An Initial Review of Microgravity Research in Support of Human Exploration and Development of Space

Committee on Microgravity Research, Commission on Physical Sciences, Mathematics, and Applications, National Research Council

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Preface

The study that is the subject of this preliminary report was initiated in early 1996 by a request to the Committee on Microgravity Research (CMGR) from the leadership of NASA's Microgravity Science and Applications Division[1] to perform an assessment of scientific and related technological issues facing NASA's Human Exploration and Development of Space (HEDS) endeavor. Because the request involved an examination of technology issues, as well as scientific ones, the committee attempted to carefully tailor the scope of the task to its own, primarily scientific, expertise before agreeing to proceed. As a result the committee decided to consider mission enabling and enhancing technologies that, for development, would require an improved understanding of fluid and material behavior in a reduced-gravity environment. The committee would then identify opportunities for microgravity research to contribute to the understanding of fundamental scientific questions underlying exploration technologies and make recommendations for some areas of directed research. The study is being carried out in two phases, of which this report is the first. NASA is still in the early stages of identifying the specific technologies needed for HEDS; therefore this first report represents a preliminary look at broad categories of HEDS technologies.

During the course of this study the committee was briefed by program managers from a number of different NASA divisions regarding the technology development needs of the agency, and it also reviewed the available NASA documentation on prior technology-forecasting activities.

Among the previous National Research Council reports relevant to this study, the committee took particular note of the following:

- *Microgravity Research Opportunities for the 1990s*, Space Studies Board, National Academy Press, Washington, D.C. (1995), reviews the various research topics currently studied within the different scientific disciplines of NASA's microgravity research program and provides research and programmatic priorities and recommendations.

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- *Space Technology to Meet Future Needs*, Aeronautics and Space Engineering Board, National Academy Press, Washington, D.C. (1987), evaluates national advanced space technology requirements and recommends a long-term technology program focus for NASA.

[1] Now the Microgravity Research Division (MRD).

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Executive Summary

The current organizational structure of NASA includes five strategic enterprises, one of which is the Human Exploration and Development of Space (HEDS). Goals set by the HEDS enterprise include (1) increasing knowledge of nature's processes by use of the space environment; (2) exploring and settling the solar system; (3) achieving routine space travel; and (4) enriching life on Earth through people living and working in space. The means by which NASA proposes to accomplish these ambitious goals include a combination of scientific research, engineering technology development, and use of the Space Shuttle and the International Space Station (ISS) as microgravity test platforms. The first objective stipulated within NASA's HEDS Goal 1 is that scientific research should be conducted to understand the roles played by gravity and the space environment in affecting the behavior of biological, chemical, and physical systems. The second objective within HEDS Goal 1 specifies the innovative use of major HEDS facilities, such as the Space Shuttle and the ISS, to achieve breakthroughs in science and technology.

This preliminary report of the Committee on Microgravity Research examines those areas of microgravity research that not only support the objectives of Goal 1, but also have the potential to contribute to the eventual development of the new technologies required to accomplish the remaining HEDS goals. An initial appraisal is made of types of exploration technologies that, for development, would require an improved understanding of fluid and material behavior in a reduced-gravity environment.

The current microgravity research program at NASA's Microgravity Research Division (MRD) includes five major disciplines: (1) fluid physics, (2) materials science, (3) combustion, (4) biotechnology, and (5) fundamental physics. In general terms, fluid physics research encompasses the phenomena of heat and mass transport in low gravity and underlies many of the scientific and technological problems associated with long-duration crewed missions exploring the Moon and inner planets. A strong emphasis remains within the MRD program on experimental microgravity fluids studies—as opposed to reliance on computational fluid dynamics (CFD)—because the boundary conditions

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encountered in many reduced-gravity fluid physics studies are less well understood than in conventional subfields of aerospace research. For example, relatively weak forces, such as thermocapillary tractions and van der Waals interactions, which may be ignored in most terrestrial flow problems, can become dominant in microgravity. Materials science research in the MRD program tends to be focused on basic subjects such as nucleation and growth of solids from melts and on the evolution of microstructures—especially those involving one or more fluid phases. These include the formation of crystal defects and solute segregation in single-phase processing, such as semiconductor crystal growth, as well as research aimed at achieving a better understanding of polyphase microstructures, such as occur in eutectics and monotectics. Microgravity materials research extends to practically important processes such as reaction synthesis and sintering, welding and solidification, and in situ resource utilization (ISRU) for producing structural materials from extraterrestrial bodies. Such materials processes seem particularly relevant to technologies contemplated for future HEDS missions. Microgravity combustion research within the MRD—especially studies on fire safety research at the fractional gravity levels found on extraterrestrial bodies or studies under microgravity as encountered in spacecraft environments during deep-space transit—is critically needed to ensure safety on future HEDS missions, where crew egress might not be an option. Such research includes studies on flammability limits, smoldering, flame spread, and flame stability—all of which contribute both to scientific knowledge and to the engineering know-how needed for successfully pursuing the HEDS goals. Research in microgravity biotechnology is considered essential for understanding and designing reliable life-support systems, for producing nutrients and food for crews during long-duration HEDS missions, and for safely and reliably recycling waste aboard spacecraft for water and oxygen recovery. Current MRD studies include activities on cell culture and bioseparations, which will contribute critically to understanding biological options for nutrient production in spacecraft as well as waste recycling. Low-temperature and atomic physics research using microgravity generally probes certain extreme physical limits in both classical and quantum systems. Research on laser cooling of atoms in microgravity can contribute directly to the development of improved navigational systems for achieving safe, efficient deep-space travel by providing practical atomic clocks with greatly increased accuracy.

Although this initial report identifies the general areas of research discussed above as having the potential to make long-term contributions to HEDS technology development, the committee has attempted to prioritize neither the research nor the affected technologies, in part because NASA is currently still in the early stages of identifying its technology needs. As these needs become more clearly defined, it should be possible to identify research that can be profitably emphasized, although the need for flexibility in HEDS mission planning suggests that a strict prioritization of research is likely to remain counterproductive. Nevertheless, it is possible at this early stage to provide a number of initial recommendations, primarily programmatic, derived in the course of this review of microgravity research in support of Human Exploration and Development of Space.

- MRD should, on a continuing basis, assist NASA in identifying critical

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technologies that would benefit future HEDS missions and then seek opportunities in microgravity research to contribute to their efficient realization. MRD should, however, remain both flexible and cautious in evaluating such opportunities. Major advances in technology can result from basic research undertaken without regard to current technological priorities, which have yet to be even identified. In addition, the timing of such technological advances is often unpredictable.

- In supporting HEDS, MRD should continue to focus on maintaining its broad program of microgravity research. Although not all of the technological advances needed for HEDS missions will be the direct result of basic research, the unfolding knowledge base and collective experience of microgravity investigators focused within the MRD program will continue to represent unique NASA resources with which to approach the scientific questions underlying many of the barriers to space exploration.

- MRD should be prepared to stimulate and support critical microgravity research to help discriminate among competing HEDS technologies, specifically providing information so that NASA can make informed choices among them.

- The process of gathering and exchanging information relevant to research selections that could support HEDS missions should be strengthened. Specialized workshops, cross-divisional teams, advisory panels, and study groups attended by mission technologists and microgravity scientists are among the suggested mechanisms for achieving this recommendation. Such activities would encourage the exchange of ideas between technologists and scientists, provide better communication and ongoing awareness of the technology needed for MRD, and also allow timely transfer of microgravity research findings to HEDS technologists.

- The goals of HEDS involve the development of complex technological systems that require integration of microgravity information derived from research in disparate fields of science. MRD may find it advantageous to initiate a limited number of cross-disciplinary projects to develop experience in selecting and managing research projects that operate across traditional boundaries of the microgravity science disciplines.

- Some HEDS missions will involve operating systems at fractional gravity levels, such as the 0.16 Earth gravity encountered on the Moon or the 0.37 Earth gravity encountered on Mars. It is, however, often unclear as to whether or not thresholds of the gravity level exist at which various physical, chemical, and biological phenomena and processes undergo change. MRD should consider giving more attention to research studies carried out at fractional gravity levels where HEDS technologies might directly benefit from the scientific advances. Knowledge generated from such studies could be used to evaluate the need to provide artificial gravity by using continuous spacecraft rotation.

- Ongoing investments by NASA in robotics and automation research

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are expected to benefit both manned and unmanned HEDS missions, which must operate sufficiently far from Earth that highly autonomous operations and control become necessary because of the long transit time of signals. MRD should ensure that microgravity issues in teleoperations and robotics research are given sufficient attention and should maintain an active and current awareness of these issues.

- The International Space Station (ISS), when available for scientific use shortly after the beginning of the next millennium, should provide MRD with unique long-duration microgravity opportunities for evaluation of technical systems deemed important to future HEDS missions. MRD should take advantage of the ISS as a microgravity platform for investigating closed-cycle, long-term operation of various physical, chemical, and biological systems considered to be within its research purview.

- In view of the normally long time-scale needed for the evolution of basic scientific concepts into practical applications, MRD should begin now to study and understand the scope and long-term implications of microgravity research areas relevant to accomplishing HEDS goals. Any adjustments to the emphasis or scope of MRD research must then be carefully assessed with respect to overall program balance, scientific merit, external interest, and HEDS mission relevance.

- The systematic and periodic application of NASA Research Announcements (NRAs) and peer review has improved the quality and selection of the science supported by MRD. These benefits to NASA and the nation are so extensive that these mechanisms should be preserved to ensure scientific objectives that support and enhance the HEDS enterprise. The recent inclusion of a call for research on ISRU and two-phase flow in the 1996 NRAs for materials science and fluid physics is commended as timely and responsive.

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1

Introduction

NASA AND THE HUMAN EXPLORATION OF SPACE

A major NASA goal continues to be the exploration of space by humans, a fact reflected by the inclusion of the Human Exploration and Development of Space (HEDS) enterprise in the current organizational structure of NASA. In 1995, NASA reorganized its programs into five strategic enterprises, each representing a core mission of the agency. The Microgravity Research Division (MRD) and Life Sciences Division, both formerly part of the Office of Space Sciences and Applications, were placed within the new HEDS enterprise. The four HEDS goals[1] promulgated by NASA are to (1) increase knowledge of nature's processes by use of the space environment; (2) explore and settle the solar system; (3) achieve routine space travel; and (4) enrich life on Earth through people living and working in space. NASA proposes that these strategic goals will be accomplished through scientific research, engineering technology, and utilization of the Space Shuttle and the International Space Station (ISS).

NASA's first objective under HEDS Goal 1 stipulates that the agency conduct scientific research to understand the fundamental role played by gravity and the space environment in biological, chemical, and physical systems. NASA's strategy for accomplishing that objective is to investigate, using a peer-reviewed research program, processes and phenomena normally obscured or complicated by the presence of gravity. The second objective under Goal 1 is to use HEDS research facilities innovatively to achieve breakthroughs in science and technology.

NASA's microgravity program has for 20 years been addressing those fundamental scientific objectives currently subsumed within the HEDS enterprise. As the present administrator of that program, MRD has met this challenge primarily by supporting a broadly based program of peer-reviewed microgravity research covering the disciplines of fluid mechanics and transport phenomena, combustion, biotechnology, materials science and processing, and fundamental

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physics.[2] (The Life Sciences Division holds a similar responsibility for research on gravitational effects on biological systems.) Currently, microgravity research is viewed as a complex of laboratory sciences conducted both on the ground and in space that generate fundamental knowledge in physics, chemistry, biotechnology, and engineering. A recent report issued by the Space Studies Board of the National Research Council[3] found that "Access to prolonged periods in space as well as to other short-duration, ground-based microgravity facilities, is beginning to provide researchers with the opportunity to apply the methods of the physical and biological sciences to a new regime of low-gravity experiments" (p. 25). As of the writing of this report, a number of dedicated microgravity spaceflights have been completed by NASA, including the Spacelab missions USML-1 and -2, IML-1 and -2, and others, which have provided major new results and accelerated progress in microgravity science.[4]

HEDS TECHNOLOGIES

As envisioned by the HEDS enterprise, the ability for humankind to expand and prosper beyond the confines of our planet depends on the continued development and integration of those advanced technologies that will provide safe, affordable access to space and the ability to carry out both human and robotic exploration of the Moon and inner planets. The pacing technologies for the currently planned human exploration and development of space must perform many terrestrially familiar technical activities, such as energy conversion, communications and control systems, construction and maintenance of habitats, fluid and thermal management, and fire safety. Included also are more specialized space-related technologies such as propulsion, life support, and the in situ extraction of materials, including water, oxygen, and propellants, from the surfaces of extraterrestrial bodies.[5]

The commonplace familiarity with a multitude of terrestrial technologies contrasts sharply with a much more limited experience in applying the technologies for the exploration and development of space. Conventional design criteria extrapolations and scaling principles, which are useful and validated for engineering systems operating in gravity environments approximating terrestrial levels, may not be applicable to systems required to function at near-zero acceleration or on small extraterrestrial bodies. This situation has the potential of greatly limiting the pace of development for some critical mission-related technologies needed to accomplish planned robotic and crewed missions to extraterrestrial bodies. In fact, even where straightforward extrapolations of terrestrial engineering experience exist to adapt systems to operate in space, or on the Moon and Mars, they still must be tested and proven by actual in-space demonstration. Moreover, where current terrestrial technologies remain immature, especially from the standpoint of engineering practice, the challenges to extend and verify them for spaceflight applications become much greater, perhaps even limiting the rate of progress in accomplishing HEDS goals.

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AN INITIAL APPRAISAL

Numerous technological barriers must eventually be overcome to accomplish long-term exploration, development, and habitation of space by humans. Many of these technical issues can be resolved only through a deeper understanding of the behavior of fluids, materials, and biological systems in a reduced-gravity environment. This report takes a preliminary look at these technical issues. Many of the technologies that may be needed to fulfill HEDS objectives, such as improved solid-state electronic systems for high-volume data transfer and communication, are not likely to be affected by gravity levels. Others, such as fluid loops for heat transfer, energy production, and life-support systems, clearly will be. This report concentrates on potential HEDS technologies that require a better understanding of the low-gravity behavior of fluids, materials, and structures. Inasmuch as most of the specific mission-related technology needs are still being identified by NASA, the committee chose at this time to consider *only* broad areas of HEDS technology, with some specific technologies cited as illustrative examples. This initial report therefore begins to identify and address those areas of technology to which NASA's microgravity science program can directly contribute by strengthening the underlying basic knowledge needed to evaluate, improve, or create the specific solutions to mission-critical problems encountered by the HEDS enterprise. It is planned that, as NASA's plans for exploration mature and specific technologies are targeted, this committee will prepare a more detailed report for the second phase of this study.

In Chapter 2, the current microgravity research program of MRD is briefly described and compared to HEDS Goal 1, and the challenges posed by the remaining HEDS goals are discussed. In Chapter 3, broad areas of HEDS technologies to which microgravity research could contribute are identified and described, and the fundamental research areas and questions connected to those technologies are reviewed. Chapter 4 contains a discussion of programmatic issues related to MRD support of the HEDS enterprise and specifies some recommendations in these areas.

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2

The Current Microgravity Research Program and HEDS Goals

HEDS GOAL 1: INCREASE KNOWLEDGE OF NATURE USING THE SPACE ENVIRONMENT

As described above, the first of the HEDS goals adopted by NASA mandates the scientific study of nature and its processes in microgravity for the purpose of increasing human knowledge. Some of these studies use microgravity as an experimental variable, and others use microgravity to enable the study of phenomena obscured by gravity. (While microgravity is technically defined as 10^{-6} of Earth's gravity, the actual spaceflight environment in which experiments are performed ranges from 10^{-3} to 10^{-6} *g*). Microgravity can also permit an experimental protocol or measurement that cannot be performed on Earth. The current MRD science program is already closely aligned to the objectives of HEDS Goal 1 and has been so almost from its inception. The science programs of each of the five current MRD disciplines, described in greater detail in a previous report of this committee,[1] are briefly presented below.

Fluid Physics

The greater part of the current MRD program deals with heat and mass transport processes in reduced gravity or microgravity that are associated with density, temperature, and concentration gradients in gaseous, liquid, and particulate matter, especially when changes of phase take place. Studies of nucleation and boiling in reduced gravity are under way, as are studies of the dynamic behaviors of droplets, bubbles, and foams and of suspensions of particulate materials as they are transported in fluid media. A variety of interfacial problems, for example in multilayer convection and jet impingement, arise in many of the current studies.

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Electrohydrodynamic forces and effects, including electrophoresis, appear in a number of these microgravity studies, in addition to capillary, thermocapillary, and diffusional effects. Theoretical studies have been initiated in which investigators have begun to examine the influence of reduced gravity (e.g., on the Moon or Mars) rather than microgravity, and some studies consider the consequences of "*g*-jitter" on gravity-sensitive flows.

The present program shows a strong emphasis on experimental research. Experiments in flow physics requiring access to a long-duration, low-gravity environment have been carried out successfully in the Space Shuttle program. For experiments that can be conducted in shorter periods, continuing use has been made of aircraft flight tests and of a number of drop-tower facilities for flow physics research. While this experimental research is strongly fundamental in character, the current MRD fluid physics program does not greatly emphasize theory or analysis, nor does it emphasize computational fluid-dynamics simulation (which is developed from theory) as much as do fluid mechanics programs in other fields of aerospace research where the boundary conditions are better understood. This is understandable for the present. However, as NASA's interest grows in the application of fundamental scientific insights to specific design conception, then theory, analysis, and computational simulation will assume greater importance in microgravity work.

In general terms, issues involving the physics of fluids in low gravity underlie a great many of the scientific and engineering technology problems of space travel, and these are more fully discussed in subsequent sections of this chapter and in Chapter 3. Therefore, elements of the broad current fluid physics program of MRD will doubtless find expression within interdisciplinary studies undertaken by NASA to support the design of general and specific systems needed for future HEDS missions.

Materials Science

The essential quest of materials science is to understand the relationships among processing, structure, and properties. Within this context, the MRD program in materials science seeks to understand the influences of gravity on those relationships. Hence, a large fraction of the science funded by MRD is focused on understanding the fundamentals of nucleation and growth of solids from liquids. Emphasis is also placed on elucidating the details of the genesis and evolution of microstructure, as well as on the formation of crystal defects and solute segregation. The ultimate goal of this research is understanding how to improve materials properties. Additionally, because the microgravity environment enables measurements of the thermophysical properties of liquids in stable (and even metastable) states that might not be possible to perform in terrestrial gravity, this area has also attracted researchers. Examples of such properties are viscosity, heat capacity, and chemical diffusivity.

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The materials research currently funded by MRD addresses most major classes of materials. At present, a strong emphasis exists on metals and their alloys as well as on electronic and photonic materials; a moderate emphasis is placed on ceramic materials, and less on polymeric materials. The reduced emphasis on viscous polymeric materials is related to the smaller effects of gravity on their structure. Indeed, conventional fluid mechanics show that buoyancy-induced convection occurring in materials processes at terrestrial gravity levels has a much greater influence on process outcomes in the case of liquid metals and semiconductor melts than it has for highly viscous melts associated with high-molecular-weight polymers and network (silica-based) glasses. Within the scope of these investigations, a number of important processes are being examined, such as directional solidification, chemical vapor deposition, containerless processing, polymerization, and co-polymerization. Combustion synthesis and welding and joining are also receiving some attention. As work progresses, additional areas of research of importance to the HEDS enterprise are expected to be identified.

Combustion

MRD currently supports a rigorous flight- and ground-based effort in combustion science in line with the fundamental science objectives of HEDS Goal 1 through work exploring effects of gravity on flammability limits, smoldering, flame spread, and material flammability, all of which are substantially affected by a reduction in gravity. Related fundamental work includes investigations of the dynamics of flame balls, structures of diffusion flames, and characteristics of droplet and particle combustion (which, at reduced gravity, give rise to a closer approach to spherical flames, new flame instabilities, and modified soot formation processes), and focuses on the importance of radiative transfer in combustion processes. Along with associated theoretical studies, this program is leading to improved understanding of combustion phenomena at altered gravity levels, thereby contributing scientific knowledge needed for the HEDS enterprise.

Biotechnology

The biotechnology discipline within MRD currently supports three areas of research: protein crystal growth, mammalian cell culture, and bioseparations. Each is a key technology for the production of biology-based products and involves processes that are affected by gravity.

Protein crystal growth provides the crystals that are required to determine the unique three-dimensional structures these macromolecules adopt to perform their biological functions. The relationship between structure and function in proteins targeted for drug intervention, for example, has been found to be of

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critical importance to the rapid design of useful therapeutic agents. (The most recent example of this structure-based drug design using protein crystallographic data is the family of new HIV protease inhibitors that are the linchpins of more effective combination therapies against AIDS.[2]) The process of protein crystal growth is sensitive to gravity because of density-driven convection at growing crystal surfaces and because of sedimentation of crystals from liquid growth media. A first phase of spaceflight experimentation has proved that growth in microgravity can, in some cases, produce crystals exhibiting improved X-ray diffraction performance and more precise structure determination. A second phase of experimentation has just begun that focuses on determining the physicochemical mechanisms of protein crystal growth so that the knowledge can be used to extend the beneficial effects of microgravity to the widest possible array of proteins.

Most of the experimentation in mammalian cell culturing supported by MRD has been aimed at the study of the basic functions of three-dimensional cellular aggregates that form in bioreactor devices on Earth. The rotating-wall, perfused-vessel bioreactor was designed to mimic the low-shear-stress environment of microgravity. This cell culturing technology provides a great advance over the use of monolayer or stirred cultures and often permits culturing of differentiated cells and tissues that cannot otherwise be achieved.[3] Culturing of mammalian cells is important to provide cells and tissues for potential production of biological products such as insulin, cartilage,[4] and cellular proteins. In addition to presenting research opportunities, these tissues would also be available for transplantation and genetic therapies.[5,6,7] It is anticipated that the further reductions in shear forces that are possible in space will allow larger and more complex tissue masses to be grown.

Biological products are isolated from culture media by a number of techniques. Gel electrophoresis, a widely used method for purification of biological products for both industrial and research purposes, involves separation by size and charge in a water-based gel. Resolution is normally limited by the gravitationally mediated phenomena of density-driven thermal convection and sedimentation. The results of electrophoretic experiments carried out in microgravity demonstrated that buoyancy-driven phenomena are diminished, but new electrohydrodynamic effects have been uncovered that limit the benefits gained by the effects of microgravity on the system.[8] Biological separations will also be important for nutrient production and waste recycling in space, which may provide the basis of future critical mission technologies.

Low-temperature Microgravity Physics

The MRD program in low-temperature microgravity physics has sponsored several flight-approved projects, covering both condensed matter physics (Confined Helium Experiment, Critical Fluid Light Scattering, and Critical Dynamics in Microgravity) and general relativity (Satellite Test of the Equivalence Principle (STEP)). These projects use extended-duration microgravity to probe

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certain extreme physical limits, such as asymptotic approaches (within microkelvins) to certain critical temperatures of classical (xenon liquid-gas) and quantum (helium's lambda point) systems, where the physics of thermodynamic fluctuations near these singularities is revealed much more clearly than on Earth. The Quick STEP mission, which falls within this subdiscipline, is a geodesy science satellite that will establish new limits on the gravitational-to-inertial-mass ratio. The detection of any departure of this mass ratio from unity would present the physics community with a significant challenge to current relativity and gravitational theories; the absence of any systematic departure from unity would, by contrast, establish new limits on the accuracy of current physics theories. These projects in microgravity physics represent unique scientific opportunities for NASA to advance our deepest understanding of how matter and energy interact with gravity.

The Importance of Fundamental Research

Taken together, the individual discipline-specific science programs within MRD represent an integrated approach to microgravity research that has already contributed important knowledge of processes occurring in space and on extraterrestrial bodies and will continue to do so in the future. Moreover, the MRD program presents a relatively comprehensive response to the scientific opportunities and challenges provided by the microgravity environment. Basic microgravity research in the core disciplines should continue to be supported as the fundamental science component of the MRD program. The fundamental insights provided by the core disciplines can also form the basis for the evolution of technologies required by the other HEDS goals.

The current research sponsored by MRD is subject to rigorous peer review and generally is of high quality. A distinguished, broadly based scientific community is involved with the execution of these investigations, and significant new results are emerging from the program.[9] This effort, specifically directed at HEDS Goal 1, should be maintained at least at its current level.

NEW CHALLENGES: HEDS GOALS 2, 3, AND 4

Although MRD has established itself as an effective basic science program and thus meets the objectives of Goal 1 as described above, it can also play a significant role in NASA's attempt to meet the remaining HEDS goals. Contributing to NASA's HEDS Goal 2, "to explore and settle the solar system," would require the recognition that the output from the MRD science program should also be used to support the HEDS mission technologies. In other words, the results of microgravity research should be used not only for terrestrial applications, but also to improve the feasibility of the eventual exploration and settlement of near-Earth space. The scientific challenges presented by this new

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approach to the use of microgravity research findings also encompass to a large extent those posed by the subsequent HEDS goals, specifically Goal 3, "to achieve routine space travel," and Goal 4, "to enrich life on Earth through people living and working in space." These new goals imply long-term exposure to, and function in, a variety of environments with gravity levels ranging from microgravity to the gravity of Earth. One should note that with the possible exception of lunar base missions, the space missions envisioned by HEDS would still spend a substantial portion of their time under microgravity conditions, affecting not only humans but also the machines, systems, and devices needed for crewed and robotic exploration. As is described further in the next chapter, many of these systems are directly or indirectly affected by the gravity level. A fundamental understanding of the low-gravity behavior of fluids and materials is likely to be critical to the successful development and performance of such systems—both to avoid the expensive alternative of trial-and-error development and to create the knowledge base for the generation of novel designs capable of increasing efficiency and decreasing cost. No list of microgravity phenomena prepared today would be sufficient in scope and depth to describe all the challenges to be encountered in spaceflight missions in the future. However, with the goals now stipulated by HEDS, at least some of the new challenges can be considered to merit near-term microgravity research support, and strategies and programs can be developed to ensure that over time all important challenges will be discovered and addressed.

In order to understand the technology needs of HEDS, and the part to be played by microgravity research in addressing those needs, NASA will need to specify target missions for study. Two possible target missions that are often cited are a return to the Moon for an extended period of human habitation and a crewed mission to Mars.[10] Such target missions help create a focus on the specifics of the appropriate technical challenges that should drive additional scientific research and technological development. Moreover, target missions, in their accomplishment, also provide unique "laboratories" for performing additional research that could help make settlement and travel to the inner planets at least possible, if not precisely routine, in the future. Definitions of target missions should not be used, however, to constrain the scope of either basic or applied research to conform to near-term purposes, nor should the range of technology interests be limited. Indeed, the technologies in which significant resources are invested should be those that are capable of evolution and extension to meet the long-range HEDS goals of interplanetary travel. It is especially important that MRD research in support of these goals not be limited to specific targets.

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An Initial Review of Microgravity Research in Support of Human Exploration and Development of Space

3

Science and Technology Needed for HEDS: Examples from an Initial Appraisal

In this chapter, all of the goals of HEDS are considered implicitly, but only the objectives of Goal 2, the human exploration and settlement of the solar system, are dealt with directly, in part because they provide the widest range of technical challenges. This chapter introduces a series of technological systems that can easily be appreciated as important to HEDS goals. Each, in turn, is discussed in terms of the impact that microgravity is expected to have and the challenges a microgravity environment is expected to present. These discussions contain implicit parallel considerations for environments intermediate in gravitational strength between microgravity and terrestrial gravity, such as those encountered on Mars or the Moon. Implicit also is the presence of humans. Through discussions, an initial survey and appraisal can be made of the challenges that the HEDS enterprise presents to NASA and the microgravity research community. At the same time, however, it should also become clear how crucial the scientific contributions required of MRD will be to meeting the overall goals of the HEDS enterprise.

FLUID MANAGEMENT SYSTEMS

Fundamental Effects of Microgravity

In microgravity, the gravitational body force is reduced by about six orders of magnitude relative to that encountered on Earth. Perhaps the most important result of this reduction is that even the most commonplace processes in fluids no longer occur in the expected manner. Quite simply, denser portions of fluids (including both liquids and gases) no longer sink beneath less dense portions when the mixture is disturbed. In multiphase materials, such as gas-liquid, solid-liquid, or solid-gas, or in other labile materials such as fine powders or granular mixtures, buoyancy-driven forces and weight-induced stresses are reduced or virtually eliminated. In the absence of any significant gravitational force, there is of course no longer an obvious vertical reference or "down direction." Thus, liquids no longer come to rest in the bottom of a container by filling the vessel's interior shape, nor do they escape from a tipped container and spill to the floor. Inasmuch as a given volume of liquid tends to assume a minimum energy configuration (shape), the idea of what

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On Earth the motions of objects and substances often involve a balance between the force of gravity and various short-range forces such as the van der Waals attraction between particles. Since gravity is a long-range force, when it is removed from the balance, radical changes in flow patterns may result. Hence, microgravity will often affect the dynamics, statics, and stability of engineering devices and systems in ways that may be overlooked, or not understood, during the system design process. Moreover, certain forces may sometimes be masked on Earth by a strong buoyancy force but then become dominant in a reduced gravity or microgravity environment. Examples of such forces include surface or interfacial tension at fluid-fluid interfaces, colloidal or osmotic forces, electromagnetic forces, and acoustic forces. Surface capillary forces are among those that often become elevated in relative importance, and it is common in microgravity that, rather than buoyancy pressure gradients, surface tension gradients associated with temperature or concentration gradients will drive convection in liquids.[1] For processes that depend critically on having buoyancy forces present, one might consider using a surrogate force, such as electromagnetic force, to compensate for the absence of gravitational body force.

A reduction of gravitational forces also suppresses flows dependent on natural convection, such as boiling, or on relative motions (sedimentation) in multiphase materials (such as gas-liquid, solid-liquid, or solid-gas systems) where the densities of the phases are unequal. In processes involving the motion of powders or other granular materials, qualitatively different regimes of motion may be expected in such systems when they occur in a microgravity environment.

In any system that contains a material in a fluid state, the elimination (in microgravity) or partial reduction (in, say, a lunar or Martian environment) of the gravitational force implies a weakening of buoyancy-driven flows and sedimentation processes. While many ground-based systems involving fluids or materials transport processes are not critically sensitive to gravity, it is nevertheless true that many technological and biological processes are profoundly affected.

Microgravity Challenges

Many of the issues in fluid management are not unique to HEDS missions but have been of concern to engineers of orbital spacecraft for decades. Some of the engineering solutions implemented for short-duration and near-Earth missions could prove feasible for HEDS missions as well. However, a better understanding of fluid behavior in low gravity will allow a more sophisticated approach to the development of technology for fluid management. In addition to new technologies, this may result in improvements in the total mass, energy efficiency, and performance of fluid management systems currently in use.

Bulk Fluid Management

Fluid behavior in microgravity has broad implications for HEDS mission systems. These include storage systems for liquids and gases used for chemical processing and propulsion and those for human consumables; circulation systems for liquids and gases; gas-liquid mixtures, such as cooling and heating systems; systems for water and air

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purification and for waste recycling; supply systems for drinking water (such as distillation); and, finally, systems using the transfer of fluids for the purposes of thermal management. Many of these fluid management systems involve phase changes and two-phase flows, which behave differently under reduced gravity. Thus, for example, consideration is needed of the expected modification of pressure drops through piping (Figure 3.1), the management of trapped gases in liquids, suppression of cavitation in pumps, the use of capillary effects in aiding and controlling fluid transport, and the coupled management of heat flow and fluid flow for achieving efficient and reliable systems operation.

Power requirements during spaceflight missions are likely to exceed those directly obtainable from solar or thermoelectric generators. Therefore, efficient thermodynamic power cycles will be required, employing either chemical or nuclear energy. The propulsion system, the major consumer of spacecraft energy, requires propellant storage and transport systems and thermal protection and management systems—all of which will be affected by microgravity—although propulsive flows in rocket chambers and exhaust nozzles are dominated by inertial effects that overwhelm effects from reduced gravity.

For example, the lack of substantial gravity means that a stored propellant is not necessarily positioned just above the tank outlet, waiting to be transferred out through the piping system. As is well known, the liquid fuel or oxidizer instead forms free surface shapes, the equilibrium configuration and motions of which depend on the fuel tank geometry, the placement of any baffles, and the location of the vapor in the tank. During station-keeping, trajectory modifications, orbital insertions, and so forth, it is crucial that all elements of the propulsion system perform well under many combinations of attitude and acceleration. Transient influences resulting from changes in the direction and magnitude of the acceleration vectors must be understood and controlled. There is also the possibility that vibrations or accelerations arising in the course of a mission will cause sloshing modes to develop in fuel tanks, unless care is taken to prevent them. The ability to control and manipulate fluids by use of acoustic or magnetic forces will no doubt be important for management of bulk fluids under microgravity conditions.

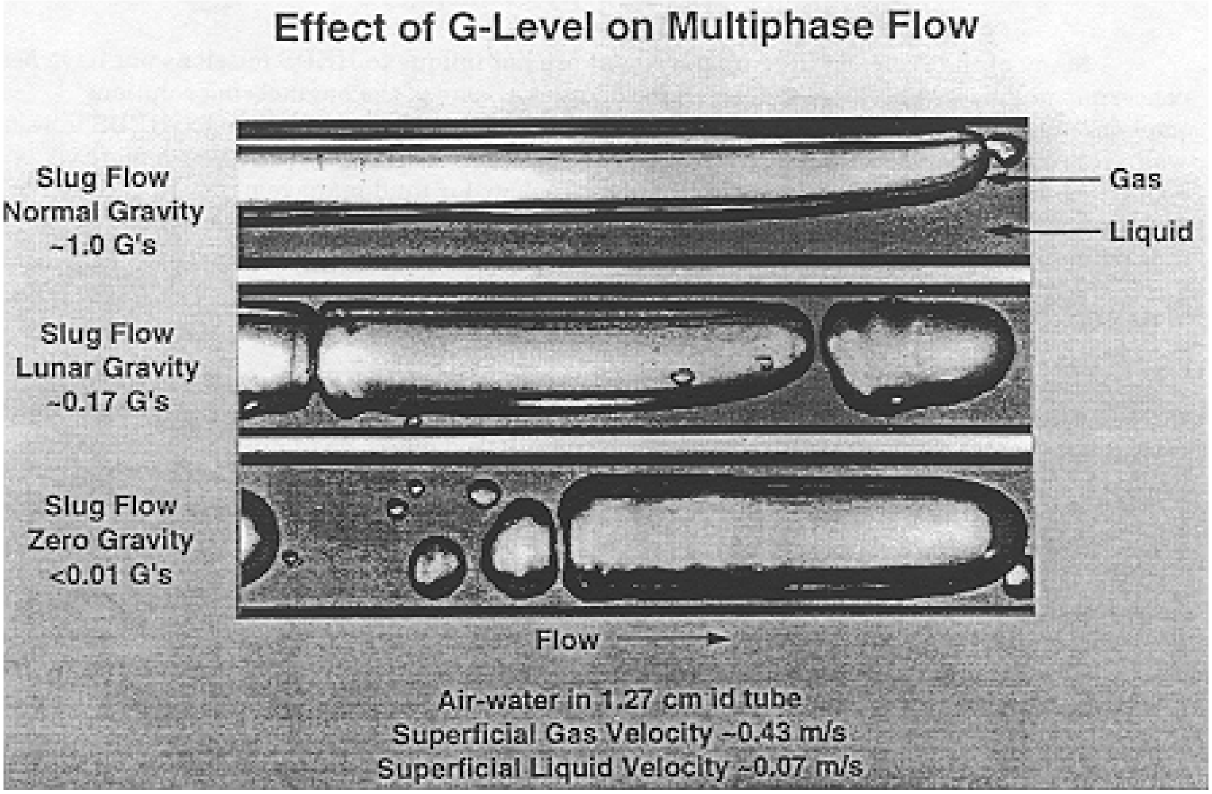

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Figure 3.1 Two-phase flow of air and water through a pipe at normal gravity (top), fractional gravity (middle), and very low gravity (bottom). (The gravity vector is directed toward the bottom of the photos.) The flow distribution of gas and liquid in two-phase systems is strongly affected by the gravity level. Currently the impact of that altered distribution on flow dynamics, heat transfer rates, and pressure drop characteristics is poorly understood. SOURCE: NASA.

Two-phase Instabilities

In microgravity, two-phase flows may exhibit technically important dynamic instabilities that would be absent in normal gravity. Nucleate boiling, propagation of density waves, and bubble and droplet dynamics are all quite different in microgravity as compared with normal gravity. For example, the behavior of multiphase systems during start-up or other transient operations clearly must depend on body force (i.e., gravity) level. The movement of particulates (important for in situ resource recovery), which might be suspended in flowing gases or liquids, will similarly show dynamic effects dependent on the presence or absence of gravity or other body forces.

Heat Transfer

A thermal management system is necessary to stabilize spacecraft environments during long-duration HEDS missions. During space transit, waste heat must be radiated to space. Fluids like Freon can be circulated through instrument panels, cabin walls, and elsewhere in the spacecraft to serve as an intermediate heat sink, collecting and then transferring heat to the space radiator. Research to extend the capabilities of "heat pipes" is clearly needed for this purpose as well. However, for high levels of heat flux, two-phase thermal control systems are generally favored, because they have lower total mass and volume than do comparable single-phase systems.[2] If the heat-carrying fluid comprises two phases, then many of the multiphase flow issues mentioned in the preceding sections apply.

Of fundamental concern for long-duration spaceflight under microgravity conditions are the freezing and thawing processes in stagnant fluid lines. Fluid lines may be either intentionally or inadvertently subjected to prolonged radiative heat loss in deep space (when shaded from Earth or the Sun) and then subjected to extended periods of solar heating.

Exchange and Separation

Special consideration of gas exchange systems is needed for oxygen recycling and for air purification. Provisions must be made for biocontainment and for quarantine in the presence of potentially hazardous or infectious agents. Separation of particulates from circulating gases and the establishment and maintenance of controlled microenvironments may be needed for many purposes aboard spacecraft and in nonterrestrial habitats.

During Earth-Mars transit (100 to 200 days each way), water and oxygen must be recycled by recovery from human waste (gas, liquid, and solid) and from fuel cells. Most terrestrial systems—biological and man-made—use buoyancy and sedimentation processes to separate gas, liquid, and particulate materials. In the microgravity environment of space, systems are needed to isolate and separate particles, liquids, and

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gases reliably and efficiently, taking into account possible alteration of biological processes. This need is a key element in the overall HEDS program, because such systems are required for environmental control, energy management, chemical processing, biological separation and isolation, and distillation and purification, and all of them must operate effectively for long periods in microgravity.

Spills

In a leak, spill, or explosion involving a liquid on Earth, the action of gravity restricts the effects of the accident to a confined area, where cleanup and repairs can be done. In space, however, a spilled liquid could be devastating, because of its unimpeded spreading along surfaces by surface tension. To restrict the spreading of liquids in arbitrary directions in reduced gravity environments (critically important for fire suppression), surface tension barriers consisting of polymeric coatings of low-surface-energy solids such as Teflon may be effective.

Flows in Fractional Gravity

Fluid flows at fractional gravity clearly require more study, with such environments as the Moon and Mars in view, and in recognition that the body force environment in HEDS missions may range from microgravity far from the Sun or planets to full Earth-gravity equivalent or greater, under conditions of acceleration. Intermediate levels of 0.16 or 0.37 Earth gravity will be experienced on the surfaces of the Moon or Mars, respectively.

During space travel, fractional gravity (relative to Earth levels) may need to be supplied deliberately by centrifuge or by general rotation of the spacecraft. Such "designed" gravity could introduce Coriolis force and gravity-gradient problems.[3] These in turn can interact with the effects of low gravity in ways that require understanding through research. For example, Coriolis forces due to spacecraft rotation could cause rotation of fluids relative to a container, and such effects should be studied in combination with anomalous fluid behavior resulting from reduced gravity alone.

MATERIALS AND STRUCTURAL SYSTEMS

Fundamental Effects of Low Gravity on Materials Processing

NASA's microgravity research on materials and materials processing attempts to explore and exploit the relationships existing among the structure, properties, and processing parameters of metals and alloys, ceramics and glasses, polymers, composites, and semiconductors. Figure 3.2 shows an example of changes in structural composition that take place in a solidifying alloy as the gravity level changes. Of particular relevance to HEDS goals are those processes in which the resultant materials properties and behavior exhibit sensitivity to, or modification by, the magnitude and direction of gravity during processing. The response to gravity in materials processing usually arises from the presence of a fluid phase, the transport properties of which become modified by flows induced by the presence of internal density gradients interacting with the molecular and gravitational body forces. Specifically, it is known[4] that solidification, crystal growth, casting,

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fusion welding, liquid-phase sintering, and containerless processing of molten materials are some of the important examples of commonplace materials processes that are influenced in major ways by gravity and would therefore be changed if carried out under nonterrestrial or microgravity conditions. For example, the energy transfer from a welding heat source to the material being welded depends on the flow state of the molten welding pool. Gravity affects the flow patterns in a welding pool and consequently alters the solidification process and changes the metallurgical structure and mechanical properties of the weld.

Another example of a materials processing technique that has been shown to be altered by microgravity processing is liquid phase sintering (LPS).[5] During the LPS of metallic alloys under microgravity conditions, the spreading of liquid along the grain boundaries and the resultant microstructural evolution have been shown to be altered.[6] Such microstructural changes are expected to affect final mechanical properties.[7] Additionally, crystal growth of compound semiconductors in microgravity has resulted in improved chemical homogeneity of the grown crystals. It has been suggested that this is due to the damping of gravitationally dependent thermosolutal convection and the resultant achievement of diffusion-controlled growth. Yet another example of the unique processing environment afforded by microgravity is in the solidification of immiscible alloys.[8,9,10,11] Under terrestrial conditions, these alloys separate upon solidification into two immiscible phases due to the density difference between phases. However, under microgravity conditions it is thought that steady-state coupled growth can be achieved, thus eliminating the undesirable phase separation in favor of an aligned microstructure. Attainment of such an aligned microstructure holds great promise for many new technologically important materials for applications such as magnetic materials, catalysts, and electrical contacts.

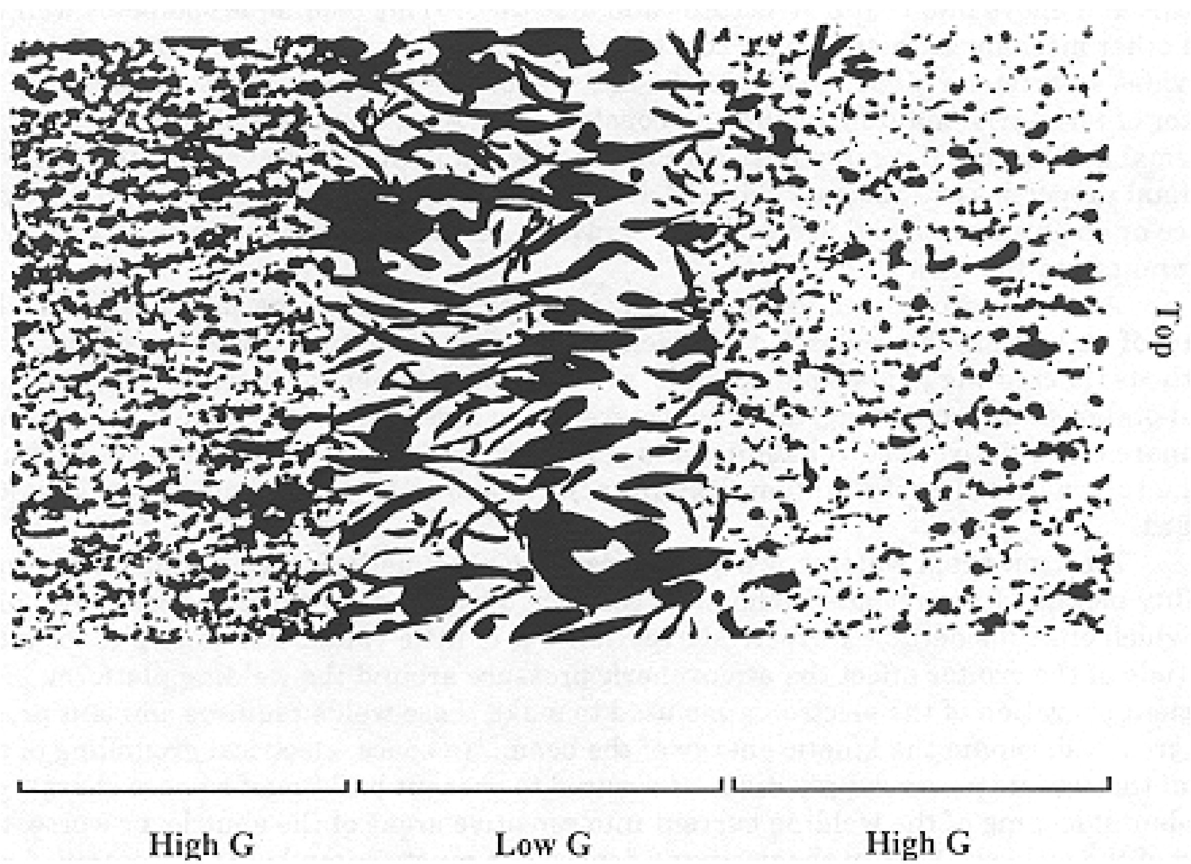

Figure 3.2 Sample of hypereutectic cast iron alloy (iron mixed with graphite carbon) directionally solidified during parabolic flight of a KC-135 aircraft. During the high-g portion of the trajectory, the solid forms at the eutectic composition (about 5% graphite) with a uniform distribution of graphite flakes or nodules, and the excess graphite floats to the top. This excess is captured during the low-*g* portion of the trajectory, demonstrating that it is possible to greatly increase the volume fraction of the second phase material by processing off-eutectic compositions in microgravity. The mechanical properties of the alloy are determined

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largely by the morphology of the graphite particles. SOURCE: NASA.

Microgravity Challenges

The construction and deployment of materials for safe human habitats and space platforms require (1) the processing of materials under nonterrestrial gravity into structural elements, such as beams, columns, trusses, and shells, and (2) integrating these elements into useful structural systems.

Welding

Welding is an example of a materials processing technique that will be critical to the creation of reliable joints in space. Fusion arc welding, in particular, is an important technique for joining metals and alloys into useful structures and machines. This technique competes well with riveting and other mechanical fasteners for construction from steel on Earth. Moreover, fusion welding provides a particularly good example of a mature joining process, because it is used in virtually every sector of terrestrial manufacturing and construction. Also, fusion welds permit retention of good thermal and electrical conductivity through seams and joints. However, parameters for achieving optimal properties of a fusion weldment are expected to change when the process is conducted in space or on extraterrestrial bodies, where gravity and atmospheric pressure and composition are different from those on Earth.

Arc or electron-beam fusion welding in space may prove especially desirable when permanent joints of high strength are desired between identical or compatible alloys. In addition, competing methods for creating joints—for example, preassembled self-erecting joints, mechanical fasteners, solid-state welding, or gluing, all of which are insensitive to gravity—should be assessed and compared for relative cost, reliability, and safety. Experience gained during the orbital construction of the International Space Station (ISS) over the next 5 to 10 years should prove invaluable in this regard.

Electron-beam welding is a sophisticated joining method, used primarily for making high-quality metallic fusion bonds. When it is conducted in space, however, several novel problems arise for which our considerable terrestrial experience is of little value. For example, the altitude and attitude of the orbiter affect the atmospheric pressure around the welding platform. Safe and efficient operation of the electron guns used to make these welds requires ambient pressures that do not greatly dissipate the kinetic energy of the beam. In space, electrical grounding of the welding beam through its power supply must be assured to prevent buildup of a space charge, or perhaps the accidental looping of the welding current into sensitive areas of the shuttle, or worse, through the body of the welder. Also, in the vacuum of space one must contend with uncontained rapid evaporation and sputtering of certain metallic components released during welding, such as magnesium and zinc from aerostructural alloys and chromium from stainless steels. The evaporated metal atoms tend to follow line-of-flight trajectories and redeposit upon striking a cool surface. Such redeposited metal films or coatings must be controlled carefully by physical shielding to prevent inadvertent damage to optical windows, electrical insulators, sensitive mechanical devices, antennas, and, of course, the astronauts themselves. Finally, while in orbit, without Earth's gravity acting to provide normal hydrostatic forces and buoyancy, a solidifying weld pool can become sensitive to thermocapillary effects induced by the severe

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thermal gradients attending fusion welding, to environmental vibrations, and perhaps even to other mechanical disturbances such as sudden releases of gas. All these microgravity effects can influence the quality and performance of welds in ways that are not currently predictable. The interactions of metallurgical variables with the appropriate welding parameters needed for successful welding in space are still poorly understood in general and are not known for specific cases of interest. Microgravity research directed toward this important joining technology would be of value to future HEDS missions that might rely on fusion welding methods for cutting and joining of metallic materials.

Structures

Nonmetallic materials that cannot be welded into useful structures will also be used in HEDS missions. Systems using composite members are likely to be fabricated using fasteners, polymeric adhesives, or both. These joining methods for nonmetallics, though less sensitive to the gravitational level, still respond sensitively to environmental factors encountered in space or on extraterrestrial bodies. To be specific, the durability, viscoelastic aging, and overall mechanical reliability of curable, organic-polymer joints must be assessed before serious consideration can be given to their use for long-term structural service in space or in nonterrestrial applications. These concerns arise for organics, especially in service applications where intense ultraviolet radiation is encountered or where energetic fluxes of atomic oxygen occur. Reliability assessments based on exposure to accelerated high-fluence radiation and oxygen or on natural long-duration exposure to the actual space environment should be contemplated early enough in the development of HEDS missions to construct engineering databases on joint performance and aging.

Erecting structures in space or in extraterrestrial settings might also involve the use of new technologies for creating the materials themselves, either terrestrially or from in situ sources. Examples could include construction from lunar materials and use of recycled metallic materials. Techniques must be developed, or adapted, for positioning these materials as structural components and finally joining them in space. (See also the section "In Situ Resource Utilization" below.)

BIOTECHNOLOGY ASPECTS OF LIFE SUPPORT

In a preliminary survey of the goals of the HEDS enterprise, the committee identified two areas currently supported in MRD's biotechnology discipline that have special relevance to space exploration and settlement. These are cell cultures and bioseparations. In the discussions below, culturing of cells is further divided into two categories, reflecting different areas of impact: (1) mammalian cell and tissue culturing and (2) microbial and plant cell culturing.

Fundamental Effects of Microgravity

The many and varied effects of microgravity on biological systems and biological processes are incompletely known. For certain microgravity effects that have been identified, it is suspected that fluid physics and transport processes are the root causes. For

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example, the culturing of mammalian cellular aggregates is enhanced in the low-shear-force environments possible in microgravity and emulated in bioreactor devices. In another example, the resolution of electrophoretic separations is limited by density-driven thermal convection and sedimentation. But many effects of microgravity on biological systems are not well-enough characterized to be understood in terms of fundamental gravitational properties. As the challenges presented by microgravity are appraised below, some of the hypotheses relating to influences of fundamental effects are described further.

Microgravity Challenges

Mammalian Cell and Tissue Culture

Biological systems exhibit many variations in function in microgravity environments. Well-documented effects on the human body from relatively short-term exposure to microgravity include such problems as loss of muscle mass, reduction of bone density, fluid shift to the upper body, and diminished immune responses. Tissues and organs, which are composed of multiple cell types, have evolved mechanisms for adapting their activity to gravity, for example, using gravity to help manage the distribution and movement of fluid required to maintain proper physiological function. It is expected that, in the absence of gravity, these systems can become imbalanced and suffer the deleterious effects that have been observed. Microgravity effects that alter fluid properties may possibly influence such processes as the interaction of cells with extracellular matrices, cell attachment and adherence, cell-to-cell communication, and the efficiency of transport of molecules through cell membranes. A number of effects of short-term exposure on cells and cell processes have been noted, such as the over expression of proto-oncogenes[12] and decreased mitogenic response of lymphocytes,[13] and have raised concerns; the effects of long-term exposure to microgravity or to fractional gravity, expressed through many generations of cells in which the gravitational environment may act as a selection pressure, are largely unknown. Experimental studies of the effects on cell cultures of long-term exposure to microgravity represent a potentially important new area of microgravity research.

The medical complications that face astronauts will be caused in large part by alterations in cell and tissue function as a result of the microgravity environment. Some of these processes may be elucidated by analysis of basic cell and tissue function in microgravity or in tissue-culturing devices, such as the bioreactor, that mimic some aspects of microgravity. Endothelial cell proliferation, platelet adherence, and secretory function are just a few of the cellular processes that may become altered by shear stress effects in the bioreactor and thus need to be examined in microgravity. Without a more complete understanding of these basic processes in reduced gravity, anticipation of life-support needs, and the ability to design systems to meet those needs, will be exceedingly difficult. While the Life Sciences Division (LSD) maintains the primary responsibility for medical research within NASA, it is likely that some of the mechanisms and techniques employed to protect astronauts' health in the future will be the direct results and developments of research sponsored, perhaps jointly with the LSD, by MRD. A component of that research should be targeted to characterize the effects of gravity, and the lack thereof, on basic cell and tissue systems and on organelles. In the broadest sense, with the knowledge provided by this research, the biological effects of microgravity can at least be anticipated and perhaps even countered at the multicellular or tissue level.

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Microbial and Plant Cell Culture

Another area of biotechnology important to the success of NASA's HEDS goals is the culturing of useful microorganisms in microgravity and extraterrestrial environments. This specialized area of cell culturing may be important to the production of nutrients, waste recycling, and maintenance of closed or partially closed environments. Yeasts and bacteria rely for growth on the gas exchange that occurs at liquid-air interfaces. Microgravity-induced effects can alter the nature of these interfaces, and, as a result, systems used for the culturing of microorganisms and the recovery of their products are likely to function differently. A recent NRC report provides a more detailed discussion of cell culture challenges in the context of advanced life support.[14]

The use of microorganisms as sources for food remains largely unexplored at present. Fail-safe operations could entail storage of desiccated yeast and other products capable of reestablishment of proliferating organisms at the time of use. This storage and regeneration technology has not been sufficiently investigated to be relied on for fail-safe operations on a spacecraft. A similar reservation applies, to a lesser extent, to plant culture technology, where seed stocks may obviate concerns about reestablishment if cultures fail at any point. Finally, in addition to sources for production of food, nonnutrient biotechnical products such as therapeutic agents with limited shelf life may eventually be required during extended space travel.

A significant role for microgravity research may exist in helping to provide the scientific understanding required to learn how to maintain an environment suitable for on-board human activities over the course of extended excursions into deep space. Technology for maintenance of the atmosphere is key, involving recycling of atmospheric gases, removal or dilution of waste gases and contaminants, and replenishment with appropriate levels of vital components. Generation of oxygen, removal of carbon dioxide, and removal of contaminants, for example, are vital processes, some of which could be carried out by appropriate microbial, cell, and plant cultures. Such uses of cell cultures will require the development of appropriate closed culture vessels with controlled atmospheric conditions that can guarantee the long-term survival and functioning of microorganisms. In such culture systems, gravity can no longer drive the separation and coalescence of liquids and gases to form an interface between phases. Solving the problems of fluid phase separations and fluid handling required to support such culture systems represents a significant technological challenge.

Safety issues relating to the containment of microbial cultures must also be addressed. Because some of the microorganisms might themselves have adverse effects if not isolated from the human habitat, biocontainment must be maintained in a fail-safe manner. A variety of related questions must be answered if microbial culture systems are to be relied on as a technical means for life support under microgravity conditions, and many of these questions concern the direct and indirect influences of microgravity.

Knowledge and experience are lacking about the use of microorganisms and other cells in culture for recycling, for biological product formation, and as sources of food for humans. More effort to design an integrated environment for recycling of waste materials and generation of needed gases and nutrients would be worthwhile as a step toward designing for the relatively more closed operations needed in challenging environments such as those in space, where reliable exchange of nutrients and waste with an outside environment is difficult or impossible. Some of the needed knowledge and experience may already have been accumulated in the design and operation of large enclosed systems,

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such as submarines and Biosphere II, and may be of help in the design and operation of closed systems required for space travel and habitation. Clearly, maintenance of an active space station will add to the knowledge and experience applicable to operation and maintenance of a relatively closed system in near-Earth orbit. But these experiments with relatively closed systems can only approximate the rigors envisioned for deep-space travel, and experience with closed systems that better simulate the challenges of space travel is also needed.

Bioseparations

The ability to separate desired nutrients or other components from the bulk secretions of microorganisms in culture is also likely to be a requirement for successful waste recycling and the reliable production of food and nutrients. The design and assembly of reliable, fail-safe separation systems, will, for example, involve containment and transport of fluids and solids, a kind of microgravity biochemical engineering that provides an integration of cell culture and the biochemical separation techniques for the manufacture of nutrients. It is possible to do this kind of integration relatively routinely at 1 *g*, but not necessarily in microgravity, where flows are significantly different. Nevertheless, such processes may be relied on to separate nutrients from waste or toxics and should be considered an important technological area for support of crewed space missions of extended duration.

Essentially all of the prior research on separations in microgravity had as a goal the harnessing of the unique attributes of microgravity to achieve separations that appeared impossible and of high value on Earth. These efforts support HEDS Goal 1 but provide little help in accomplishing other HEDS goals. Bioseparation applications in support of the exploration goals of HEDS would require the reliable functioning in space of those separation techniques that are now dependable and predictable on Earth. This redefinition of bioseparation needs represents a change of mind-set for research on microgravity effects on biological separations and, it should be noted, is a redefinition that characterizes research on microgravity effects on cell culture before and after HEDS as well. In sum, although there has been considerable past research on cell culture and bioseparations in microgravity, some key research areas remain to be explored in support of NASA's HEDS goals.

Current MRD Biotechnology Research Applicable to HEDS

MRD supports biotechnology research in several of the areas identified in the previous section as having benefits for HEDS. Currently, cell culture studies are being carried out in terrestrial bioreactor devices to examine basic mammalian cell function. These research programs address cellular processes and growth requirements under rotating gravity-vector conditions.[15,16] However, much remains unknown, and the differences between bioreactor-emulated and true microgravity conditions have yet to be explored. Support for development of the rotating-wall, perfused-vessel bioreactor continues at MRD. Current studies of cultured cells in the bioreactor system have shown that the size of cellular aggregates, which may form by a process analogous to the multicellular aggregation that forms tissues and organs, is limited by the ability of nutrients and gases to reach cells near the center of the cell mass. Whether this phenomenon will occur in true microgravity is unknown.

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Studies of electrophoretic separation of cells and particles and analyses of electrophoretic technologies are currently supported by MRD, and these begin to address fundamental differences in the behavior of separation systems in microgravity. Future developments targeted by MRD that relate to the HEDS mission include research that would support development of subsystems for optimization of media and nutrient supply and replenishment, sensors for monitoring and controlling cell and tissue metabolism, and cell and tissue oxygenation and waste-gas removal. Projected areas of study also include development of long-term storage systems for cells and biospecimens, as well as alternative systems for culturing mammalian cells and tissues in space.

SPACE NAVIGATION

Some of the current research efforts funded by MRD's fundamental physics program, on the basic aspects of the behavior of matter under microgravity conditions, are directly relevant to the area of navigational systems for deep-space travel. This part of the MRD research program is supported under the first goal of the HEDS enterprise, that is, to increase knowledge of the role of gravity in nature by using the space environment, but it also has applications to other HEDS goals.

An example of an important area within the fundamental physics program is that of laser cooling and the development of microgravity atomic clocks. This area of atomic physics research will prove to be relevant to certain near-term goals of the HEDS enterprise, specifically, improving the accuracy and reliability of spaceflight navigational systems through improved time and frequency standards. At present, atomic clocks provide the primary time and frequency standards required for spacecraft navigation. Fundamental restrictions on the accuracy of all atomic clocks follow from the Heisenberg uncertainty principle, which is the law of quantum physics that couples the observation time of atomic transitions to the uncertainty in the measured frequency of the emitted photons. The longer the time of observations, the greater is the precision to which the atomic transition energies can be determined, and consequently, the better is the frequency known. Most atomic clocks use electronic quantum transitions in either cesium or rubidium atoms in the form of a dilute vapor. Perturbing effects that degrade the performance of quantum oscillators arise from wall collisions, stray radiation, and the influence of containment forces required when an atom trap is used to cool and localize the atom. The development of an atomic clock that could operate under the stable free-fall conditions of a microgravity environment, thereby avoiding wall and container effects, would allow a large increase in the observation time of the atomic oscillations. Increasing the time of observation during free fall permits, through the Heisenberg uncertainty principle, a commensurate increase (by several orders of magnitude) in the frequency stability of the atomic clock system, which is well beyond that achieved for Earth-bound clocks (about 1 part in 10^{13}). The combined errors of the atomic clocks operating both on the tracking and data relay satellites and on the spacecraft being guided limit the precision to which the position and speed of a craft can be calculated. Errors accumulated over lengthy missions covering tens of millions of miles can be reduced with better clocks on board, thereby requiring fewer navigational fixes and thruster corrections.

Recent developments in atom cooling using lasers, which were anticipated in the NRC report *Microgravity Research Opportunities for the 1990s*,[17] now promise frequency standards and atomic clocks with stabilities that are several orders of magnitude better than

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what is currently possible on Earth. The determination of local position and velocity, as is required for all space navigation, relies heavily on precise time and frequency standards, and a significant improvement in this area will provide an immediate benefit to the safety and efficiency of human and robotic exploration of space.

FIRE SAFETY

Fundamental Effects of Low Gravity on Combustion Processes

Several important combustion phenomena are influenced strongly by buoyancy because of large density differences that appear at 1 *g*. These include mixture flammability, combustion instability, gaseous diffusion flames, droplet combustion, particle-cloud combustion, smoldering, and flame spread.[18,19,20] The importance of these combustion phenomena to NASA's HEDS missions stems largely either from their importance with respect to fire safety and reliability of systems operations during space travel or from their relevance to the production of chemical species and new materials. The latter concerns combustion carried out safely and efficiently in environments to be encountered in the exploration and habitation of the Moon and planets. The combustion processes that are most significant to HEDS goals are discussed below with special emphasis on fire safety, and the impact of reduced gravity on those processes is described.

Flammability Limits

Fuel-air mixtures exhibit lean and rich flammability limits on Earth, with the limits for upward propagating flames being wider than for downward propagating flames. These limits represent the minimum and maximum fuel concentrations, respectively, at which flame propagation, at a finite speed, occurs. Outside these limits, flames fail to propagate at all, such that the propagation speed at a limit is finite on Earth. At reduced gravity it is possible for the limits to be outside of the normal-gravity limits, thus increasing potential flammability hazards.[21,22] This can require special fire safety considerations at reduced gravity.

At one time, because flammability limits were thought by some to exist only because of the influence of gravity, it was suggested that flammability limits at zero gravity would not exist and that the flame propagation speed would approach zero smoothly as either the fuel or oxidizer concentration was continually decreased. However, flammability limits at reduced gravity have been found to exist and are hypothesized to occur because of the enhanced influence of radiative losses at reduced gravity along with the effects of chemical kinetics.[23]

Near-limit premixed flames at reduced gravity exhibit unusual behaviors not observed at normal gravity.[24] For highly diffusive fuels, spherically expanding flames propagate and then extinguish. The extinction occurs as a result of enhanced radiative loss and reduced effects of flame stretch as the flame radius increases, flame stretch embodying the effects on flame propagation of flow nonuniformity and flame curvature, neither of which is present in classical, one-dimensional, planar flames.[25] Under certain circumstances, stationary spherical flames, or "flame balls," have been observed. Flame balls require radiative heat losses for their stability and are "convectionless," so that the

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likelihood of their occurrence is decreased at normal gravity because of the presence of natural convective flow.[26,27]

Flame-front instability, resulting in flames with nonsmooth surfaces that contain cellular structures, is due to heat and mass diffusional processes and hydrodynamic and buoyancy effects that shape upward propagating flames. With buoyancy absent, a strong influence on flame-front instability in near-limit flames is removed, making the remaining effects dominant and allowing for the near-limit phenomena (such as flame balls) observed in reduced gravity.[28] Phenomena of this kind affect evaluations of fire safety.

Diffusion Flames

In gas-jet diffusion flames, in which the flame is formed from a jet of gaseous fuel issuing from a burner tube into an oxidizer, buoyancy is almost always important. The flame stabilizes near the burner rim, and because buoyancy influences the flow speed there, reduction of buoyancy affects the stabilization mechanism. Laminar flames are wider in reduced gravity than in normal gravity and can generate more soot; additionally, radiation losses increase, and consequently, flame temperatures decrease.[29] Diffusion flames surrounding stationary liquid fuel droplets become more spherical in the absence of gravity and instability, mirroring the configuration employed in classical quasi-steady droplet-burning theory, in which the square of the droplet diameter decreases linearly with time, and the ratio of the flame diameter to the droplet diameter is independent of time. But at reduced gravity, unsteady effects, including those caused by fuel vapor accumulation near the droplet surface, are observed in which burning rates and flame diameters initially increase with time, contrary to classical theory.[30] These modifications in the behavior of diffusion flames revise considerations of fire safety problems in space.

Smoldering

Smoldering combustion—the slow surface oxidation of a combustible solid—has practical ramifications with respect to safety considerations. In normal gravity, buoyancy enhances oxygen transport to, and product removal from, the reacting surface. In reduced gravity, this transport mechanism is absent. Results to date show that carbon monoxide production in smoldering combustion is enhanced substantially in reduced gravity under suitable conditions.[31] Findings of this kind are relevant to determination of fire hazards of many different solid materials and technological components encountered in HEDS.

Flame Spreading

Flame spreading over solid and liquid surfaces has direct implications with respect to fire safety and materials selection. Flame spreading can be classified as involving either opposed or concurrent flow, depending on whether the air flows counter to or in the direction of flame propagation. Upward flame spread in normal gravity is concurrent and tends to be acceleratory. Opposed-flow spread allows a steady spread to develop. In the absence of a wind, flame spread at reduced gravity tends to be of the opposed-flow type.[32] In opposed-flow flame spread, flame extinction occurs at high velocities as a result of kinetic effects and flame blowoff. Flame extinction has also been found or predicted to occur at low velocities in reduced-gravity quiescent environments through radiation-loss

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effects, suppressed in normal gravity by buoyancy-induced flow.[33] These influences of gravity on limiting conditions for flame spread need to be considered in evaluating fire dangers.

Microgravity Challenges

In terms of fire safety, Earth is a hospitable environment for humans, permitting them fire protection in inhabited structures by allowing safe and rapid egress for escape. The external environments encountered by humans exploring space simply do not afford sanctuary, and so egress no longer is a viable protection measure. Careful attention therefore needs to be paid to the selection of materials and module environments for fire prevention and to robust methods for fire detection and suppression in reduced gravity.

Fire-safety detection systems, originally designed for terrestrial applications where buoyancy is present, such as smoke detectors, need rethinking when used in spacecraft. Technologies are needed that either are fundamentally different from those usually used on Earth, such as radiation sensors, or are novel applications of existing terrestrial technologies, as in the use of forced ventilation for environment throughput, such as opposed buoyancy-driven flows for Earth-bound smoke detectors. Fire suppression systems, moreover, must not produce end products that are toxic to humans, as may occur with halon extinguishers, and they must not produce situations that potentially could initiate additional safety concerns, such as liquid invasion of electrical systems.

Although the human respiratory system responds to the partial pressure of oxygen, fires respond to the concentration of oxygen. Small reductions in oxygen partial pressures, and small increases in partial pressures of nitrogen or other inert gases, have surprisingly large influences in reducing flammability and improving fire safety. Attention must be given to how reduced gravity affects the extent of improvement that can be achieved by atmosphere adjustment and to the intersections between fire safety and other aspects of life support and of human well-being. Designs of space vehicles and extraterrestrial structures must address tradeoffs in these areas. Selection of materials for construction and for interior use similarly require consideration of fire safety. Continuing microgravity combustion investigations can provide added information relevant to such selections and to general improvement of fire safety for HEDS.

IN SITU RESOURCE UTILIZATION

Fundamental Effects of Low Gravity on Materials and Chemical Processing

In the absence of large pumping systems, gravity controls the maximum transport rates in fluids, even though its influence on chemical thermodynamic properties is negligible. The modifications of materials and chemical processes induced by changes in the gravitational acceleration have little to do, per se, with the interactions between the gravity field and the controlling thermodynamic properties, such as the chemical potentials or intermolecular forces. Instead, it is the gravitationally mediated modifications of fluid-phase transport processes (both thermal and solutal) that are directly responsible for any

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changes observed in the process kinetics. At the quasi-static microgravity acceleration levels encountered typically in low-Earth orbit, most buoyancy-induced convection currents virtually cease. The near elimination of such flows severely diminishes convective momentum and any associated heat and mass transport and thereby restricts the process of energy transport and mixing in fluids to molecular diffusion, thereby limiting the useful energy transfer modes to pure thermal conduction and radiation.

The large reduction of buoyancy forces experienced in microgravity environments can also cause fluid systems to exhibit unusual behaviors governed by the emergence, and even dominance, of weak "secondary" molecular forces, such as the surface tension, thermo-capillary, or Marangoni forces, and van der Waals interactions. These weaker forces are ordinarily overshadowed by much stronger buoyancy forces. Thus, it is not surprising that the kinetic behavior of most fluid-based materials and chemical processes operating in microgravity, or in the reduced gravity levels found on nonterrestrial bodies, might be changed from that expected or experienced under terrestrial conditions. As a result, one might expect some modification of the physical and chemical characteristics of the materials produced by any process in which heat and mass transport is altered by reduced gravity.

Microgravity Challenges

Resource Materials

Extended stays by astronauts in deep space, on the lunar surface, or on Mars, will require at least occasional access to certain bulk materials for (1) life support, (2) basic habitat, (3) energy production, and (4) radiation protection. The use of local materials, if available in situ, could eliminate at least some of the energy penalty and attendant high costs of transporting bulk materials from the surface of Earth to space, or to some distant extraterrestrial body. Initially, in situ resource utilization (ISRU) will incorporate systems that process simple molecules, such as water and carbon dioxide, for the production of oxygen and fuel. More complex materials will be required in order to quickly evolve an infrastructure. Those materials range from simple radiation shields and road-building materials through locally derived structural elements requiring raw material identification, beneficiation, and processing prior to the manufacture of finished products. More complex materials needed for construction and habitat, which also tend to be massive, offer major opportunities and efficiencies for ISRU. The full gamut of materials production must therefore be analyzed in the context of the known parameters of the extraterrestrial environment, including gravity. Basic materials production processes such as slip casting of ceramics and sintering of "green" compacted powder forms to create basic shapes like bricks, blocks, plates, and shells, as well as ordinary manufacturing operations, will all be influenced to some extent by the altered force of gravity. Even routine machining processes like cutting, drilling, shaping, and grinding need to be analyzed in detail to identify and anticipate all the effects introduced by specific extraterrestrial environmental parameters, such as reduced gravity.

In near-Earth space, the recovery and utilization of orbital debris as an extraterrestrial resource should be studied by NASA planners from the perspective of reducing the potential long-term hazard to the International Space Station and for developing the methodologies that will be required to intercept and steer Earth-crossing asteroids and comets that may threaten Earth. The ability to rendezvous with and

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manipulate materials on surfaces of objects with virtually no gravity can be evolved more systematically and at lower cost by concentrating on processing orbiting objects like the Soviet C-1B booster,[34] which have known shapes and compositions, rather than by developing resource utilization systems for comets and asteroids of opportunity.

Energy Production for In Situ Resource Utilization

The types of power systems used for ISRU will be, to a great extent, determined by the quantity and quality of energy available on the lunar and planetary locations being inhabited. Thermoelectric or solar generators may not suffice in satisfying this energy need, in part because of either their intermittent availability, power capacity, or size. Larger energy systems, heretofore restricted to terrestrial applications, will need to be engineered and deployed for HEDS missions. Nuclear reactor systems can be developed that are nearly inert during the launch and landing phases of interplanetary travel and that can provide appropriate levels of thermal and electrical power on demand. The possibility of environmental contamination nevertheless must be addressed at both ends of the missions, and the unique requirements associated with reduced gravitation must be delineated. For example, certain fission reactors require for their operation a heat-exchange fluid that is circulated by natural convection, which would not be available in microgravity and which probably would not be effective in lunar and planetary gravity.

It is possible that the Rankine (phase change) cycle, being relatively efficient, will find applications in providing space power, perhaps in conjunction with nuclear power generators. Equipment for the Rankine cycle abounds, by definition, in liquid-vapor interfaces (e.g., boilers, vapor collectors, condensers), all of which will present special operating problems in microgravity or even fractional Earth gravity.

Energy Storage

Production and storage of extraterrestrial resources, and ultimately space colonization, will depend critically on energy management and storage. Electric power will be limited and can be highly intermittent and variable in the case of solar electric power generation on the Moon or Mars. The electric power levels required for resource processing and storage nearly always translate to requirements for very large solar arrays with associated battery or fuel cell systems that can store electrical energy for nighttime operation. Those arrays and their associated energy storage systems introduce significant problems associated with deployment and operation, particularly in reduced gravity or microgravity conditions. Therefore, the nuclear power generator and solar power satellite options become attractive because of their ability to provide nearly continuous electric power on demand while avoiding many of the surface deployment and energy storage problems. The ability to store and recover energy efficiently, in response to actual power requirements, is an important concern for HEDS missions. Chemical batteries are used to store energy in the kilowatt-hour range, but they are supplanted by fuel cells and other devices when the energy storage requirements go much beyond a few kilowatt-hours. The most common terrestrial means for achieving massive energy storage utilizes water that is pumped against gravity, producing recoverable potential energy. Potential energy storage is not available in space and does not offer attractive opportunities on the Moon or Mars. Furthermore, kinetic energy storage systems introduce additional hazards when large quantities of energy are involved. In reduced gravity, energy stored either via fluid heat capacity or phase change appears to be the most attractive approach in terms of size,

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reliability, and safety. Those system designs, along with thermal control systems, are influenced strongly by alterations in the heat and mass transfer processes in reduced gravity.

Impacts on HEDS Goals

The process for extracting oxygen from the Martian atmosphere is now understood sufficiently well to have been demonstrated in terrestrial laboratories.[35] The converting of locally available atmospheric carbon dioxide into oxygen, for example, depends on an overall process design that is beginning to be shaped by higher-order questions related to the influence on thermal and chemical processes of the reduced gravity encountered on the Martian surface. The extraction of carbon monoxide from the Martian atmosphere, the production of methane using the Martian atmosphere, and in situ water recovery are less well developed chemical processes but are still well within current technological capabilities. Furthermore, the thermochemical processes needed for realizing these Mars-based systems are remarkably similar to those processes that may be employed for advanced life-support systems that will be used on the forthcoming ISS.[36] The study of the influences of microgravity on system and subsystem behavior, as well as the overall reliability, controllability, and autonomy of system designs for HEDS exploration, can be addressed uniquely by testing and development on the ISS.

Extraction of oxygen from lunar materials (see Figure 3.3) is a process that has been studied in sufficient detail to identify some of the major fundamental questions concerned with the manipulation of solid materials in environments exhibiting reduced gravity and high vacuum. The ISRU processes that can be used to produce oxygen on the Moon include electrolysis of silicate/oxide melts[37] and pyrolysis of lunar regolith[38] (soil), which use raw materials that are not site dependent but require large quantities of energy per unit mass of oxygen. Systems that collect and concentrate lunar ilmenite ($FeTiO_3$), which is found in abundance in surface fines in some areas and which is relatively easy to reduce to oxygen, require less energy and may be more attractive.[39,40]

Water has been predicted to exist in permanently shadowed regions near the lunar poles,[41] and the recent Clementine radar measurements[42] taken in permanently shadowed polar craters suggest that significant quantities of water ice may have accumulated from comet impacts during the last several million years. Obviously, oxygen and hydrogen can be produced from these polar ice deposits if they can be authenticated, and systems can be designed to extract and electrolyze water. Solar-wind-derived hydrogen and helium-3 can also be extracted from lunar fines, but those systems require machinery that can acquire huge quantities of lunar fines and extract thermally those volatile gas molecules that have mass concentrations typically in the parts per billion range.[43]

Mars offers a wide range of in situ resource materials including water; photographic evidence suggests that a liquid-water-driven climate existed previously. At this time, water can be extracted from the Martian atmosphere,[44] or it can be processed directly from polar ice (Figure 3.4) deposits.[45] In addition, spacecraft-derived data suggest that water is still available over much of the surface in the form of permafrost, which can be processed.[46]

The evolution of technologies in support of ISRU on Mars has moved from the

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earlier concepts of mining relatively unknown mixtures of near-surface materials to the more recent recognition that simple water and carbon dioxide molecules are actually preferred feedstock materials for early application of ISRU systems. Those molecules are also available as waste or by-products from energy production and from other human and biological activities that will occur on the ISS. Furthermore, in support of the HEDS enterprise, it must be recognized that a crewed mission to Mars will occur primarily in the microgravity environment imposed during the long journeys from Earth to Mars. Hence, the ability to use ISS as a test bed to develop extremely reliable autonomous systems for processing or recovering simple molecules represents a unique opportunity to develop advanced waste recycling and life-support systems that translate directly into early resource utilization systems.

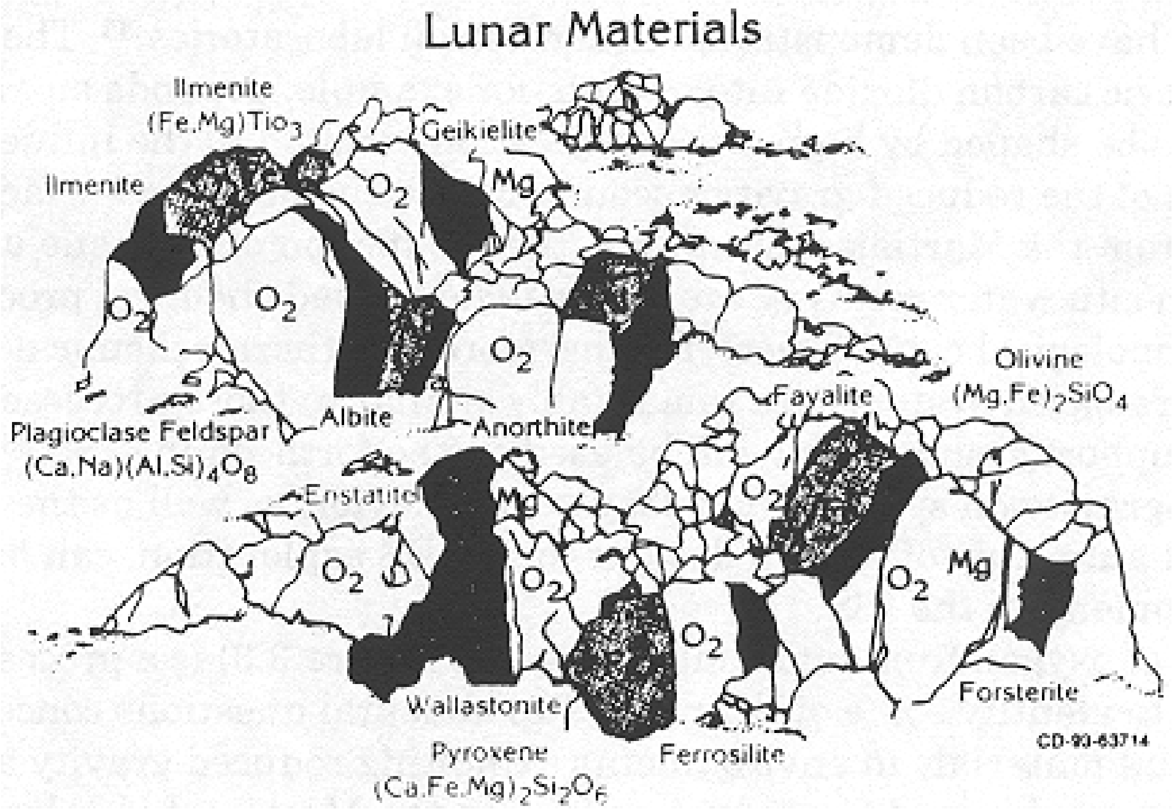

Figure 3.3 O_2, Si, Al, Fe, Mg, and Ti are all prevalent on the moon but are chemically bound into various metals. In order to isolate any of these elements, mining, beneficiating, and processing steps are required. And not all minerals and elements are found everywhere. For example, the anorthositic mineral (a type of plagioclase feldspar), which contains most of the lunar aluminum, is found mostly in the lunar highlands. Conversely, the ilmenite minerals, which have a high concentration of iron, are predominantly in the lowlands, or mare, regions. SOURCE: NASA.

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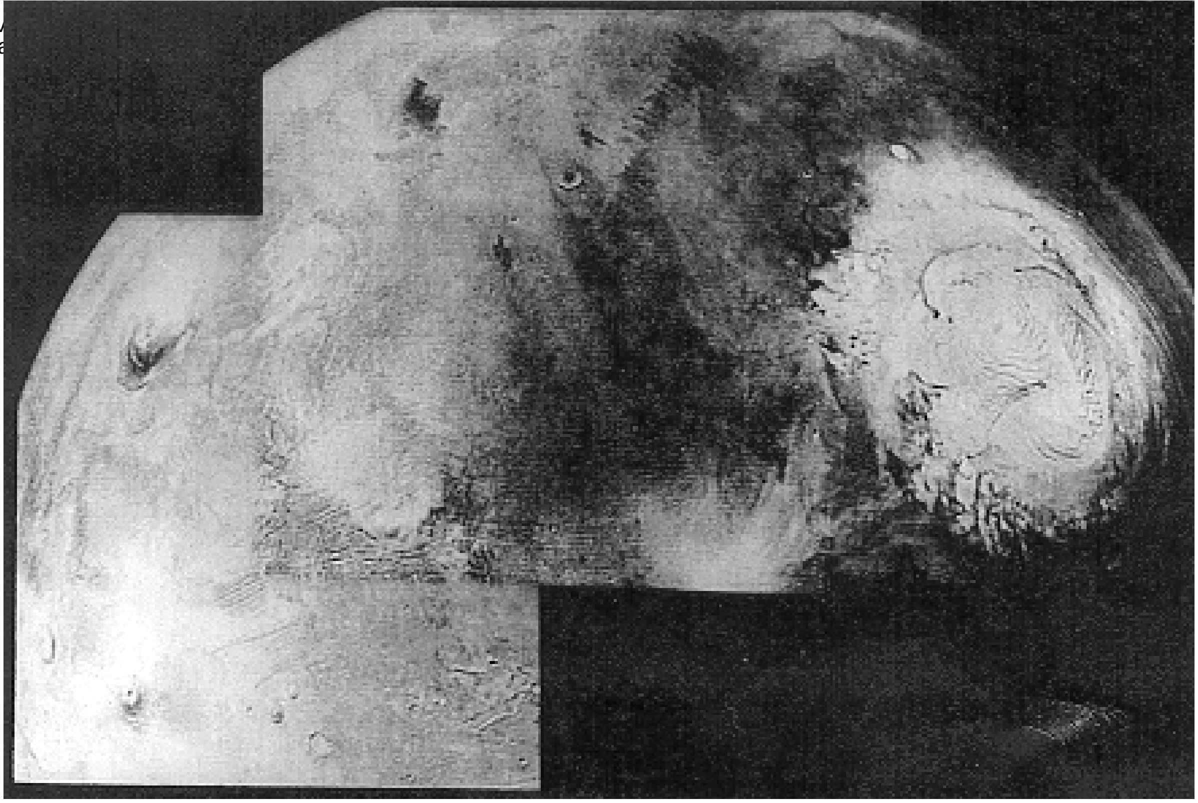

Figure 3.4 Viking photograph of water ice cap at Mars' North Pole. SOURCE: NASA.

Relevance of Current MRD Research

Current MRD materials-related research is directed toward understanding fundamental processes associated with the formation of crystals and alloys in microgravity, and this experience will be useful in developing ISRU programs. In fact, MRD has recently recognized the importance of this area by calling for proposals on in situ resource development as part of the materials science NRA.[47] Some elements of that research, especially those associated with solidification and transport processes, could be used directly in the design of in situ resource processing systems associated with microgravity environments—particularly for the production of materials for use in orbit.

Near-term ISRU systems are also being addressed, to a limited extent, via the systematic study of fundamental fluid synthesis and transport processes in fractional and microgravity environments. Issues associated with phase separation and particle removal are being addressed, but they will probably require more direct connections with those practical processes, such as waste recycling and generation of water and energy, that will become critical for lunar and Martian ISRU missions.

DYNAMICS AND MACHINES

The elaborate infrastructure needed for space travel and for establishing extraterrestrial human habitation will include many complex machines to carry out mission tasks. Some of these machines will be robotic, while others will carry out fluid handling operations, employing pumps, turbines, motors, and articulated structures. In many instances, although the basic physical operations of particular devices may not be affected

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by microgravity, their designs must be flexible enough to function within a system that may, in fact, depend sensitively on the presence or absence of gravity.

The longer and more adaptable missions become, the more complex their systems will tend to be, in part because the absence of gravity must be compensated for by a proliferation of specially engineered devices, such as pumps to help distribute, separate, and control fluids. Since a spacecraft is, for practical purposes, also a closed system, with highly interactive components having limited redundancies, critical components of any HEDS mission systems must remain failure-free for long periods—perhaps up to a decade or more. Design for reliability of this magnitude will require development of new design disciplines and approaches, probably quite different from those now in general use. Microgravity remains central to this issue and is generally a source of uncertainty (e.g., fluid interfaces float, load directions fluctuate, screws loosen), and uncertainty is the enemy of reliability. Therefore, research on microgravity should address the control of such uncertainties.

Perhaps, paradoxically, the human presence on long missions may well prove to be the most effective way to provide the redundancy required for extremely high system reliability, because the human, perhaps within narrow limits, is the only capable "system" for efficiently making unanticipated repairs and adjustments.

The following paragraphs explore how the absence of gravity would affect certain devices having obvious importance for HEDS.

Film Bearings for HEDS Applications

Most pumps, turbines, motors, and other rotational elements needed for HEDS technology will require bearings. It is plausible that film bearings might generally be preferred for long space missions over rotating-element bearings, because contact wear is eliminated, greatly extending life. The bearing loads themselves in the absence of gravity will be different—no doubt lower—but such loads might behave in fluctuating, unstable, or unfamiliar ways. Film bearings will often be chosen because they can be light and efficient.[48,49] The lubricating films of interest for space might employ available cryogenic substances such as liquid hydrogen. Research will be needed to explore the effectiveness of such substances in microgravity environments. The use of magnetic bearings may often be preferable for use in low-gravity environments, and their use will need to be explored as a research issue.

Liquid flows, associated with the collection and recirculation of lubricants for bearings and their seals, conventionally depend on gravity. In the absence of gravity, film bearings would presumably need to be entirely encapsulated, or "flooded," a difficult matter for bearings operating at high speed and high pressure. Possible phase changes or "flashing" of liquids used for bearing films could trigger problems associated with multiphase flow in microgravity. Analysis and experiments concerning the thermal behavior in realistic microgravity environments of bearing designs will clearly be needed. The matter of bearings for space machinery provides an example of research and development that is needed because of microgravity effects, even though the device using the bearing itself may not require microgravity research. In effect, the needed microgravity research pertains to the whole spacecraft system and the choices to be made in evolving its design.

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Multibody Dynamics and Space Robotics

The dynamical behavior of mechanical devices in microgravity certainly merits consideration along with fluid mechanics and heat transfer. The extreme structural flexibility of low-mass components of space robots, for example, means that dynamics are likely to be complex and perhaps difficult to analyze with precision. Structural damping of unwanted oscillations is anticipated to be correspondingly weak. Without gravity, joints of articulated structures may fail to position members precisely, and joint hysteresis may become a problem. In addition, other mechanical devices such as beams, chains, and tethers can be expected to exhibit complex dynamic behavior in microgravity, and their suitability for specific HEDS systems will require careful study. These topics, which are generally discussed under the heading of "multibody dynamics" (Part 4 of *Teleoperation and Robotics in Space* [50]), may represent an area where fundamental microgravity research can play a role.

The problem of general system integration of robotic and human capabilities is discussed at length in Part 2 of *Teleoperation and Robotics in Space*,[51] balancing issues of cost, weight, reliability, power, crew safety, and health. Of course, the mission goals and tasks must be specified before any optimization can be attempted. Further, although human design parameters are fixed, robot design is not. Presumably, robots will be especially well adapted for operations in microgravity, and they should be designed for the longest possible endurance. Therefore, how to design failure-proof joint bearings for robots and how to provide appropriate dynamic controls for robots are important topics for future microgravity research.

Propulsion and Power in Microgravity

Propulsion systems, both as a means for space travel and for use in energy-conversion systems for long-term colonization, pose many problems of fluid handling and heat transfer in microgravity. The exact nature of the problems, and their degree of severity, depend on which propulsion and power systems are adopted. For the purposes of this discussion, it is assumed that electric propulsion and power, possibly with a nuclear energy source,[52] constitute the basic system of choice. Indeed, studies have indicated that electric propulsion could offer travel time advantages for missions to Mars and, especially, beyond Mars. Also, an electric power system is most desirable for power in permanent space settlements. For the explicit purposes of this report, electric propulsion and power pose a particularly wide range of microgravity problems, especially if a Rankine cycle is adopted for reasons of thermal efficiency. While previous studies[53] have recognized that nuclear-electric propulsion and power generation provide highly desirable technology for such missions, they do not obviate the need to continue research into alternate technologies.

An electric power plant, perhaps as small as 10 megawatts, could accelerate the propellant electromagnetically to high velocity in a thruster, in order to maintain a steady, low-level thrust with high specific impulse for most of the travel time. The power plant could also provide station power to support a human colony. Energy storage would be a requirement for any long-duration HEDS mission. During the full-thrust phase of the space

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journey, which might last for years, the thrust could be on the order of 0.1 *g*; thus, the system would need to operate without failure for a long time in severely reduced, but not zero, gravity equivalent. At other times, when providing only vehicle or station power, the power system might need to operate in microgravity.

In the paragraphs that follow, the major elements of a hypothetical electric propulsion and power system are briefly discussed, with emphasis on the microgravity issues.

The Thruster

Various electromagnetic thruster concepts have been studied[54] in which an ionized gas is accelerated by electric fields. Proposed propellant gases include hydrogen, oxygen, ammonia, noble gases, and metal vapors. These presumably are to be stored in liquid or solid form prior to use and must therefore change phase in a vaporizer.[55] The vaporizer might be a low-pressure flash boiler, but, in any case, vapor with a low liquid content must be formed in fractional gravity or microgravity. Control of this vaporization process in microgravity will certainly require continued research and testing.

The Power Cycle

If a thermoelectric generator is used, then there appears not to be an obvious microgravity issue associated with the power generation per se. However, for efficiency and high power, the closed Rankine (condensing) thermodynamic cycle is commonly proposed, with, for example, potassium as the working fluid. This system would doubtless encounter many microgravity-related problems, including evaporation of the working fluid in a boiler, its passage through a vapor turbine, and its condensation back to a liquid metal, with heat rejection, to complete the cycle. In the evaporator[56] and associated pumps and piping operating in a reduced or microgravity environment, capillary forces will become important in the process of liquid-vapor separation. Such a vapor turbine will also encounter problems of bearing design for microgravity discussed elsewhere (so too will any electric generator that it may drive). The condensation step poses problems of droplet flow in microgravity. A condenser on the Earth collects liquid by gravity. In microgravity, by contrast, condensation is expected to occur in a shear zone established in a channel where vapor is brought into contact with a liquid film. Condensation may not be completed, and vapor bubbles may persist in the flow system, altering heat transfer efficiency.

Thermal Control Systems

The waste heat from the various sources on the spacecraft or station will be collected and conveyed to a space radiator for rejection to space.[57] The largest source would probably be the power plant condenser, but there would be contributions from a myriad of other sources, including life-support systems. Typically, heat will be absorbed in a circulating fluid, most efficiently involving phase change (ammonia would be a typical heat-transfer fluid). The fluid would then be conveyed to the radiator system through a potentially elaborate thermal network. The pumping power to accomplish this distribution would be supplied by mechanical pumps sized for the largest flows required, but also by electromagnetic pumps or capillary pumps (heat pipes) where appropriate.

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Details governing such a thermal control system will clearly depend on mission requirements, but in general, one can expect the system to have a large and flexible thermal capacity and to be able to deal with expected or accidental load changes. Furthermore, because it is likely that efficiency and weight will dictate a two-phase circulating system, microgravity issues will undoubtedly be important. Pertinent data are available for individual components of interest, but collective, or systemwide, behavior of thermal control in microgravity requires evaluation on the ISS, if possible. (See Chapter 1 of *Thermal Hydraulics for Space Power, Propulsion, and Thermal Management System Design*,[58] especially the articles by Alario and by Braun, for a discussion of planning for ISS thermal control system evaluation.)

Need for Design Simplicity

The foregoing discussion for HEDS propulsion and power technology makes it clear that system definition must precede the listing of specific problems entailing microgravity. Accommodation to microgravity is one among many issues yet to be settled. This discussion should also make clear the importance of simplicity of design; the complexities introduced by microgravity, together with the need for an unprecedented high level of reliability, should establish simplicity as a central requirement for HEDS technology.

Relevance of Current MRD Research

The current MRD program includes many research projects that are highly relevant to the heat-transfer and fluid-handling issues discussed above, especially those of concern in the propulsion field. However, additional research of an applied (system focused) nature may be needed to exploit efficiently the applicability of fundamental scientific results to the design of systems and components for HEDS missions.

In addition, an active research community is currently studying structural dynamics and robotics for space,[59] and while NASA is heavily involved in supporting that work, MRD does not have a large role in this at present. Research on film-lubricated bearings for space applications is being supported by NASA; the interest is quite applied at present. A review by MRD of current activities in structural dynamics and film lubrication might uncover new opportunities for MRD to do HEDS-related research in this field.[60]

Artificial Gravity

Previous sections have indicated how the absence of gravitational body force generally tends to complicate equipment and system designs and to be harmful to human health. Therefore, it would seem to be a matter of basic importance for HEDS that NASA explore ways to supply appropriate degrees of artificial gravity. As of 1987[61] and for several years thereafter,[62] NASA recognized the potential value of such measures. However, the subject seems to have been neglected in recent years. With the new HEDS goals in mind, NASA should allow for the possibility that provision of a body force substitute for gravity may prove to be an absolute necessity for ambitious manned space missions of the future.

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In principle, this may be done by imparting and maintaining rotation of the spacecraft. Quite apart from the technological means that might be employed for this purpose, only the MRD research program can provide the research basis for evaluating the needs and merits involved. For example, above what gravity level will a two-phase heat-transfer loop be preferred over a single-phase arrangement?

For a given desired gravity equivalent, the needed angular velocity is inversely proportional to the square root of the radius of rotation. An undesirable by-product of rotation is the Coriolis force, which is proportional to the angular velocity. Thus, a large radius would be desired, to the degree that costs are balanced by the benefits of avoiding Coriolis effects. A similar issue is posed by body force gradient. How, then, should the undesirable Coriolis and gravity-gradient effects of spacecraft rotation be evaluated against the benefits of rotation? Little is known about such effects, especially in the various combinations that seem possible.

The MRD research program should include studies that will answer the questions posed above, to enable the scientific evaluation of artificial, fractional gravity schemes that may be proposed in the future.

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An Initial Review of Microgravity Research in Support of Human Exploration and Development of Space

4

Programmatic Issues

In the previous chapters of this report, an initial identification was made of the scientific and related technological issues facing NASA's HEDS endeavor. In looking specifically at mission enabling and enhancing technologies, the committee identified several scientific challenges that need to be addressed by the research community. It is clear that fundamental scientific questions in the physical and biological sciences need to be answered before many exploration technologies can be efficiently developed. MRD's major contribution to NASA is its support of fundamental research that examines the role of gravity in physical and biological systems, but there are steps that MRD can take to strengthen the contribution of that science to HEDS. Discussed below are several points of consideration and recommendations that the committee believes important to MRD's support of the HEDS enterprise.

- MRD should be prepared to stimulate and support critical microgravity research to help discriminate among competing HEDS technologies, specifically providing information so that NASA can make informed choices among them.

- MRD should, on a continuing basis, assist NASA in identifying critical technologies that would benefit future HEDS missions and then seek opportunities in microgravity research to contribute to their efficient realization. MRD should, however, remain both flexible and cautious in evaluating such opportunities. Major advances in technology can result from basic research undertaken without regard to current technological priorities, which have yet to be even identified. In addition, the timing of such technological advances is often unpredictable.

- The process of gathering and exchanging information relevant to deciding research selections that could support HEDS missions should be strengthened. Specialized workshops, cross-divisional teams, advisory panels, and study groups attended by mission technologists and microgravity scientists are among the suggested mechanisms to achieve this recommendation. Such

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activities would encourage the exchange of ideas between technologists and scientists, provide better communication and ongoing awareness of the technology needs for MRD, and also allow timely transfer of microgravity research findings to HEDS technologists.

- The goals of HEDS involve the development of complex technological systems that require, for example, the integration of knowledge from such apparently disparate fields as biotechnology, fluid physics, and materials science. Examples might include studies of biologically based systems and fluids management systems that could address life-support needs or the multiple disciplines required for in situ resource recovery. MRD may find it advantageous, where appropriate, to initiate a limited number of projects focusing on cross-disciplinary research topics, in order to develop experience in cross-disciplinary research selection and project management. Various scientific disciplines must be integrated in order to design and evaluate complex systems, and MRD could provide the necessary research methodologies for this purpose.

- While robust scaling laws involving the g level may be available for some microgravity disciplines, allowing predictions and extrapolations between microgravity and terrestrial g_0, this usually does not hold true in more complex systems. Furthermore, for many phenomena and processes affected by gravity reduction, it is not yet known whether a threshold effect occurs at some g level. This remains particularly true, for example, in biological areas, where it is difficult to model multistep processes, which may include significant shifts in the relative importance of gravity. Recognizing that some of the missions envisioned by HEDS involve significant encounters with fractional g_0 environments (lunar gravity = 0.16 g_0, Martian gravity = 0.37 g_0), MRD should consider giving more attention to studies conducted at fractional g_0 where applicable to HEDS technologies.

- NASA's ongoing investments in automation and robotics are expected to benefit both human and robotic HEDS missions, both in space and in terrestrial and extraterrestrial settings. HEDS missions will often involve spacecraft operations that are sufficiently far from Earth to demand high levels of autonomous operations and control in part because of the unacceptably long time lags associated with speed-of-light communications. Improved automated and teleoperational capabilities can enhance the science and commercial return on NASA's investment, reducing operating costs and improving safety and comfort on space operations. MRD should carefully follow these efforts to make sure that microgravity issues, especially for robotics, receive appropriate research attention.

- It is expected that the ISS will provide a unique platform for conducting long-duration microgravity scientific research and assessing the efficiency and long-term suitability of many technical systems important to HEDS. In addition to its program of basic research aboard ISS, MRD should take advantage of the station and its subsystems for test bed studies of science concepts applicable to HEDS technologies. This could include, for instance, a role for applied

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An Initial Review of Microgravity Research in Support of Human Exploration and Development of Space

Appendix: Glossary

A B C D E F G H I J K L M
N O P Q R S T U V W X Y Z

Atomic clock frequencies A clock whose timing is governed by the natural resonance of atoms or certain molecules

Atom trap Spatial localizations of an atom by interaction with a laser beam

Beneficiation Process of transforming raw materials into more concentrated or beneficial forms

Bioreactor system A cell culture device that permits cell and tissue culturing in suspension and is designed to allow a fluid flow that results in a low-stress environment with minimal shearing of cell aggregates; the rotating-wall, perfused vessel bioreactor developed by NASA consists of two concentric cylinders, the innermost of which is permeable and can be used to replenish nutrients and adjust growth conditions in the culture chamber, which is between the cylinders

Cell culture/tissue culture The in vitro growth of cells and tissue masses in a nutrient solution or gel

CFD Computational fluid dynamics

Coriolis force In a rotating system, a force proportional to the angular velocity

Endothelial cells Cells that line the blood vessels; excessive proliferation of these cells can lead to reduced blood flow

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Extracellular matrix Proteins that are produced by cells and are deposited outside the cell; these proteins often form the physical basis for cell adherence and migration in a tissue

Film bearing A bearing in which forces are transmitted through thin but continuous fluid films (gas or liquid) that separate solid machine components

G-jitter High-frequency acceleration spectrum

Gel electrophoresis A process used to separate molecules by subjecting them to an electric current

Heat pipe A container of two-phase fluid used to transfer heat efficiently

Heat sink A reservoir to absorb thermal energy

HEDS Human Exploration and Development of Space

ISRU In situ resource utilization

ISS International Space Station

LPS Liquid phase sintering

LSD Life Sciences Division (NASA)

Marangoni force Surface tension-driven force

MRD Microgravity Research Division (NASA)

NRA NASA Research Announcement

NRC National Research Council

Organelles Small intracellular compartments and structures within the cell, e.g., mitochondria

Quantum oscillator Frequency associated with electron transitions in atoms

STEP Satellite Test of the Equivalence Principle

van der Waals forces Short-range attractive intermolecular forces

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