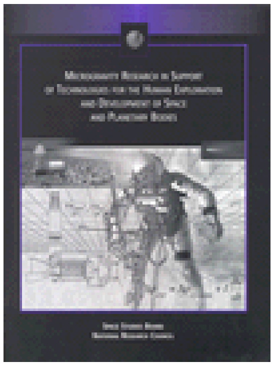

Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies

Committee on Microgravity Research, Space Studies Board, National Research Council

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Executive Summary

CHARGE TO THE COMMITTEE AND REPORT ORGANIZATION

The primary charge to the Committee on Microgravity Research (CMGR) from the Microgravity Science and Applications Division (MSAD)[1] of NASA reads:

> CMGR will undertake an assessment of scientific and related technological issues facing NASA's Human Exploration and Development of Space (HEDS) endeavor. The committee will look specifically at mission enabling and enhancing technologies which, for development, require an improved understanding of fluid and material behavior in a reduced gravity environment. These might range from construction assembly techniques such as welding in space, to chemical processing of extraterrestrially derived fuels and oxygen. The committee will identify opportunities which exist for microgravity research to contribute to the understanding of fundamental science questions underlying exploration technologies and make recommendations for some areas of directed research.

In addition to the above charge, which is stated in full in Appendix A, the committee was asked to give some consideration to radiation hazards and shielding.

The committee and MSAD mutually interpreted the main thrust of the charge to be the determination of the gravity-related physicochemical phenomena most relevant to HEDS technology needs and the recommendation of fundamental research on those phenomena. The technologies considered were those judged to be relevant in the next one to three decades.

The organization of this report reflects the committee's interpretation of the charge. Following the introduction and brief descriptions of relevant phenomena and concepts, the report surveys a set of selected HEDS-enabling technologies, classified according to function. The survey is intended not to be comprehensive but to identify those underlying scientific phenomena that are vital to the technologies, that are gravity related, and that present a compelling need for research. The committee defines a gravity-related phenomenon as a phenomenon that is either directly affected by reduced gravity or that becomes significant as gravity level is reduced. A

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[1] Now the Microgravity Research Division.

phenomenon of the latter type may sometimes be used to compensate for the loss of gravity (an example is surface-tension-driven flow in wicks and heat pipes in the absence of gravity-induced convection). Selected phenomena and their dependence on, or importance in, reduced gravity are then discussed, along with the research needed to develop predictive models and better databases for characterizing the phenomena. The remainder of the report deals with other gravity-related features of HEDS technologies, discusses microgravity countermeasures (e.g., artificial gravity), and offers research and programmatic recommendations.

TECHNOLOGIES SURVEYED

The selected technologies are discussed according to their functions: (1) power generation and storage, (2) space propulsion, (3) life support, (4) hazard control, (5) materials production and storage, and (6) construction and maintenance. They were examined for their dependence on gravity level by considering the gravity dependence of the components (subsystems) or processes of which they are made up. In many instances, the subsystems (e.g., pumps or boilers) or processes (e.g., electrolysis) are common to many technologies, so the phenomena underlying them were recognized as especially important for HEDS. An example of a strongly gravity-dependent subsystem is a heat exchanger subsystem, such as a boiler or a condensation-based space radiator, that uses a two-phase fluid (i.e., liquid and vapor). Its operation is radically affected by microgravity because the phenomena of buoyant convection and density stratification are absent. An example of a strongly gravity-dependent process is liquid electrolysis, common to life support and fuel production systems. The phenomenon of buoyancy-driven migration of the gases (i.e., bubbles) in the liquid does not occur in microgravity, so phase separation of the product gases from the liquid must be accomplished by other means.

Although the charge to the committee did not specifically include an evaluation of technologies, a remark on this point seems in order. Now and in the past NASA has chosen not to use active, high-power-density systems that involve heat transfer by phase change (e.g., condensation and boiling) to meet energy needs but has chosen instead to use lower-power-density, passive systems such as solar collectors, fuel cells, and radio isotope generators. This approach has been motivated by the requirement to reduce risk and to ensure reliability, since the performance of multiphase (two or more phases) flow and heat transfer processes in reduced gravity is not well understood and was therefore considered risky. Unfortunately, however, the lower-power-density systems will not be able to supply enough energy for proposed long-duration, crewed space and interplanetary missions. The high efficiency and high power-to-weight ratio of closed-cycle multiphase systems, based on the use of the latent heat of phase change (i.e., condensation and evaporation) to transfer energy, are so attractive that the committee believes it is imperative for NASA to undertake a directed research program on multiphase flow and heat transfer that will enable it to decide if systems dependent on these processes can be successfully controlled and utilized in space. Accordingly, one of the higher-priority recommendations in this report proposes this research.

PHENOMENA IDENTIFIED AS AFFECTED BY OR DOMINANT IN REDUCED GRAVITY

Phenomena that are identified as underlying HEDS-enabling technologies and that either are directly affected by gravity level or emerge as dominant factors in reduced gravity are generally organized in Chapter IV of this report as follows: (1) surface and interfacial phenomena, referring to effects stemming from surface wetting and interfacial tension; (2) multiphase flow and heat transfer, referring to the flow of more than one fluid phase in pipes, pumps, and phase-change components, and flow in porous media, exemplified by the flow of fluids in the packed and fluidized particulate beds used in chemical reactors; (3) multiphase system dynamics, which deals with the global instabilities that may occur in multiphase systems; (4) solidification, referring to the phase change of a liquid to a solid, as occurs in casting or welding; (5) fire phenomena and combustion, used in some power generation and propulsion systems and occurring in accidental fires; and (6) granular mechanics, referring to such topics as the response of granular media and soils to geotechnical loads and the flow of granular materials in chutes and hoppers.

RECOMMENDED HIGHER-PRIORITY RESEARCH ON FUNDAMENTAL PHENOMENA

Of the specific areas recommended for research in this report, those discussed below were considered by the committee to have higher priority based on their potential to affect a wide range of HEDS technologies that are mission enabling. In each area, the technological importance of the phenomena is briefly explained first.

Surface or Interfacial Phenomena

Surface tension effects are of critical importance in such diverse HEDS technologies as welding, liquid-phase sintering, the operation of wicks in heat pipes for thermal management, the use of capillary vanes (wet by the liquid) in cryogenic storage tanks to control the position and movement of liquids, lubrication, and boiling/condensation heat transfer, including the rewetting of hot surfaces. A special (Marangoni) effect occurs when the surface tension varies over the surface of a liquid (or the interface between two liquids) because of thermal and composition gradients. Marangoni effects can produce strong gravity-independent convection, which may be beneficial, as in the stirring of weld pools and the enhancement of the critical heat flux in multicomponent boiling, or detrimental, as in the migration of fluid in a thermal gradient to unwanted locations.

The committee's recommendations, which are based on the critical issues underlying the technologies, call for research on the following topics:

- *The physics of wetting*, with an emphasis on hysteresis effects, the dynamics of the wetting process, and the molecular basis of wetting, to elucidate the wetting of both solid and porous media (e.g., wicks and nanoscale media) and to provide a basis for the choice of material combinations and conditions for optimal wetting and wetting agents; and
- *Capillary-driven flows,* with modeling of the flows induced by the Marangoni effect, which are complicated because of the feedback between the flow and the surface temperature and composition gradients that drive the flow.

Multiphase Flow and Heat Transfer

Multiphase flow and heat transfer are the fundamental processes in systems using a fluid of two or more phases (e.g., liquid and vapor) to transport mass, momentum, and energy. They are critical to the operation of many power production and utilization systems and other systems that require high energy-transport efficiency and high power-to-weight ratios. Multiphase systems have these characteristics because they are able to utilize the latent heat of evaporation/condensation to efficiently transfer energy. Their successful operation in Earth's gravity often depends on buoyancy-driven convection and density-induced stratification of the phases, processes that are reduced or absent in microgravity. Moreover, new flow regimes may occur in which the spatial distribution of the phases reflects the absence of a gravitational force. Therefore, to exploit the attractive advantages of multiphase systems under microgravity conditions, it is imperative to determine how they can be used and controlled in the absence of gravity.

It is recognized that there will probably be a continuing need for experimental microgravity data and appropriate empirical correlations, since some physical phenomena and HEDS design issues go beyond current, and anticipated near-term, computational capabilities. Nevertheless, the primary objective of the proposed research is the development of a reliable, physically based,[2] multidimensional two-fluid model for the computational fluid dynamics (CFD) analysis of multiphase flow and heat transfer phenomena of importance to the HEDS program. Indeed, the following recommended research is aimed at developing predictive models of multiphase flow and heat transfer and testing these models against reduced-scale data taken in microgravity environments:

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[2] In the context of this report, a physically based model is one that is developed from fundamental principles and physical mechanisms, as opposed to an empirical model. See the glossary, Appendix C.

- *The development of physically based models to predict the flow regimes, flow regime transitions, and the multiphase flow and heat transfer that occur in fractional gravity and microgravity environments.* These models should include the effects of two-phase turbulence, surface-tension-induced forces, and the axial and lateral interfacial and wall forces on the flowing phases (i.e., the flow-regime-specific interfacial and wall constitutive laws). They should be suitable for use in three-dimensional CFD solvers.
- *Assessment of the predictive capabilities of these models by comparing them with the results of reduced-scale and separate-effects experiments performed under microgravity conditions.* In particular, detailed data are needed on flow-regime-specific phenomena in simple and complex geometry conduits (where gravity dependence may occur even at high flow rates); the distribution and separation of the phases for the various flow regimes, including the effect of phase separations induced by swirl; and the local velocity, temperature, void fraction, and turbulence fields.
- *A program parallel to the one described above for assessing the effect of gravity level on forced convective flows*, especially the forced-flow boiling curve for different boiling regimes (e.g., nucleate and film). Such a program is essential, since forced flow can compensate for some of the problems arising from the loss of buoyancy.

Multiphase System Dynamics

In systems using multiphase flow, effects on a global scale may emerge from the interaction of the components. In particular, phase or time lags in feedback loops can cause potentially dangerous instabilities that are revealed only by analysis of the system as a whole. The following research is recommended:

- *The development of models and the collection and analysis of stability data on boiling and condensing systems at fractional gravity and microgravity levels.* In particular, the effect of gravity level on excursive instabilities, as well as on those dynamic instabilities that can be induced by compressibility and lags in the propagation of density waves around closed loops in multiphase systems, needs to be investigated and analyzed.

Fire Phenomena

Accidental fires are a major hazard in the confined quarters of spacecraft. The structure and dynamics of fires and flames are drastically altered in microgravity, primarily because there is no buoyancy-driven convection or sedimentation (e.g., of smoke particles). Accordingly, the following research is recommended:

- *Experimental, theoretical, and computational studies of flame spread over surfaces of solid materials in microgravity and fractional gravity.* These studies should focus on generic materials, both cellulose and synthetic polymers, and should include ignition requirements, flame-spread rates, and flame structure. Parallel studies on the production of gaseous fuel from solid-fuel pyrolysis are needed.
- *Gravity effects in smoldering, as in the case of electrical cable fires.* In particular, the research should look at the initiation and termination of smoldering, propagation rates of smoldering fronts, and the production of hazardous or flammable products from smoldering, including conditions for transition from smoldering to flaming combustion.

Granular Mechanics

The granular materials encountered in lunar and Martian soils will serve both as the physical foundation that supports people, equipment, and buildings and as a raw material to be mined and used for construction and for the extraction of valuable resources. Granular material in the form of dust is expected to be a serious environmental problem on the Moon and Mars. The behavior of granular materials in response to loads and digging, with respect to their flow in chutes and hoppers, or in atmospheric transport (i.e., dust) and adhesion to surfaces, is affected by gravity level. Accordingly, the following research is recommended:

- *The response of granular material to applied stress.* The knowledge gained will allow researchers to examine separately the effects of gravity and shearing using both analytical and experimental studies. Predictive models of granular deformation and flow under reduced gravity need to be developed that include the effects of particle size and shape, the effects of particle constitution, and the effects of particle agitation and of electrostatic charge, especially at low pressures.
- *Predictive models of the behavior of dust in spacecraft and extraterrestrial environments.* An understanding of this behavior will permit the reliable prediction of dust transport and deposition. An understanding is also needed of the cohesion and adhesion mechanisms that control dust attachment, where the attraction mechanism appears to be electrostatic.

OTHER CONCERNS

Reduced-Gravity Countermeasures

Because reduced or variable gravity is generally a troublesome complication of system design for HEDS (and has harmful consequences for human health), research should be carried out on means to counter the adverse effects. Such means would probably be mechanical in nature, involving rotation or vibration, and could be implemented at a range of levels, from that of the whole spacecraft down to the level of small but critical components. Design studies of structural and system problems would be required to establish technical practicality and costs for large-scale artificial-gravity concepts.

Applied research looking toward economic and effective artificial gravity should emphasize solutions that would apply to both technical and biological systems.

Research on and development of reduced-gravity countermeasures are given high priority in the report and must obviously proceed hand in hand with the microgravity research recommended elsewhere in this report, because the latter will establish the target gravity levels desired for various components and systems. In turn, the specific benefits of an artificial gravity system must be understood and weighed against the penalties (e.g., weight and cost) so that design trade-offs can be made. In other words, it is to be expected that artificial gravity will be part of integrated system designs for HEDS.

Indirect Effects of Reduced Gravity

Reduced gravity will have indirect effects on systems and components, necessitating designs different from the corresponding, more familiar ones on Earth. For example, seemingly mundane components such as piping, valves, and bearings will have to be adapted to the altered structural forces and loads in reduced- and variable-gravity environments. Then, too, products of wear and decay are presumably less easily managed in microgravity. Such concerns are additional elements in a central HEDS issue, namely the effect of reduced and variable gravity on system reliability and safety.

RECOMMENDED RESEARCH WITH A LOWER PRIORITY

The committee also recommends research on other fundamental phenomena in addition to those described above. These phenomena, listed below in no particular order, were judged to be somewhat less critical to mission success, so the research has a lower priority.

- Marangoni material parameters;
- Static equilibrium capillary shapes;
- The effect of gravity on convective condensation heat transfer;
- The effect of gravity on the heat transfer characteristics of fluid flow in porous media;
- The transport of flame suppressant to fires in reduced gravity;
- Diffusion-flame structure of fuels and flame products as affected by gravity levels;

- Flammability and flame behavior of gaseous combustible mixtures, sprays, and dust clouds; and
- The effect of gravity on nucleation and growth of solid from the melt.

PROGRAMMATIC RECOMMENDATIONS

It should be clearly understood that the committee's research recommendations deal with fundamental phenomena associated with fluid and material behavior rather than with the direct development of subsystems and their integration into technologies operable in a reduced-gravity environment. However, the committee recognizes that blending conceptual design needs and phenomenological research findings requires a great deal of communication, coordination, and interdisciplinary collaboration among designers and researchers. For this reason, it makes recommendations in this report concerning the goals, research planning, and programmatic activities of NASA that support gravity-related research for HEDS. Similar recommendations made in the phase I report (NRC, 1997) are reflected in this more extensive study as well. It was thought then, and is still believed, that in view of the long time scale needed for the evolution of basic scientific concepts into practical applications, the suggested research programs will require a sustained commitment on the part of NASA to achieve an understanding of gravity-related issues.

A Research Approach for the Development of Multiphase Flow and Heat Transfer Technology

For NASA to be able to decide whether multiphase and phase-change systems can be used and controlled in future HEDS missions, a well-focused experimental and analytical research program will be needed to develop an understanding of how multiphase systems and processes behave in reduced gravity. Since parametric full-scale testing in space is not feasible, NASA should consider developing a reliable three-dimensional, two-fluid CFD model that can be used to help design and analyze multiphase systems and subsystems for HEDS missions. The approach that has been recommended is that a reliable, physically based analytical model be developed and qualified against appropriate terrestrial and microgravity data. The resulting computational model could then be used to analyze and optimize final designs and to scale up the reduced-scale data obtained in space. While this is expected to be the most reliable, least expensive, and quickest means of developing the potentially enabling technology required by HEDS, programmatic changes would be required to accomplish this goal. In particular, it would be necessary for NASA to refocus its multiphase fluid physics research program and to be much more proactive than it has been in defining and managing the research needed to develop predictive capabilities for multiphase flow and heat transfer. In this context, NASA should investigate the possibility of consulting the U.S. Department of Energy-Naval Reactors program for help in designing research programs aimed at developing the required multivariate, physically based computational models.

Coordination of Research and Design

The NASA office responsible for microgravity research should diligently inform NASA at large about the issues of reduced gravity that are foreseen for space hardware design, so that such considerations may enter design thinking at the concept stage. It should also apprise the microgravity research community of design issues relevant to microgravity research, and NASA should encourage the blending of conceptual design and phenomenological research. This will require active communication and coordination among basic researchers and system designers and users, which should be specifically encouraged by such means as regular workshops and study groups in which both mission technologists and microgravity scientists participate.

Microgravity Research and the International Space Station

It is expected that the International Space Station (ISS) will provide a unique platform for conducting long-duration microgravity scientific research and assessing the efficiency and long-term suitability of many of the technical systems important to HEDS. The committee reiterates a recommendation from its phase I report (NRC, 1997, p. 39): in addition to carrying out basic research aboard the ISS, NASA should take advantage of the station and its subsystems, using them for testbed studies of scientific and engineering concepts applicable to HEDS technologies. In particular, the ISS can play an important role in the multiphase flow and heat transfer research program recommended above.

Peer Review for Reduced-Gravity Research

The NASA Research Announcement process and its peer review system have greatly enhanced the productivity and quality of NASA's gravity-related research. These mechanisms should be maintained as steps are taken to develop areas of science affecting HEDS technologies.

REFERENCE

National Research Council (NRC), Space Studies Board. 1997. An Initial Review of Microgravity Research in Support of Human Exploration and Development of Space. Washington, D.C.: National Academy Press.

MICROGRAVITY RESEARCH IN SUPPORT OF TECHNOLOGIES FOR THE HUMAN EXPLORATION AND DEVELOPMENT OF SPACE AND PLANETARY BODIES

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

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Preface

The study that is the subject of this 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. The committee agreed 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 was to be carried out in two phases. The phase I report, *An Initial Review of Microgravity Research in Support of Human Exploration and Development of Space*, was published in 1997 (National Academy Press, Washington, D.C.). That first report represented a preliminary look at broad categories of HEDS technologies and contained primarily programmatic recommendations. For the second phase of the study, the committee undertook a more in-depth examination of a wide range of specific technologies that might be applicable to human exploration. As no single office at NASA had assembled a list of critical technologies needed for HEDS, the committee has included the results of its own technology survey in this report. This survey was carried out by canvassing the available literature, participating in relevant workshops, and receiving extensive briefings from experts in NASA, industry, and academia. The goal of this phase II report was to provide specific recommendations for areas of research on fundamental phenomena. The phenomena recommended for study would be those that had the potential to significantly affect the operation of future exploration technologies and that needed to be better understood to enable the optimization or eventual development of those technologies. Since the time frame for technology development from fundamental research is generally quite long, the committee chose to focus, in this phase II report, primarily on those technology areas that might be important for space exploration one to three decades into the future.

In its study, the committee utilized a large number of past reports from various sources. Among the previous National Research Council reports relevant to this study, the committee took particular note of the following:

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

- *Microgravity Research Opportunities for the 1990s*, Space Studies Board, National Research Council (National Academy Press, Washington, D.C., 1995), reviewed the various research topics currently studied within the different scientific disciplines of NASA's microgravity research program and suggested research and programmatic priorities and recommendations. The report focused on fundamental research that could contribute to basic advances within individual disciplines.
- *Space Technology for the New Century*, Aeronautics and Space Engineering Board, National Research Council (National Academy Press, Washington, D.C., 1998), examined space technology needs in the post-2000 time frame and identified a few high-risk, high-payoff areas where research investments might benefit a range of future missions.
- *Advanced Technology for Human Support in Space*, Aeronautics and Space Engineering Board, National Research Council (National Academy Press, Washington, D.C., 1997), reviewed the NASA programs that support development of technologies for human life support and recommended improved strategies for managing the development process.
- *Space Technology to Meet Future Needs*, Aeronautics and Space Engineering Board, National Research Council (National Academy Press, Washington, D.C., 1987), evaluated national advanced space technology requirements and recommended a long-term technology program focus for NASA.

Acknowledgment of Reviewers

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

Rino Buonamici, Westinghouse Hanford Company (retired),
Daniel C. Drucker, University of Florida (emeritus),
Jerry P. Gollub, Haverford College,
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Julio M. Ottino, Northwestern University,
Frederick G. Pohland, University of Pittsburgh,
William C. Reynolds, Stanford University, and
William A. Sirignano, University of California at Irvine.

Although the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

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APPENDIXES