most precise atomic clocks on Earth, have an accuracy of 1 part in 10^{15} (or an error of 30 billionths of a second per year). However in space PARCS and RACE systems are poised to improve the performance of cold-atom clocks by a factor of 10 or even 100 (RACE). Such improvement is possible because in space the laser-cooled atoms will not be subjected to the influence of gravity and will not "fall" relative to the measuring apparatus. The increased atom interaction time and thus improved precision available on the ISS will make it possible to address a number of fundamental and interesting questions about the nature of our physical world. The impacts of these improved space clocks on science and technology will probably be wide and deep but difficult to fully anticipate and appreciate at this time.

The key to maximizing the scientific gain from the space clock experiments PARCS and RACE is to fly simultaneously another type of high-performance clock that can serve as a comparison local oscillator. An excellent candidate for this second type of clock is SUMO, discussed above. By comparing its microwave cavity frequency (based on its cavity geometry) with that of the local atomic clocks, it will be possible to measure—as a function of position and gravitational potential—the gravitational redshift. These measurements will be a powerful test of Einstein's weak equivalence principle, which states that the rates of clocks are independent of their composition and have the same change with gravitational potential. A European atomic clock experiment on the ISS, called PHARO, will enhance and be enhanced by the three U.S. clock experiments, PARCS, RACE, and SUMO.

These very precise atomic clocks will enable sensitive searches for the possible time dependence in the basic numbers in physics. As an illustration of the latter issue, consider the fine structure constant $e^2/(2\varepsilon_0 hc)$, usually denoted by α, which shows up in atomic spectra and hence in atomic clocks. (Here e is the electron charge, h is Planck's constant, c is the speed of light, and ε_0 is called the permittivity of the vacuum and is a constant from the theory of electromagnetism.) The present value of α is 1/137.035 999 77(61) and is one of the most precisely determined values in all of physics. This number expresses the strength ratio of atomic interactions arising from electrostatic and velocity-dependent magnetic origins, and so it should be obtainable from a basic theory, but such a theory does not yet exist. Lacking reliable predictions, it has been suggested that the value of α might not be constant (Webb et al., 2001) but rather might have an exceedingly small—but not zero—time rate of change. The projected performance of the space clocks makes this a target of opportunity to ascertain if the hypothesized changes are indeed real. The recent progress in atomic clocks has been so powerful that clock tests at the level of parts in 10^{14} per year have already been reported (Udem et al., 2001). These experiments will get another great resolution increase with the use of space. In the not-so-distant future, optical atomic clocks based on different atoms, or even different physics (Coulomb versus vibrational versus hyperfine energies) will be measured on a common basis, even though they are operating at different frequencies.

This will be enabled only by using the femtosecond-laser comb-based approach to comparing atomic clocks, which has recently come from programs funded in part by NASA, as discussed above.

Concerning the BEC effect, of most significance for future NASA missions will probably be the prospect of interferometers that use not light waves but matter waves, coherently obtained from a BEC sample. Such an “atom laser” can produce atom waves with discipline and coherence, just as a conventional laser produces well-organized light waves. These matter wave interferometers promise inertial sensing at a precision scale unimaginable with mechanical or conventional laser gyros. They will give us new insight into general relativity and cosmological questions. It is no surprise that many of these future dream space experiments are being pursued as ground-based research with NASA support: It is because the full experiment will require access to space.

The physics community’s excitement at having access to microgravity has generated a large number of ideas for experiments. Most are in the discussion stage, and some have a modest level of NASA funding as ground-based research, sometimes from outside the fundamental physics program. Several of these new space experiments make use of some of the NASA-supported developments and related techniques noted above. The list of future missions includes long-baseline, space-based interferometers such as LISA, deep-space coherent communications, and specialized interferometers designed to detect any possible local curvature of our space. SIM needs subnanometer control and stabilization of its optical element positions to measure the relative positions and distances of stars: 1 nm is required to carry out successful experiments of starlight nulling, 200 pm for wide-angle astrometry, and 50 pm for narrow-angle astrometry. The ST3 and TPF are missions to be carried out with separated-spacecraft interferometry, leading to an elevated requirement on control and stability. Laser frequency stability of about 1×10^{-14} at 1 second will make these tasks realistic. The need for a more stable atomic clock will always be there as researchers try to depict the entire universe on a finer and finer map.

Laser metrology between satellites will improve the precision of enhanced formation flying. For example, in the GRACE program, Earth’s gravity field is being mapped by measuring the along-track separation between two spacecraft using microwave techniques. A follow-on program, EX-5, calls for a drag-free spacecraft and laser-based distance tracking to achieve a >100-fold precision improvement (to ~1 nm). This enhanced capability will improve the sensitivity to changes in Earth’s gravity field by between one and two orders of magnitude compared with GRACE.

Several other ongoing flight experiments are not fully supported within the fundamental physics program. These include LISA, Gravity Probe B, and STEP. One other the committee has so far not mentioned is the alpha magnetic spectrometer. These experiments complement and extend the broad nature of NASA’s fundamental investigations.

More generally, several interesting future fundamental physics (particle astrophysics to be more exact) science experiments can be done in space, possibly on the ISS:

- *Antimatter search and measurements*. The alpha magnetic spectrometer experiment slated to fly on the ISS is aimed mostly at searching for heavy antimatter, such as anticarbon nuclei, but also will search for positrons and antiprotons. While there is no theoretical basis to expect success, a positive finding would be highly significant for astrophysics and cosmology.
- *Elemental composition survey*. Measuring the cosmic-ray elemental composition up to and beyond the “knee” in the cosmic-ray spectrum should provide the best clues about the origins of cosmic rays. Moreover, such a survey perhaps could also provide useful input into the larger “origins” question.

In the most recent NRA (2000), two additional experiments were chosen by the Physical Sciences Division as possible future flight experiments:

• The condensation laboratory aboard the space station (CLASS), which aims to create and study Bose-Einstein condensation in the gravity-free environment onboard the ISS, and

• Quantum interference tests of the equivalence principle (QuITE), which aims to test Einstein's equivalence principle using freely falling cesium and rubidium atoms.

Other future experiments will compare clocks moving at different relative velocities. In these ways, the ISS will allow a number of important questions in gravitational physics and general relativity to be addressed with improved clarity and resolution. These questions concern our "reasonable" assumptions about physics, including the Einstein equivalence principle, spatial isotropy in the speed of light (the Kennedy-Thorndike and Michelson Morley experiments), the local Lorentz invariance, the exact universality of gravity, and a host of other interesting issues.

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Materials Science Research Program

INTRODUCTION

Materials science provides the technical foundation for many of the nation's most vital industries: Semiconductors, optoelectronics, ceramics, and steel making are a just a few examples. Because the structure of a material determines its properties, the ability to produce a specific structure at will, and hence tailor a material's properties for a particular application, has been a continuing goal for materials scientists and engineers. However, understanding the fundamental relationship between process history, structure, and properties is complicated by the fact that material processing often involves the liquid or vapor state, so that buoyancy-driven convection, surface tension effects, sedimentation, and container reactions can mask the critical effects under study.

Materials scientists were among the first to recognize that the unique aspect of space experimentation—the absence of buoyant fluid effects and sedimentation—could provide insights that would be difficult, or impossible, to gain by any other approach. Thus, the materials science program has been in existence longer than any of the other microgravity disciplines. The objective of this space-based, or microgravity, experimentation was to gain a deeper understanding of materials phenomena that could then be used to improve Earth-based science and technology.

Early microgravity materials experiments were rudimentary and discovery-driven. In one of the first experiments, tiny lead-tin solder ingots solidified in a teacup-size furnace during an Apollo mission, were examined for microstructural improvements expected from the low-gravity environment. The Skylab and Apollo-Soyuz test programs of the 1970s successfully demonstrated the processing of semiconductor, metal alloy, and halide crystals by solidification and vapor techniques. These platforms used a specially designed multipurpose furnace to achieve a variety of experimental conditions that took advantage of microgravity conditions to process different materials. Among the results of these early studies was a demonstration that the low-convection conditions of space eliminated the compositional variations due to oscillatory convection in semiconductor crystals—these variations degraded the electronic properties of Earth-grown material. (Later, magnetic suppression of convection became standard procedure in the silicon industry.)

The space shuttle provided access to space for performing microgravity material science experiments after Skylab. During the period of shuttle-based experimentation, NASA developed a cadre of ground-based and flight investigators and improved flight hardware; it also developed new analytical tools, computational modeling techniques, and advanced materials theories. Materials science experiments in space evolved to become driven more by hypothesis and theory and less by discovery-oriented goals. As is noted below, many of the successful experiments were directed at producing benchmark data sets. Within materials science, the present microgravity research program, described below, has strongly influenced scientific understanding in several technologically important areas, for example:

- Control of impurity segregation, interface stability, and dendrite formation in metals and semiconductors;
- Control of coarsening, liquid-phase sintering, and grain structure in industrial alloys; and
- Measurement of accurate thermophysical properties, such as surface tension, viscosity, and diffusion, that are required for effective computational modeling.

In the early 1990s NASA broadened its program significantly beyond just those experiments that were destined to be flown. The ground-based program now contains a number of experimental and theoretical investigations. The purpose of the ground-based experimental program is to provide the opportunity to establish conclusively the need for performing an experiment in microgravity and to develop the protocols necessary to perform the experiment prior to the development of spaceflight hardware. In addition, theoretical programs directed at modeling the processes under investigation are funded through the ground-based program.

The current microgravity materials science program has a dual focus. Projects are conducted in each major materials system, but they are organized by research themes that are common to all materials systems. These research themes are fundamental in nature, but many also impact a range of practical problems. The materials systems being investigated currently are electronic and photonic materials, glasses and ceramics, metals and alloys, polymers, and more recently, biological materials. Common to these materials systems are the phenomena that form the key microgravity research themes: (1) nucleation and metastable states, (2) prediction and control of microstructures, (3) interfacial and phase-separation phenomena, (4) transport phenomena, and (5) crystal growth and defect control. Additionally, work is under way to improve the radiation resistance of shielding materials for use in the human exploration of space.

IMPACT OF NASA'S MATERIALS RESEARCH

The materials science program currently funds research across a broad spectrum of areas, ranging from crystal growth to materials for radiation shielding. Of the approximately 115 investigators who have been in the program over the past 2 years, 9 are members of the National Academies of Engineering and Sciences, 5 are fellows of the Mining, Metals and Materials Society (TMS), a large materials society with 100 living fellows and 10,000 members, 11 are fellows of ASM International, another major materials society, and 17 are fellows of the American Physical Society. These are large numbers given the comparatively narrow focus of the NASA materials program compared to the breadth of the interests represented by each of these materials societies. NASA has funded outstanding materials science investigators during the formative period of their careers, two of whom have been subsequently elected to the National Academy of Engineering. A major focus of the materials science program is solidification and crystal growth. The Bruce Chalmers Award, sponsored by the TMS, is given to individuals who have made outstanding contributions to the science and technology of solidification processing. There have been only 12 winners of the award to date. Of the nine Americans who have received that award, eight have been, or are, in the NASA materials program. It is clear that the program has been successful in creating a community of high-quality investigators.

Discussed below is the impact of the materials science program in the five research-theme areas mentioned previously. Not addressed are the new areas, since the research program in these areas is just beginning. Research was judged to have had a significant impact on the field if the paper received 50 or more citations or, for more recent publications, if it is being cited at a high rate. Other metrics were also used to assess impact; these are mentioned under the particular program. All of these papers were published as a result of NASA research funding.

Nucleation and Metastable States

Probing the thermophysical properties of liquids cooled significantly below their melting points, or deeply undercooled, poses a great challenge for those systems in which nucleation of the stable crystal occurs. By melting samples that are levitated it is possible in some cases to forestall nucleation of the crystal as the liquid cools, thus allowing the properties of the undercooled liquid to be measured. A recent example of this approach is provided by the study of alloys that form metallic glasses under slow cooling rates. Usually metals crystallize upon cooling significantly below their melting points. In contrast, in these "bulk metallic glasses" it is possible to form a metallic glass under very slow cooling rates. These materials have garnered much attention recently because they display unusual properties such as strength (they are two to three times stronger than their crystalline counterparts) and the ability to withstand very high strains and still remain linearly elastic, while enabling standard casting processes to be employed to produce objects with large volumes. The thermodynamic properties of these novel bulk metallic glasses were investigated using electrostatic levitation (Kim et al., 1994; Busch et al., 1995). In these studies, the heat capacity of the glass, crystal as well as the levitated undercooled liquid, was measured. By comparing these measurements with those of more standard metallic glass alloys it was possible identify certain thermodynamic properties that favor bulk metallic glass formation, thus pointing the way to the development of other bulk metallic glass alloys. Flemings and coworkers have investigated phase selection within levitated liquid steel droplets for many years. It was found that through deep undercooling of the liquid below the liquidus it is possible to nucleate phases that are not normally found during near-equilibrium solidification, thus allowing a careful investigation of the thermodynamics and kinetics of metastable phase formation. Similar phases are found during strip casting of commercial steel alloys. This work thus has the potential to lead to better control of the processing parameters during strip casting and to improvement in the quality of the steel (DiMicco, 2000).

Prediction and Control of Microstructure

As a liquid is cooled below the melting point the solid phase forms and grows into the liquid phase. The growing solid displays a rich variety of morphologies, ranging from treelike objects called dendrites to undulating solid-liquid interfaces, termed cells. This process is of intense interest from both scientific and commercial viewpoints. Of scientific interest is the fact that these processes involve the formation of patterns governed by highly nonlinear, but simple, equations. Understanding the factors that control these patterns has been of great interest in the physics and materials communities. More practically, these patterns control the distribution of chemical elements in the solid and thus the resulting properties of a casting. Since the solidification process occurs from a liquid phase, buoyancy-generated convection of the liquid can strongly perturb these processes, and thus the focus of the work funded by NASA has been to understand the role of convection in these processes and to study the processes in the absence of convection, which is usually not possible on Earth even with the application of magnetic fields.

An analysis of the citations clearly indicates that there has been a long history of important theoretical work funded by NASA in this area. The effects of convection driven by composition and thermal gradients on the morphological stability of a solid-liquid interface during solidification were first investigated by Coriell et al. (1980). They showed that both morphological and convective instabilities can occur and that the ability of the solid-liquid interface to deform leads to conditions for the onset of instability that can be quite different from those in the absence of such a deformable boundary. Ungar and Brown (1984, 1985) examined the formation of deep cells during directional solidification. They did this through a direct numerical solution of the defining equations. They showed clearly the rich bifurcation structure of these nonlinear systems and the conditions for cellular interfaces to form drops of liquid at their roots like those observed experimentally. More recently, the numerical modeling of solidification processes has been revolutionized by the introduction of the phase-field method. The strength of this approach is that it is not necessary to track explicitly the location of the solid-liquid interface during the solidification process while still accounting for the thermodynamics of the interface. The phase field model thus enables numerical simulation of the myriad topologically complex solidification morphologies that are sensitive functions of the interfacial thermodynamics. NASA researchers have been at the forefront of the development of this method by providing phase field models for systems with realistic anisotropic interfacial energies (McFadden et al., 1993), thermodynamic constraints on phase field models (Wang et al., 1993), and the first phase field model for the isothermal solidification of binary alloys (Wheeler et al., 1992).

Treelike structures known as dendrites are ubiquitous. They are found in processes ranging from crystallization from the vapor—in this context they are called snowflakes—to solidification of a liquid metal. An important advance (this paper received over 370 citations) in the study of dendritic solidification was made by Huang and Glicksman in their work on dendritic growth in succinonitrile (Huang and Glicksman, 1981). They showed that dendrites grow into a liquid cooled below its melting point with a velocity and a tip radius that are unique for a given liquid temperature. In addition, they documented clearly the influence of the buoyancy-driven convection of the liquid that accompanies dendritic growth on the dendrite morphology and growth rate. This work stimulated significant theoretical studies in the physics and mathematics communities in an attempt to understand why dendrites select the unique growth velocity and tip radius that was measured experimentally. The results of the experiments have been included in an undergraduate textbook on solidification (Kurz and Fisher, 1989) and in more advanced monographs (Davis, 2001). To remove buoyancy-driven convection and produce a data set that can be compared directly to theory, the experiments were flown aboard USMP-2 in 1994 and two subsequent missions (Glicksman et al., 1994). The experiments showed that the data on Earth are compromised by convection, and that once these convective effects are removed there are significant long-range thermal interactions between both neighboring dendrites and secondary dendrite arms that form back from the dendrite tip. Analysis of the data is continuing not only by the PI but by many others in the materials, physics, and mathematics communities, as evidenced by the numerous downloads of the spaceflight data. The experiments have produced a set of benchmark data that will serve as a test of existing and future theories of dendritic growth.

Interfacial Effects and Phase Separation

Liquid-phase sintering is a widely employed industrial process that can be used to produce an array of advanced materials, from cutting tools to automotive turbochargers. The process begins with powders that are compacted into a desired shape and then heated to produce a two-phase, liquid-solid mixture. The liquid provides a pathway through which vapor pores can escape. The goal is to reduce the shape changes of the compacted powder that occur during sintering so that little machining is required following processing. Experiments performed in space by German show, surprisingly, that the shape distortion of samples processed in microgravity is considerably greater than that of terrestrially processed samples. This finding, coupled with other insights gained from ongoing research at Kennametal, Inc., enabled a better understanding of the underlying causes of the changes in shape of powder compacts during liquid-phase sintering. Kennametal, Inc., is a market leader in the metal-cutting tool industry, with annual sales revenues of $1.8 billion. Approximately 40 percent of the production cost of its cutting tools is associated with the post-sinter machining necessary to bring the dimensions of the tool into specification. Using this insight, it was possible to nearly eliminate the final, expensive grinding step in the fabrication of parts (Latrobe et al., 1988).

If a solid-liquid mixture is held isothermally, the solid particles will evolve in time to decrease the total solid-liquid interfacial area, and so the average size of the solid particles will increase in time. This process, called Ostwald ripening, is observed in nearly all two-phase mixtures, from raindrops in clouds near the equator to solids composed of mixtures of different crystals. As a result, the ripening process influences the properties of many commercially important materials, among them a wide variety of aluminum alloys and high-temperature materials used in jet turbines. NASA-funded work has provided many new insights into this important phase transformation process. Akaiwa and Voorhees predicted theoretically the interparticle spatial correlations and the kinetics of ripening in systems with the high-volume fractions of ripening phase that are typically employed experimentally (Akaiwa and Voorhees, 1994). In agreement with theory, terrestrial experiments showed that the ripening process in model solid-liquid mixtures was a function of the volume fraction; however, the mixtures were found to ripen faster than predicted by theory (Latrobe et al., 1988). To avoid the sedimentation of the solid particles that accompanies terrestrial experiments, ripening experiments were performed in space. As a result of the ideal conditions afforded by the microgravity environment, it was possible to show that the classical theory for ripening, first postulated in the 1960s, did not describe the experimental results (Alkemper et al., 1999). The experiments have produced a set of benchmark data that has been used by other investigators in their research and teaching. The finding that systems undergoing Ostwald ripening may not be described by the classical theory influenced the development of software that is used to simulate the nucleation, growth, and ripening process in commercial alloys. In particular, the Precipicalc software that has been developed by the materials design company Questek was designed to take advantage of the spaceflight results. General Electric, and Pratt and Whitney, two jet engine manufacturers, are currently using this new software.

Measurement of Thermophysical Data

With the advent of fast computers and powerful algorithms, it is now possible to simulate many important processes that are used to produce materials. However, for such models to be truly predictive, it is necessary to employ accurate values for the thermophysical properties for the material being modeled. Many of these thermophysical parameters, such as diffusion coefficients of elements in high-temperature semiconductor and metallic liquids, are extremely difficult to measure, and when measured on Earth their values are frequently perturbed by buoyancy-driven convection. Thus, spaceflight experiments are required to produce benchmark sets of thermophysical data. These experiments, however, will involve only a limited number of systems due to the constraints imposed by space experimentation. While these experiments have yet to be performed in space, the importance of performing this work is well recognized by industry, as evidenced by letters of support for this research from the staff of the Brimrose Corporation (Murphy, 2001) and the chairman and chief executive officer of the II-VI Corporation (Johnson, 2001). Both companies are involved in the production of semiconductor materials for sensor and electro-optic applications. In addition, certain II-VI materials have been and will be used in NASA space-based telescopes, indicating that this work may have a direct impact on NASA if allowed to proceed.

Crystal Growth and Defect Control

Nearly all materials used for structural applications are composed of more than one chemical component. As a result, a mushy zone, a partially solidified region of significant spatial extent, forms during solidification. Convection within the mushy zone can occur due to the variation of the liquid density with temperature and composition. This leads to the formation of vertical plumes of liquid, or freckles, within the mushy zone. The resulting strong microstructural inhomogeneity in the solidified material has a considerable adverse impact on the properties of many cast materials. Major insights into the physics underlying freckle formation were made by Hellawell and coworkers early in the NASA materials science program (Sample and Hellawell, 1984; Sarazin and Hellawell, 1988). They showed by direct observation that convection was responsible for the formation of freckles and that rotating the sample can damp the formation of freckles. Porier and coworkers were among the first to propose physics-based models of convection and solute segregation within mushy zones (Felicelli et al., 1991; Ganesan and Poirier, 1990).

Since crystals are grown from a melt or solution, buoyancy-driven convection of the fluid can play an important role in the resulting distribution of chemical components and defects in the crystal. A nonuniform distribution of chemical components can be quite deleterious to certain electronic and mechanical properties. Before the infusion of NASA funding, understanding of the effects of convection on crystal growth was limited to a few simple models of the convection process, many of them ad hoc. While providing some insight into the role of convection on the crystal growth process, these theories did not address the coupling between fluid flow and mass transfer in a self-consistent manner. A solution to the Navier-Stokes equations during crystal growth is required wherein the solid-liquid interface is allowed to deform in concert with the diffusive and convective processes in the liquid. Coriell et al. were the first to employ such an approach to examine the effects of solutal and thermal convection on the stability of a solid-liquid interface during directional solidification (Coriell et al., 1980). Chang and Brown (1983) performed numerical simulations that allowed for large deformations of the solid-liquid interface and both thermal and solutal convection in the liquid. They examined the dopant distribution in the resulting crystal and correlated the distribution with the levels of convection, the shape of the solid-liquid interface, and the design of the Bridgman furnace. They found that the segregation can be as large as 60 percent of the mean concentration and that the design of the furnace can change the degree of segregation. Further work by Adornato and Brown found that solute segregation was minimized for near-diffusion controlled growth or for situations where there is intense laminar mixing (Adornato and Brown, 1987). The implication of this result is that intermediate levels of convection, such as those found at certain levels of reduced gravity or in weak magnetic fields, can actually produce larger segregation and thus more undesirable material. In addition to these results, the support provided by NASA had an impact on the theory and understanding of Czochralski growth (Derby et al., 1985; Derby and Brown, 1986) and float zone growth (Coriell et al., 1977). NASA-funded research aided in the development of a community of scientists working on the mathematical modeling of crystal growth and solidification.

FUTURE DIRECTIONS IN MATERIALS RESEARCH

Materials science has played a central role in many of the discoveries that have shaped our world, from integrated circuits to low-loss optical fibers and high-performance composite materials. The recommended research areas for NASA's materials science program, given below, will continue this tradition of science-driven discoveries of great importance to the nation and to NASA. Many of these promising areas build on research currently in the program, while others are new and unrelated to the existing program. Furthermore, the committee expects that many other new and exciting areas will emerge from the nation's research community.

Nucleation Within and Properties of Undercooled Liquids

The properties of many materials are strongly linked to the phases that nucleate during crystallization. Hence, to tailor the properties of a material for a given application conditions must be chosen such that only desirable phases nucleate during the processing of the material. Thus the nucleation process plays a prominent role in setting materials properties. Unfortunately, the conditions governing the nucleation of new phases are not well understood. Experiments in microgravity can play an important role in providing a basic understanding of the nucleation process, since they eliminate a potent site for nucleation—the walls of a container—while still permitting large volumes of liquid to be employed in the experiment. In systems where nucleation on foreign particles in the bulk is not a problem, it is possible to study carefully the nucleation process in bulk samples using a wide range of sample volumes. An example is the formation of a glass from a liquid. Glasses typically form when a liquid is cooled sufficiently fast to prevent the atoms from arranging themselves in a crystalline lattice. A new class of metallic alloys has been discovered that can form glasses under very slow cooling rates, making it easy to cool significant volumes of the liquid alloys far below their melting points. The ability of the bulk metallic glass alloys to undercool allows the properties of the undercooled liquid state to be examined. For example, recent studies appear to indicate that the classical theory for crystal nucleation from a liquid is inapplicable in these materials and that the liquid alloys exhibit atomic transport and rheological characteristics that are very different from standard liquid metallic alloys. These materials also exhibit novel properties: They are twice as hard as stainless steel with similar toughness. For example, bulk metallic glass composites have recently been found to have significant ductility in tension, opening a wide range of applications, from aircraft materials to medical implants. Fundamental studies of the undercooled liquid state of these bulk metallic glasses can be performed in microgravity since it is possible to undercool large volumes of liquid using containerless methods and thus avoid heterogeneous nucleation due to the container. For example, if the properties of the melt that lead to bulk metallic glass formation are better understood, this might allow aluminum-based bulk metallic glass alloys to be formulated. Such bulk metallic glasses could have a huge impact on both industry and NASA since they would possess high specific strength and tensile ductility and thus would be ideal for a number of aerospace applications. Another example of nucleation from a liquid is quasicrystal formation. Quasicrystals are crystals with an unusual fivefold crystallographic symmetry. Here the issue is whether there are structural precursors to the quasicrystal in the undercooled liquid, a liquid that is cooled below its melting point. Establishing such a link between the structure of the liquid and quasicrystal formation will shed new light on why certain alloys form quasicrystals and others do not.

Dynamics of Microstructural Development During Solidification

The microstructures of solidifying materials provide beautiful examples of spontaneous pattern formation. The development of dendritic and cellular microstructures is governed by relatively simple partial differential equations whose solutions are complex, possibly chaotic, and extremely sensitive to small perturbations. Moreover, since the majority of metallic materials are cast, the solidification process is of enormous industrial importance. The ability to directly link processing conditions to the resulting materials properties is still not at hand as the mechanisms governing the development of dendrite and cell morphology are not well understood. Outstanding questions include the effects of interactions between individual dendrites or cells on their spatial distribution and morphology, the evolution of dendrite morphology during transient heating or cooling, and the effects of noise and initial conditions on the resulting patterns. The interactions between dendrites are particularly important in the development of the mushy zone. A National Research Council study on the future of condensed matter and materials physics identified the mushy zone as "perhaps the most important theoretical challenge" in metallurgical pattern formation and also chose the study of the mushy zone as one of the research priorities in nonequilibrium physics (NRC, 1999). A major impediment to the study of these solidification processes, however, is convection of the liquid phase, since convection makes it nearly impossible to compare results with theoretical predications and greatly complicates the interpretation of experimental data. Performing experiments in a microgravity environment where convection is much reduced is thus crucial to understanding these complex pattern-forming systems that are of great commercial importance.

Morphological Evolution of Multiphase Systems

Materials used commercially are usually composed of more than one phase—for example, the strength of a jet turbine blade is linked to the size, shape, and spatial distribution of the precipitates that are embedded in the matrix of the blade. These multiphase systems are created by a nucleation, growth, and Ostwald ripening process through which a single phase decomposes into two or more phases. Examples of such phase transformation processes abound. They occur in systems as diverse as polymers, wherein a second phase of different composition can form by either spinodal decomposition or nucleation with a liquid matrix, and in metallic alloys, wherein the morphology of dendrites in mushy zones evolves in time by Ostwald ripening. In other cases, a two-phase mixture is created by physically mixing two phases, such as the solid-liquid mixture found during liquid-phase sintering. During thermal processing, the morphology of the mixture evolves and the volume fraction of vapor bubbles decreases. Despite the clear commercial relevance and scientific importance, an understanding of the dynamics of phase transformation processes is not at hand. Phase separation and the processing of materials where one of the phases is liquid inevitably leads to sedimentation due to the density difference between the component phases. Performing experiments in a microgravity environment greatly reduces the rate of sedimentation and allows the dynamics of the transformation process to be investigated carefully. As a result, microgravity experiments can provide new and important insights into the dynamics of the evolution of multiphase materials. Research into Ostwald ripening and liquid-phase sintering has affected industrial practice in the past, and the committee expects that there is a good probability that it will in the future.

Computational Materials Science

Materials are typically designed using an extremely tedious and expensive trial-and-error approach. However, with the advent of high-speed computers and modern algorithms, it is possible to simulate the behavior of materials using a computer. Since the properties of materials are a function of processes that occur over an enormous range of length scales, from the nanometer to the meter scale, a wide variety of methods is required. On the smallest scales, quantum mechanical methods are used to simulate properties that depend on the electronic structure of a material. In the tens of nanometers to micrometer scales, mesoscopic methods (such as the phase field method described earlier) are employed to describe the evolution of the morphology of the constituent phases. Finally, the methods of computational mechanics are used on the largest scales. As a result, numerical simulation is being viewed as an equal partner with experiments in determining the properties of materials. A recent example of the power of this approach is the work of Johannesson et al., wherein density functional theory was used to find the most stable phases in alloys with four chemical components that can be constructed using 32 different metals or 192,016 possible alloys (Johannesson et al., 2002).

On the mesoscale, three-dimensional calculations of morphological development in alloys, while still challenging, are becoming commonplace. The practical ramifications of such an approach are profound; it is now possible to design a material using simulations to yield a desired set of properties. No longer are parametric models required, since the calculations are predictive, efficient, and accurate. This will yield a new paradigm for designing industrially relevant materials, since the materials will be created with a minimum of costly, time-consuming experiments. This approach can have a significant impact on NASA because it ensures that the materials properties of interest to NASA will be attained, in much less time and at a lower cost. Such computational efforts are a natural outgrowth of the strong effort in process modeling research currently supported by the program. Computational materials science promises to yield a revolutionary new approach to designing new materials processes as well as tailoring materials properties for a given application. Furthermore, the integration of process modeling and diagnostics promises to one day be the key to rapid implementation of new materials-processing technologies. These approaches are just beginning to be embraced by industry.

Thermophysical Data of the Liquid State in Microgravity

Computational modeling of materials processing requires accurate thermophysical data of the liquid state. Obtaining such data on the ground that are not affected by convection is very difficult in low-melting-point systems and nearly impossible for high-melting-point materials. For example, there are very few accurate measurements of the solute diffusivities in liquid metallic or semiconductor alloys as a function of temperature. Performing such experiments in microgravity will provide insights into the physics of the liquid diffusion process as well as much needed thermophysical data for industry. Accurate thermophysical data along with computational models will yield realistic predictions of quantities such as the degree of microsegregation following solidification. The magnitude of the microsegregation in turn can have a significant deleterious effect on a wide array of materials properties

Nanomaterials and Biomimetic Materials

There are many new avenues for materials research at the nanoscale and at the interface between the biological and materials sciences. These new directions are discussed in Chapter 7.

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6

Biotechnology

INTRODUCTION

The NASA program in biotechnology, under the auspices of its Physical Sciences Division, is of relatively recent origin compared to the programs in other disciplines. Programs in protein crystal growth and cell science began informally in the mid- to late 1980s; the first NASA Research Announcement was issued in 1991. These programs were reviewed recently by a task group whose mandate was to evaluate NASA's biotechnology facility for the ISS. The report of that group (NRC, 2000) gives an up-to-date account of the program, commenting extensively on its achievements and its shortcomings, and makes a number of recommendations for improvements, specifically in relation to research to be undertaken on the ISS. In view of the recent and detailed nature of the task group report, including recommendations for future directions, NASA excluded review of the biotechnology program from this committee's mandate. However, for the convenience of the reader, the Executive Summary of the task group report is included in the present report as Appendix A.

Some of the issues and areas related to biotechnology are discussed elsewhere in this report, particularly in Chapter 7, dealing with emerging areas.

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7
Emerging Areas: New Opportunities at the Nanoscale and at the Interface Between Biology and the Physical and Engineering Sciences

INTRODUCTION

Generating the base of fundamental knowledge needed for the development of technologies that would allow NASA to accomplish more with fewer resources and learning how reduced gravity affects human health in space are central to NASA's programs. Much of NASA's past work has focused on finding solutions to the challenges at the macroscopic and micron scales, some of which is summarized in previous chapters. Novel nanoanalytical techniques and methods for engineering materials at the nanoscale are opening new frontiers with the potential to have a major impact on NASA's technologies, including technologies for remote and miniaturized sensing, and smaller, faster and integrated devices and systems. The Physical Sciences Division (PSD), which has already begun to invest in research in fields such as nanomaterials, biomolecular physics and chemistry, and tissue engineering, is in a good position to make significant contributions to exploiting the nanoscale if its limited resources are used well. Many agencies, including the National Science Foundation (NSF), the National Institutes of Health (NIH), the Department of Energy (DOE), the Department of Defense (DOD), and the Defense Advanced Research Projects Agency (DARPA), as well as other NASA divisions, are rapidly increasing their investments in nanotechnology. The PSD can make unique contributions to these emerging fields by applying the expertise and tools of the physical science community to (1) address certain challenges faced by the biomolecular sciences, (2) develop a pipeline of (initially) ground-based experiments that probe how stress-mediated subcellular processes are affected by microgravity, and (3) develop a knowledge base on how to store and convert energy using emerging technologies.

In accordance with the committee's earlier recommendation set forth in its phase I report (NRC, 2001, p. 2), the PSD should invest in a given topic in an emerging field only if both of the following criteria are met:

> 1. [The topic] directly address[es] challenges at the interface between the physical sciences, engineering, and biology in support of NASA's mission, preferentially capitalizing on existing expertise or infrastructure in the Physical Sciences Division, and

2. [The topic] support[s] research either not typically funded by other agencies or to be conducted in close partnership with other agencies.

Based on these criteria, the committee assessed in which areas nanoscale science at the convergence of the physical sciences, biology, and engineering is most likely to have a major impact on NASA's space programs. After selectively reviewing in this chapter the current state of the art in a number of disciplines, including a far larger number of areas than the PSD could possibly fund, the committee suggests how the PSD could optimize its impact in select areas by either leveraging investments made by other agencies or taking a leading role itself. Among those areas recommended for research, summarized in Chapter 8, the highest priority is given to areas where the potential exists for the PSD to assume a leadership role.

A unifying theme of the research discussed in this chapter is that new frontiers are opening at the nanoscale whose technological exploitation requires systems integration at different length scales. The scientific and technological potential and the social and ethical impacts of nanotechnology were explored recently in a series of workshops and reports that are now available to the public, among them the reports of the Interagency Working Group on Nanoscience, Engineering, and Technology (WTEC, 1999; NSTC/CT/IWGN, 2000); the report of the NSET workshop "Societal and Ethical Implications of Nanoscale Science and Nanotechnology" (NSTC, 2001); and the report of the NIH workshop "Nanoscience and Nanotechnology: Shaping Biomedical Research" (NIH, 2000); as well as a report by DOE, "Biomolecular Materials" (DOE, 2002). The NRC recently concluded a review of the National Nanotechnology Initiative, which resulted in the report entitled *Small Wonders, Endless Frontiers* (NRC, 2002). According to yet another report issued by the National Science and Technology Council of the Executive Office of the President of the United States (NSTC, 2000), "Nanoscale science and engineering promises to become a strategic, dominant technology in the next 10-20 years, because control of matter at the nanoscale underpins innovation and progress in most industries, in the economy, in health and environmental management, in quality of life, and in national security." Hundreds of experts in academia and industry have made significant contributions to the above-mentioned reports, the content of which is highly relevant to the PSD, and U.S. funding agencies are well prepared to make major investments in these emerging technologies.

Because the PSD is expected to have limited resources to invest in these emerging areas, clearly it must invest in research that will have a maximum impact on NASA's future flight technologies. Research in emerging areas focused on NASA applications is unlikely to have the requirement for low gravity that characterizes most areas of current PSD research. Thus most, but not all, of the recommended research is likely to be ground-based. The PSD must strive to find unique technical niches in support of NASA's core missions. For example, novel insights into nanoscale phenomena and the availability of an increasing number of nanoanalytical tools could have a major impact on NASA's ability to generate and store power in space, manufacture lightweight materials on the ground and in space, design materials with integrated sensory functions, and develop new sensor technologies. The confluence of the biological, physical, and engineering sciences at the nanoscale is an ideal point at which NASA could leverage the investments made by NSF, NIH, DOE, DOD, DARPA and others to enhance its own missions. The committee believes that, in addition to the programs the PSD develops in synchrony with other agencies and other NASA programs, there are select topics in the emerging areas that provide promising opportunities for the PSD to assume leadership with limited financial resources. The PSD needs to ensure, however, that it takes an integrative approach such that the new knowledge it develops is consistent with overarching larger programs that target particular needs of

NASA. For example, a coordinated multidisciplinary effort could quickly result in compact biosensors and medical diagnostic devices, both of real use to NASA's human exploration efforts.

NANOSCALE MATERIALS

Recent technological advances have made it possible to engineer materials on the nanometer length scale by exploiting self-assembly processes. Materials engineered at the nanoscale exhibit unique structural and functional phenomena not achievable with conventional materials. For example, materials are envisioned that can sense emerging internal defects in materials and alert the user in a timely fashion, before there is a catastrophic failure. Other materials might sense environmental cues and respond to them by, for example, delivering drugs, healing defects, undergoing mechanical motion, or altering an optical or magnetic response. Simultaneously, modern biology, with its new genetic and analytical tools, is providing insights into how nature synthesizes and processes materials. Cellular processes such as light harvesting, energy conversion, data storage and processing, self-replication, and locomotion occur at the nanoscale. Nature has devised sophisticated solutions by evolving complex molecules and molecular assemblies to perform these tasks. By emulating nature, researchers have begun to develop new processing strategies for the fabrication of synthetic materials and the integration of biological systems into artificial materials. Merging the biological and the synthetic world at the nanoscale promises revolutionary technological developments, particularly for sensors and diagnostics.

Nanoscale materials, a rapidly expanding field involving many different disciplines, is being supported by a number of different government agencies. As with many areas discussed in this chapter, the committee concluded that any investment that the PSD might make in nanomaterials should focus on research that will have the greatest impact on NASA's missions and that is consistent with the criteria cited at the beginning of this chapter. This requires that the PSD identify the questions that are relevant to NASA before soliciting solutions from the community through peer-review processes. The examples below illustrate how such an approach could provide NASA with enabling technology to meet its goals. For each of the topics, the significance to NASA is given and the background, state of the art, and any research recommendations are discussed.

Nanoparticles

New materials with tailored properties are important to achieving NASA's goals of low-cost spaceflight and establishment of a permanent human presence in space. A promising approach to the production of such materials involves the assembly of nanoparticles or the hybridization of nanoparticles with organic and/or inorganic matrices. This approach extends the novel materials properties derived from nanoscale phenomena to larger scales and tailors them to the requirements of macroscopic applications. These tailored nanomaterials can exhibit unique sets of complementary structural, magnetic, optical, thermal, chemical, and electric properties. One impediment to converting these research findings into products is the difficulty of synthesizing most nanoparticles in large quantities. Precise control of their size (and their quantum phenomena), their stabilization over extended time periods, and control of assembly processes are also critical issues.

Significant progress has been made in growing inorganic and organic nanoparticles and in assembling certain nanomaterials and giving them temporal stability. A particle's size and shape strongly influence its properties, and scaling up the synthesis of nanoparticles to large quantities is of interest. Researchers have made much progress in growing monodisperse nanoparticles of metallic and semiconductor materials, including gold, silver, and magnetic nanoparticles. To exploit nanoscale phenomena for technological applications, future experimental and theoretical work will focus increasingly on the mechanisms for growing nanoparticles with more complex shapes (Manna et al., 2000) and on the use of complex shapes to fine-tune properties (Li et al., 2001; Hu et al., 2002). Indeed, the periodic table leaves much room for the synthesis of more nanoparticles with unique shapes and properties from other combinations of elements.

Far-from-equilibrium processing of nanostructured materials is another emerging area of scientific interest and potentially great technological importance. For example, the superplastic formability of a nanocomposite ceramic having three constituent nanophases with comparable volume fractions has been demonstrated (Liao et al., 1997, 1998; Colaizzi et al., 2001). The key to this application has been the ability to produce metastable powders by a rapid melt-quenching process, followed by controlled decomposition into the final stable, three-phase nanocomposite structure. Possible applications include the superplastic forming of rocket engine and space vehicle components, where there is a need for light weight and resistance to heat, radiation, and erosion.

Magnetic nanocomposites that result from the decreased size of the domains or grains within the material are also of significance to NASA. These include composites having enhanced magnetocaloric effects, which enable both high- and low-temperature magnetic refrigeration; higher-density recording media; and giant magnetoresistance materials that provide large changes in resistance for a given magnetic field. Ferromagnetic materials of small diameter promise to further enhance the giant magnetoresistance effect (Xiao et al., 1993). Hard magnetic materials are used in a wide range of applications such as motors. Nanocomposites consisting of materials with hard magnetic domains within a nonmagnetic phase, such as those produced in Nd-Fe-B alloys (for a review, see Buschow, 1988), are particularly promising routes to enhanced coercivity. Nanocomposites involving the coupling between atomic spins over atomic length scales promise to greatly enhance magnetocaloric efficiencies and, in particular, to enable efficient magnetorefrigeration at close to room temperature. Because magnetic refrigerants are widely used in a host of NASA missions, from satellites to refrigerators on the ISS, enhanced magnetocaloric properties could have a major impact.

Perhaps no nanoparticle has received more attention than the single-wall carbon nanotube (SWNT), with a predicted Young's modulus of about 1 terapascal (TP) and excellent electrical conductivity. Applications ranging from ultralight high-performance SWNT structural composites to molecular-scale electronics are being actively investigated, often with NASA support.[1] With NASA already heavily engaged in this rapidly emerging area, the committee felt that additional investment in nanotubes by PSD would be unwarranted.

Nanoparticles in isolation will have limited use—instead they should be seen as building blocks with which to fabricate materials and devices tailored to NASA's needs. The PSD should set its priorities carefully when considering what it might contribute to this area. The fields of molecular electronics and magnetic nanosystems, for example, are likely to be rapidly dominated by other agencies and industry.

Functionalized Nanoparticles

For many classes of material, it is essential to develop methods for stabilizing the surfaces of

[1]For example, NASA has teamed with recent Nobel Prize winner Richard Smalley of Rice University in a multiyear program to develop cost-effective nanotubes for space applications. The Johnson Space Center is working extensively on nanotube-reinforced composite materials, while NASA Ames is a leader in nanotube-enabled electronics. Other divisions of NASA are also major players in nanotube R&D (see NASA Web site for details).

inorganic nanoparticles against atomic restructuring or unintended chemical reactions. For example, in highly luminescent semiconducting nanoparticles, ZnS shells have been used to stabilize the CdSe core, whose quantized electronic states give rise to narrow emission bands that can be continuously tuned by changing the particle diameters (Dabbousi et al., 1997). Engineering that uses nanoparticles as building blocks will require unique ligands that specifically recognize each class of material. Furthermore, the ligands will have to bind selectively to particular crystal faces. Selective binding enables the control of nanoparticle self-assembly into hybrid materials or onto designated surface areas within devices. Thiol chemistry has been broadly employed to functionalize gold particles, and silica coatings have been introduced to conjugate nanoparticles to biomolecules in an attempt to render them biocompatible (Gerion et al., 2001; Michalet et al., 2001; Chan et al., 2002). In the search for alternative chemistries that bind specifically to nanoparticles of interest, phage display technology has been recently demonstrated that can select, out of a random library, peptides that selectively bind semiconductors, even exhibiting selectivity for particular crystallographic faces (Whaley et al., 2000). Much work is needed to identify high-affinity ligands for a wider range of technologically important materials and to allow their coassembly into hybrid materials.

If the PSD is to develop nanotechnology along the lines of interest to NASA, it will have to ensure the development of a nucleus of investigators with expertise in the foregoing foundation technologies for the chemical modification of nanoparticle surfaces. Special attention should be paid on the one hand to the search for novel chemistries and biochemistries that specifically enable binding to materials of interest to NASA and on the other hand to the search for heterofunctional linker molecules that enable the assembly of nanoparticles of dissimilar materials with complementary properties. However, since the chemical modification of nanoparticles is at the core of much ongoing nanotechnology work, the committee suggests that the PSD support topics in functionalized nanoparticles indirectly, either by funding only the technology applications and encouraging investigators to look elsewhere for funding specific to these foundation technologies, or by forming close alliances with other NASA divisions or outside agencies[2] to support research into foundation technologies for which there is a particular NASA need.

Hybrid Materials with Multiple Functions

Meeting its technology challenges will require that NASA have access to future materials and devices that incorporate nanosystems with complementary properties and functions. Examples range from materials with high strength and low weight to materials with integrated sensory functions. The challenges of producing such materials are many. Self-assembly could potentially be combined with templating technologies or with micro and nanofabrication to produce these complex structures. For example, use of proteins, DNA, and other biomolecular processes could open new routes to the nanoassembly of high-performance, silicon-based materials (Cha et al., 1999, 2000). DNA and biomolecular ligands (Whaley et al., 2000; Seeman and Beecher, 2002) could be used to connect, and control the self-assembly of, nanoparticles (Mirkin et al., 1996; Storhoff and Mirkin, 1999), nanowires (Huang et al., 2001; Hu et al., 1999; Wilson et al., 2003; Sapp et al., 1999), viruses (Lee et al., 2002), and devices (Yan et al., 2002; Nam et al., 2002).

[2]For example, NASA has collaborated with the National Cancer Institute to solicit proposals for basic research on technology development related to biosensors.

Since the properties of materials depend on the ordering of the building blocks at different length scales, technologies that induce or impose a long-range hierarchical ordering of the blocks will be pivotal (Whitesides and Gryzbowski, 2002). The long-range ordering of liquid crystals, for example, has been used to serve as a template for mesoporous molecular sieves (Kresge et al., 1992; Ryoo et al., 1999) and inorganic solids (Braun et al., 1999). Colloids have been used to impose hierarchical order on sol-gel ceramics (Shin et al., 2001b). Crystal-imprinted polymers have been used to direct the nucleation of biominerals (D'Souza et al., 1999). And ordered cellular structures in wood tissues have been mineralized using a surfactant-templated sol-gel process (Shin et al., 2001b). Finally, micromolding, combined with polystyrene sphere templating and the cooperative assembly of inorganic sol-gel species with amphiphilic triblock copolymers, has been used to pattern porous silica, niobia, and titania with three-dimensional structures over multiple length scales. The resulting materials show hierarchical ordering over several discrete and tunable length scales, from 10 nanometers to several micrometers (Yang et al., 1998).

The committee's recommendation to the PSD in the preceding section, "Functionalized Nanoparticles," applies equally to future PSD research on the fabrication of nanomaterials. Namely, the development of integrated nanomaterials should take advantage of expertise developed in already existing programs such as those described above, and build naturally on the PSD program's expertise in surface chemistry and interfacial phenomena. For example, NASA's work in colloidal condensation and surfactant chemistry is relevant to advancing the sophistication of hybrid materials using self-assembly strategies.

Nanoscale Systems for Energy Conversion and Defect Repair

Research into technologies to fabricate hybrid materials must be complemented by research into nanoscale systems for signal transduction, so that sensory functions and readout capabilities can be integrated into artificial materials, or biological molecules can be manipulated on demand by external signals. Areas on the verge of being emphasized by several agencies (including DOE, DOD, DARPA, and others) are nanoscale systems that interconvert chemical, electrical, optical, thermal, mechanical, or magnetic signals. Many different avenues are currently being explored to transduce signals in manmade systems at the nanoscale. For example, the conductance of single molecules can be altered through conformational changes in the molecule (Donhauser et al., 2001). Electronically programmable memory devices can use molecular self-assembled monolayers (Reed et al., 2001). Elastic protein-based polymers have been developed that convert environmental stimuli into shape changes (Urry, 1997). Materials with continuously adjustable pore size have been made by templating silicates (McGrath et al., 1997). Temperature-sensitive hydrogels have been utilized for various sensing applications, including thermally switchable diffractive arrays (Weissman et al., 1996) and thermosensitive clay nanocomposites (Liang et al., 2000). Furthermore, ligand binding to proteins has been environmentally controlled using polymer-protein conjugates (Ding et al., 2001), and drug release from porous channels has been controlled using hybrid nanogels (Shin et al., 2001a). While these are important first steps, biology has evolved the most sophisticated nanoscale systems for the conversion of energy from one form into another. Examples include motor proteins, which convert chemical into mechanical energy. Photosynthetic membranes in chloroplasts harvest light to pump protons across membranes, thereby establishing an energy source for plants. The energy sources of aerobic cells are mitochondria, which use the metabolic oxidation of nutrients to pump protons across their active membranes to power other metabolic processes.

Insights into the mechanisms by which these biological systems work provide inspirations for new design principles for converting energy forms more efficiently. For example, inspired by nature, researchers have designed a photocatalytic dendrimer reactor (Hecht and Frechet, 2001), and block copolymers have been designed that capture features of their natural protein counterparts to synthesize ordered silica structures (Cha et al., 2000). An examination of biological systems may also suggest new solutions for integrating nanoscale machines into functional systems at different length scales, since biological materials display an exceptionally high degree of spatial and temporal organization. This effort could build on already existing expertise in the PSD program on self-assembly, interfacial phenomena, nanotubes and nanowires, and protein-protein interactions. Challenges related to systems integration are discussed in the next section, "Integrated Nanoscale Devices."

Considering the many possible approaches to converting signals at the nanoscale, any PSD investments in this field should be driven by clearly defined technological challenges that would determine which molecules, systems, and processes would be investigated at the fundamental level.

Finally, to protect human health in space and for extended flight missions, NASA has to find solutions to the problem of identifying incipient materials defects before they result in a catastrophic failure of materials and devices and repairing defects during spaceflight. This is a particularly relevant issue since aging of materials is considerably accelerated by radiation damage. While concepts of self-healing are absent in industrial materials, biological systems are remarkable in their ability to self-repair molecules such as DNA, to self-heal materials such as bone or the skin after injury, and to grow or reconfigure materials on demand. NASA could invest in developing new strategies that potentially would borrow design principles from nature to introduce attributes of self-healing and repair that would extend the lifetime of manmade materials and devices. First approaches to the engineering of self-healing or self-repairing materials have been explored. For example, encapsulated adhesive or prepolymer has been distributed throughout a composite material. At the damage site, the adhesive is locally released or the prepolymer is locally polymerized, leading to partial recovery of the material's strength. In contrast, the self-repair mechanisms of biological materials are far more elaborate, because they involve the rapid exchange and replacement of damaged building blocks by energy-driven processes. Accordingly, molecular motors have been integrated into synthetic materials to carry molecular- or nanoscale cargo to user-specified locations (Hess et al., 2001), opening the possibility of locally repairing defects. It might also be possible to integrate molecules and nanoscale particles that can act as reporters into structural materials to monitor the material's properties in real time. This would enable lighter and safer structural materials for space exploration, including astronaut suits, and would greatly benefit the quality of life on Earth and in space.

INTEGRATED NANOSCALE DEVICES

The novel phenomena, properties, tools, and processes provided by nanotechnology advances have much to offer when it comes to addressing the challenges of human space exploration over extended time periods. They could be applied in areas such as power generation and energy storage, advanced life-support systems, water purification, human waste management, management of accidents and hazardous conditions, human health monitoring and diagnosis, and integrated sensors for the detection of threats to human life, to name a few. The high launch and operating costs of current space systems are usually proportional to their weight or mass, which in turn is a determining factor in the amount of functionality of a particular system or subsystem. The integration of micro- and nanoscale technologies into selected spacecraft subsystems could increase functionality and reliability while simultaneously decreasing weight. To capitalize on emerging nanotechnologies for advancing space exploration, NASA should focus on integrating large numbers of nanoscale subsystems into devices, potentially covering many different length scales. This requires a multidisciplinary approach and cross-disciplinary expertise. Furthermore, scientists should collaborate with engineers early on to ensure the successful integration of nanoscale systems into the operational systems of relevance to NASA's mission. Three areas of particular interest are energy storage and chemically driven nanosystems; microfluidics; and integrated microelectrochemical and nanoelectrochemical systems.

Energy Storage and Power Generation

What energy sources will power NASA's macroscopic and microscopic devices in the future? Advanced miniaturization and exploitation of nanotechnologies could play an important role in the development of next-generation batteries and fuel cells. For example, hierarchically structured electrodes and nanostructured electrolytes would have broad applicability to different types of electrochemical devices and would have the potential to significantly improve their performance compared to that of existing technologies. Finding more efficient approaches to increasing energy density at minimal weight is critical to NASA's space missions. A number of other near-term potential applications of nanotechnology are also emerging, such as novel matrices for hydrogen storage, including metal hydrides and nanotubes; ionic conducting membranes; efficient utilization of sunlight; and direct production of biological nutrients and their reconversion into energy.

Batteries, fuel cells, and other electrochemical devices often involve complex mass and charge transfer mechanisms. The fuel cell electrode, for example, requires pathways for electrical conduction, gas flow, and ion conduction. Configuring these pathways for optimal performance involves complex structural hierarchies with design issues that span nanometer- to millimeter-length scales. Typically, part of the electrode fabrication process involves slurry coating the electrode surface, a technique that does not offer sufficient control to fabricate complex hierarchical structures. The recent application of templating methods (Lellig et al., 2002; Velev et al., 1998) has resulted in a highly porous three-dimensional network with enough surface area for efficient electrode mass transfer. Chemical printing techniques might be another way to fabricate hierarchical structures that could even accommodate compositional variations across the electrode surface. This would facilitate the interdigitation of different conduction pathways.

Nanostructured electrodes, which are formed with two or more types of nanoparticles, can increase mechanical strength while decreasing the electrode thickness and increasing the electrode conductivity (Sata et al., 2000). Nanostructured electrodes can be fabricated using a variety of techniques, from molecular beam epitaxy and chemical vapor deposition to traditional colloidal processing techniques. In addition, it has been demonstrated that nanoscale devices have an inherent capacity for storing energy (Che et al., 1999; Gomez-Romero, 2001) and for efficient electrochemical energy conversion in micro fuel cells (Chen et al., 2001). These findings suggest that the field of energy storage and power generation can be pushed beyond the capabilities of conventional technologies. As space missions become longer in duration and more demanding in terms of energy usage, these new technologies will become increasingly important.

Solid-state electrical power generation, based on the Peltier effect, is achieved when a temperature difference is maintained across a thermoelectric material. These thermoelectric devices offer the advantage of being environmentally friendly and not requiring moving parts. However, for thermoelectric generation to become a competitive source of power, the energy conversion efficiency has to be significantly improved by engineering superior thermoelectric materials that are not available naturally in elemental form. Promising thermoelectric materials include semiconductors with a high Seebeck coefficient, tailored to exhibit high electrical conductivity and controlled heat flow with relatively low thermal conductivity. For this purpose, multimaterial nanostructures can be engineered, using techniques that increase the resistance to heat flow in the lattice responsible for thermal transport. Promising approaches have recently been reported including superlattices (Venkatsubramanian et al., 2001) and nanostructured thermoelectric materials with quantum confinement of electrons and phonons (Hicks et al., 1996; Dresselhaus et al., 1999). Superior thermoelectric properties can be achieved by confining semiconductors in the 5- to 100-nanometer-size range (Sun et al., 1999), including quantum confinement of electrons in nanowires, to tailor the electronic band structure. Thermal conductivity can also be reduced by enhancing boundary scattering in nanowires that influences the phonon spectra and lifetime (Dresselhaus and Eklund, 2000). Thermoelectric properties may be further enhanced by tailoring nanowire array composites.

Advances in nanotechnology also offer promising solutions for converting energy from one form into another—for example, light into electrical, chemical, optical, magnetic, or mechanical energy, as discussed in the section "Nanoscale Systems for Energy Conversion" above. While conventional solar cells have rather low conversion efficiencies compared with those of biological systems, molecular photonics—mimicking how nature harvests light—offers more efficient avenues for light harvesting and charge separation (Schwarz et al., 2000). The efficiency of bioinspired synthetic molecules designed to separate charges when light is adsorbed has increased significantly (Gust et al., 1998). Many new designs, such as conjugated π-electron systems or quantum dots incorporated into matrices to facilitate charge separation and storage, will benefit from advances in the tailoring of materials—from block copolymers to dendrimers, and nanotubes to colloidal systems—at the nanoscale.

The advances described above will not be realized without the ability to successfully integrate multiple nanosystems, which in turn requires the knowledge to assemble and synchronize their functions. Synchronizing their functions, for example, requires that the rate constants of the systems feeding from each other are properly adjusted with respect to the local transport rates and relative spatial separations of the systems. The physical science expertise within the PSD program, particularly the expertise in fluids and transport, could be applied to solving this problem. For example, computational models could be developed to simulate coupled nanosystems, potentially operating in confined spaces, or the behavior at their interfaces with larger systems, for example, fuel reservoirs or other material sources.

Microfluidics

Control of fluid and transport processes is essential to the fabrication and operation of many submicron-scale devices, with applications that range from chip-based chemical assays through human health monitoring and diagnosis to transport in proton exchange membrane fuel cell microchannels.

Microfluidic flows can be driven by pressure gradients, electric or magnetic fields, or themocapillary flows. For each of these mechanisms, the details of the flow and the degree to which it can be manipulated depend on geometric factors and on length scale roughness—that is, the length scale of the roughness of the channels in which the fluid flows. The production of devices that use microfluidic processing, or the use of microfluidics as a delivery mechanism, poses significant challenges to the designers, builders, and users of such systems (Unger et al., 2000; Beebe et al., 2000) and would require, for example, microfabricated components such as valves and pumps (Quake and Scherer, 2000). These emerging research areas might rely on some form of microfluidic components such as so-called microchip-based assays (Wang et al., 2002) for electrochemical detection and on microfluidic chips for clinical analysis (Verpoorte, 2002), both of which will be technologies important to an array of human and robotic spaceflight applications.

The control of fluid flow and transport of components will also play an important role in the operation of microreactors and miniaturized analysis systems, where flow and transport conditions can be controlled through the introduction of local microstructures (Beebe et al., 2000). Many processes will require the mixing of two or more fluids or the dispersion of one phase in a host "carrier" fluid. Some applications will require thorough mixing of two or more components in a short time. However, design constraints and the low Reynolds numbers obtained in these systems prohibit the use of traditional mixing techniques, such as mechanical actuators or a reliance on turbulence. Even though some difficulties have been overcome in specific instances (Stroock et al., 2002), a further knowledge of microfluidics is required for the realization of useful microfluidic devices. While many micro- and nanofluidic investigations do not require a microgravity environment, for others it is essential, such as for flows whose behavior depends critically on the motion of the fluid-solid contact line (a subject currently under investigation in the PSD fluid physics program). In addition, for flows in integrated arrays of microfluidic devices, the presence or absence of gravity significantly affects the large-scale distribution of the liquid within the system, even though capillary or molecular forces dominate the local fluid motion. If cell-based microdevices emerge as an important element in future missions, then the interaction between cells and microfluidic processes in micro- and nano-engineered environments will become a significant research area. There is an opportunity for NASA to capitalize on the existing expertise in the PSD fluid physics program in such areas as capillary-dominated flow, and to have an impact in the field of microfluidics, fostering its development to benefit spaceflight technology.

Integrated Microelectromechanical Systems and Nanoelectromechanical Systems Devices

Microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) devices can sense, actuate, and control mechanical, physical, chemical, optical, and biological processes. Revolutionary advances promise to come from integrating MEMS and NEMS components into large structures (NRC, 2002), which could then play an important role in space exploration. MEMS and NEMS applications of importance to NASA range from their use as multiple sensing devices, microreactors, and microfluidic systems for spaceship operation to their use as biosensors for crew health and automated medical treatment. In many of these uses, they could simultaneously satisfy the technological and economic demands for smaller, faster, integrated space exploration systems.

Examples of NEMS devices include nanoengineered and biomimetic sensors with advanced properties and functions that would allow for in situ monitoring of humans in space. The development and application of sensors could be extended to allow the rapid treatment of diseases and injuries—a capability that will be needed for long-term human space travel. Another example, noted in a previous section, is the development of near-room-temperature, direct-methanol protein exchange membrane fuel cells for efficient energy storage, safe operation, and on-demand power supply. Such fuel cells could produce anywhere from kilowatts to megawatts of electricity to power spacecraft or could be scaled down to milliwatts to power electronic or biological sensors. Advances in nanomaterial self-assembly or MEMS- and NEMS-based manufacturing will enable the fabrication of protein exchange membrane porous membranes and electrodes with tailored mechanical and electrochemical properties. However, the successful integration of the micro- and nanoscale devices means addressing the system-level integration concurrently, as well as using the emerging knowledge in areas such as microfluidic handling and control and two-phase flow separation at the micro- and nanoscale.

Investments in integrated MEMS and NEMS devices are poised to lead to new multiple sensor technologies, power-generation systems, and smart materials with integrated functionalities, including "intelligent" space suits for astronauts. Other applications of interest to NASA include biosensors and bioelectrodes for the detection and monitoring of chemicals and toxins; blood-glucose sensors; and detectors of bacterial or other toxic contamination. Bio-MEMS and microrobotics can be adapted for use in systems for noninvasive telesurgery and for other micromechanical machines with biomedical applications. Systems for sensing biomedical and inorganic substances in both aqueous and gaseous phases will be important to life-support systems. The use of nano- and microtechnology in radiation monitoring and dosimetry, and the development of methods for connecting biomedical microtechnology and biotelemetry equipment, would also clearly be of interest to NASA's bioastronautics program as well.

To capitalize on emerging technologies such as those discussed in previous sections, NASA will have to be able to integrate them in order to produce innovative systems with application to advanced space technology. To ensure this successful integration into operational systems requires multidisciplinary expertise and scientists working closely with engineers. Modeling of fluid behavior in fluid-fluid and fluid-material systems is one key to understanding nanoscale phenomena, their interactions with macroscopic components, and their final integration into systems. Overcoming the challenges of such work will require computational modeling and simulation across several length scales when designing functional devices. Research on modeling nanodevices, nanosystems, and nanoarchitectures, as well as on the physics of nanoscale devices, is needed to develop reliable predictive capabilities for the design of integrated nanosystems for space exploration. Alliances with NIH, such as cooperative research agreements, on some of these topics would be an attractive way for NASA to further explore this frontier.

MOLECULAR AND CELLULAR BIOPHYSICS

One of the toughest challenges faced by NASA is maintaining human health and handling medical emergencies in space. While NIH invests heavily in point-of-care technology to diagnose and treat disease remotely, NASA is the only agency with a vested interest in learning how human health is affected by low gravity and how to maintain human health on extended flight missions. An example is the need to develop countermeasures for the rapid loss of bone mass and the muscle atrophy that occur in long-duration spaceflight. Although many low-gravity-related physiological phenomena and their medical implications are well documented, there is little insight into the underlying cellular and molecular mechanisms. It is at those levels that these phenomena will have to be understood if there is to be significant progress in overcoming their deleterious effects. Further research is required into the role of mechanical forces (including shear, loading, and stretching) and low gravity in molecular recognition and cell signaling, and significant new insights are expected based on rapid advances in novel tools for nanoanalysis and biotechnology.

Since there is a significant amount of U.S. research, including research in other NASA divisions, into the molecular basis of cell signaling and how the equilibrium structure of proteins relates to protein function, the PSD can have the most impact by focusing on the pertinent physical aspects of these processes. Discussed below are the specific topics where the committee believes PSD could have the greatest impact.

Protein Stabilization for In-Space Applications

Long-term preservation of protein function is essential to using proteins in space in sensors, for diagnostics, and in bioreactors on extended flight missions. For instance, to be of the most utility in space, sensors assembled on the ground would be stored in spacecraft under ambient conditions and would be ready for use with no need for thawing, freezing, or other damaging preparatory operations. In addition, sensors worn by astronauts would have to operate, perhaps for extended periods, at physiological temperatures. Proteins, unless frozen, typically lose their function within days or weeks; this is well recognized in biotechnology and medicine. However, frozen proteins weigh more and require more storage space, nor are all the desired functions likely to be preserved in proteins stored for extended periods. Proteins can degrade by various mechanisms, including gradual thermal or interfacially induced denaturation,[3] enzymatic activity, and precipitation. Indeed, many proteins in the body, e.g., plasma proteins, have a natural half-life ranging from a few minutes (like tissue plasminogen activator) to several weeks (like albumin). On the ground, equipment-intensive procedures and single-use devices are often used to cope with the inherent instability of proteins. Once protein-containing materials or devices are brought into contact with water, their lifetime is reduced to a few days. For extended-flight applications, components or devices with such short lifetimes are completely inadequate.

Although a number of methods have been explored for the stabilization of proteins used in materials applications or devices, most of the methods were based on biochemical approaches. For example, it has been shown by limited site-directed mutagenesis involving a few amino acid residues that protein stability can be altered without changing function significantly (McGuire et al., 1995). Protein stability can also be increased by the addition of disulfide bonds, by cross-linking surface histidines by external tethers (Kellis et al., 1991), by directed evolution of the primary structure through random mutagenesis (Arnold et al., 2001), and by the use of chaperones and conjugates (Goes and Martin, 2001; Sheffield et al., 2001). The use of artificial amino acids is also a promising new route for engineering novel properties into proteins or for preventing their enzymatic degradation. For example, protein stability can be increased by introducing fluorinated amino acid side chains, thereby enhancing hydrophobicity and stabilizing the conformation (Tang et al., 2001; Niemz and Tirrel, 2001). Recently, the introduction of nonnatural amino acids into the primary sequence of proteins made possible the chemoselective modification of proteins at specific locations (Kiick et al., 2002; Lei et al., 2002b).

Although physical approaches to protein stabilization, as opposed to the biochemical ones discussed above, appear to be feasible, they have received little attention to date. It is here that the NASA PSD program can make a valuable and unique contribution. One example of such physical approaches is to slow the gradual denaturation of proteins adsorbed to surfaces by embedding or surrounding the molecules of interest in an otherwise nonadhesive surface coating. For example, antibodies have been stabilized for short-term use on the surface of polyethylene glycol, with obvious importance for immunochemical-based sensing. Also, recent experiments suggest that native protein structures may be stabilized if the proteins are immobilized in liposome (Corvo et al., 2002), polymer matrices (Schwendeman, 2002; Baran et al., 2002), peptide matrices (Battistuzzi et al., 2003), or nanoengineered environments, for example nanopores (Lei et al., 2002a). Attempts have also been made to encapsulate proteins during sol-gel formation (Eggers and Valentine, 2001; Kato et al., 2002). Finally, it has been shown that the topography of a protein surface and some aspects of its surface chemistry can be imprinted into nonbiological surfaces using templating technologies (Vlatakis et al., 1993; Plunkett and Arnold, 1995; Shi et al., 1999; Boal and Rotello, 2000; Liu et al., 2000).

Thus, it can be seen that several physical-science-based methods are beginning to emerge that can address the difficult challenge of how to preserve or mimic protein function. The PSD is ideally suited

[3]For example, proteins can degrade if they are adsorbed to a surface such that their hydrophobic moieties are exposed.

to assume leadership of research on these methods based on its expertise in such physical sciences areas as the microscale physics at the interfacial zone. In addition, new approaches to these problems are required, and they should be encouraged and fostered by studying the underlying mechanisms of protein structure stabilization by physical constraints. Such studies would require interdisciplinary teams bringing together the frontiers of nanotechnology and molecular biology.

The topic of protein stabilization could be expanded to include the stabilization of RNA that has been shown to exhibit catalytic activity. Similarly, biologically or synthetically produced oligonucleotides might provide an alternative route to biorecognition in a nonbiological environment.

The area of biomolecule stabilization would benefit enormously from a more focused effort, such as could be mounted by NASA, with an emphasis on physical interactions such as capillary effects and diffusive transport processes. It is relevant to note that some of the expertise to address this challenge already exists in NASA's protein crystallization community, which is concerned with protein structure and protein-protein interactions.

Long-Term Stabilization of Cell Cultures

The sensing, diagnosis, and remote treatment of disease will be a key element of a successful human presence in space. Many attractive approaches to these critical capabilities involve the use of cells as active biosensors or bioreactors to sense or synthesize the many molecules critical for human survival during extended flight missions. Cells cultured ex vivo often lose their phenotype after short time periods. This limits their applications in bioreactors and their integration into material scaffolds (tissue-engineered constructs), sensors, and other devices. Moreover, although cells can be stored frozen for extended periods at cryogenic temperatures, this approach again carries a weight and volume penalty. In addition, it is clear that cells should be available that remain stable indefinitely under the conditions in which they normally function.

Our understanding of the fundamental biology of cell interactions with their natural environment and how cell behavior can be regulated by engineered environments is still in its infancy. Again, as in the protein stabilization work, research at the most fundamental level is needed to make progress and ultimately to learn how to preserve cell structure and function over extended time periods.

Some applications allow one to circumvent mammalian cell instability ex vivo by exploiting less complex cells—for example, yeast or plant cells—rather than mammalian cells for sensor applications. Owing to its smaller genome compared with that of mammalian cells, yeast has been a preferred platform for many microbiologists trying to identify regulatory mechanisms and metabolic pathways. Of most interest to NASA, however, is the fact that yeast can be frozen and stored for extended time periods. Only minutes after contact with nutrients, the yeast cells recover fully and function normally. The first attempts to use yeast cells for sensor applications are under way. With financial support from the PSD program, one start-up company (LifeSensors) is developing a microfabricated platform to use the saliva of astronauts to test for early stages of diseases in space.

Applications that require the use of mammalian cells will depend on advanced insights into how to engineer micro- and nanoenvironments for mammalian cells that allow controlling and regulating cell function and preventing cell death. Fundamental in this connection is an understanding of the physical and chemical cues that allow cells to function properly.

Our knowledge of cell interactions with nonbiological systems has been expanded considerably in recent years by bringing modern cell biology together with chemical and engineering technologies. Biophysical methods used to modulate cell function include sequestration in three-dimensional matrices that incorporate or release regulatory molecules (e.g., growth factors and enzymes) at controlled rates, the use of controlled environmental conditions, and the use of contacting surfaces in which the chemical and physical properties are controlled and patterned at the micro- and nanoscales. The responses of cells to such controlled surface chemistries, surface chemical patterns, and specified surface topologies have been studied in the last 10 years. For example, using microcontact printing of self-assembled monolayers of alkanethiolates on gold, adhesive, micrometer-scale islands of extracellular matrix proteins separated by nonadhesive regions were manufactured, and the size and geometry of the islands were shown to control cell shape (Mrksich and Whitesides, 1996). Controlling the cell shape by micropatterning has provided new insights into selected aspects of cell interactions with extracellular matrix proteins as well as into how cell shape relates to other cell functions, including cell signaling, growth differentiation, and—ultimately—apoptosis (Chen et al., 1998; Whitesides et al., 2001; Boxer and Kam, 2001). Cell function has also been shown to depend on the presence of other cell types in coculture, and this relationship was probed in more detail by copatterning different cell types in two dimensions (Folch and Toner, 2000).

The flow of nutrients and degradation products is another regulatory cue for cell function. Systematic studies on the dependence of cell function on nutrient and metabolic flows are now emerging—for example, in cells entrapped in microfabricated devices (Sun and Chiu, 2003). In this context, work on the response of hepatocytes to the supply of oxygen should be mentioned (Roy et al., 2001; Tilles et al., 2001). Efforts are also under way to study single cells in microfabricated environments that contain nanopores to control complex nutrient fluxes in spatially and temporally well defined patterns (Desai, 2002; Sun and Chiu, 2003).

While the above approaches are important first steps in understanding how selected chemical and physical cues can regulate cell function, it should be recognized that cells in their native environment are suspended in a complex fibrillar matrix composed of sophisticated multifunctional macromolecules. Controlling surface chemistries by functionalizing the surfaces with one or another element of this matrix—for example, peptide sequences or sugars—may be well suited to invoking one or another cellular response. Such reduced environments, however, inherently fall short in mimicking the complexity of the signals cells can receive from their natural environments. Nature has evolved multidomain proteins that carry multiple functional sites, and the self-assembly of these molecules into the extracellular matrices is tightly regulated by the cells. It is well accepted that mechanical forces acting on cells can affect gene expression and the cells' eventual fate, and that cells remodel their extracellular environments based on mechanical cues (Ingber and Folkman, 1989; Hynes, 1999; Brown et al., 1998; Ohashi et al., 1999). Considerable evidence has also emerged that the activity of molecular recognition sites exposed on the extracellular matrix can be regulated by stretching matrix proteins (Ohashi et al., 1999; Baneyx et al., 2002; Vogel et al., 2001; Thomas et al., 2002).

Thus, success in exploiting cells that are integrated into materials and devices is dependent on a considerable extension of our knowledge of how the cell cycle, cell proliferation, differentiation, and, finally, apoptosis relate to the physical and chemical properties of the matrix that serves as the host for the cell, and on the nanoscale transport of nutrients to the cell and of cellular products away from it. The PSD research community has both expertise and novel technology to offer and could make meaningful contributions to understanding how physical cues complement the much better understood biochemical cues in regulating cell function. For example, the PSD biotechnology program has already made investments in the past to better understand how mechanical stresses (e.g., gravity) acting on the cell and cell matrix affect the cell cycle, cell proliferation, and apoptosis (NRC, 2000). The PSD could capitalize on its existing expertise in biotechnology—particularly its programs in cell science, surface chemistry, materials science, and fluid physics, all of which are essential topics, for example, in engineering cell surface interactions and controlling the nutrient flow.

Developing a scientific basis for the parameters that are essential to stabilizing and controlling cell phenotypes over extended time periods will revolutionize our knowledge of how cells can be exploited for use as sensors, for the cleanup of waste, and for the production and recycling of nutrients, enzymes, and hormones in space. In addition, learning how to stabilize cell cultures will undoubtedly have an impact on the research in tissue engineering being funded by other agencies, notably NIH. While the committee does not recommend that NASA launch a broad research program in tissue engineering, the much more focused objectives discussed above are of great relevance to NASA's manned spaceflight programs and will ultimately have an important impact on many other fields, including biotechnology and regenerative medicine.

Cellular Responses to Gravity-Mediated Tissue Stresses

A large body of data has been accumulated clearly indicating that the microgravity environment causes significant physiological problems for astronauts. For example, significant and continuous bone loss is intimately linked to the prolonged exposure of astronauts to a microgravity environment, but the underlying causes of this loss are not well understood. While much has been done to study the physiological effect of low gravity on organisms, organs, and cells, the underlying mechanisms by which gravity (or the lack of it) regulates cell signaling—thereby triggering larger systemic responses—remain unknown.

The loading on various elements of the human anatomy is changed or eliminated as gravity is reduced. Even on Earth, many pathologies—including osteoporosis, hypertension-related cardiovascular disease, atherosclerosis, and pulmonary hypertension—are thought to be associated with or even caused by increased or reduced levels of mechanical strain (Pelouch et al., 1993; Maniotis et al., 1997; Chaqour et al., 1999; Prajapati et al., 2000). Mechanical forces are also known to play an important regulatory role in tissue development and have been demonstrated to regulate gene expression (Owan et al., 1997; Goldspink et al., 2002; Mourgeon et al., 2000; Li and Xu, 2000; MacKenna et al., 2000; Geng et al., 2001). At the cellular and particularly the molecular levels, little is known about how mechanical forces affect cell signaling and gene expression, despite the fact that several of the molecular players in mechanically regulated signaling pathways have been identified (Shyy and Chien, 1997; Chicurel et al., 1998; Li and Xu, 2000; Carson and Wei, 2000). Much of the gap in our understanding of how nature uses mechanical forces in synchrony with chemical cues has been due to the lack of appropriate tools for studying protein structure and mechanical properties under nonequilibrium conditions. This has been changing in the last few years as a result of emerging nanotechnologies, including optical tweezers, atomic force microscopy, and advances in optical spectroscopy (Block et al., 2003; Galbraith et al., 2002; Oberhauser et al., 2002; Benoit and Gaub, 2002). Preliminary experimental and computational data suggest that mechanical forces regulate the functional states of some proteins by stretching them into nonequilibrium states (Vogel et al., 2001; Baneyx et al., 2002; Thomas et al., 2002; Onoa et al., 2003; Oberhauser et al., 2002). Furthermore, external mechanical stretching may change the mass transport and induce shear stresses on cells that could directly affect the cytoskeletal organization (Ingber, 1999; Bhadriraju and Hansen, 2002; Pommerenke et al., 2002; Balaban et al., 2001; Karlon et al., 1999; Galbraith et al., 1998; Satcher et al., 1997), and the transport of growth factors and nutrients could be altered under mechanical stimulation. These stresses are a direct function of the applied load on the biological entity.

NASA should support research aimed at developing a mechanistic understanding of how applied loads and stresses affect cellular processes, including the underlying molecular processes. New insights from molecular biology, combined with the development of novel nanoanalytical tools, promise to rapidly advance our understanding of the underlying physical mechanisms by which the loss of gravity ultimately affects human health. NASA has already contributed to this field—for instance, by developing rotating bioreactors and studying three-dimensional cell cultures in space. Further research is now needed to understand the mechanisms by which gravity affects cell signaling and gene expression at the molecular level. Since mechanical forces are typically induced or transmitted by the supporting matrix, fluid shear, or hydrostatic pressure, contributions to understanding these mechanisms are likely to come from the fields of cell biology, nanotechnology, fluid dynamics, materials science, chemistry, and physics. Many of these are areas in which the PSD has developed significant expertise. Major efforts are under way at NIH to understand how cells function as systems—the field of proteomics. Nevertheless, since NIH often focuses on the molecular level, the mechanoregulation of integrated molecular systems falls largely between the seams at the institutes even though an understanding of this process is critical for both health and disease. The process evokes even less interest at NSF and DARPA. The PSD might contribute to such work by bringing its experience in developing programs that bridge the interface between biology and the physical sciences to bear on how applied loads and stresses affect cellular and molecular processes, perhaps ultimately learning how low-gravity conditions affect proteomics and cellular metabolomics. NASA can also leverage its investments in microtechnologies, micromechanics, nanoparticles, and bioreactors to assist this effort.

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8

Research Priorities

INTRODUCTION

In previous chapters of the report the committee discusses the past impact of gravity-related research in each of the disciplines that have been traditionally supported by the Physical Sciences Division (PSD) and recommends future research important to each of those disciplines. It also reviews emerging areas of research in fields such as nanomaterials, in which the PSD is now beginning to invest. In this chapter the committee summarizes the findings of previous chapters to provide guidance to the PSD in setting priorities across the microgravity disciplines, summarizes the recommendations for research in emerging areas, and makes recommendations on overall program directions.

In order to assess and compare research across the microgravity disciplines, the committee critically examined the potential impact of the given research on the scientific field of which it is part, on NASA's technology needs, and on industry or other terrestrial applications. The committee's evaluation of the research in each of these categories is expected to assist NASA program planners by providing insight into the likely risks and potential rewards of the research that would be needed to create a vibrant microgravity research program that impacts all of these areas.

Because most of the fields of research discussed in Chapter 7 have a brief history and are developing very rapidly, it was not possible to evaluate them using the same criteria used for the research in combustion science, fluid physics, fundamental physics, and materials science. (As indicated in Chapter 6, research in the biotechnology areas of tissue culturing and protein crystal growth was recently reviewed by the NRC and was not included in this evaluation at the request of NASA.) While the likelihood that PSD-funded research in emerging areas will result in significant impacts on NASA capabilities cannot be evaluated at this time, the magnitude of the impact of successful research is potentially very high. Accordingly, the committee prioritized the research topics in emerging areas only relative to one another and suggests that the PSD utilize the list of high-priority areas given below to help make allocations within the share of program funds set aside for these emerging areas.

RESEARCH PRIORITIES IN EMERGING AREAS

In the committee's phase I report (NRC, 2001), it was recommended that the PSD should focus its research in emerging areas on topics that meet the following criteria:

1. Directly address scientific challenges at the interfaces between the physical sciences, engineering, and biology in support of NASA's mission, preferentially capitalizing on existing expertise or infrastructure in the Physical Sciences Division, and
2. Support research either not typically funded by other agencies or to be conducted in close partnership with other agencies.

While many areas in nanotechnology research are already highly supported by other agencies and other divisions within NASA, the PSD does have an opportunity to focus work on a select number of topics that can meet these criteria. Research in these emerging areas has the potential to provide powerful new tools and approaches that will greatly benefit NASA's capabilities. In addition, the considerable potential of the microgravity research disciplines to yield important and even paradigm-shifting results (as discussed in the next section) argues for a balanced program of research in the PSD that retains the unique potential for studying gravitational effects on phenomena in combustion, fluids, materials, fundamental physics, and biotechnology topics such as tissue culturing. For these reasons, the committee concluded that the fraction of the physical sciences program devoted to the recommended research in emerging areas should remain relatively modest, perhaps 15 percent of the ground-based program, until such time as a clear justification arises for increasing its size based on the criteria above as well as the ability of research in emerging areas to compete with existing programs. This fraction, which would bring the emerging research program into parity with the other major areas of research funded by the PSD, will allow NASA to have an impact on a limited number of highly focused topics within the broad purview of emerging areas while leveraging the research of other agencies. It also permits the majority of the research in the microgravity areas to continue to produce the high-impact results described in previous chapters. In addition, the amount of research currently funded in the emerging areas should increase gradually toward this fraction, which will allow the quality of the investigations chosen for funding to remain as high as possible. Because NASA is likely to have a need for unique applications of nanotechnology, the PSD should develop a level of research expertise in these fields that will allow it to effectively evaluate and apply new advances in its own programs. In order to do so it will be particularly important to develop strong programs and connections with the leaders in these fields. Whenever possible, the PSD should seek to apply the findings of other agencies to topics that could directly benefit technologies of unique interest to NASA.

It should be noted that some of the research discussed in Chapter 7 does look at gravitational effects, and these may be areas into which some research in microgravity combustion, fluid physics, fundamental physics, materials science, or biotechnology research could naturally evolve. Examples might be certain types of nanomaterials research in the microgravity materials program or gravitational effects on subcellular assemblies in the biotechnology program. The recommendation regarding the proportion of emerging areas research in the PSD is not meant to restrict such eventual evolution of existing microgravity areas. However, such research must be competitive with other areas of research in the discipline and should be funded only if it is deemed to be a high priority on the basis of the rigorous selection criteria outlined in the discipline chapters and in the next section.

Within the proportion of the program devoted to the emerging areas, the committee has recommended several of the topics discussed in Chapter 7 that appear to be particularly promising based on their potential to help address NASA technology needs and the ability of the PSD to make a unique contribution of knowledge or expertise. All of the areas recommended below satisfy the criteria identified in the phase I report for choosing research in the emerging areas. The development of methods for the long-term stabilization of proteins in vitro and research on cellular responses to gravity-mediated tissue stresses are of higher priority than the other areas, because they are not typically supported by other agencies. The research on exploiting nanotechnology for power generation and energy conversion is also ranked "most important" because of the great importance of power generation and energy conversion in NASA's spaceflight program, and the major impact these technologies may have on this program. The remaining areas (ranked "important") are heavily supported by agencies such as the Defense Advanced Research Projects Agency, the Department of Energy, the National Science Foundation, and the Department of Defense as well as by other divisions within NASA. Thus for the PSD to pursue research in these areas it must partner with these agencies or with other divisions within NASA. (The PSD has successfully partnered with other agencies in the past, such as the National Cancer Institute.)

These recommendations are summarized below, and the reader is referred to the relevant sections of Chapter 7 for a more detailed discussion of their significance to NASA. Note that the topics are not rank-ordered within the priority categories.

Most Important

- Develop methods for long-term stabilization of proteins in vitro (pp. 72-74).
- Work on understanding cellular responses to gravity-mediated tissue stresses (pp. 76-77).
- Exploit nanotechnology for power generation and energy conversion (pp. 67-68 and pp. 69-70).

Important

- Develop enabling technologies to produce nanoengineered hybrid materials with multiple functions (pp. 66-67).
- Develop integrated nanodevices (pp. 71-72).
- Study the stabilization of cellular function in vitro (pp. 74-76).

MICROGRAVITY RESEARCH PRIORITIES

In assessing the promise of a microgravity research area, it was first necessary to look at the impact of the research on the field of which it is a part and the quality of the investigators in the program, since the impact of the past research provides insight into the ability of the program to select important research topics to fund and the quality of investigators in the program strongly affects the likelihood that future research will yield important results. As is shown in Chapters 2 through 5, NASA-supported investigations in combustion, fluid physics, materials science, and fundamental physics have had a major impact on these fields—thus the PSD has been successful in funding high-impact research. Moreover, as NASA has successfully attracted a cadre of distinguished investigators as well as promising young investigators in these areas, there is a very good probability that high-quality research will emerge from these communities in the future.

Chapters 2 through 5 contain suggestions for future research directions in the microgravity disciplines, and only the areas considered to be of high priority within those disciplines are recommended in the chapters. It should be kept in mind that there are many additional areas of promising research in

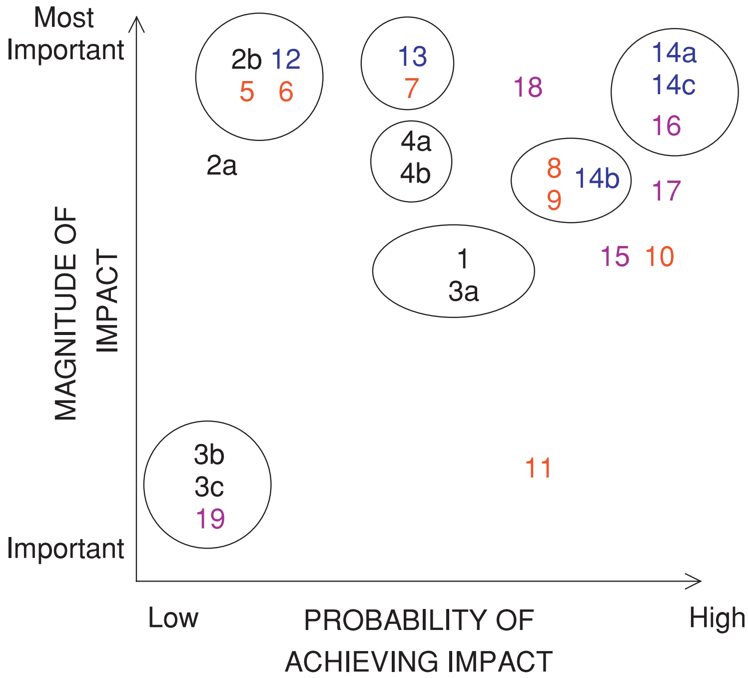

FIGURE 8.1 Assessment of research topics in terms of their likely impact on scientific knowledge and understanding.

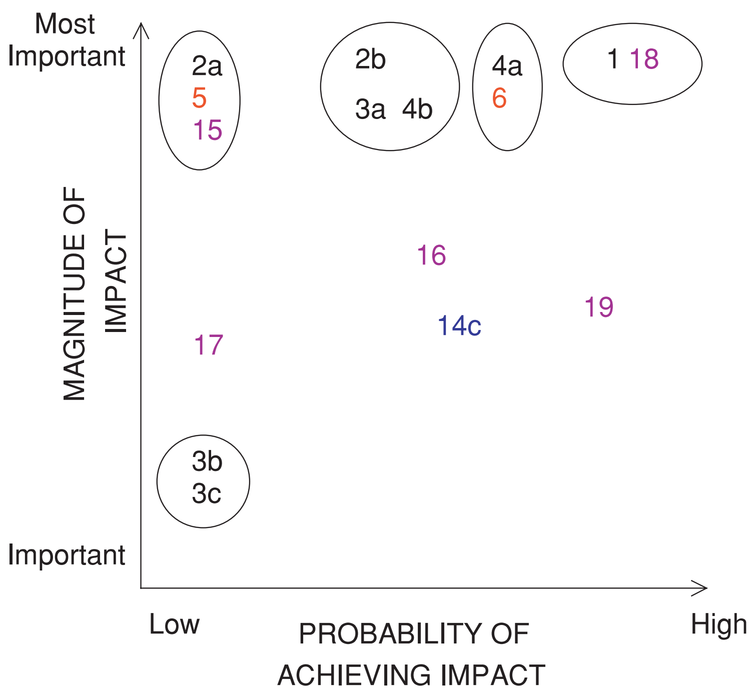

FIGURE 8.2 Assessment of research topics in terms of their likely impact on terrestrial applications such as industry's technology needs.

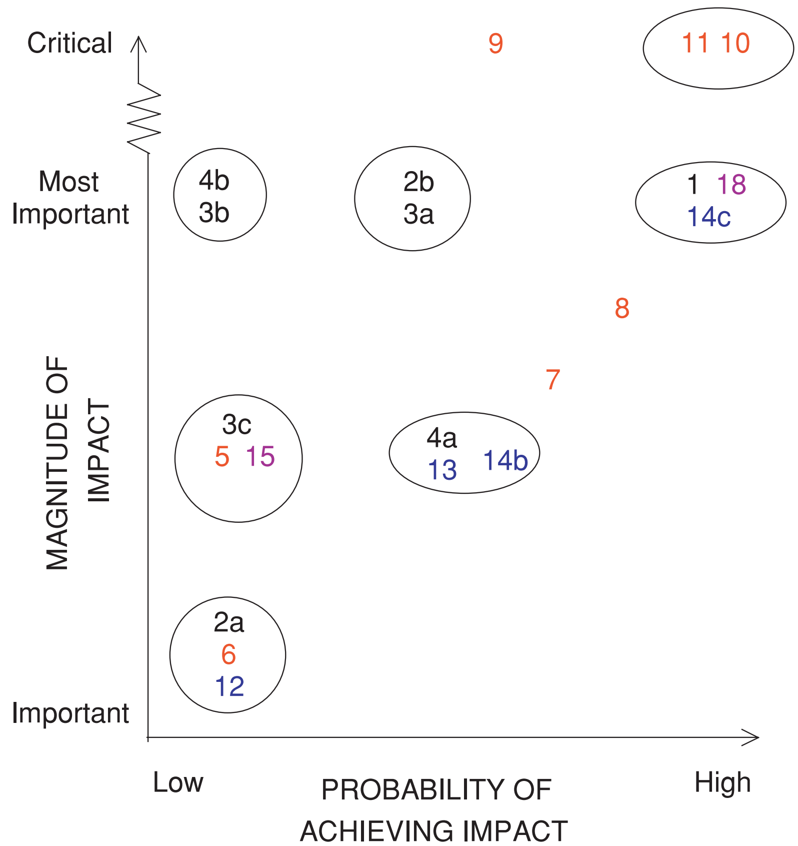

FIGURE 8.3 Assessment of research topics in terms of their likely impact on NASA's technology needs.

Figures 8.1, 8.2, and 8.3:

Only subjects already considered by the committee to be of high priority in at least one discipline are included in this analysis, and therefore the magnitude scale ranges only from important to very important (or critical). A subject may not have a high impact in every category and therefore may not appear in every figure. Numbers inside the same circle should be considered to occupy approximately the same position in the figure. The numbers in the figures represent the research topics as follows:

1. Multiphase flow and heat transfer;
2. Complex fluids: (a) self-assembly and crystallization, (b) complex fluid rheologies;
3. Interfacial processes: (a) wetting and spreading, (b) capillary-driven flows and equilibria, (c) coalescence and aggregation (liquid phase);
4. Biofluid dynamics: (a) cellular biotechnology, (b) physiological flows;
5. Turbulent combustion;
6. Chemical kinetics;
7. Soot and radiation;
8. Smoldering combustion;
9. Development of computer simulations of fire dynamics on spacecraft;
10. Oxygen systems fire safety;
11. Ignition, flame spread, and screening techniques for engineering materials;
12. Antimatter search/measurements;
13. Elemental composition survey;
14. Complete the current set of fundamental physics ISS experiments: (a) low-temperature experiments, (b) relativity and precision clock experiments, (c) other NASA clock application experiments;
15. Nucleation process within, and the properties of, undercooled liquids;
16. Dynamics of microstructural development during solidification;
17. Morphological evolution of multiphase systems;
18. Computational materials science;
19. Collection of thermophysical data of liquid state in microgravity.

each of those disciplines that were not given the highest priority at this time and thus were not explicitly recommended. Some of these areas might rise to a higher priority in the future. In addition, the committee expects that in future years the communities will generate new research topics whose promise will equal that of the topics recommended here. In this chapter, however, the committee limits its assessment to those areas described in the earlier chapters as currently being of high priority. Those recommended areas are as follows:

- Multiphase flow and heat transfer
- Complex fluids
  —Self-assembly and crystallization
  —Complex fluid rheologies
- Interfacial processes
  —Wetting and spreading
  —Capillary-driven flows and equilibria
  —Coalescence and aggregation (liquid phase)
- Biofluid dynamics
  —Cellular biotechnology
  —Physiological flows
- Turbulent combustion
- Chemical kinetics
- Soot and radiation
- Smoldering combustion
- Development of computer simulations of fire dynamics on spacecraft
- Oxygen systems fire safety
- Ignition, flame spread, and screening techniques for engineering materials
- Antimatter search/measurements
- Elemental composition survey
- Complete the current set of ISS experiments in fundamental physics
  —Low-temperature experiments
  —Relativity and precision clock experiments
  —Other NASA clock application experiments
- Nucleation process within, and the properties of, undercooled liquids
- Dynamics of microstructural development during solidification
- Morphological evolution of multiphase systems
- Computational materials science
- Collection of thermophysical data of liquid state in microgravity.

To evaluate these recommended research areas across disciplines, the committee separately judged the likelihood that the research would have a significant impact in each of three categories: (1) the scientific field of which it is part, (2) industry or other terrestrial applications, and (3) NASA technology needs. Within each of these categories the committee specifically looked at both the magnitude of the potential impact that the research could have on its category, and the likelihood that the research would be successful in achieving that impact. The impact and likelihood of success were assessed independently of each other since it was possible for areas with a potential for high impact to have a low probability of success and vice versa. The results of the committee's assessment are shown in Figures 8.1, 8.2, and 8.3 (see pp. 86-87), which plot the magnitude of the impact that research on the topic could have in a given category, against the probability that the impact will be achieved. Note that the justification for the magnitude of the expected impact is given in the discipline chapters and is not discussed further here. It should be kept in mind that the setting of actual research priorities must depend on NASA programmatic goals, and those goals determine both the desired end result, such as scientific discovery, and the level of acceptable risk. The purpose of these plots is to provide NASA with the tools to rationally select the best research, regardless of which combination of scientific discovery (Figure 8.1), Earth applications (Figure 8.2), or NASA technology needs (Figure 8.3) NASA chooses to emphasize or what trade-offs between research risk and reward it is willing to accept.

PEER REVIEW

The committee has commented numerous times in past studies on the role that rigorous peer review has had in greatly improving the quality of the research funded by the Physical Sciences Division, and it strongly recommended the continued use of peer review in future funding selections (NRC, 1994, 1997, 2000). As the program moves into new areas of research it is worth emphasizing again that any research proposal submitted to the program—no matter how relevant to an area considered highly desirable for inclusion in the program—should only be funded if it has undergone a rigorous peer review and has received both high marks for scientific merit and a high ranking compared to competing proposals.

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Appendixes

A

Future Biotechnology Research on the International Space Station, Executive Summary[1]

BACKGROUND AND SCIENTIFIC SCOPE OF NASA PROGRAMS

The National Aeronautics and Space Administration (NASA) manages research programs in two areas of the rapidly expanding field of biotechnology: protein crystal growth and cell science. The protein crystal growth work focuses on using microgravity to produce higher quality macromolecular crystals for structure determination and on improving understanding of the crystal growth process. The cell science work focuses on basic research that contributes to understanding how the microgravity environment affects the fundamental behavior of cells, particularly in relation to tissue formation and the effects of space exploration on living organisms. The National Research Council's Task Group for the Evaluation of NASA's Biotechnology Facility for the International Space Station was formed to examine and evaluate the use of the International Space Station (ISS) as a platform for research in these two areas. In this report, the task group offers a variety of recommendations and suggestions for improving the NASA biotechnology research program. It believes these changes are necessary if the NASA program is to fulfill the potential for scientific discovery and impact that is also outlined in this report.

Protein Crystal Growth

The task group heard a great deal about experiments to date in NASA's macromolecular crystallography program. The results so far are inconclusive, and the impact of microgravity crystallization on structural biology as a whole has been extremely limited. At this time, one cannot point to a single case where a space-based crystallization effort was the crucial step in achieving a landmark scientific result. In many of the cases that have so far been listed as successful, the improvements obtained have been incremental rather than fundamental. In addition, the difficulty of mounting simultaneous efforts to produce the best

[1]Note: Reprinted from Space Studies Board, National Research Council, 2000, Future Biotechnology Research on the International Space Station, National Academy Press, Washington, D.C.

possible crystals both on the ground and in space has limited the ability of researchers to make the comparisons between microgravity and Earth crystals that would be necessary to demonstrate that the microgravity environment can produce superior crystals.

Finding: The results from the collection of experiments performed on microgravity's effect on protein crystal growth are inconclusive. The improvements in crystal quality that have been observed are often only incremental, and the difficulty of producing the appropriate controls limit investigators' ability to definitively assess if improvements can be reliably credited to the microgravity environment. To date, the impact of microgravity crystallization on structural biology as a whole has been extremely limited.

Despite the lack of impact of microgravity research on structural biology up to now, there is reason to believe that the potential exists for crystallization in the microgravity environment to contribute to future advances in structure determination. Today's ground-based protein crystallization projects are increasingly sophisticated, and yet the diffraction characteristics of crystals of many important targets are still suboptimal. Improvements in diffraction that move a system from the margins of structure determination to well beyond that boundary will have a significant impact on the ability of the resulting structure to provide important insights into biological mechanisms. All research on protein crystallization in space has, up to now, been done under suboptimal conditions (short-duration experiments, insufficient vibration control, etc.), so the improved conditions for research provided by the ISS have the potential to produce much better results.

Finding: While enormous strides have been made in protein crystallization in the last decade, it is still the case that there are very important classes of compelling biological problems where the difficulty of obtaining crystals that diffract to high resolution remains the chief barrier to structural analysis of the crystals. It is here that the NASA program must look to maximize its impact.

In order to engage the research community, NASA must focus its support on programs that are developing technologically innovative equipment and engaging in the structure determination of crystals with important biological implications. While past NASA-supported research on the crystallization process has not been without value, NASA's priority should now be to resolve the community's questions about the usefulness of protein crystal growth in the microgravity environment for tackling important biological questions. Until the uncertainty about the value of space-based crystallization is resolved, a program of this fiscal magnitude is bound to engender resentment in the scientific community.

Although many pharmaceutical and biotechnology companies have participated in microgravity crystallization research, not one has yet committed substantial financial resources to the program. This is likely to remain the case until the benefits of microgravity can be convincingly documented by basic researchers and until facilities in space can handle greatly increased numbers of samples in a much more user friendly manner.

Cell Science

NASA's cell science program focuses on studying the influence of low gravity on fundamental cell biology as it relates to tissue formation and on providing insight into the effects of microgravity on cell, tissue, and organ system function, especially as it might affect participants in space exploration.

Finding: It is appropriate for NASA to support a cell science program aimed at exploring the fundamental effects of the microgravity environment on biological systems at the cellular level. Results from such basic research experiments could have a significant impact on the fields of cell science and tissue engineering. However, the specific important questions within cell biology that can best be tackled on *the ISS do not seem to have been defined yet. Narrowing the broad sweep of the current program may focus instrument development efforts and accelerate progress toward complete understanding of the effects of microgravity on specific biological phenomena.*

A key to determining the success of cell science experiments in space will be designing appropriate controls for experiments. In space, cell cultures experience a low gravitational environment that reduces convection, buoyancy-driven flows, and sedimentation, and it is difficult to separate the various factors causing differences between space- and Earth-grown samples. In addition, the tremendous progress that has been made in three-dimensional tissue development on Earth, under unit gravity, provides a wide range of options for ground-based experiments that may produce results similar to those achieved in microgravity. To evaluate the relative merits of various experimental control groups and also to enable the detailed evaluation of samples returned from space, it is important that quantitative measures of cell and tissue structure and function be developed and studied.

Finding: Appropriate experimental controls for space-based cell science experiments have not yet been determined. The best controls would be those that enable researchers to separate and investigate the multiple factors—including launch and reentry, effects of microgravity on the culture medium, and direct effects of microgravity on cellular behavior—that produce the changes observed in cells and tissues grown in space. Analytical techniques that measure the molecular mechanisms underlying cellular functions will be essential to provide data for comparing proposed experimental controls and quantifying the observed changes in cell and tissue samples.

At NASA, the work viewed by the task group was being carried out in the biotechnology section of the Microgravity Research Division. The themes of the cell science research under way in this program overlap with the scope of work ongoing in the NASA Life Sciences Division. The complementary nature of these two programs needs to be recognized so that NASA personnel and external researchers can take full advantage of the potential synergies. While there is already a sharing of flight hardware, a mechanism to establish projects that are jointly funded by the Life Sciences Division and the Microgravity Research Division should be considered.

Recommendation: The research strategies and projects of the cell science work in the biotechnology section of the Microgravity Research Division should be more closely coordinated with the work of NASA's Life Sciences Division to take advantage of overlapping work on bone and muscle constructs and of potential synergies between in vitro and in vivo research projects.

INSTRUMENTATION

The International Space Station (ISS) is currently under construction; assembly is scheduled to be complete in 2005. However, NASA plans to begin research on the facility as early as 2000, using equipment that has been flown on the shuttle and that can be temporarily installed in modules of the ISS as they are completed. As the ISS grows and more station-specific hardware is ready, the research program will expand and more permanent instrumentation will be fitted into the ISS.

Protein Crystal Growth

A variety of equipment has already been used to grow and observe crystals in space, and innovative hardware continues to be developed today. Having multiple laboratories involved in this process encourages variety and creativity and also prevents NASA from getting locked into a single hardware approach. However, the efforts of hardware developers need to be coordinated and communications between them must be improved to ensure that different programs are not producing instruments with duplicative capabilities and that technological advances are quickly shared and integrated into all equipment where appropriate.

Recommendation: The efforts of external hardware developers should be coordinated to ensure that instruments are compatible, to prevent duplication of efforts, to ensure that technical innovations are shared, and to facilitate input from the scientific community in defining the goals and capabilities of protein crystal growth equipment for the ISS. NASA must also be prepared to discontinue development projects that do not use cutting-edge technologies or that are out of tune with the most current scientific goals.

A significant factor affecting equipment development is the instability in the budget for the ISS. If money is repeatedly siphoned off from the hardware development work, the equipment on the ISS will be of much lower quality than the cutting-edge hardware available on the ground, and researchers will not be interested in using the outdated equipment or willing to entrust precious samples to it.

The equipment developed by and for NASA should aim to provide a high level of control over samples, equipment, and procedures. On the ISS, crew time will be limited, and the human access to samples and the feedback to the investigators enabled by shuttle trips will be infrequent, so automation and ground-based control of experiments are essential. If principal investigators are able to make decisions about experimental parameters and to adjust experiments in real time, the research results produced in each experiment will be of higher quality, and involvement in the NASA program will be more attractive. Therefore, hardware development efforts should emphasize the importance of automation, monitoring, real-time feedback, telemanagement, and sample recovery (via mounting and freezing).

Effective analysis, preservation, and reentry of promising crystal samples is especially necessary given the key role synchrotrons are playing in protein structure determination. If the NASA program is to attract researchers interested in important and challenging biological problems, ISS hardware must be designed to produce and safely return to Earth crystals of the appropriate size and quality to be analyzed at a synchrotron. However, it is not NASA's responsibility to arrange or guarantee this next step. Building a synchrotron beam line is expensive and would not be the most efficient use of NASA's scarce resources. Assuming that NASA's peer review process is selecting the most scientifically rigorous and interesting projects, successful crystallization should enable researchers to compete effectively for the necessary beam time, and success in this extra layer of peer review should further validate the NASA program within the scientific community.

The X-ray Crystallography Facility (XCF) being designed for the ISS is a multipurpose facility designed to provide for and coordinate all elements of protein crystal growth experiments in space: sample growth, monitoring, mounting, freezing, and X-ray diffraction. The task group was impressed by the XCF, by the robotics, the remote control, and the range of experimental capabilities provided. The X-ray diffraction module provides valuable information about whether a given crystal will diffract. This real-time feedback is key to making decisions about the success or failure of a particular crystallization experiment and will help allocate scarce freezer resources by ensuring that the most promising crystals are preserved and returned to Earth.

Finding: Automation, monitoring, real-time feedback, telemanagement, and sample recovery (via mounting and freezing) will be vital for successful protein crystal growth experiments on the ISS. The XCF, through its use of robotics and a variety of experimental and observational capabilities, provides many of the tools researchers need to take full advantage of the microgravity environment.

The XCF is typical of several hardware development projects for NASA in that the technologies it employs can be applied to ground-based research capabilities as well as to those based in space. Currently, however, the scientific community is mostly unaware of the quality of the automation displayed in the prototype of the robotic crystal sample preparation system and of the combined capabilities of the X-ray optics and the low-power source that will be used in the XCF. While commercial entities may need to protect their proprietary work, scientists must have access to full information about all relevant technologies and equipment for the ISS in order to effectively design and execute cutting-edge research in space.

Cell Science

A variety of instruments are being developed to support cell science research on the ISS, including a basic incubator, a perfused stationary culture system, and a rotating-wall perfused vessel (a bioreactor). Overall, the NASA-funded cell science work to date has emphasized the use of bioreactors to support three-dimensional tissue growth. While the development of rotating-wall vessels has had, and should continue to have, a significant impact on cell and tissue culturing methodology on the ground, the task group has a variety of concerns about the effectiveness and appropriateness of this approach for research in the microgravity environment. Issues include the relatively small amounts of data generated per unit volume and the difficulty of accessing the vessel on orbit.

Recommendation: Given the current status of equipment in development, finite fiscal resources at NASA, and the limited amount of volume on the ISS, the task group recommends that future research on the ISS should deemphasize the use of rotating-wall vessel bioreactors, which are already established, and continue to encourage the development of new technologies such as miniaturized culture systems and compact analytical devices.

The final determination on what sort of instrumentation will be most effective for cell and tissue growth in microgravity has yet to be made, and it is important that the relative merits of various pieces of instrumentation be carefully evaluated and that NASA maintain the necessary administrative and engineering flexibility to adopt the most effective systems employing the most advanced technologies and to discontinue hardware development projects that are not attuned to the most current scientific needs of the cell science communities. Close interaction is needed between scientists and the NASA operational personnel responsible for developing and constructing the hardware to ensure maximum flexibility and responsiveness to evolving research goals.

Cellular systems are very sensitive to environmental perturbations. A continuous power supply to maintain appropriate and stable environments during experiments and for sample storage and transport is essential to ensure valid results. A variety of systems are under development to manage power distribution, and care must be taken, particularly during ISS construction, to ensure that cell science experiments are not compromised by power fluctuations. Another issue that will be problematic, particularly during ISS construction but also after the station is complete, is the limited amount of crew time available for research. The automation of routine tasks and ground-based control of experiments will be essential if investigators are to make efficient use of the ISS platform.

Two key supports for automation and ground-based control are (1) sensors to enable physiological control of the cell/tissue culture media environment and (2) analytical equipment to provide feedback about the status of cell and tissue samples. The data from the sensors and the on-orbit analyses should be transmitted electronically in real time to investigators to enable ground-based control of experiments. Scientists on the ground then could select the most important samples for the scarce storage space and could study the changes wrought in samples by freezing and reentry.

Finding: The limited amount of crew time available for research-related work and the infrequency with which investigators will have access to their samples via shuttle trips mean that automation of routine tasks, ground-based control of experiments, on-orbit analytical capabilities, and real-time transmission of digital data are vital for conducting effective cell science research on the ISS.

Refrigeration and freezer capability and transport space are not the only factors limiting the throughput of cell science research on the ISS. Other factors that will affect the size of the program and the number of primary publications include crew time required for the experiments, the amount and reliability of the power supply, adequate storage space and appropriate environments for samples and supplies, shuttle flight schedules to and from the ISS, the volume of materials to be transported, and, of course, the size of the budget provided for cell science hardware development and research support. A window of opportunity has been created by the advances in molecular, cellular, and biochemical approaches (e.g., functional genomics and proteomics) that are occurring as the ISS research platform becomes available. The task group recommends that to most efficiently exploit this opportunity, emphasis should be placed on integration of the different approaches and on collaboration between principal investigators and other researchers inside and outside NASA.

Recommendation: Mechanisms should be developed to enable collaborative research projects that maximize the amount of data obtained from each cell or tissue sample by executing multiple analyses on each sample.

Overall Volume Allotment for Biotechnology Research on the ISS

Currently, NASA plans call for peer-reviewed biotechnology research to occur within one rack on the ISS. This rack would be shared by protein crystal growth and cell science work. In addition, two racks are reserved for the hardware associated with the X-ray Crystallography Facility (XCF) being developed for the NASA Space Product Development Division. The task group considered this arrangement and the needs of the various research communities and recommends a shift in the allotments. Namely, the XCF rack devoted to crystal growth and monitoring should be transferred from Space Product Development to the Microgravity Research Division's protein crystal growth program, where experiments are selected by a centralized peer-review process and a full complement of hardware is available. The rack currently scheduled to be shared by cell science and protein crystal growth can then be dedicated entirely to cell science research.

The task group makes this recommendation based on several considerations. A primary issue is the basic incompatibility between the technical needs of cell science and protein crystal growth equipment on the ISS. The flow of gases and fluids required to maintain rigorous environmental control for cell and tissue culture will produce vibrations that cannot be tolerated by a crystal growth facility. If cell science and protein crystal growth equipment are housed in one rack, one or both of the disciplines will be forced to operate under suboptimal conditions.

The task group also carefully considered the needs of the various research communities expected to use the biotechnology facilities on the ISS. For cell science, there was concern that the amount of data and results generated by half a rack of equipment would not be substantial enough to maintain interest within the scientific community, whereas a full rack's worth of instrumentation could raise the program to a critical threshold. For protein crystal growth, the research community is still uncertain about the benefits of growing crystals in a microgravity environment, so protein sample flight programs are undersubscribed and commercial interest is low. By focusing the protein crystal growth research efforts on biologically challenging problems and by emphasizing hardware capable of monitoring and preserving samples, NASA could direct its resources to validating the program. The current volume commitment of half a rack of general macromolecular research is insufficient to establish the value of the crystal growth program, but a full rack, filled with peer-reviewed experiments that employ all types of available hardware and have access to the capabilities of the XCF, should be adequate to give the program a fair chance of success. If, after several years, the results from the protein crystal growth work have provided sufficient proof of microgravity's benefits and the academic and commercial demand for facilities on the ISS increases, then high-throughput hardware should be developed and the allotment of space on the ISS reconsidered based not only on the demand for macromolecular crystallography research volume but also on the results to that point from the cell science program. Alternatively, if the work done through the augmented commitment recommended here fails to clearly demonstrate the value of microgravity for work on structural biology, then the protein crystal growth program can justifiably be terminated.

Recommendation: The volume allotment for biotechnology work on the ISS should be redistributed as follows:

- *The mounting, freezing, and diffracting equipment of the X-ray Crystallography Facility (XCF) should occupy one rack (as currently planned).*
- *The cell science work should occupy the entirety of what is currently designated the Biotechnology Facility.*
- *The rack presently assigned to the XCF growth equipment and managed by NASA Space Product Development should be officially dedicated to the peer-reviewed macromolecular research run out of the Microgravity Research Division.*

SELECTION AND OUTREACH

NASA research in cell science and protein crystal growth is funded through a collection of approximately 90 active 4-year grants; the total size of the program is roughly $19 million per year. Both ground-based and flight projects are selected through a peer-review process that occurs every other year. While the current grant solicitation mechanism (NASA Research Announcements, or NRAs) is appropriate, it is inadequate to attract the involvement of the best scientists or bioengineers. The task group believes that as the program goes forward, it would benefit from a strengthening of the outreach, selection, and support offered by NASA to ensure that the proposals submitted for consideration are of the highest quality and that everything possible is done to give flight experiments the best chance of success.

Both protein crystal growth scientists and cell science researchers identify themselves with a variety of professional organizations, publications, and conferences, so NRAs should be disseminated to a wider variety of newsletters and announcements in order to reach the multiple communities that might be interested in using NASA biotechnology facilities on the ISS. Another approach to expanding the pool of potential researchers would be to issue NRAs in collaboration with other federal agencies, such as the National Institutes of Health (NIH), the Biotechnology Program in the Engineering Directorate of the National Science Foundation (NSF), the NSF Biological Sciences and Regulatory Biology Divisions, and the Department of Energy. More could also be done to provide sufficient background information for potential investigators who are not familiar with NASA programs. More detail about the special opportunities and constraints of space-based research as well as about the hardware available for the ISS would make it easier for NASA to recruit new applicants for its grants and for those researchers unfamiliar with the NASA program to put together appropriate proposals. Access to information about failed projects would also improve the quality of experiments designed with NRAs in mind and would increase the likelihood of success. In general, results of projects already under way could be more broadly disseminated; however, the task group cautions that presentations should give a balanced portrayal of successes and limitations so as not to raise unrealistic expectations. Misperceptions about the accomplishments of NASA programs can also be gained from press releases that target the general public and portray potential future applications of NASA-funded research as completed or current work. This dissemination of vague or even inaccurate descriptions of its programs seriously diminishes NASA's credibility within the scientific communities.

Recommendation: NASA should improve its outreach activities in order to involve a broader segment of the scientific community in its biotechnology research program and to increase the number of cutting-edge projects submitted for funding. It needs to disseminate NRAs and program results more widely and to provide more complete background information on failed projects and how to design flight experiments.

As the pool of applicants expands, the process of evaluating proposals may also need to be adjusted. NASA's program suffers from longer time scales than are compatible with the current pace of biotechnology research. For example, the 2-year gap between NRA grant submission opportunities is likely to inhibit applications directed at the most cutting-edge research issues. Also, the delay between project selection and flight manifesting of an experiment means that NASA does not always have the hardware flexibility to respond to changes in the field based on new developments in ground-based research (for example, the increased reliance on cryoprotection and freezing of crystals or the use of scaffolding for three-dimensional tissue constructs). Finally, the uncertainties surrounding the NASA budget and the continual schedule changes make people cautious about getting involved in a program that is unable to reliably predict how much money will be available or the schedule for access to the ISS.

One critical step toward raising the profile of the NASA program and the quality of the grant application pool would be to counter the current perception of recipients of NASA funds as a closed community with a fixed membership. On the whole, external input into NASA's priorities for the biotechnology program seems to be relatively limited. Advisory groups are composed of many of the same people that make up the pool of grantees and contribute to the perception that NASA is not really interested in outside input. By reaching out to a broader slice of the protein crystal growth and cell science communities, NASA would not only increase the quality of the advice it receives but would also be able to educate a new group of people about its programs.

According to NASA, the biotechnology Discipline Working Group (DWG) is the main mechanism for receiving advice about the strategic direction of the Microgravity Research Division's biotechnology programs. The group is responsible for providing input to both the protein crystal growth and cell science sides of the program, but in view of the very different scientific objectives and instrumental requirements, having a single working group for these two disparate areas serves no real purpose. If the DWG is split into two groups, each would be able to focus on the issues most relevant to its own scientific area, and the increased number of slots available for each area would give greater breadth to the groups. Care must be taken in selecting new members to ensure that there is not a bias toward those already working with the NASA program. To attract prominent outside researchers to the DWG, the task group suggests that the name be changed to more accurately reflect the group's role as a high-level advisory panel with input on the scope of research announcements, peer review practices, and future programmatic directions.

Recommendation: The separate identities of the protein crystal growth and cell science sections of NASA's biotechnology research program should be emphasized. One key step should be splitting the Discipline Working Group into two strategic advisory committees to reflect the different issues facing each area of research. Prominent scientists not familiar with NASA's programs but aware of the broader issues facing the fields should be recruited to serve on these committees.

An important issue for execution of research in the unforgiving environment of space is the potential for conflict between the scientific goals of an experiment and the engineering limitations associated with a space-based platform like the ISS. Within the biotechnology scientific community, there is the perception that the NASA culture does not emphasize the importance of communication between scientists and operations personnel, nor does it provide tangible assurances to the research community that the execution of high-quality research in hardware designed to answer the most cutting-edge scientific questions is a NASA priority. The community would be reassured by seeing NASA place bioengineers and biological scientists with the appropriate appreciation of research goals and scientifically oriented reflex responses in high enough decision-making positions to ensure that research opportunities are optimally utilized.

Recommendation: The NASA culture tends to limit communication and coordination between operations personnel and researchers during hardware development; between astronauts and investigators before and during experiment execution; and between decision makers and scientists about the allotment of resources in times of crisis. To attract the best investigators to its biotechnology program, NASA must create an environment geared toward maximizing their ability to perform successful experiments.

Protein Crystal Growth

At present, the primary goal of NASA's protein crystal growth program should be to demonstrate microgravity's effect on protein crystal growth and to determine whether studies of macromolecular assemblies with important biological implications will be advanced by use of the microgravity environment. To this end, the task group proposes that NASA instigate a high-profile, nationwide series of grants to support researchers engaging in simultaneous efforts to get both the best possible crystal on the ground and the best possible crystal in space of biologically important macromolecules. The projects funded by these grants should address the uncertainties that have plagued the NASA protein crystal growth program, by using the ISS for a reliable, long-term microgravity environment, by comparing space-grown crystals to the best ground crystals, and by focusing on challenging systems and hot scientific problems. Their results should definitively show whether the use of microgravity can produce crystals of a higher quality than those grown using the best technologies available on Earth. If none of the projects produces a space-grown crystal that enables a breakthrough for the structure determination of a biologically important macromolecular assembly, then NASA should be prepared to terminate its protein crystal growth program. However, if the projects supported by this high-profile, nationwide series of grants succeed in validating the use of crystallization in microgravity to tackle important and challenging problems in biology, demand for the facilities on the ISS can be expected to increase. At that time, NASA should develop an external user program (similar to synchrotron user programs) in which projects are selected by a peer-review committee that includes NASA staff representatives.

Recommendation: NASA should fund a series of high-profile grants to support research that uses microgravity to produce crystals of macromolecular assemblies with important implications for cutting-edge biology problems. The success or failure of these research efforts would definitively resolve the issue of whether the microgravity environment can be a valuable tool for researchers and would determine the future of the NASA protein crystal growth program.

Cell Science

NASA has built a very productive relationship with the NIH based on the development and use of rotating-wall vessels. The NASA/NIH Center for Three-Dimensional Tissue Culture was started in 1994 to expose a wider community to bioreactor technology by allowing researchers from government agencies (e.g., NIH, the Food and Drug Administration, and the Department of the Navy) to test new model systems for biomedical research and basic cell and molecular biology in the rotating-wall vessel hardware with technical assistance from experienced NASA personnel. The task group believes that this outreach program is an excellent idea and recommends that a wider range of investigators be reached by opening this introductory phase of this program to extramural (nongovernment) researchers.

B

Letter of Request from NASA

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

DEC 15 2000

Reply to Attn of: UG

Dr. John McElroy
Space Studies Board, HA 584
National Academy of Sciences
2101 Constitution Avenue, NW
Washington, DC 20418

Dear Dr. McElroy:

The NASA Microgravity Research Division underwent reorganization in October 2000. As a result, the division took on a new name, Division of Physical Sciences Research, and new responsibilities. In its new assignment, the division will extend the focus of its current programs in the physical and engineering sciences and biotechnology beyond experiments for the International Space Station, and will establish cutting edge, university-focused, interdisciplinary research efforts in the areas of nanoscience, biomolecular physics and chemistry, and exploration research. While the former microgravity division's scope has been expanded beyond the scientific examination of gravity-related phenomena, its new role within NASA is not yet fully defined, and the additional resources available for new investigations are expected to be limited.

Therefore, it would be useful for NASA to have the Space Studies Board's guidance on the overall direction of the Division of Physical Sciences Research and on particular topics within its new breadth of responsibility. Specifically, we would ask that the Committee on Microgravity Research undertake a two-phase study. The focus of the first phase would be development of an overall unifying theme, or "mission statement," for NASA's program in microgravity and physical sciences within the Office of Biological and Physical Research. In the second phase the committee would assess the current status of the division's research program, identify and define more specific topics within the new discipline areas on which the division could most profitably focus, and attempt to prioritize future research directions. In doing so, we ask that the committee consider the following four issues for each major research topic currently funded by our program:

1. The contribution of important knowledge from microgravity research on each topic to the larger field of which the research is a part;
2. The progress in understanding the microgravity research questions posed on each topic;
3. The potential for further progress to be made in each area of microgravity research; and
4. The potential for contributions of significant knowledge from continued research on each topic that will aid NASA in goals such as technology development for human exploration.

In order to address the first two items, extensive knowledge of past and current work in microgravity will be necessary. We will ask our discipline working groups to provide to the Committee on Microgravity Research an assessment of these two questions for each discipline that the committee can evaluate in turn.

We understand that the study would require approximately two years to complete from its inception. Delivery of the report on the first phase would be expected at the end of the first year and delivery of the report on the second phase report at study completion.

Sincerely,

Eugene Trinh

Eugene Trinh, Ph.D.

C

Glossary and Acronyms

BEC	Bose-Einstein condensation. At a temperature near absolute zero, atoms behave as a "superatom." In rubidium, this phase change is made at ~170 billionths of a degree above absolute zero.
BEST	boundary effects near the superfluid transition
biopolymer	a macromolecule in a living organism formed by linking together several smaller molecules (i.e., protein from amino acids or DNA from nucleotides)
BTC	Biotechnology Temperature Controller
CHEX	confined helium experiment
CIR	Combustion Integrated Rack
colloid	any gas, solid, or liquid in a fine state of subdivision, with particles too small to be seen in an ordinary microscope, that is dispersed in a continuous gaseous, liquid, or solid medium and does not settle, or settles very slowly
CRADA	Cooperative Research and Development Agreement
CVX	critical viscosity experiment
dendrite	a mineral crystallizing in another mineral in a branching or treelike form
DOE	Department of Energy
DYNAMX	critical dynamics in microgravity experiment
FDA	Food and Drug Administration
Froude number	a dimensionless number equal to the ratio of buoyancy to pressure forces
gelation	solidification by cooling or freezing
GRACE	gravity recovery and climate experiment
HEDS	human exploration and development of space
ISS	International Space Station

LISA	Laser Interferometer Space Antenna
LPE	lambda point experiment
MEMS	microelectromechanical systems
microgravity	an environment in which there is very little net gravitational force, such as in free fall or in orbit
MISTE	microgravity scaling theory experiment
mosaicity	a measure of misalignment between small coherent blocks of individual molecules within a protein crystal. Lower mosaicity results in higher-quality X-ray diffraction data
nanoscale	lengths between 1 and 100 nanometers, or 10^{-7} to 10^{-9} meters
NASA	National Aeronautics and Space Administration
NCCU	NASA Cell Culture Unit
NCI	National Cancer Institute
NIH	National Institutes of Health
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
OBPR	Office of Biological and Physical Research
OMEGA	Orbiting Medium Explorer for Gravitational Astrophysics
PARCS	primary atomic reference clock in space experiment
PI	principal investigator
proteomics	systematic analysis of the protein expression of healthy and diseased tissues
PSD	Physical Sciences Division of OBPR
RACE	rubidium atomic clock experiment
rheology	study of the deformation and flow of matter
RWB	Rotating Wall Bioreactor
SIM	Space Interferometry Mission
ST3	Space Technology 3
STEP	satellite test of equivalence principle
SUMO	superconducting microwave oscillator experiment
superfluid	a fluid, such as a liquid form of helium, exhibiting a frictionless flow at temperatures close to absolute zero
thermocapillary	referring to changes in surface tension due to temperature variations that can generate fluid motions
TPF	Terrestrial Planet Finder
ZENO	critical fluid light scattering experiment

D

Committee Biographies

Peter Voorhees is the Frank C. Engelhart Professor in Materials Science and Engineering at Northwestern University. He received his B.S. in physics and Ph.D. in materials engineering from Rensselaer Polytechnic Institute. Upon graduation he joined the Metallurgy Division at the National Institute of Standards and Technology as a postdoctoral fellow and then stayed on as a staff member. In 1988 he was appointed as an associate professor in the Materials Science and Engineering Department at Northwestern University. Professor Voorhees has held visiting positions at the Institute for Theoretical Physics, University of California at Santa Barbara; Groupe de Physique des Solide, Université Paris VII; Institut fur Angewandte Physik, ETH Zurich; Université de Montpellier II, France; and Institut für Werkstofforschung, GKSS-Forschungszentrum. He has received the National Science Foundation Presidential Young Investigator Award, Acta Metallurgica et Materialia Outstanding Paper Award, McCormick School of Engineering and Applied Science Award for Teaching Excellence, ASM International Materials Science Division Research Award (Silver Medal), and a National Science Foundation Creativity Extension and is a fellow of ASM International. He has published over 110 papers in the area of the thermodynamics and kinetics of phase transformations. Professor Voorhees' research interests include coarsening phenomena, the morphological evolution of thin films during heteroepitaxy, and large-scale numerical simulations of microstructural evolution.

J. Iwan D. Alexander is a professor in the Department of Mechanical and Aerospace Engineering and is chief scientist for fluids, National Center for Microgravity Research on Fluids and Combustion (NCMR), Case Western Reserve University (CWRU). He joined NCMR and CWRU after spending more than 10 years at the Center for Microgravity and Materials Research at the University of Alabama, where he began research programs in fluids and transport problems in crystal growth (with an emphasis on microgravity-related problems) and computational and experimental fluid dynamics, most of which were involved with NASA microgravity activities. His current research areas include fluids and transport phenomena, surfaces and interfaces, and computational fluid dynamics. Dr. Alexander has served on the scientific staff at Carnegie Mellon University, where he worked on elastic inclusion problems related to phase transitions in the solid state. He has also served as a visiting scientist at NASA's Marshall Space Flight Center, where he became involved in assessing the effects of vibration and spacecraft disturbances on materials and fluids experiments that were to be conducted in low gravity.

Cristina Amon is the director of the Institute for Complex Engineered Systems and is Raymond J. Lane Distinguished Professor of Mechanical Engineering and Biomedical Engineering at Carnegie Mellon University. Her research interests focus on computational fluid dynamics and heat transfer, concurrent thermal design, stability and transition to turbulence, heat transfer enhancement techniques, micro and nano heat transfer phenomena, thermal management of electronics, aneurysm hemodynamics and mass transport in intravenous blood oxygenators. She is the recipient of several awards for excellence in research and education, including the ASME 2000 Gustus L. Larson Memorial Award, WE 1999 Distinguished Engineering Educator Award, ASEE 1997 George Westinghouse Award, and 2002 Ralph Coats Roe Award. She has contributed six book chapters, one McGraw Hill Custom Textbook, and over 140 refereed articles in the education and research literature. She is a fellow of the ASME and IEEE and an associate fellow of AIAA. Cristina Amon currently serves as chair of the ASME HTD K-16 Committee on Electronics Cooling (2000-2003) and executive member of the ASME Electronic and Photonic Packaging Division. Her editorship roles include associate editor for the ASME *Journal of Heat Transfer*, IEEE *Transactions on Components and Packaging Technology*, associate editor for *Electronic Packaging G&B Book Series*, and co-editor of *Journal of Heat and Mass Transfer* and ASME publications. She was elected general chair of the IEEE/ASME ITherm 2002 Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems.

Howard R. Baum, National Academy of Engineering (NAE), is a fellow of the National Institute of Standards and Technology. Dr. Baum has research interests in the fluid mechanics of fires, turbulent combustion, computational methods for fire phenomena, and smoke aerosol physics and transport. His research in fire-induced flows and turbulent combustion led to a U.S. Department of Commerce Silver Medal Award in 1981 and the Gold Medal Award in 1985. He was named Russell Severance Springer Visiting Professor at the University of California, Berkeley, in 1985 and was an invited lecturer at the Second International Symposium on Fire Safety Science in l988. He received the Medal of Excellence from the International Association for Fire Safety Science in 1991 and 1999. Dr. Baum was a member of the U.S. delegation to the 1991 Japan-U.S. Heat Transfer Joint Seminar as primary participant and invited lecturer. He was awarded a Japan Society for the Promotion of Science fellowship for a 1994 visit to the University of Tokyo Institute of Industrial Science. Dr. Baum has published more than 100 papers and reports. His analysis of ventilation in containership holds is the technical basis of international standards for containership ventilation. He has served on NRC panels convened by the Naval Studies Board in 1986 and 199l to consider Office of Naval Research (ONR) opportunities in solid and fluid mechanics, and a panel in 1987 to consider the status of nuclear winter research. Dr. Baum serves on the editorial boards of the journals *Combustion and Flame* and *Combustion Theory and Modeling*.

John L. Brash is a professor in the Department of Chemical Engineering at McMaster University and a member of the Brockhouse Institute for Materials Research. His research involves studies in biotechnology and biomaterials, polymerization and polymer characterization, and modification of surfaces for biotechnology and medical applications. A major goal is to understand the interactions of proteins and cells at the tissue-material interface, with particular emphasis on blood. Materials based on preventing the nonspecific adsorption of proteins and promoting the specific adsorption of targeted proteins are being developed. Professor Brash has been a member of several advisory committees of the Natural

Sciences and Engineering Research Council (Canada) and was chair of the Chemical and Metallurgical Grants Review Committee. He has also served on committees of the Canadian Institutes of Health Research and the NIH. He received the Clemson Award for Basic Research of the U.S. Society for Biomaterials in 1994 and an honorary doctorate (docteur honoris causa) from the University of Paris (XIII) in 1996. He was awarded the title "University Professor" by McMaster University in 2001.

Moses H.W. Chan, National Academy of Sciences (NAS), is the Evan Pugh Professor of Physics at Pennsylvania State University. His primary field of research involves the study of condensed matter. Dr. Chan is known for his innovative and precise experimental studies of phase transitions in quantum and classical fluids, especially in reduced dimensions, restricted geometries, and the presence of impurities and disorder. He is the recipient of the Fritz London Prize, 1996, and was a Guggenheim fellow in 1987.

Jayavant P. Gore, the Vincent P. Reilly Professor in the School of Mechanical Engineering at Purdue University, is widely known in the combustion field. His research areas of interest are in combustion and flame radiation phenomena with emphasis on efficiency, productivity enhancement and pollutant reduction in gas turbine combustors and industrial burners and furnaces, and fire safety with understanding of flow and radiation phenomena including advanced detection. Dr. Gore is a member of American Society for Mechanical Engineers and the American Institute of Aeronautics and Astronautics.

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Richard Hopkins retired in 1999 from the position of senior consultant, microelectronics, Northrop Grumman Science and Technology Center. Currently, he heads an electronic and optical materials consulting activity, Hopkins, Inc. Dr. Hopkins has 30 years of experience in materials and device research, including program management and senior line management positions, most recently as head of the Microelectronics Department at the Northrop Grumman Science and Technology Center. His technical expertise includes crystal growth methods for inorganic, organic, and metallic materials and the application of unique semiconductor, optical, and metal alloys to device fabrication. Dr. Hopkins has published 130 papers in refereed journals and holds 20 U.S. patents in materials and materials processing. He is president of the Eastern Region of the American Association for Crystal Growth and a fellow of ASM International. He previously served as a member of the NRC Task Group on Institutional Arrangements for Facilitating Research on the International Space Station.

Michael Jaffe is a research professor with the New Jersey Institute of Technology in the Biomedical Engineering Department. He is also chief scientist for industrial programs and director of the Medical Device Concept Laboratory in the New Jersey Center for Biomaterials and an associate research professor at Rutgers University. His expertise is in innovative materials research such as biomimetics as well as Department of Defense (DOD) system applications. His work has focused on understanding the structure-property relationships of polymers and related materials, the application of biological paradigms to materials design, and the translation of new technology to commercial realty. Dr. Jaffe was the recipient of the 1995 Thomas Alva Edison Patent Award, presented by the Research and Development Council of New Jersey. He is a fellow of AAAS and a member of the NRC Committee on Materials Research for Defense-After-Next, the National Materials Advisory Board, and the U.S. National Committee for the International Union of Pure and Applied Chemistry.

Bernard H. Kear, NAE, is State of New Jersey Professor of Materials Science and Technology at Rutgers University. For more than 35 years, Dr. Kear's research interests have centered on the synthesis, processing, structure, and properties of inorganic solids for a broad range of structural applications. His current research is concerned with chemical processing of nanophase metals, ceramics, cermets, and composites, starting from aqueous solution or metal-organic precursors. Primary objectives of the research are to develop scalable processes for the production of nanostructured powders, thin films and multilayered structures, diffusion and overlay coatings, particle-dispersed and fiber-reinforced composites, and net-shape bulk materials. Dr. Kear's previous work addressed the fundamental aspects of dislocation interactions, phase transformations, and solidification behavior in nickel-base superalloys. This work contributed to the successful development of directional solidification of single-crystal turbine blades, rapid solidification powder atomization, and laser surface treatments. From 1981 to 1986 he worked at Exxon, where his research activities were focused on developing methods for CVD (chemical vapor deposition) surface passivation treatments and for catalytic growth of carbon whiskers from hydrocarbon precursors. Dr. Kear has published 220 technical papers, edited 9 books, and been granted 35 patents. He was chair of the National Materials Advisory Board from 1986 to 1989, and he has served on numerous NRC panels, including the Panel for Materials Science and Engineering and the Panel for a Review of ONR Research Opportunities in Materials Sciences.

Jan D. Miller, NAE, is Ivor Thomas Professor of Metallurgical Engineering at the University of Utah. Dr. Miller's research covers the areas of minerals processing, specializing in particulate systems, aqueous solution chemistry, colloid and surface chemistry, and environmental processing technology, hydrometallurgy, flotation surface chemistry, and colloid chemistry. He is widely noted for his contributions to the fundamental theory and practical technology of flotation, minerals processing, and hydrometallurgy. In 1991 he received the Robert H. Richards Award for his advancement of the art of minerals processing by "prolific innovation of concepts reflecting the highest quality spirit of an educator, engineer, inventor and dedicated researcher." Dr. Miller served as principal investigator in 1998 for a project conducted at the Great Plains-Rocky Mountain Hazardous Substance Research Center and titled "Removal of Chlorinated Hydrocarbons from Contaminated Water Using Air-Sparged Hydrocyclone Technology." He also served as conference co-chair for the Environmental Technology for Oil Pollution 2nd International Conference, "Analysis and Utilization of Oily Wastes."

G.P "Bud" Peterson, provost of Rensselaer Polytechnic Institute (RPI). Before accepting the position of provost, he was the College of Engineering Tenneco Professor, associate vice chancellor, and executive associate dean of engineering at Texas A&M University. A fellow of both the American Society of Mechanical Engineers and the American Institute of Aeronautics and Astronautics, Dr. Peterson's research interests are in the field of thermodynamics and heat transfer. His most recent work analyzing heat transfer at the microscopic dimensions used in semiconductor devices presents enormous commercial potential for use in the thermal control of high-power semiconductor devices and for the elimination of cancerous tissue in situ. He has developed techniques for NASA to study the behavior of heat pipes in the reduced gravity environment of space. Dr. Peterson is recognized internationally for his work in boiling and phase change heat transfer.

Peter Staudhammer, NAE, is vice president for science and technology at TRW, Inc. As the company's chief technical officer, Dr. Staudhammer is responsible for overseeing TRW's acquisition, management, and application of technology. Prior to his current position, Dr. Staudhammer had served as vice president and director of the Center for Automotive Technology, which combines the technical strengths of TRW's automotive, space, and defense businesses. He also serves as a member of the company's Management Committee. Dr. Staudhammer was one of the principal architects and the chief engineer of the Apollo Lunar Descent Engine. He also managed the development of space power and space instrument systems, including the Mars Viking Biology Instrument, atmospheric analysis instruments on Pioneer Venus, Earth observation instruments, and two ultraviolet spectrometers for the Voyager mission to Jupiter, Saturn, Uranus, and Neptune. Dr. Staudhammer subsequently managed TRW's Central Research Staff, directing research in solid-state devices, space physics, high-energy lasers, and plasma physics. He has received achievement awards from NASA and from the Institute for the Advancement of Engineering.

Viola Vogel is the director of the Center for Nanotechnology and professor in the Department of Bioengineering at the University of Washington. After completing her graduate research at the Max-Planck Institute for Biophysical Chemistry in Goettingen, she received her Ph.D. in physics (1987) at Frankfurt University, followed by 2 years as a postdoctoral fellow at the University of California, Berkeley (1988-1990). She received the Otto-Hahn Medal from the Max-Planck Society (1988) and the NIH "First Award" (1993-1998), and she served on President Clinton's Presidential Committee of Advisors in Science and Technology preparation panel that prepared the Presidential Nanotechnology Initiative (1999). Dr. Vogel's interests include molecular assembly processes at interfaces, single-molecule mechanics and spectroscopy, self-assembled monolayers and Langmuir-Blodgett films, biomineralization, biomaterials and cell signaling, and optical spectroscopy and microscopy. Dr. Vogel is the principal investigator of the NSF-funded Integrative Graduate Education Training Program in Nanotechnology at the University of Washington and an investigator on the NSF-Engineering Research Center project "University of Washington Engineered Biomaterials" (1996-2005) and the project "Microscale Life Science Center" (2001-2006) funded by the National Institutes of Health–Centers for Excellence in Genomic Science and Technology.

Staff

Sandra J. Graham received her Ph.D. in inorganic chemistry from Duke University in 1990. Her past research focused primarily on topics in bioinorganic chemistry, such as the exchange mechanisms and reaction chemistry of biological metal complexes and their analogs. From 1991 to 1994 she held the position of senior scientist at the Bionetics Corporation, where she worked in the science branch of the Microgravity Science and Applications Division at NASA headquarters. Since 1994 Dr. Graham has been a senior program officer at the Space Studies Board of the National Research Council, where she has directed numerous studies in both space life sciences and microgravity sciences.