Future Materials Science Research on the International Space Station

Commission on Engineering and Technical Systems, National Research Council

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Future Materials Science Research on the International Space Station

Committee on Materials Science Research on the International Space Station
National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council

NMAB-491

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The committee also thanks the staff of the National Materials Advisory Board, particularly Robert M. Ehrenreich, senior program manager, Pat Williams, senior project assistant, and Bonnie A. Scarborough, research associate.

Finally, the chair of the committee thanks the committee members for their dedication and patience during the course of this study. This report could not have been completed without their diligence and goodwill.

Preface

The deployment of the Space Station Furnace Facility (SSFF) Core, which was originally scheduled for June 1999, has been delayed until November 2002 because of revisions in the construction schedule of the International Space Station (ISS). The National Aeronautics and Space Administration (NASA) is attempting to capitalize on this delay by reviewing the SSFF Core project with respect to the specific research capabilities afforded by the facility, the technology being developed and its usefulness to the U.S. materials science community, and the procedures for identifying the research to be conducted using the SSFF Core.

To facilitate its review, NASA requested that the National Research Council conduct a study to (1) examine NASA's research plan for high-temperature microgravity materials science; (2) assess the ability of the current SSFF Core concept to support the range of high-temperature experiments and associated specialized furnaces; (3) evaluate the usefulness of the high-temperature microgravity materials-science projects planned and technology developed to the research and industrial materials-science communities in terms of already identified needs and planned activities through the year 2010; (4) assess the ability of NASA's high-temperature microgravity materials-science plan to respond to evolving interests and priorities in the field of materials science; and (5) examine the procedures used by NASA to select experiments for the ISS and determine if they encourage active participation by the broader materials-science research community.

The Committee on Materials Science Research on the International Space Station was convened under the auspices of the National Materials Advisory Board to conduct this study and write this report. Because of the limited time allotted the study process, the committee worked on the assumption that NASA's microgravity materials research program would continue unabated into the foreseeable future. The committee therefore focused on the fundamental aspects of the project: the ability and flexibility of the current SSFF Core concept and the NASA selection process to identify and support research in the expansive and evolving field of materials science and engineering. No effort was made to evaluate current or previous research projects.

The nine committee members for this study were carefully selected to provide a suitable range of expertise and an appropriate balance of experience in microgravity research. Committee members included experts in solidification science, semiconductor materials, metals and alloys, ceramics, glasses, polymers, and biomaterials. To provide the committee with insight into the advantages and difficulties of conducting microgravity research, two members were actively involved in microgravity research programs with the Marshall Space Flight Center, and three were members of previous National Research Council committees on microgravity materials research. To ensure a balanced assessment, five of the committee members had no previous experience in the field and were selected solely for their reputations as materials scientists.

In order to accomplish its task, the committee collected information from four main sources:

- extensive briefings from the technical staff of the Marshall Space Flight Center on (1) the microgravity materials-science solicitation and selection process, (2) the history of the microgravity materials-science program, (3) the development of the systems science requirements for the SSFF Core, (4) the ISS candidate investigations for the microgravity materials-science program, and (5) the current SSFF Core concept
- a site visit to the SSFF Core development facilities at the Marshall Space Flight Center in Huntsville, Alabama
- a wide range of NASA and National Research Council publications on NASA's microgravity research program, including (1) NASA's *Research Announcement for Research and Flight Experiment Opportunities* (issued December 4, 1996), (2) NASA's *SSFF Core Systems Science Requirements Envelope Document*, (3) NASA's *SSFF Core Experiment Module Accommodations Handbook*, (4) NASA's *SSFF Core Science Working Group Meeting Minutes* , (5) NASA's *Microgravity Science and Applications Program Tasks and Bibliography for Fiscal Year 1996*, and (6) the

National Research Council's *Microgravity Research Opportunities for the 1990s* report

- the 13 research projects that were recently selected from responses to the 1991 and 1994 NASA Research Announcements, which the committee considered a representative sample of the research to be conducted throughout the lifetime of the SSFF Core (i.e., through 2010)

NASA also supports some in-house research and experiments through the University Space Research Association, but these projects follow a separate funding process and were not reviewed for this report.

The committee's deliberations are organized into three chapters. Chapter 1 provides an overview of the background information for this study, including the reasons for conducting microgravity research and the capabilities of the current SSFF Core concept. Chapter 2 reviews NASA's microgravity research selection process and its ability to ensure that the research projects selected and conducted are of the highest-quality. Chapter 3 discusses (1) the relevance of microgravity research to the study of metals, semiconductors, ceramics and glasses, polymers, and biomaterials and (2) the ability of the current SSFF Core concept to support these important areas of materials-science research.

JULIA R. WEERTMAN

CHAIR, COMMITTEE ON MATERIALS SCIENCE RESEARCH ON THE INTERNATIONAL SPACE STATION

Contents

Appendices

Figures and Tables

FIGURES

TABLES

Executive Summary

The microgravity environment ($10^{-6}g$) of space provides a unique opportunity to further our understanding of various materials phenomena involving the molten, fluidic, and gaseous states by reducing or eliminating buoyancy-driven convection effects. The space environment also permits containerless processing, thus eliminating impurities and stresses introduced by contact with container walls. The anticipated scientific results of microgravity materials-science research range from establishing baselines for fundamental materials processes to generating results of more direct commercial significance. The specific objectives of the microgravity materials-science program of the Microgravity Research Division (MRD) of the National Aeronautics and Space Administration (NASA) include:

- advancing our knowledge base for all classes of materials
- designing and facilitating the executive of microgravity experiments that will help achieve this goal
- determining road maps for future microgravity studies
- contributing to NASA's Human Exploration and Development of Space enterprise
- contributing to the national economy by developing enabling technologies of value to the U.S. private sector

The Space Station Furnace Facility (SSFF) Core was conceived to provide the *mechanical, power, and control infrastructure* for an array of experiment modules (EMs) in which a wide range of high-temperature, microgravity, materials-science experiments could be conducted on the future International Space Station (ISS). The SSFF Core was specifically designed for crystal growth and solidification research in the fields of electronic and photonic materials, metals and alloys, and glasses and ceramics in order to permit the experimental determination of the role of gravitational forces in solidification, crystallization, and thermophysical property measurement. The common infrastructure of the SSFF Core is intended to (1) reduce experiment implementation times by providing major generic subsystems that have long lead times; (2) reduce the up-mass and down-mass required for materials-science investigations; (3) provide flexibility in responding to evolving priorities of the materials-science research community; (4) reduce costs by eliminating the development, fabrication, and verification of redundant hardware and software systems; (5) reduce costs by providing common ground-support equipment, laboratory hardware, and operations support; and (6) facilitate the integration of new experiments. The EMs will contain the actual hardware (e.g., furnaces, samples, thermocouples) in which the experiments will be conducted. Whereas the SSFF Core is being developed and constructed by NASA, the EMs will be separately developed by the Principal Investigators in conjunction with independent equipment manufacturers.

Although the deployment of the SSFF Core was originally scheduled for June 1999, it was delayed until November 2002 because of revisions in the construction schedule of the ISS. NASA is attempting to capitalize on this delay by reviewing the current SSFF Core project in terms of the specific research capabilities afforded by the facility, the technology being developed and its usefulness to the U.S. materials-science community, and the procedures for selecting the research projects to be conducted in the facility.

To facilitate its review, NASA requested that the National Research Council conduct a study to (1) examine NASA's research plan for high-temperature, microgravity materials science; (2) assess the ability of the current SSFF Core concept to support the range of high-temperature experiments and associated specialized furnaces; (3) evaluate the usefulness of the planned high-temperature microgravity materials-science projects and developed technologies to the research and industrial materials-science communities in terms of already identified needs and planned activities through the year 2010;[1] (4) assess the ability of NASA's high-temperature microgravity materials-science plan to accommodate evolving interests and priorities in the field of

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[1] The committee took the 13 projects that NASA has already selected as candidate investigations for the ISS as a representative sample of the research investigations that will be conducted throughout the lifetime of the SSFF Core.

materials science; and (5) examine the procedures used by NASA to select experiments for the ISS and determine if they encourage active participation by the broader materials-science research community.

The Committee on Materials Science Research on the International Space Station was convened under the auspices of the National Materials Advisory Board to conduct this study and write this report. Because of the limited time allotted the study, the committee worked on the assumption that NASA's microgravity materials research program would continue unabated into the foreseeable future. The committee therefore focused on the fundamental aspects of the project: the ability and flexibility of the current SSFF Core concept and NASA's selection procedures for identifying and supporting research within the expansive and evolving field of materials science and engineering. No effort was made to evaluate current or previous research projects.

Meaningful research within the SSFF Core will only be possible if a quality microgravity environment can be successfully maintained. To maintain microgravity conditions, the instrument racks (IRs) for the Core will be isolated from the transient and oscillatory accelerations (termed "*g*-jitter") of the ISS via the active rack isolation system (ARIS), which is currently being developed by Boeing. ARIS is designed to compensate for vibratory accelerations between 0.01 and 300 Hz. The performance of ARIS will be compromised if vibratory accelerations are outside the specified range (e.g., if a rack is accidentally jarred) or if IR operation exceeds maximum allowed payload disturbance levels. In order to minimize the vibration levels controlled by ARIS and ensure that *g*-jitter levels remain within IR specifications, NASA has also stipulated that all cables and hoses for the IRs must have minimal stiffness. The umbilicals are still being developed, and a recent space shuttle flight test of ARIS was not successful.

Finding. Meaningful research in the SSFF Core will be impossible if a microgravity environment cannot be successfully maintained. The success of the SSFF Core therefore depends on the perfection of ARIS or the development of an alternative system for controlling *g*-jitter.

NASA'S MICROGRAVITY RESEARCH PROGRAM

The research areas originally identified by the MRD included the following classes of materials: electronic and photonic materials, glasses and ceramics, metals and alloys, and polymers and nonlinear optical materials. The MRD subsequently formed an 11-member Materials Science Discipline Working Group (DWG), primarily to review the science priorities, implementation plan, and long-term strategy of the materials-science program. The primary mechanism for soliciting broader input into the MRD materials-science program and for informing the community of the current program content and future research opportunities has been through biannual Microgravity Materials Science conferences. Two conferences organized by the DWG and hosted by the Marshall Space Flight Center in 1994 and 1996 (NASA 1996) were attended by approximately 300 to 350 scientists. Additional information was provided by two National Research Council reports: *Towards a Microgravity Research Strategy* (NRC, 1992) and *Microgravity Research Opportunities for the 1990s* (NRC, 1995).[2] Based on the conferences and reports, the DWG identified fundamental physical and chemical phenomena research areas that it believed would benefit from long-duration microgravity conditions. Promising subjects for investigation included:

- nucleation and metastable states
- prediction and control of microstructure, pattern formation, and morphological stability
- phase separation and interfacial phenomena
- transport phenomena
- crystal growth, defect generation, and control
- extraterrestrial processes and technology development (e.g., welding in a vacuum and exploiting extraterrestrial materials for fuel, etc.)

NASA'S MICROGRAVITY RESEARCH SOLICITATION AND SELECTION PROCESSES

For NASA's microgravity materials-science research program to conduct basic and applied research that expands our knowledge base of materials behavior, the research program must be able to stimulate

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[2] NASA also supports some in-house research through the University Space Research Association, but these activities follow a separate funding process and were not reviewed by the current committee.

and identify research proposals of the highest caliber. Thus, the inventory of materials-science experiments in the microgravity research program ultimately depends on the success of the proposal solicitation and selection processes.

In the committee's opinion, the 1996 NASA Research Announcement (NRA) soliciting proposals is well conceived and thoroughly describes the research areas and the ground-based and flight-based facilities. The solicitation also encourages and targets undergraduate participation in the microgravity research enterprise. The sections of the NRA concerning the current SSFF Core concept are not of the same high quality, however. Whereas the descriptions of the ground-based facilities provide researchers with sufficient descriptions and parameters for reduced gravity environments, the section on the current SSFF Core concept does not provide an adequate description of its flexibility. Even the name of the SSFF Core suggests that it is suitable only for high-temperature experiments. Although the committee recognizes that the SSFF Core is still in the concept and development stage, the key issue is whether the baseline facilities are sufficiently flexible to support a broad range of research opportunities.

Recommendation. NASA should provide more information in future NRAs on the flexibility and usefulness of the current SSFF Core concept. NASA should also consider changing the name of the SSFF Core to the Space Station Materials Research Facility or some other more inclusive title that would give researchers more insight into its scientific objectives and experimental flexibility.

The evaluation and selection process is also effectively conceived and designed. A strong feature of the process is that it includes extensive external peer review by scientists with and without microgravity materials-science research experience. Another proven evaluation strategy that is incorporated in the present external peer-review process is the grouping of proposals according to common themes, which facilitates comparative evaluations.

The factors used to evaluate priorities during the Initial Proposal Review segment of the selection procedure, which leads to initial funding decisions, are related to scientific merit. Although researchers must explain their need for a microgravity environment—preferably in quantitative terms—they are not required to argue the ultimate viability of their projects as flight experiments. Thus, decisions are not based on perceptions of present or future hardware capabilities, which is critically important both for ensuring opportunities for investigators who may not be knowledgeable initially about the details of flight systems and operations and for ensuring that hardware-based biases do not inadvertently work against scientific experiments with high intrinsic merit.

Finding. System design should not be the criterion that defines program opportunities. The programs selected for flight must be those that benefit science, engineering, and technology, and thus society, most significantly.

Recommendation. NASA should continue to ensure that perceived flight viability (i.e., current and projected hardware capabilities) does not influence the Initial Proposal Review segment of their selection process.

In the committee's opinion, a potential weakness in the current NASA review process is that the same panel is used during two different phases. During the second phase of the review process (i.e., the Science Concept Review phase), a panel is convened to recommend whether projects merit further ground-based research in preparation for potential flight experimentation. During a portion of the third phase (i.e., the Requirements Definition Review phase), the same experts are reconvened to conduct the Science Review and recommend whether projects merit hardware design and development in preparation for flight experimentation. Although the committee acknowledges that continuity and familiarity with research projects are important, NASA must ensure that reviewer ownership and advocacy do not compromise the evaluation process. One way to do this is to use only a fraction (e.g., less than half) of the Science Concept Review panel members in the later Science Review.

One indication of the success of a solicitation and selection process is by the scientific balance of the inventory of research experiments that are chosen. Although the first priority must always be scientific merit, a concentration of proposals in a subset of research areas could indicate that the solicitation process is not reaching the entire community or that a segment of the community has not been convinced of the merit of the program and the applicability of the facilities. The microgravity materials-science program is currently skewed toward the metals and alloys research area (i.e., 32 out of 71 Principal

Investigators have expertise in this area) and the electronic and photonic research area (26 Principal Investigators). The current selection procedure has had limited success in developing a broad-based, high-impact research program for either polymeric materials (6 Principal Investigators) or glasses and ceramics (7 Principal Investigators).

Many factors may have contributed to this imbalance in the research program, chief among them the nature of the materials themselves. The nature of the sintering process in ceramics and the viscous character of typical high-polymer melts greatly desensitizes their responses to gravitational acceleration, making the value of a microgravity environment in experiments on these classes of materials less obvious than on metals and semiconductors. The underrepresentation of polymeric, glass, and ceramics materials research within the materials-science microgravity program may thus result from a perceived lack of benefits of the environment by these research communities.

Promising areas of microgravity research do exist in these areas, however. To increase their participation, the communities must be effectively informed of the potential benefits of the research program as well as opportunities for participation. NASA needs to develop effective outreach methods to establish links to the best and brightest members of the community and thus to promote an understanding and appreciation of the microgravity research program, the opportunities it offers, and the ways researchers can make contact with relevant personnel within the NASA-affiliated programs and organizations.

NASA must also determine how programs of microgravity research in these areas can best be identified and developed given a flight schedule that provides limited opportunities and requires lengthy lead-times. The current average time to reach flight status—seven years—is an extremely long event horizon for a senior scientist and an eternity for a junior one. The time factor is especially important if the NRA process is to attract the best possible proposals. To ensure the strong growth of the program and the selection of cutting-edge research, topics and areas previously identified by NASA for support must be continually challenged by new program ideas. The strongest possible programs will only evolve through broad-based, open competition.

Recommendation. Although the first priority in selection must always be scientific merit, the microgravity materials-science program should be proactive in developing an effective outreach program (e.g., via organized sessions at professional society meetings) that conveys the benefits of the microgravity research program and stimulates proposals from segments of the materials research community that appear to be underrepresented in the current research portfolio.

In the opinion of the committee, identifying research opportunities in ceramic, glass, and polymeric materials and disseminating them to the targeted communities would be aided by increasing the representation of these research areas on the DWG, decreasing the representation of recipients of NASA funds, and eliminating representation of NASA employees. The DWG has made significant contributions to the materials-science microgravity program, but its membership is currently weighted toward metallurgical and semiconductor research with some ceramics representation and no polymer or biomaterials representation. Experts in those fields are needed to identify high-impact research opportunities, develop an active program in those areas, and ensure that the SSFF Core is applicable to their needs. A large number of the researchers on the DWG have also received NASA funding to conduct microgravity research. Although NASA made a concerted effort to limit this number, many of the members have applied for and received microgravity research grants since joining the DWG. Two are also NASA employees. NASA is attempting to introduce a protocol for rotating a third of the DWG each year and for holding regular biannual meetings.

Recommendation. The membership of the DWG should be reconstituted so that its collective expertise covers not only the scientific areas of the current microgravity experiments but also all materials-science areas that could benefit from microgravity research (e.g., ceramics, glasses, polymers, and biomaterials). To ensure objectivity, the MRD should also institute and vigorously maintain a protocol that ensures that the membership of the DWG is balanced between recipients and nonrecipients of NASA funds (e.g., 1:1) and that the DWG is independent of NASA personnel who could be directly involved in the program.

SPACE STATION FURNACE FACILITY CORE CAPABILITY

The initial SSFF Core concept was devised during the late 1980s and early 1990s based on recommendations from the DWG; the SSFF Intercenter Science Advisory Panel, which consisted of two representatives from the NASA Langley Research Center, one from the NASA Marshall Space Flight Center, and one from the NASA Jet Propulsion Laboratory; five public workshops; and a study by Teledyne Brown, a hardware fabricator for NASA with headquarters in Huntsville, Alabama. The SSFF Science Working Group (SWG) was formed in 1995 to provide advice directly to the SSFF project scientists during the development and early operational stages and to provide guidance on the functional and operational design. The SWG consists of 22 members from government, academia, and industry. SWG members are appointed for two years, and two SWG members are on the DWG. The SWG has met twice: once in March 1995 to review the SSFF Core concept prior to its Critical Design Review and once in March 1997 to review the project status and assess potential new science requirements. Although the SWG has a protocol for rotating its membership, it has some of the same problems as the DWG: significant weighting towards metals and electronics research and a large representation of NASA employees and recipients of NASA funding.

Recommendation. The SWG should have expertise that covers all of the classes of materials likely to be the subject of microgravity experiments. To ensure the objectivity of the SWG, a protocol should be developed that will ensure a proper balance between recipients and nonrecipients of NASA funds and independence from NASA personnel who may be directly involved in the program.

The committee did not have the expertise to assess the perceived cost/benefit advantages of a SSFF Core by providing a common experimental platform. The committee believes, however, that hardware integration with the SSFF Core could shorten instrument-development time by providing standardized interfaces—both in space and on the ground—to which researchers and equipment designers could efficiently and accurately respond. Over time, these standard interfaces would also permit the accumulation of experience that could be passed on to new users and provide them with the lessons learned by prior investigators.

The current SSFF Core concept was intended to function as a dedicated facility for high-temperature materials-science research. The question now is whether its capabilities can be extended to permit it to become a general facility for microgravity research in materials science and engineering. Most of the scientific and engineering issues of concern in high-temperature materials processing have counterparts in more modest temperature ranges. All experiments in microgravity materials science and engineering will require data input/output and storage capabilities, control hardware, power distribution, and active vibration isolation. The current SSFF Core concept has all of these capabilities, and, therefore, there is every reason to believe that the Core, with some redesigning, could accommodate important experiments in more broadly defined areas of materials science and engineering. Although the committee can only speculate about microgravity research in areas other than those for which the Core was originally designed, any concerns are likely to be more than offset by the broader range of experiments that could become possible and materials classes that could become involved.

Recommendation. To expand the range of experiments and classes of materials that the SSFF Core can support, the current concept should be adapted to serve a broader range of experimental instruments than the modular furnaces for which it was originally designed.

To support this expanded research program, NASA should consider making the following modifications to the current SSFF Core concept:

- re-examining all equipment in the current SSFF Core concept in terms of its applicability to the broadest range of materials research areas and experiments
- extending the temperature-control capabilities to lower temperatures
- adding capabilities to support containerless experiments
- installing a suitable vacuum system
- accommodating (1) small quantities of other gases (e.g., oxygen or air) within safety guidelines, (2) fire-suppression systems so oxidizing gases could be used, (3) larger quantities of gases, and (4) control elements for gas handling (e.g., mass flow control and venting systems control)
- adding liquid-mixing and liquid-flow control capabilities for materials research involving a liquid state
- re-examining the adequacy of the power supply to produce the requisite high temperatures, levitation, and damping

The committee believes that some aspects of polymer, ceramic, and glass research merit serious consideration for inclusion in the microgravity materials research program, but enlarging the program raises two issues of concern. First, the desire to expand the program could unintentionally cause the implementation of a quota system. In expanding the range of the microgravity research program's interests, NASA must not allow diversity to become a driver unto itself, which could result in the displacement of projects with great potential value or impact. Second, the current SSFF Core concept is best suited for experiments on metals and semiconductors in which high temperatures and their rates of change are the principal variables. The desirability of substantially redesigning the SSFF Core hardware systems to enable research on polymer, ceramic, or glass materials requires careful consideration. Redesigns should probably be undertaken in areas where modifications will clearly enable a broader program with little effort or collateral costs. Any substantial redefinition of the microgravity materials science research plan or redesign of the SSFF Core must be driven by the needs of a coherent, broad-based, high-impact program of materials research carried out in a microgravity environment, and any potential studies of polymeric, ceramic, and glass materials must be evaluated in the context of this larger research program.

Recommendation. If potentially high-impact polymeric, glass, and ceramic materials research is to be pursued, NASA should make it a priority of the *reconstituted* DWG and SWG to determine which programs have the highest potential for making significant contributions to the field of microgravity materials science research, what ranking among these programs is appropriate when they are placed in competition with each other, and what design modifications to the SSFF Core concept should be implemented to accommodate these new areas. These determinations will only be valid, however, if they are performed by new working groups with representatives from all the possible areas of microgravity materials science research and thus can debate the issues in a balanced and objective manner.

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Microgravity Research and the Space Station Furnace Facility Core

This chapter is divided into two sections. The first section is an overview of the materials-science microgravity research program implemented by the National Aeronautics and Space Administration (NASA) and a discussion of the relevance of microgravity research to the material science and engineering community. The second section contains a description of the specifications and capabilities of the current Space Station Furnace Facility (SSFF) Core concept.

NASA'S MICROGRAVITY MATERIALS-SCIENCE RESEARCH PROGRAM

The general goal of the programs within NASA's Microgravity Research Division (MRD) is to conduct basic and applied research under microgravity conditions (10^{-6} g) that will further our understanding of fundamental physical, chemical, and biological processes. Specifically, the five main areas of research within the MRD are biotechnology, combustion science, fluid physics, fundamental physics, and materials science.

The microgravity environment of space provides a unique opportunity to further our understanding of various materials phenomena involving the molten, fluidic, and gaseous states by reducing or eliminating buoyancy-driven convection effects. The space environment also permits containerless processing, thus eliminating impurities and stresses introduced by contact with the container walls. Although under special circumstances density-matching can be used to eliminate convection in the Earth's gravity field, the selection of the component materials is limited. Furthermore, density-matching occurs at only one temperature. Sample levitation for containerless processing can sometimes be accomplished in a terrestrial environment, but it requires large induced currents or acoustic pressure gradients.

The anticipated results of microgravity materials-science research range from establishing baselines for fundamental materials processes to generating results with more direct commercial significance. NASA's objectives for the microgravity materials-science program include:

- advancing our knowledge base for all classes of materials
- designing and facilitating the execution of microgravity experiments that will help achieve this goal
- determining road maps for future microgravity studies
- contributing to NASA's Human Exploration and Development of Space enterprise
- contributing to the national economy by developing enabling technologies valuable to the U.S. private sector

To accomplish these goals, the materials-science program has tried to expand both its scientific scope and the research community's involvement in microgravity research. Based on their requirements for experimental facilities, most of the current materials-science microgravity experiments can be divided into four general categories. The first category involves melt growth experiments, such as those used for processing multicomponent alloys from the liquid. The experiments in this category frequently require high temperatures and closed containers or crucibles to prevent elemental losses. The second group includes aqueous or solution growth experiments for materials like zeolite or triglycene sulfate. These experiments usually require moderate to low temperatures. Hydrothermal processing of inorganic compounds and sol-gel processing also fit in this category. The third category of experiments involves vapor or gaseous environments, such as those used for growing mercury iodide or plasma processing. Unlike the first three categories that use containers for the parent materials and products, the fourth category involves processes and experiments that require containerless processing environments. Examples of these experiments include the formation of metallic and nonmetallic glasses during levitation melting and solidification, the float-zone growth of crystals, and the measurement of thermophysical properties like diffusion coefficients and surface tension.

Although the SSFF Core on the International Space Station (ISS) is envisioned as the primary dedicated facility for materials-science microgravity research, a number of other facilities are currently available for short-time, low-gravity experiments (e.g., drop towers and parabolic flights of aircraft and sounding rockets). These reduced gravity facilities are used primarily for preflight developmental work. The ISS will also be able to accommodate experiments using the EXPRESS racks, microgravity science glove-boxes, and other facilities that are currently used on the Space Shuttle missions.

The research areas originally identified by the MRD included the following materials classes: electronic and photonic materials, glasses and ceramics, metals and alloys, and polymers and nonlinear optical materials. The MRD subsequently formed an 11-member Materials Science Discipline Working Group (DWG) to review the science priorities, implementation plan, and long-term strategy of the materials-science program; develop advocacy and outreach programs for the MRD to promote microgravity research; and help the MRD compile information and assessments of the microgravity program for external review bodies. The primary mechanism for obtaining broader input into the MRD materials-science program and for informing the community of the current program content and future research opportunities has been through biannual Microgravity Materials Science conferences. Conferences organized by the DWG and hosted by the Marshall Space Flight Center in 1994 and 1996 (NASA 1996) were attended by approximately 300 to 350 scientists. Additional input was provided by two National Research Council reports: *Towards a Microgravity Research Strategy* (NRC, 1992) and *Microgravity Research Opportunities for the 1990s* (NRC, 1995).[1] Based on the input from these conferences and reports, the DWG identified fundamental physical and chemical phenomena research areas that it believed would benefit from long-duration microgravity conditions. Promising subjects for investigation identified by the DWG included:

- nucleation and metastable states
- prediction and control of microstructure, pattern formation, and morphological stability
- phase separation and interfacial phenomena
- transport phenomena

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[1] NASA also supports some in-house research through the University Space Research Association, but these activities follow a separate funding process and were not reviewed by the current committee.

- crystal growth, defect generation, and control
- extraterrestrial processes and technology development (e.g., welding in a vacuum and exploiting extraterrestrial materials for fuel, etc.)

The DWG also recommended the support of such ground-based activities as process modeling and materials characterization that support microgravity research projects.

SPACE STATION FURNACE FACILITY CORE CAPABILITY

The SSFF was conceived to provide a set of common services that would support a wide range of high-temperature microgravity materials-science experiments on the ISS. NASA defines the purpose of the SSFF as follows:

> The purpose of the Space Station Furnace Facility project is to provide a modular facility for materials research in the microgravity environment of the International Space Station. The SSFF will be designed for crystal growth and solidification research in the fields of electronic and photonic materials, metals and alloys, and glasses and ceramics. The SSFF will allow for experimental determination of the role of gravitational forces in solidification, crystallization, and thermophysical property measurement. The facility will provide a capability for basic scientific research, and will evaluate the commercial viability of low-gravity processing of selected technologically important materials.
>
> (NASA, 1994)

This report focuses on the Core of the SSFF, which will provide the *mechanical, power, and control infrastructure* to support an array of experiment modules (EMs). The EMs will contain the actual hardware (e.g., furnaces, samples, thermocouples) in which the experiments will be conducted and, whereas the SSFF Core is being developed and constructed by NASA, the EMs will be separately developed by Principal Investigators in conjunction with independent equipment manufacturers.

The reasons for providing a common infrastructure via the SSFF Core are to (1) reduce experiment implementation times by providing major generic subsystems that have long lead-times; (2) reduce the up-mass and down-mass required for materials-science investigations; (3) provide flexibility in responding to evolving priorities of the materials-science research community; (4) reduce costs by eliminating the development, fabrication, and verification of redundant hardware and software systems; (5) reduce costs by providing common ground-support equipment, laboratory hardware, and operations support; and (6) facilitate the integration of new experiments. The committee did not have the expertise to assess the perceived cost/benefit advantages of a SSFF Core. The committee believes, however, that hardware integration with the SSFF Core could reduce instrument-development time by providing standardized interfaces—both in space and on the ground—to which researchers and equipment designers could efficiently and accurately respond. Over time, these standard interfaces would also permit the accumulation of experience that could be passed on to new users and provide them with the lessons learned by prior investigators.

The SSFF Core concept was initially devised during the late 1980s and early 1990s, based on recommendations from the DWG; the SSFF Intercenter Science Advisory Panel, which consisted of two representatives from the NASA Langley Research Center, one from the NASA Marshall Space Flight Center, and one from the NASA Jet Propulsion Laboratory; five public workshops hosted by the Marshall Space Flight Center; and a study by Teledyne Brown, a hardware fabricator for NASA with headquarters in Huntsville, Alabama. The SSFF Science Working Group (SWG) was formed in 1995 to provide advice directly to the SSFF project scientists during the development and early operation of the Core and to guide its functional and operational design. The SWG consists of 22 members from government, academia, and industry. Members are appointed for two years. The present membership is heavily weighted toward metals and semiconductor specialists, most of whom have active microgravity research projects with NASA. Two of the members are also on the DWG. The SWG has met twice: once in March 1995 to review the SSFF Core concept prior to its Critical Design Review and once in March 1997 to review the project status and assess potential new science requirements.

To support a broad range of high-temperature materials-science experiments, the SSFF Core must be able to support a wide variety of "simple" and "intelligent" EMs. Simple EMs do not contain computer or control circuitry and are totally dependent on the Core for all of their control resources (e.g., command, control, signal conditioning), as well as for basic infrastructure requirements (e.g., power, cooling, gas, communications, vacuum/waste-gas systems). Intelligent EMs have their own computer and control capabilities and only rely on the Core for their infrastructure needs. The technical specifications for the Core are provided in Appendix A.

The current SSFF Core concept consists of three racks (Figures 1-1 and 1-2). The central, or core, rack will contain the support equipment, and each of the side racks, or instrument racks (IRs), will contain connection equipment to accommodate two standard-sized or one larger EM. In the current concept, two EMs are supposed to be able to run simultaneously, one in each IR. The operation of the EMs would have to be carefully orchestrated to ensure that their combined infrastructure-requirements remain within the limits currently specified for the Core facility (e.g., amount and quality of power, gases, vacuums). Thus, although some functionality can be provided within individual EMs, the SSFF Core imposes overall constraints.

The SSFF Core will operate for 120 days per year. Time limits for the Core were established based on the resource needs (e.g., power, microgravity, crew time) of the other scientific research facilities on the ISS. Each research facility on the ISS can function for only 20 to

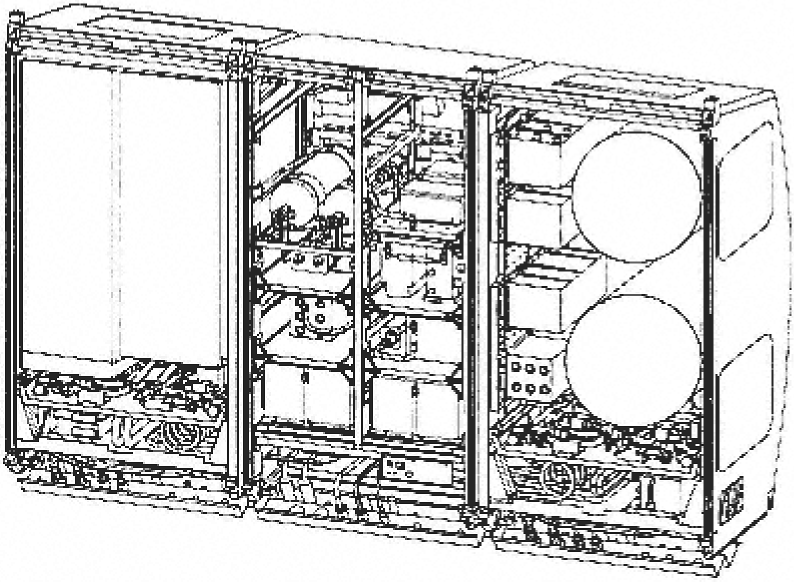

Figure 1-1
Schematic illustration of the Space Station Furnace Facility (SSFF) Core with experiment modules. Source: Microgravity Research Program Office, Marshall Space Flight Center.

30 percent of the year. This time will usually be broken down into 30-day segments. These segments will also be interrupted by periodic events that will compromise the microgravity environment (e.g., docking by space shuttles, exercising by astronauts, reorienting the ISS). One IR will be replaced every two years; thus, each IR will remain on the ISS for a total of four years. EMs can be changed within an IR if the wiring configurations are similar and crew time is available. Samples can also be changed within an EM on the ISS, depending on the complexity of the process and the availability of crew time.

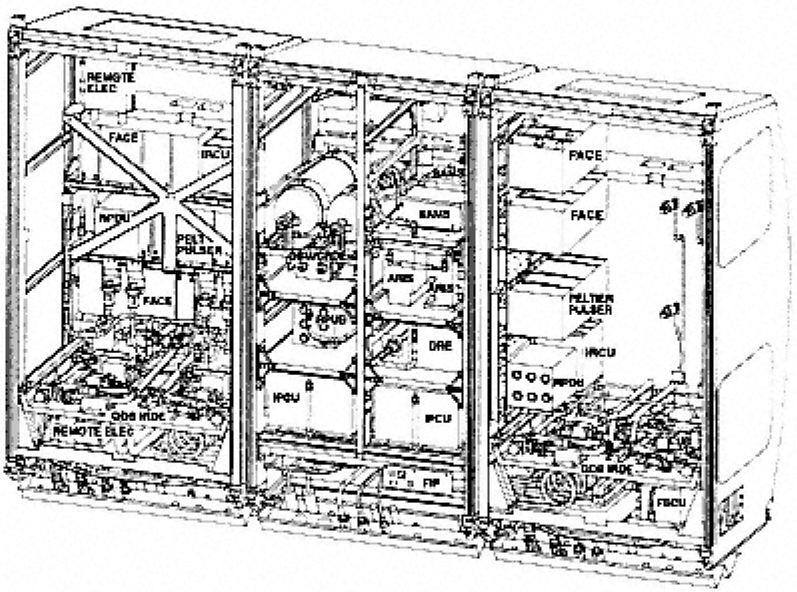

Figure 1-2
Schematic illustration of the Space Station Furnace Facility (SSFF) Core without experiment modules. Source: Microgravity Research Program Office, Marshall Space Flight Center.

Meaningful research in the SSFF Core will be impossible if a microgravity environment cannot be maintained. When the ISS was initially conceived, microgravity conditions were supposed to be maintained on a station-wide basis. In the current ISS concept, however, the IRs must maintain their own microgravity conditions.

In order to maintain microgravity conditions, the IRs must be isolated from the transient, oscillatory accelerations (termed "*g*-jitter") of the ISS via the active rack isolation system (ARIS), which is currently being developed by Boeing. ARIS consists of mechanical, electrical, and electronic assemblies that will be installed in the IRs and connected to the ISS via stabilizing rods. When ARIS detects a vibratory acceleration, it will actuate devices on the IR to compensate by either pushing or pulling on the connector rods in the opposite direction of the acceleration. ARIS is designed to compensate for vibratory accelerations between 0.01 and 300 Hz. The performance of ARIS will be compromised if the vibratory accelerations are outside the specified range (e.g., if a rack is accidentally jarred) or if IR operation exceeds maximum allowed payload disturbance levels. ARIS will require approximately 2.5 cm of rattle space between racks and approximately 8 cm of floating space at the top of the racks. To minimize the levels of vibration to be controlled by ARIS and ensure that *g*-jitter levels remain within IR specifications, NASA has also stipulated that all umbilicals (cables and hoses) for the IRs have minimal stiffness. The umbilicals are still being developed, and a recent space shuttle flight test of ARIS was not successful.

Finding. Meaningful research in the SSFF Core will be impossible if a microgravity environment cannot be maintained. The success of the SSFF Core therefore depends on the perfection of ARIS or the development of an alternative system for controlling *g*-jitter.

2

NASA's Microgravity Research Solicitation and Selection Processes

The general goal of NASA's microgravity materials-science research program is to conduct basic and applied research under microgravity conditions ($10^{-6}g$) that expands the knowledge base of materials behavior. To accomplish this goal, the research program must be able to stimulate and identify research proposals of the highest caliber. The inventory of materials-science research experiments in the microgravity research program ultimately depends on the success of the proposal solicitation and selection processes.

This chapter is divided into two sections. The first section is an overview of the solicitation and selection processes of NASA's microgravity materials-science program. The second section is a discussion of the inventory of research projects in NASA's microgravity materials-science program and an evaluation of the effectiveness of these processes. Committee recommendations are contained in both sections.

OVERVIEW

All scientific organizations stimulate and identify research proposals in a two-step process. The first step is the solicitation or announcement process, through which the agency advertises research grant opportunities. The second step is the evaluation and selection of the proposals. The following sections contain overviews of these two steps in NASA's materials-science microgravity research program.

Solicitation Process

The solicitation process affects the range and quality of proposals that are stimulated within a research community. The manner in which program goals and characteristics are defined and articulated to the community determines who responds and how they respond.

The materials-science microgravity program solicits research proposals through NASA Research Announcements (NRAs). An example is the NRA issued on December 4, 1996, for awards for the government fiscal year 1998. In the opinion of the committee, the 1996 NRA is thorough and well conceived, and the recommended areas of research are described in great detail. The in-depth description of both flight-and ground-based facilities are particularly important. In the former case, both baseline capabilities and options for investigator-initiated enhancements are described. The descriptions generally indicate the flexibility of available baseline systems and NASA's willingness to work with investigators to customize portions of the facility for special experiments.

Another strength of the 1996 solicitation is that it prominently encourages undergraduate participation in the microgravity research enterprise. In addition to the intrinsic merit of providing opportunities for undergraduates to participate in real research projects, this initiative could significantly increase interest in the microgravity program among future professionals.

Unfortunately, the sections concerning the current SSFF Core concept are not of the same high quality. Whereas the descriptions of the ground-based facilities provide researchers with sufficient descriptions and parameters for reduced gravity environments, the description of the current Core concept does not provide an adequate description of its flexibility. The very name of the SSFF, in fact, suggests that it can only support high-temperature experiments. Although the committee recognizes that the SSFF Core is still in the concept and development stages, the key issue is whether the baseline facilities will be sufficiently flexible to support a broad range of research opportunities.

Finding. The 1996 NRA is well conceived and thoroughly describes the research areas, the ground-based and flight-based facilities, and the desirability of undergraduate participation. The NRA does not provide a similar level of detail about the flexibility and usefulness of the current SSFF Core concept.

Recommendation. NASA should provide more information in future NRAs on the flexibility and usefulness of the current SSFF Core concept. NASA should also consider changing the name of the SSFF Core to the Space Station Materials Research Facility or some other more inclusive title that would give researchers more insight into its scientific objectives and experimental flexibility.

Evaluation and Selection Process

The evaluation and selection process is also effectively conceived and designed. A strong feature of the process is that it contains extensive external peer-review by scientists both with and without microgravity materials-science research experience. Another proven evaluation strategy that is incorporated in the present external peer-review process is the grouping of proposals according to common themes, which facilitates comparative evaluations.

The total review process has been divided into three stages: (1) Initial Proposal Review, which leads to initial funding decisions for basic ground-based microgravity research; (2) Science Concept Review, which recommends further ground-based research in preparation for potential flight-based experimentation; and (3) Requirements Definition Review, which recommends hardware design and development in preparation for final flight-based experimentation (i.e., Flight Definition). The Requirements Definition Review process is also divided into three sections: (1) Objectives of Requirement Definition Review, (2) Science Review, and (3) Engineering Review. The evaluation factors for each stage of the review process appear to be defined precisely and appropriately.

For the Initial Proposal Review, the evaluation factors are related to scientific merit. Although the proposals must articulate a need for a microgravity environment—preferably quantitatively—arguments for the ultimate viability of the research as a flight experiment are not required. Thus, decisions are not based on perceptions of present or future hardware capabilities, which is critically important both for ensuring opportunities for investigators who may not be knowledgeable initially about the details of flight systems and operations and for ensuring that hardware-based biases do not inadvertently work against scientific experiments with high intrinsic merit.

Finding. System design should not be the criterion that defines program opportunities. The programs selected for flight must be those that will benefit science, engineering, and technology, and thus society, most significantly.

Recommendation. NASA should continue to ensure that perceived flight viability (i.e., current and projected hardware capabilities) does not influence the Initial Proposal Review segment of the selection process.

The assignment by NASA of a project scientist to work with the Principal Investigator to develop the Science Requirements Document, which is the basis for the second stage of the review cycle (i.e., the Science Concept Review), is an effective method of assisting Principal Investigators in making the transition from fundamental research idea to flight experiment concept.

In the committee's opinion, a possible weakness in the current NASA review process is that the same panel is used both for the second-phase Science Concept Review and for the Science Review component of the third-phase Requirements Definition Review. Although the committee recognizes that continuity and familiarity with a given research project are important, NASA must ensure that reviewer ownership and advocacy do not compromise the evaluation process. One way to do this is to use only a fraction (e.g., less than half) of the Science Concept Review panel members in the later Science Review.

INVENTORY OF RESEARCH PROJECTS

One indication of the success of a solicitation and selection process is by the scientific balance of the inventory of research experiments that are chosen. Although the first priority must always be scientific merit, a concentration of proposals in a subset of research areas could indicate that the solicitation process is not reaching the entire community or that a segment of the community has not been convinced of the merit of the program and the applicability of the facilities.

As Table 2-1 shows, the greatest number of materials-science microgravity projects in 1997 was in the area of metals and alloys (i.e., 32 of 71 Principal Investigators have expertise in this area). The number of projects in the area of electronic and photonic materials was also high (26 Principal Investigators), with most involving semiconductor research. The current selection procedure has had less success in developing a broad-based, high-impact program of research for either polymeric materials (6 Principal Investigators) or glasses and ceramics (7 Principal Investigators). Only 22 polymer proposals were received in response to the 1996 NRA compared with 75 proposals in metals and alloys and 70 proposals in electronic and photonic materials.

TABLE 2-1 Expertise of Materials-Science Microgravity Principal Investigators in 1997

	Number of Principal Investigators (PIs) in Ground-Based Research		Number of PIs in Flight Definition Research		Number of PIs in Flight Research	Total
	Ongoing	New	Ongoing	New		
Metals and Alloys	9	11	1	3	8	32
Electronics and Photonics	6	11	1	2	6	26
Glasses and Ceramics	3	4				7
Polymers	1	5				6
Total	19	31	2	5	14	71

Many factors may have contributed to this imbalance in the research program, chief among them the nature of the materials themselves. The nature of the sintering process in ceramics and the viscous character of typical high-polymer melts greatly desensitizes their responses to gravitational acceleration, making the value of a microgravity environment in experiments on these classes of materials less obvious than on metals and semiconductors. The underrepresentation of polymeric, glass, and ceramics materials research within the materials-science microgravity program may thus result from a perceived lack of benefits of the microgravity environment by these research communities. Promising areas of microgravity research do exist for these materials classes, however, as will be seen in Chapter 3. To increase their participation, the communities must be effectively informed of the potential benefits of the research program as well as opportunities for participation. NASA needs to develop effective outreach methods to establish links to the best and brightest members of the community and thus to promote an understanding and appreciation of the microgravity research program, the opportunities it offers, and the ways researchers can make contact with relevant personnel within the NASA-affiliated programs and organizations.

NASA must also determine how programs of microgravity research in these areas can best be identified and developed, given a flight schedule that provides limited opportunities and requires lengthy lead-times. The current average time to reach flight status—seven years—is an extremely long event horizon for a senior scientist and an eternity for a junior one. The time factor is especially important if the NRA process is to attract the best possible proposals. To ensure the strong growth of the program and the selection of cutting-edge research, topics and areas previously identified by NASA for support must be continually challenged by new program ideas. The strongest possible programs will only evolve through broad-based, open competition.

Recommendation. Although the first priority in selection must always be scientific merit, the microgravity materials-science program should be proactive in developing an effective outreach program (e.g., via organized sessions at professional society meetings) that conveys the benefits of the microgravity research program and stimulates proposals from segments of the materials research community that appear to be underrepresented in the current research portfolio.

In the opinion of the committee, identifying research opportunities in ceramic, glass, and polymeric materials and disseminating them to the targeted communities would be aided by increasing the representation of these research areas on the DWG and SWG. The DWG and SWG have made significant contributions to the materials-science microgravity program, but their membership is currently weighted toward metallurgical and semiconductor research. Broader expertise would enable both groups to identify high-impact research opportunities, develop an active program in those areas, and ensure that the SSFF Core can meet their needs. For example, limitations on the Core capabilities at low temperatures (less than 500°C) and lack of other specialized needs will limit its usefulness for research on polymeric, ceramic, or glass materials.

A significant number of members of the DWG and SWG are also recipients of NASA funds to conduct microgravity research. Although NASA made a concerted effort to limit the number of DWG members receiving NASA funds, many of the members have applied for and received microgravity research grants since joining the DWG. Two members of each group are also NASA employees.

Recommendation. The membership of the DWG and the SWG should be reconstituted so that their collective expertise covers not only the scientific areas of the current microgravity experiments but all materials areas with the potential for meaningful microgravity research (e.g., ceramics, glasses, polymers, and biomaterials). To ensure objectivity, the MRD should also institute and vigorously maintain a protocol for the DWG and the SWG that ensures a proper balance between recipients and nonrecipients of NASA funds (e.g., 1:1) and independence from NASA personnel, who may be directly involved in the program.

The committee believes that some aspects of polymer, ceramic, and glass research merit serious consideration for inclusion in the microgravity materials research program (see Chapter 3), but enlarging the program raises two issues of concern. First, the desire to expand the program could unintentionally cause the implementation of a quota system. In expanding the range of the microgravity research program, NASA must not allow diversity to become a driver unto itself, which could result in the displacement of projects with great potential value or impact. Second, the current SSFF Core concept is best suited for experiments on metals and semiconductors in which high temperatures and their rates of change are the principal variables. The desirability of substantially redesigning the SSFF Core hardware systems to enable research on polymer, ceramic, or glass materials requires careful consideration. Redesigns should probably be undertaken in areas where modifications will clearly enable a broader program with little effort or collateral costs. Any substantial redefinition of the microgravity materials science research plan or redesign of the SSFF Core must be driven by the needs of a coherent, broad-based, high-impact program of materials research carried out in a microgravity environment, and any potential studies of polymeric, ceramic, and glass materials must be evaluated in the context of this larger research program.

Recommendation. If potentially high-impact polymeric, glass, and ceramic materials research is to be pursued, NASA should make it a priority of the *reconstituted* DWG and SWG to determine which programs have the highest potential for making significant contributions to the field of microgravity materials science research, what ranking among these programs is appropriate when they are placed in competition with each other, and what design modifications to the SSFF Core concept should be implemented to accommodate these new areas. These determinations will only be valid, however, if they are performed by new working groups with representatives from all the possible areas of microgravity materials science research and thus can debate the issues in a balanced and objective manner.

3

Ability of the Space Station Furnace Facility Core to Support Materials Science Experiments that Require a Microgravity Environment

This chapter contains descriptions of the broad categories of microgravity materials-science experiments that could yield significant information that is unattainable in a terrestrial gravity field. It also contains assessments of the ability of the current SSFF Core concept to support research on metals and alloys, semiconductors, ceramics and glasses, and polymers. The chapter ends with the committee's overarching conclusions and recommendations about the current SSFF Core concept.

The committee's evaluations of the applicability of the current SSFF Core concept to the needs of the metals and alloys research area and the electronic and photonics (semiconductor) research area are largely based on the 13 projects NASA has already selected as candidate investigations for the ISS (Table 3-1). Because the ceramics, glasses, and polymers areas are underrepresented in the current microgravity materials-science program, potential areas of high-impact research were suggested by the committee and thus are more speculative. Core capabilities required by expanding the program to accommodate areas not included in the current list of 13 are then specified in the report.

The committee also attempted to evaluate the ability of the SSFF Core to support biomaterials research but could not identify any areas in which the Core could directly serve the needs of this research community. Biomaterials researchers will be more likely to exploit the

TABLE 3-1 Principal Investigators, Affiliations, and Program Titles for the Research Projects Selected in Response to 1991 and 1994 NRAs

Principal Investigator	Affiliation	Title	Materials
Prof. B. Andrews	University of Alabama, Birmingham	Coupled Growth in Hypermonotectics	Al-Mn
Prof. D. Stefanescu	University of Alabama, Birmingham	Particle Engulfment and Pushing by Solidifying Interfaces	Al and Al-Ni + SiC and zirconia particles
Prof. D. Mattiesen	Case Western Reserve University	Diffusion Processes in Molten Semiconductors	Ge:Ga Ge:Sb Ge:(Si,Ga)
Prof. K. Bachmann	North Carolina State University	Fundamental Aspects of Vapor Deposition and Etching under Diffusion Controlled Transport Conditions	$Ga_xIn_{1-x}P$ and $Ga_xIn_{1-x}N$ on Si, Ge, sapphire, and III–V
Prof. R. Bayuzick	Vanderbilt University	Investigation of the Relationship between Undercooling and and Solidification Velocity	NiSn NiSi NiTi TiAl Ti-Oxygen
Prof. C. Beckermann	University of Iowa	Equiaxed Dendritic Solidification Experiment	ultrapure succinonitrile
Prof. W. Johnson	California Institute of Technology	Physical Properties and Processing of Undercooled Metallic Glass Forming Liquids	metallic glasses containing Zr, Ti, Be, Ni, Nb, Cu, Co
Prof. D. Larson	State University of New York, Stony Brook	Orbital Processing of Eutectic Rod-Like Arrays	Bi/MnBi
Prof. A. Ostrogorsky	Rensselaer Polytechnic Institute	Space-Based and Ground-Based Crystal Growth Using Magnetically Coupled Baffle	Doped GaSb and Ge (possibly GaInSb)
Prof. D. Poirier	University of Arizona	Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments	Pb:23%Sn Al:15%Cu
Prof. F. Rosenberger	University of Alabama, Huntsville	Self-Diffusion in Liquid Elements	up to 20 elements
Dr. C.-H. Su	NASA/Marshall Space Flight Center	Crystal Growth of ZnSe and Related Ternary Compound Semiconductors by Vapor Transport	ZnSe, ZnS_xSe_{1-x} $ZnSe_{1-x}Te_x$ $Zn_{1-x}Cd_xSe$
Prof. R. Trivedi	Iowa State University	Interface Pattern Selection Criterion for Cellular Structures in Directional Solidification	Al:4wt%Cu Al:15wt%Cu

unique microgravity capabilities of the space station through specifically designed experimental modules that will be housed outside the SSFF Core. NASA should continue to monitor this potentially high-impact materials-science research area, however.

METALS AND ALLOYS

An analysis of the entire microgravity materials-science research program (Table 2-1) and the candidate investigations selected for the ISS (Table 3-1) shows that the subdiscipline of metals and alloys currently constitutes a substantial portion of the entire MRD materials-science research program. The importance of metals and alloys in NASA-sponsored microgravity research was recognized in the National Research Council report, *Microgravity Research Opportunities for the 1990s*: "The microgravity environment, by reducing . . . gravity-driven phenomena, clearly offers new opportunities to metallurgists to understand and enhance control of materials processing" (NRC, 1995).

Nucleation and Metastable States in the Microgravity Environment

In many materials systems, phase transformation occurs through a nucleation and growth process. In heterogeneous nucleation, nuclei form on heterogeneities in the system, such as container walls, impurity particles, or line defects. In homogeneous nucleation, nuclei form spontaneously through thermodynamic fluctuations within the volume of the parent phase. In almost all cases, heterogeneous nucleation occurs before conditions are reached that would permit homogeneous nucleation. Containerless processing eliminates many of the nucleation sites that prevent significant undercooling of the melt. Deep supercooling may lead to the formation of new, nonequilibrium crystalline and amorphous phases. A microgravity environment makes containerless processing possible without resorting to levitation by induced currents or acoustic pressure gradients. Research on containerless processing to attain deep undercoolings in metals and alloys is a key sector of the current MRD flight program (Bayuzick, 1997a; Flemings, 1997a), as well as of the extensive ground-based research program (Arnold, 1997; Bayuzick, 1997b; Flemings, 1997b; Robinson, 1997; Spaepen, 1997).

Microstructures Resulting from Solidification in a Microgravity Environment

Understanding of the microstructures that result from alloy solidification can be increased by critical experiments conducted in a microgravity environment. Microstructures in cast materials, for example, can be manipulated by controlling the alloy composition and rate at which solidification takes place. During solidification, an initially smooth liquid/solid interface can behave in an unstable manner, developing an interface structure containing bumps or even tree-like structures called dendrites. A mixed-phase region known as a "mushy zone" develops before the portion solidifies. Heat and mass transfer processes that occur in the mixed-phase zone determine the final microstructure and properties of the solid (Chalmers, 1964).

A considerable body of theoretical and experimental research has been accumulated on interfacial instabilities and microstructure formation upon solidification (e.g., Glicksman and Marsh, 1993; Martin et al., 1997). Theories generally ignore the influence of fluid convection, although it occurs in experiments carried out in a terrestrial environment. A series of experiments conducted on sounding rockets, aircraft flying in parabolic orbits, and space shuttles have shown that the microstructure is indeed affected by a reduced gravity environment (Johnston and Parr, 1982; Glicksman and Koss, 1994; Fripp, 1996; Abbaschian, 1997).

Most engineering alloys contain two or more phases in the solid state. If certain eutectic (Pirich and Larson, 1982), peritectic (Lograsso, 1997), or monotectic (Andrews, 1997) alloys are directionally solidified in either terrestrial or reduced gravity, aligned microstructures result. These alloys may be regarded as in situ composites. A technologically important example of a eutectic alloy with an aligned microstructure is manganese-bismuth, which has an extraordinarily high magnetic coercivity that approaches the theoretical limit (Pirich and Larson, 1982). The size and spacing of the magnetic phase in material solidified on earth with a strong convective flow agree with theory, whereas a pronounced discrepancy is found in samples solidified in a microgravity environment. Similar discrepancies have been observed in other low-gravity experiments (Spacelab-I and D-1, which flew in 1985). There is still much to be learned about eutectic solidification.

Phase coarsening (or Ostwald ripening) is another phenomenon that can contribute to the microstructural evolution of an alloy. Prolonged exposure to elevated temperatures causes the larger particles in a particle-strengthened alloy to coarsen at the expense of the smaller ones. This process, which is driven by a reduction in the free energy associated with the interfacial energy, degrades the strength of the alloy. Similar changes occur to dendrite arms in castings. On a recent shuttle flight that was terminated prematurely, a "glove-box" style experiment was attempted to obtain convection-free kinetic and microstructural coarsening data on tin-lead alloys (Voorhees, 1997). Similar, well defined microgravity experiments conducted at larger scales and for longer durations are needed to quantify the underlying physics of phase coarsening under purely diffusive solute transport. These experiments might require relatively long durations (many weeks) at microgravity levels (10^{-6} g) to gather data of sufficient quality to draw meaningful scientific conclusions.

Phase-Separating Systems and Interfacial Phenomena

Another class of multiphase materials of interest in microgravity research are immiscible systems. At any temperature below a critical temperature, a range of compositions exists for which the melt separates into two distinct liquids. In the Earth's gravity, the two liquids will stratify before they solidify because of mass-density differences. The result is a macroscopically segregated solid. However, buoyancy-driven sedimentation should be largely eliminated in a microgravity environment. So far, microgravity experiments have been only partially successful in producing uniform dispersions (Lacy and Otto, 1975), indicating that effects other than buoyancy-driven sedimentation are also important. An extensive series of ground-based experiments has uncovered a rich variety of interfacial effects, such as critical wetting and particle pushing (Stefanescu, 1997a). The microstructures of immiscible alloys have now been scientifically classified with the help of microgravity research (Grugel et al., 1982).

Brazing, soldering, and welding are technologically important processes for the Human Exploration and Development of Space enterprise that are influenced by interfacial phenomena (Boatner, 1997). Both wetting and surface-driven flows are primary factors in the successful production of a join.

Solutal Transport

Convective mixing of solute-enriched melt adjacent to an advancing solid/melt interface causes segregation to occur throughout the solidified specimen. When the flow rate varies in time, a solid may result with a composition profile that exhibits periodic bands of composition. These important but complex phenomena have been studied throughout the entire history of microgravity research. MRD research currently supports experimental flight programs on solutal segregation (Lehoczky, 1997; Matthiessen, 1997). MRD also supports ground-based studies on the modeling and measurement of complex solutal transport phenomena (Brown, 1997; Stefanescu, 1997b; Alexander, 1997). In a microgravity environment, unique microstructures could potentially be produced in a variety of systems (e.g., off-eutectic compositions, monotectics, syntectics, and peritectics) that would normally separate into different phases in terrestrial gravity as well as in solid solutions that are subject to double-diffusive convection. Liquid-phase sintering of heavy metal particles dispersed in lower-density transition alloys (typically cobalt-based) is the basis of the hard-materials industry for machine tools and a good example of a commercially important process that was recently investigated as a small-scale microgravity experiment (German, 1997).

Ability of Space Station Furnace Facility Core to Support Microgravity Metallurgical Research

The current SSFF Core concept is particularly useful for high-temperature metals and alloys research. However, the concept does not support studies on low-temperature metals and alloys, which are not only scientifically and technologically important but can also serve as models for high-temperature materials, thus reducing the cost and time of experimenting at high temperatures. In addition, the current SSFF Core concept does not have the levitation capabilities required for containerless experiments. Some of the candidate experiments require containerless environments, however, so the Core should incorporate provisions for levitation capabilities in both gaseous and vacuum environments.

SEMICONDUCTORS

Five of the 13 research projects selected by NASA as candidate investigations for the ISS (Table 3-1) are directly pertinent to semiconductor crystal growth. Based on these five investigations and the 1996 NRA, this section discusses the relevance of the type of semiconductor research to be conducted in the microgravity environment and the ability of the current SSFF Core concept to support this research.

Microgravity Semiconductor Research

The two goals of studies of semiconductor growth should be to provide information that improves the understanding of the crystal growth process and/or improves the growth of terrestrial bulk crystals. The three fundamental physical phenomena identified by the DWG (Chapter 1) as worthy of study under long-duration microgravity conditions that are directly relevant to semiconductor growth are transport phenomena, defect generation control, and surface tension gradient driven flows. The same consideration of the effects of interfacial instabilities during solidification and the advantages of eliminating buoyancy-driven convection discussed in the section on the growth of metals applies to the growth of semiconductors. In the case of single-crystal growth of semiconductors, simply providing crystals that are grown in space, that have lower defect densities, or that are clearly grown in the diffusion regime is not particularly useful to the crystal growth community, even for semiconductors that are difficult to grow on Earth. Unfortunately, previous studies of semiconductor growth in space have only occasionally achieved the two goals specified above.

The section on crystal growth and defect generation control in the December 4, 1996, NRA clearly shows that the elimination of fluid flow in the microgravity environment is complicated by surface-tension-driven convective flow and density-driven flows that might actually be suppressed at one *g* but are enhanced by *g*-jitter and by residual low *g* in directions not normally encountered in terrestrial growth. The suggested solution is the application of magnetic damping during crystal growth in the microgravity environment. This presumably would permit reproducible diffusion-controlled growth.

The NRA goes on to explain that defects, "whether they are impurity atoms or lattice defects, have a major impact on electrical and optical properties." Defects are generated at the container wall/solid/liquid interface, and the degree of fluid motion affects defect concentration and distribution. The detailed relationships between the various parameters for any material, growth method, or container material are unknown, however. The announcement suggests that microgravity experiments "should provide an excellent method for learning more about this important topic." In fact, it is not clear that microgravity studies are required or have a significant chance of generating significant new and useful knowledge in semiconductor research. Careful terrestrial studies using the advanced characterization methods mentioned in the announcement (e.g., atomic force microscopy and synchrotron x-ray topography, along with magnetic damping and even the magnetically coupled baffle) might provide more useful opportunities in semiconductor research, given the scarceness of space-based research opportunities compared with terrestrial ones. The committee hopes that NASA will vigorously support such terrestrial studies and be particularly careful in selecting for flight only studies for which a successful outcome can reasonably be expected to lead to a deeper understanding of the growth process and the formation of defects.

Also included in the NRA is a section on transport phenomena. The study of transport properties in the liquids from which crystals are grown can provide important experimental data for modeling crystal growth from the liquid. These data are extremely difficult to obtain on earth because of buoyancy convection, and even in the microgravity environment residual *g* effects and surface-tension-driven convection can cause severe problems. However, magnetic damping could be beneficial in this respect.

Three of the five semiconductor-related candidate investigations for the ISS (Table 3-1) are entirely or partly for the study of transport properties in molten semiconductor materials. These experiments could provide valuable data for modeling terrestrial growth. The other two experiments are studies of crystal growth from the vapor. One is intended to provide organometallic chemical vapor deposition growth in the diffusion-controlled regime with reflectance spectroscopy as a diagnostic. The other is presumably a sealed tube experiment for the growth of II–VI compounds, the constituent elements of which are volatile at the growth temperature. It is not obvious in either of these latter studies how studying the growth parameters will provide insights into the fundamentals of how and why defects are formed.

Ability of Space Station Furnace Facility Core to Support Semiconductor Research

The current design for the SSFF Core is particularly well suited to studies of the growth of inorganic crystals by methods conventionally used to grow semiconductors from a melt. These methods generally employ sealed tubes, and growth takes place within the temperature range currently specified for the Core. These methods do not generally require gases or vacuum pumping. The current Core design is also well suited for experiments to determine the diffusivities of the components of the semiconductor (including impurities) in the liquid source because the research projects can be designed as sealed-tube experiments. NASA should consider adding levitation capabilities to the Core concept to support the containerless experiments discussed above, however. Three of the five candidate experiments should be able to take advantage of the current SSFF Core concept. One, or possibly two, require or might benefit from the use of magnetic suppression of residual convection. Two may have requirements beyond the SSFF Core or EM specifications.

CERAMICS AND GLASS

None of the 13 research projects selected by NASA as candidate investigations for the ISS (Table 3-1) can be classified as a true ceramic or glass experiment. One, however, involves semiconductors and crystal growth by vapor phase, which is a process related to some potential ceramic studies, and one is related to metallic glasses. There are eight ongoing and six recently completed ground-based studies that could be classified as ceramic or glass experiments. Current and potential microgravity projects in ceramics and glass, including both high-and low-temperature processing or characterization, and the ability of the SSFF Core to support them are reviewed in this section.

Ceramics Research in Microgravity

Microgravity research in ceramics tends to be less prominent than microgravity research in other materials areas because the major effects of the microgravity environment (e.g., suppression of density-driven transport and reduced convection) are more important in systems that contain a liquid or are in a low-viscosity molten state at some point in the process. Ceramics processing is generally performed in the solid state because the very high melting point and dissociation behavior of ceramics make them unsuitable for processing from melts. Even for processes in which ceramic-metal or other composites are produced via some molten phase, the effect of convection tends to be minimal because of the high viscosities of the melts.

Ongoing ground-based studies provide some insight into the kinds of ceramics research that might be included in the microgravity flight program and would require support by the SSFF Core. Research areas are vapor-phase sintering; oxide melts, including glass synthesis and diffusion; and superconductor processing. Of the six recently completed ground-based projects, two are concerned with vapor-phase sintering, one is based on ambient or low-temperature processing in a liquid, and three concern molten-state glasses or ceramics. The vapor-phase sintering studies require elevated temperatures and possibly reactive atmospheres. The liquid-phase study does not require high temperatures but does require convection and sedimentation control. The melt processing and diffusion studies require elevated temperatures, and one also requires levitation. Of the eight ground-based programs that are currently being conducted, three concern solution processing, one concerns modeling, four concern processing or investigation of oxide melts, and one concerns both oxide melts and metallic glasses. The modeling study appears to have no experimental component at this stage. All of the other projects require elevated temperatures, and at least some will require an oxygen atmosphere. For example, the oxygen content of superconductors is critical, and some processing in air or oxygen will be required in relevant studies. The investigation of immiscibility gaps in mullite may also require an oxygen atmosphere.

There are two areas in which microgravity ceramics research could be important: (1) vapor-phase convection in sintering and degradation and (2) low-temperature solution processing. Convection in the vapor phase is important to certain ceramic sintering processes and in the degradation of ceramics. Vapor-phase sintering studies that have been supported by the microgravity program are relevant. Possible oxidation, corrosion, or vaporization studies would also be important where a gas phase either interacts with a ceramic or vaporizes from a ceramic.

The effects of microgravity on ceramics are most relevant to processes that involve a liquid phase. These are often low-temperature processes that involve solutions or suspensions in which convection and density gradients and differences play a major role in determining homogeneity and final properties. For example, some powder syntheses and certain shape-forming processes are performed in a liquid environment (e.g., sol-gel, coprecipitation, sedimentation and filtration, and hydrothermal synthesis). Although convection is often used to promote mixing thereby producing homogeneous powders or materials, it is possible that processing in microgravity could lead to improved ground-based processing by elucidating the effects of sedimentation and agglomeration on the microstructure of ceramics. Low temperatures also play a role in the use of preceramic polymers for processing ceramics and forming new composite materials or coatings.

In line with the above discussion, the benefits of microgravity research in ceramics are specialized, and the ceramics community in general does not appear to be substantially involved in the program. However, this is only true for ceramic synthesis and processing as it is generally done at this time. There is considerable interest in the ceramics community in developing new, inexpensive methods of fabricating ceramics. Recent trends in ceramics research suggest that additional candidate studies could involve ceramic-metal composites, especially if the metal phase is molten; further work in oxides; and diffusion either in melts or from melts into ceramic preforms, as is done in some composite processing. In many of these experiments, microgravity would elucidate mechanisms. It is possible that future ceramics research might benefit substantially from microgravity research, so it is incumbent upon NASA to provide as fully as possible for ceramics research in the current SSFF Core concept.

Glass Research in Microgravity

Because glasses are processed from melts, melting and crystallization (also called devitrification) of glass are research areas that might benefit from the microgravity environment. Ceramic-glass melting is a capital-intensive process; therefore, modeling is an industrially important prelude to building or modifying a glass tank. Empirical data obtained in a microgravity environment might provide better input for models that are used to predict thermal convection and bubble movement in glass melts. Containerless processing, which would eliminate interactions with crucibles or nucleation from crucibles, could allow for the formation of new glasses with potentially useful properties. The suppression of volatilization of certain species from glass melts because of the suppression of convection may also allow new glass compositions to be produced. Thus, two research trends may be germane to microgravity research: the development of glass compositions with novel properties and the measurement of some thermophysical properties.

Ability of Space Station Furnace Facility Core to Support Ceramic and Glass Research

The committee has four major concerns about the ability of the current SSFF Core concept to support ceramics and glass microgravity research: the lack of levitation capability; the lack of environmental control, especially the lack of gases other than argon and nitrogen (specifically, the lack of oxidizing gases) and the poor vacuum capabilities; the amount of power available to allow a furnace to reach high temperatures (greater than 1200 to 1500°C); and the lack of temperature control from ambient to 500°C.

The current concept design for the Core does not have the levitation capability required to conduct containerless processing experiments on glass. The ground-based experiments also require controlled atmospheres (e.g., inert gases, air/oxygen, and other reactive gases) or vacuum. Gas availability in the current Core concept, both type and quantity, and vacuum quality are also limited. Relatively small quantities of inert gas will be available according to the present Core concept, and no provision has been made for oxygen, air, or other gases in the Core itself. Space and weight considerations clearly prevent the use of large volumes of gas, and fire-containment constraints will limit the use of some gases. Unless suitable alternatives can be devised within the EMs, the lack of oxidizing gases in the Core will preclude some of the current ground-based experiments from becoming flight experiments, and the relatively poor vacuum capabilities will affect experiments that require high-purity conditions.

Many of the current studies require high temperatures. Although none of the temperatures is beyond the current specifications for the SSFF Core (higher than 2300°C), considerable power will be needed to produce the required high temperatures. Actual temperature capability will depend on the furnace design, volume, insulation, gas, and gas throughput. There will clearly be restrictions on running more than one high-temperature (greater than 1200 to 1500°C) furnace at a time, and careful planning will be required to ensure that sufficient power can be delivered to each unit.

Many ceramic experiments are performed at temperatures between ambient and 500°C, a regime for which the current SSFF Core is not designed. To make the current SSFF Core concept more generally useful for ceramics, the temperature capability would have to be extended by the installation of cooling circuits and control strategies that would permit temperature ramps and temperature control in lower temperature ranges. Although the current SSFF Core was designed generally to support higher-temperature studies, the importance of microgravity to low-temperature ceramic processes, the limited volume available in the EMs for experimental hardware, and the lack of other suitable services (e.g., gas availability) make it important to consider changes to the current Core concept to accommodate more ceramic and glass experiments.

POLYMERIC MATERIALS

None of the 13 research projects selected by NASA as candidate investigations for the ISS (Table 3-1) can be classified as a polymeric materials experiment. There are six ongoing ground-based studies that could be classified as polymeric experiments, however. Potential microgravity projects in polymeric materials, including low-temperature processing, and the ability of the SSFF Core to support them are reviewed in this section.

Polymeric Materials Research in Microgravity

A previous National Research Council report (NRC, 1995) concluded that NASA's polymer microgravity materials research was not as well developed as metals and alloys and semiconductor materials because polymers and their solutions are usually too viscous for gravity-driven convection to play an important role in their phase formation or processing. This view is overly simplistic, however. Polymers and their assemblies can be constituted in diverse, complex forms that exhibit low viscosities. Even when non-fluid phases are employed, gravitationally mediated deformations may be of substantial concern. Indeed, there are many reasons to suppose that research conducted in microgravity will enable significant progress in the field of polymeric materials. Given the breadth of this class of materials, it should be considered a strong candidate for further study.

Gravity does affect diverse areas of polymer and organic materials structural development in terms of crystallization and polymerization. Notable examples include the effects of gravitationally mediated shear flows on chain orientation during crystallization, size and shape distributions in emulsion polymerization, and thin-film formation by vapor-phase-transport crystallization of metal coordination complexes. New program directions identified by NASA via the NRA process include aspects of transport and fluid mechanics that impact polymerization processes involving liquid monomers, suspensions, and other complex fluid phases.

Polymers and related materials also present many issues of interest beyond crystallization and polymerization, the understanding of which might benefit from research conducted in a microgravity environment. For example, mesoscale self-assembly is currently an important theme in broad areas of materials research and could constitute the basis for new initiatives in polymer microgravity materials research. These systems, which aggregate particles into large assemblies via forces determined by molecular recognition, also have close analogies in the research themes identified in the colloids and biomaterials initiatives of NASA's microgravity research program. Polymer microfabrication is another area in which structure is affected by mechanical or interface directed deformations, effects that might be subject to manipulation in microgravity.

Ability of Space Station Furnace Facility Core to Support Polymer Research

A major concern in microgravity polymer research is how well the current SSFF Core design will be able to contribute to establishing a broader program in this area. Unless the definition for NASA's microgravity materials science research program is revised, it seems likely that the current polymeric microgravity materials-science program will simply migrate to the Space Station platform in its present form. The availability of the SSFF Core is not likely to have a major impact.

To support a more generalized program of polymer microgravity materials research, three shortcomings would have to be corrected in the current design of the SSFF Core. First, the gas-handling capabilities of the present SSFF Core design are limited. As in ceramics research, the amounts and varieties of gases, including oxygen, would have to be expanded to support polymer research. Second, the ability to control liquid mixing and flows is not included in the Core's envisioned control functions. These capabilities may be essential to studies involving the synthesis of macromolecules. Third, temperature control for polymer research is generally required within the ambient to 500°C range, for which the SSFF Core was not originally designed. Extending the temperature capability by installing cooling circuits and control strategies would be necessary for control within these lower temperature ranges.

CONCLUSIONS AND RECOMMENDATIONS

The current SSFF Core concept was intended to function as a dedicated facility for high-temperature materials-science research. The question now is whether its capabilities could be extended in order for it to become a general facility for microgravity research in materials science and engineering.

Most of the scientific and engineering issues of concern in high-temperature materials processing have relevant counterparts in more modest temperature ranges. All experiments in microgravity materials science and engineering will require data input/output and storage capabilities, control hardware, power distribution, and active vibration isolation. These capabilities are already included in the current SSFF Core concept. Therefore, there is every reason to believe that with some redesigning, the Core could support significant research in broader areas of materials science and engineering. Although the committee can only speculate about microgravity research in areas other than those for which the SSFF Core was originally designed, any concerns are likely to be more than offset by the broader range of experiments that could become possible and materials classes that could become involved.

Recommendation. To expand the range of experiments and classes of materials that the SSFF Core can support, the current concept should be adapted to serve a broader range of experimental instruments than the modular furnaces for which it was originally designed.

To support an expanded research program, NASA should re-examine the facilities in the current SSFF Core with the view of eliminating highly specialized capabilities. For example, a Peltier pulser will serve only a fraction of the experiments in the metals and alloys research area. Its presence should be weighed against the benefit of equipment (e.g., vacuum pump, fire-suppression, or levitation systems) that could be applicable to a larger number of experiments in more materials science research areas.

Recommendation. All equipment in the current SSFF Core concept should be re-examined in terms of its applicability to the broadest range of materials research areas and experiments.

NASA should consider redesigning the current SSFF Core concept in the following ways to facilitate microgravity materials-science research: extending the temperature-control capabilities, adding levitation capabilities, improving vacuum quality, adding gas handling capabilities, adding liquid handling capabilities, and re-examining power availability.

Temperature-Control Capabilities

The temperature-control hardware in the current SSFF Core concept is designed to maintain and program temperature conditions between 500°C and 2300°C. For certain types of experiments in all of the materials research areas, however, it will be important to control temperatures and program conditions well below 500°C (i.e., at temperatures of 25°C to 500°C). The SSFF Core was not originally designed to support experiments in this lower temperature range.

Recommendation. The following changes to the current SSFF Core concept should be considered in order to increase the temperature-control capabilities to lower temperatures and expand the range of experiments in all materials science research areas: increasing the variety of temperature-measuring and temperature-control sensors (e.g., resistance thermometers, thermistors, and pyrometers) that can be accommodated; and adding a coolant loop (e.g., using water or freon) to support low-to moderate-temperature experiments.

Levitation Capabilities

The space environment offers unique opportunities for more precise measurements of some thermophysical properties by allowing the production of containerless or float-zone environments. The current SSFF concept, however, does not have the capability to support levitation research.

Recommendation. NASA should consider adding levitation capabilities to the SSFF Core to support containerless experiments.

Vacuum Quality

The relatively poor vacuum (10^{-3} torr) available in the current SSFF Core concept will have an adverse impact on materials science experiments that require high-purity conditions, unless suitable alternatives can be devised within the EMs.

Recommendation. NASA should consider installing a suitable vacuum system in the SSFF Core.

Gas Handling

In the current SSFF Core concept, only relatively small quantities of inert gas will be available, and no provision has been made for handling oxygen, air, or other gases. Space and weight considerations clearly preclude the use of large volumes of gas, and fire-containment constraints will limit the use of some gases. Nevertheless, the lack of oxidizing gases will limit flight experiments, especially in ceramics and solution research.

Recommendation. NASA should consider methods for accommodating the following in the SSFF Core: small quantities of gases other than argon (e.g., oxygen or air), within safety guidelines; fire-suppression systems to allow for the use of oxidizing gases; and larger quantities of gases and the associated crew time required to change gas cylinders. Control elements for gas handling (e.g., mass flow control and venting systems control) should also be considered.

Liquid Handling

The control functions of the current SSFF Core concept do not include controlling liquid mixing and flows. The effects of microgravity on ceramics will be most relevant to processes that involve solutions or suspensions in which convection and density gradients and differences play a major role in determining homogeneity and final properties. Liquid-control capabilities may also be essential for studies involving the synthesis of polymers, the growth of crystals, and the precipitation from solutions.

Recommendation. NASA should consider adding liquid-mixing and liquid-flow control capabilities to the current SSFF Core concept to support materials research that involves a liquid state.

Power Availability

Considerable power will be required to produce the high temperatures, levitation, and magnetic damping required for many of the experiments currently planned for the SSFF Core. Careful planning will be required to ensure that sufficient power can be delivered to each unit.

Recommendation. NASA should review the power supply to ensure that it is adequate for producing high temperatures, levitation, and damping.

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Acronyms

ARIS	active rack isolation system
DRE	data recording equipment
DWG	Discipline Working Group
EM	experiment module
FACE	furnace actuator control electronics
FIP	facility interface panel
FSCU	furnace signal conditioning unit
GDS IRDE	gas distribution system instrument rack distributed equipment
GSM/CRDE	gas supply modules/core rack distributed equipment
IPCU	instrument power conditioning unit
IR	instrument rack
IRCU	instrument rack control unit
ISS	International Space Station
MRD	Microgravity Research Division
NASA	National Aeronautics and Space Administration
NRA	NASA Research Announcement
SAMS	science acceleration measurement system
SSFF	Space Station Furnace Facility
SWG	Science Working Group
RPDU	remote power distribution unit

Appendices

Appendix A

Summary of Space Station Furnace Facility Core Systems Science Requirements

Minimum volume	3 racks
Total facility peak power	12 kW
Heat rejection	as required to dissipate energy used
Video	National Television Standards Committee standards; upgradable
Magnetic field generation	3.0 kW power available
Field stability	≤ 1.0% of desired field
Inert gas requirements per increment mission	
SSFF provided inert gas	8.16 kg 99.9995% pure argon
ISS provided nitrogen	11.34 kg 99.995% pure
Control	
Range	10–200 kPa
Minimum flow rate	4 kg argon/hr
Measurement	
Range	5–250 kPa
Resolution	0.1 kPa
Vacuum (access provided to ISS system)	
Range	$1\text{x}10^{-6}$–5 kPa
Absolute accuracy	10.0% of measured value
Heating rate	60 to 300°C/hr
Cooling requirements	active or passive
Heater element control	
Control set-point stability	±0.1°C
Absolute control set-point accuracy	±1.0°C
Number of controlled heaters	45 total: 15 in IR1, 30 in IR2

Temperature measurement	
Range	20.0–2,300.0°C
Resolution	0.1°C
Absolute accuracy	±0.9°C
Data rate	10 scans/s
Translation capability	
Rate range	0.005 to 500.0 cm/hr
Control range	60.0 cm
Rate stability	< 5.0 of set-point at lowest rate to < 2.0% of set-point at highest rate
Rate stability rate	< 1.0 mm/s^2
Translation rate measurement	
Absolute accuracy	±2.5% of set-point at fastest rate, ±10.0% of set-point at slowest rate
Resolution	2.0% of set-point
Sampling rate	up to 1 scan/s
Sample position measurement	
Absolute accuracy	±1.1% of provided signal
Resolution	0.1 mm
Current pulsing	
Pulse amplitude	5.0 to 60.0A; selectable
Accuracy	±0.5% of setting at 5 A ±0.25% of setting at 60 A
Resolution	1.0 A
Pulse width	10–4,000 ms
Accuracy	±5.0% of setting
Resolution	1.0 ms
Pulse shape	variable
Transition time	≤5.0% of pulse width
Minimum time between pulses	250 ms
Pulse power	
Peak	1,600 W
Time averaged	640 W (40% duty cycle)
Pulse voltage	up to 60 V at core/module interface
Pulse polarity	reversible
Voltage and current input measurements	
Accuracy	±0.1 V and ±0.1 A

Appendix B

Biographical Sketches of Committee Members

JULIA R. WEERTMAN (chair) is Walter P. Murphy Professor in the Department of Materials Science and Engineering at Northwestern University. She was awarded a D.Sc. from the Carnegie Institute of Technology (now Carnegie-Mellon University). Dr. Weertman's list of awards includes the National Science Foundation's Creativity Research Award, a Guggenheim fellowship, and the Society for Women Engineers Achievement Award. Her research interests include the mechanical behavior of metals and alloys, especially nanostructured materials and structural characterization. Dr. Weertman is a member of the National Academy of Engineering and the American Academy of Arts and Sciences. She is also a Fellow of both ASM International and The Minerals, Metals, and Materials Society. She was previously a member of the National Research Council Committee on Microgravity Research.

REZA ABBASCHIAN is chairman and professor of the Department of Materials Science and Engineering at the University of Florida. He received his Ph.D. in materials science and engineering from the University of California, Berkeley. Dr. Abbaschian has more than 180 scientific publications to his credit on subjects ranging from metals processing, space processing, solidification, and composites to phase diagrams. He also holds four patents. Dr. Abbaschian has been active in several educational and professional organizations, including the National Materials Advisory Board; The Minerals, Metals, and Materials Society Board of Directors; and the National Science Foundation Materials Research Advisory Committee. He is also a trustee of the Federation of Materials Societies and chairman of the University Materials Council.

I. MELVIN BERNSTEIN is academic vice president at Tufts University. He has held prior academic appointments as chancellor of the Illinois Institute of Technology and professor and head of the Department of Materials Science and Engineering at Carnegie-Mellon University. He was a two-term member of the National Materials Advisory Board and is currently on the Board of Governors of Ben Gurion University in Israel. Dr. Bernstein's current research interests include the roles of microstructure and hydrogen on the mechanical properties of metals, alloys, and intermetallics and new approaches to learning in higher education.

MARTIN E. GLICKSMAN is John Tod Horton Professor in the Department of Materials Science and Engineering at the Rensselaer Polytechnic Institute. His research interests include fundamental research on energy and solutal transport during solidification and crystal growth, especially the influence of gravity on dendritic and eutectic solidification. He is currently preparing the third microgravity space-flight of the isothermal dendritic growth experiment, which will be launched by NASA in late 1997. Professor Glicksman is a member of the National Academy of Engineering, director of the Microgravity Science and Applications Division of the Universities Space Research Association, and chair of the National Research Council Committee on Microgravity Research.

JOHN HOPPS, JR., is provost, senior vice president for administrative affairs, and professor of physics at Morehouse College. He has served as the second ranking official of the college since 1996 and is responsible for all college functions related to students, faculty, and academic programs. He was previously director of the Materials Directorate at the National Science Foundation and was responsible for establishing the Materials Directorate's program goals, metrics, plans, priorities, and budgets to advance U.S. materials research and education.

SYLVIA M. JOHNSON is program manager of ceramics for SRI International. She was awarded a B.Sc. from the University of New South Wales and an M.S. and Ph.D. from the University of California, Berkeley. Her areas of expertise include the synthesis of oxide and non-oxide ceramic powders, the processing of ceramics, the use of preceramic polymers, and the characterization and evaluation of structural ceramics. Dr. Johnson is a member of the National Materials

Advisory Board and a fellow of the American Ceramics Society. She was vice president of the American Ceramics Society for 1996 and 1997.

RALPH G. NUZZO is a professor of both chemistry and materials science and engineering at the University of Illinois, Urbana. His research concerns the surface chemical phenomena important in the synthesis, processing, and modification of organic solid-state and thin-film materials. Dr. Nuzzo has also conducted research on the molecular self-assembly of organic adsorbates on a variety of solid substrates.

MORTON PANISH recently retired as distinguished member of the technical staff of Bell Laboratories. His areas of expertise are the epitaxial crystal growth of semiconductor materials and the development of new semiconductor materials for product applications. He was awarded the Electronics Division Award and the Solid State Sciences Award from the Electrochemical Society, the NEC C&C Prize from Japan, and the Morris Liebruen Award from the Institute of Electrical and Electronics Engineers. Dr. Panish is a member of the National Academy of Sciences and the National Academy of Engineering. He was also a member of the National Research Council Committee on Microgravity Research.

JAMES W. WAGNER is professor and chair of the Department of Materials Science and Engineering at The Johns Hopkins University. He also holds a joint faculty appointment in the Department of Biomedical Engineering. His areas of research interest include nondestructive evaluation and characteristics of materials, including materials for biomedical implants. Dr. Wagner is a member of the National Materials Advisory Board.