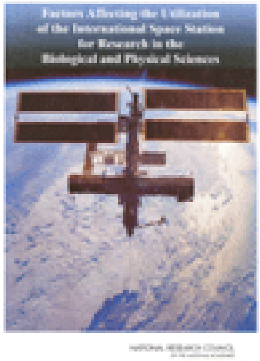

Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences

Task Group on Research on the International Space Station, National Research Council, National Academy of Public Administration

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Preface

This report constitutes phase II of a two-part study examining specific questions related to the utilization of the International Space Station (ISS) for research in the biological and physical sciences. In 1999, during formulation of a proposed NASA authorization bill, the House of Representatives first indicated that the National Research Council (NRC) should undertake such a study, but it did not enact a bill in that year. However, when the NASA Authorization Act of 2000 became law it contained provisions directing NASA to seek a study by the NRC and the National Academy of Public Administration (NAPA) on specific ISS utilization issues.

The Space Studies Board of the NRC, in cooperation with NAPA, agreed to organize a two-part study of the status of life sciences and microgravity research on the ISS. The Space Studies Board established the ad hoc Task Group on Research on the International Space Station, with members having expertise in space life sciences and microgravity physical sciences (see Appendix M for the biographies of task group members, the SSB liaison, and NAPA consultants). The task group held its first meeting for the study in April 2001. During the first phase of the study, in response to the first two tasks of its charge, it conducted an assessment of the readiness of the U.S. scientific community to use the ISS for life sciences and microgravity research and of the relative costs and benefits of either dedicating an annual space shuttle mission to life sciences and microgravity research during assembly of the ISS or maintaining the current schedule for ISS assembly. The phase I report, *Readiness Issues Related to Research in the Biological and Physical Sciences on the International Space Station* (National Academy Press, Washington, D.C., 2001), was released to the public on September 12, 2001.

In the second phase of the study, the task group addressed the remaining two tasks given to the NRC and NAPA:

(3) Assess the current and projected factors that may limit the U.S. scientific community's ability to maximize the research potential of the ISS, and
(4) Make recommendations for improving the community's ability to maximize the research potential of the ISS.

While the design of the ISS and its experiment capabilities were relatively stable at the time this study was first requested, both were extensively altered during the course of the study as a result of ISS construction cost overruns. This turn of events brought considerable uncertainty regarding the final ISS configuration. This uncertainty increased the difficulty of the task group's work and, more importantly, shifted the relative emphasis of the task. In language included in the House-Senate Conference Committee report on FY 02 appropriations for NASA, Congress requested that the task group add the following to its ongoing task: "compare and evaluate the research programs of the ISS which can be accomplished with a crew of three and a crew of six" and perform "an assessment of the probable cost-benefit ratios of those programs, compared with earthbound research which could be funded in lieu of research conducted on the ISS."

After discussion with NASA and congressional staff, the task group concluded that the first of the two latest requests already fell within the scope of the committee's current task and that it would consider this question when assessing the scientific community's ability to maximize the research potential of the International Space Station. The second item, however, did not fall within the scope of the current task and could not be accomplished within the agreed-upon schedule and given expertise of the task group, so the task group did not attempt to address it in this report.

As noted above, both phases of the study were conducted jointly with NAPA at the request of Congress. Coordination included joint planning for the study and agreement on allocation of responsibilities at the beginning of the project, NAPA representation at all task group meetings, regular communication during the fact-finding stages, and general agreement on the principal conclusions of the report.

Information for this study was collected from NASA briefings to the task group, research program documentation provided by NASA, interviews with representatives of the scientific user community for the ISS, European Space Agency documents, and online NASA databases and documents. The committee also examined available material from groups internal and external to NASA that had been commissioned to review various aspects of the ISS. One such group was the International Space Station (ISS) Management and Cost Evaluation Task Force, which was chartered in 2001 to conduct an independent external review and assessment of ISS cost, budget, and management. NASA also provided a range of data on its flight research programs and ISS science capabilities in response to lists of detailed questions developed by the task group.

Acknowledgment of Reviewers

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

Andreas Acrivos, City University of New York,
John Buckmaster, University of Illinois at Urbana-Champaign,
Richard Christensen, Stanford University,
Glenn C. Hamiliton, Wright State University,
Joseph Kerwin, Krug Life Sciences,
Robert Moser, Canyon Consulting,
Robert Recker, Creighton University,
Andrew Staehelin, University of Colorado, and
Joan Vernikos, Thirdage LLC.

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

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Prologue

This report was first released to the public in prepublication form in September of 2002. Since that time the language of the report has been edited but the body of the report has not been altered to reflect any events that have taken place during the past several months. Two of these events had or are expected to have a significant impact on topics discussed in this report. The first was the passage of the Fiscal Year 2003 Appropriations Bill, which directed that funding be restored for the completion of the ISS combustion rack and for initial development of the advanced animal and plant growth habitats for use on the ISS centrifuge. These were among the several important pieces of experimental equipment cited as issues of concern by the task group. The second event is the catastrophic loss of the space shuttle Columbia with all of its crew on February 1, 2003. This tragedy is expected to have numerous, but currently unknowable, downstream consequences for the future of the International Space Station and laboratory research in space.

Executive Summary

Construction of the International Space Station (ISS), under development since the late 1980s, began with the launch of its first element in November 1998 and is ongoing. In the spring of 2001, the National Aeronautics and Space Administration (NASA) announced that it would make major changes in the final configuration of the ISS in order to address serious construction cost overruns. The new ISS configuration is referred to by NASA as "Core Complete"; the earlier configuration was based on NASA's Rev. F design documentation. Some decisions regarding the new configuration are yet to be finalized, but the changes from Rev. F currently include the deletion of a crew return vehicle, which will force a reduction in the number of ISS crew from six or seven to three; the deletion of a number of the major science facilities planned for the ISS; and a reduction in the number of annual shuttle flights to the ISS. Serious concerns have arisen within the science community and elsewhere that these changes would jeopardize the ability of the ISS to support the world-class science that has often been cited as its primary purpose. This report examines the factors, including ISS design changes, that limit the ability of the science community to utilize the ISS for research and makes recommendations for maximizing the ISS's research potential.

IMPACT OF CORE COMPLETE DESIGN ON RESEARCH

The task group reviewed individually most of the principal areas of science that were intended to be supported on the ISS and considered the impact that the design changes would have on each. The level and type of impact resulting from the design changes in the ISS vary considerably from discipline to discipline. The physical sciences received the majority of the cuts made in facilities and equipment for experiments. Two of the three materials science research racks planned for the ISS were canceled, along with all but two of the experiment modules for the remaining materials facility. More than half of the planned materials investigations on the ISS were deselected, and the scope of work for those that remain has been reduced dramatically. One of the two facilities supporting fluids research (it was also intended to support combustion research) was canceled, along with a number of experiment modules. About 28 percent of the planned fluid physics experiments have been canceled so far, with the remaining experiments now expected to fly in 2005-2008 if funds become available for the development of the experiment modules. The only remaining facility for combustion research was canceled and then reinstated, but its future remains uncertain. The stowage space for combustion research was reduced by half and its allocation of crew time by 70 percent. The result is that each set of combustion experiments has been replanned and will be constrained to fewer tests over a smaller range of conditions, thus reducing their scientific value.

Fewer cuts were made in the equipment needed for research in bioastronautics, but the lengthy delay in availability of the centrifuge and the delay or cancellation of animal habitats will prevent research on the animal models needed to study radiation effects and bone and muscle loss until those facilities can be built and installed. Cell science and biotechnology research, which includes research on bone and muscle cells, will now be limited to two EXPRESS racks instead of six. The reduction in crew size will reduce by at least half the number of subjects from which critical data on human physiology and behavior can be collected, thus doubling the number of years needed to obtain a statistically significant data set. In areas such as plant biology and radiation studies, considerable specialized training is needed to perform experiments, and this training is far less likely to occur with a smaller crew. In fundamental biology many experiments are labor-intensive, and the reduction in crew time is expected to critically compromise experiments in this area.

LIMITING FACTORS

While some research areas are more severely affected than others by the changes, clearly NASA's revision of the ISS to the Core Complete configuration has drastically reduced the overall ability of the ISS to support science. The reduction, singly or in combination, of upmass capability, research facilities and equipment, and available crew time for science activities severely limits or forecloses the scientific community's ability to maximize the research potential of the ISS. Moreover, the absence of any overarching, well-articulated goal on which to base scientific priorities that would unify or guide the downsizing process has further exacerbated the already significantly diminished capability of the ISS. The impact on the various scientific disciplines of revising the ISS to the Core Complete configuration varies but in all cases is substantial. Although NASA's stated goal for its ISS program is to create a world-class laboratory, it is the opinion of the task group that the actions taken with regard to crew time, equipment, facilities, and logistics make this unlikely. Specifically, the task group found the following to be the most significant factors limiting the ability of the science community to maximize the research potential of the ISS:

- *Interdisciplinary priorities not in place.* Decisions to cancel or greatly delay experimental facilities and equipment vital to specific scientific disciplines were made in the absence of cross-disciplinary priorities to guide the selection process. In many cases these decisions were made based primarily on what equipment had not yet been built, without any apparent weighting of the impact on overall scientific objectives.
- *Crew time.* The most widespread and significant impact of ISS design revisions on the achievement of scientific objectives stems from the more than 85 percent reduction in crew time available for scientific activities.[1] This limitation has an impact on every discipline examined, ranging from a potential total elimination of the ability to achieve even a modicum of meaningful work on the ISS in the areas of radiation biology, systems physiology, crew behavior and performance, and fundamental biology, to lesser impacts on disciplines such as plant science, materials science, fundamental physics, combustion science, and fluid physics. Even these potentially less seriously affected fields will probably sustain significant negative impacts when they are forced to compete with the remaining scientific complement for the minimal time available.
- *International partner participation.* ISS partners will also experience major reductions in their ability to perform science on the ISS as a result of the Core Complete design. As a result, serious questions have been raised about whether international partners will continue to support ISS development at originally planned levels. Such reductions could seriously reduce the remaining science capabilities of the ISS since the international partners are responsible for elements critical to many U.S. investigators. Loss of the Japanese experiment module exposed facility, for example, would all but eliminate research in fundamental physics.
- *Science facilities and equipment.* Many U.S. experiment racks have been eliminated or delayed indefinitely in the redesign of the ISS. In addition, the modules containing the functional equipment that goes into the remaining racks have also been reduced significantly in number, worsening an already dramatically reduced capability. The scientific disciplines affected most severely by these reductions are materials science, fluid physics, fundamental biology, and muscle and bone physiology.
- *Shuttle upmass capacity.* The upmass and stowage volumes for many of the experiments are expected to be severely curtailed as a result of the reduction in shuttle flights and facility changes in Core Complete, and the quantity of scientific work is expected to be reduced accordingly. In fact, the constraints of meeting ISS operational needs with only four shuttle flights per year is expected to leave

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[1] Since at least 2.5 crew are needed for the maintenance of the ISS, the maximum number of crew available to perform science was 4.5 or 3.5 in Rev. F and is down to 0.5 in Core Complete.

very little shuttle volume for ferrying supplies and equipment to experiments on orbit or for returning samples to the ground.

- *Research community readiness.* The factors cited above, when combined with the poor track record of NASA and the ISS in meeting schedule, budget, and scientific performance targets, further detract from the ability of the ISS to garner the support of the scientific community. The uncertainty and instability in the ISS program are disincentives to participation by both established and next-generation scientists, whose careers can be seriously damaged by the failure of the ISS program to provide the promised scientific opportunities.

MAXIMIZING RESEARCH POTENTIAL

In considering ways in which the research potential of the ISS could be maximized, the task group looked at two possibilities: options based on the restoration of certain critical capabilities to the ISS, and options based on the current Core Complete configuration. Described below are the steps that would have the greatest impact on the overall research potential of the ISS. Suggestions for additional steps that would maximize research in specific disciplines are made in the discipline chapters of the report.

Scientific Priorities

Currently a tension seems to exist between using ISS research resources (such as crew time) to enable the human exploration of space, and using those resources to perform research that has intrinsic scientific importance. These two goals are not mutually exclusive, but without cross-disciplinary prioritization both within and across the research supporting the two goals, intelligent use of the scarce and costly resources of the ISS is impossible. As this report is being written, no cross-disciplinary prioritization plan exists.[2] This lack of cross-disciplinary prioritization exacerbates the uncertainty that is undermining the confidence of the scientific community and its readiness to support the program.

Recommendation: NASA should create a cross-disciplinary research prioritization plan with accompanying rationale, based on overall program goals for the ISS, that permits ranking and can be used to effectively manage the scientific program.

Research Coordination

In the life sciences, the human physiology research and operational medicine programs both involve activities that influence or perturb the same physiologic parameters in astronauts. Currently, these activities are not coordinated systematically, which can result in inadvertent corruption of scientific data as well as inefficient expenditure of resources.

Recommendation: NASA should establish systematic coordination between human physiology research and operational medicine on the ISS so that crew care is not compromised and coordinated acquisition of scientific data is facilitated.

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[2] An internal NASA committee, the Research Maximization and Prioritization (ReMaP) Task Force, has been charged with developing priorities upon which such a plan could be based, but it has not released a final report as of this writing.

Crew Time

As already noted, the time available for science activities on the ISS is wholly inadequate and is the single biggest factor that is limiting achieving science objectives. Of the approximately 20 hours of crew time per week currently identified by NASA for science-related activities, the United States will be allotted only 7.5 hours. This is not sufficient to take advantage of even the reduced scientific capabilities of the Core Complete ISS. According to NASA, the factor currently limiting the crew size to three is the inability, in the event of an on-board emergency, to deorbit more than three crew members due to the limited capacity of the Soyuz and the indefinite postponement of the planned Crew Return Vehicle.

Recommendation: In view of the effect of crew return options on crew size, NASA should reevaluate the assumption that the crew return requirement in case of an emergency is the best approach to maintain crew safety and achieve mission success. For example, there may be other options such as safe haven concepts that would maintain crew safety and permit a crew of seven. If it is determined that there is a requirement to return the ISS crew to Earth immediately, NASA should develop a plan whereby the original complement of seven crew members can be accommodated by a return vehicle so that the scientific objectives of the ISS can be met.

Recommendation: NASA should evaluate the adequacy of the time allotted to perform the science that is scheduled for the ISS, taking into account interdisciplinary priorities and the equipment and facilities that are available. Caution should be used when allocating the hours available for science investigations, since small allocations to individual crew members often involve overhead that may render the time operationally ineffective for research even though the total time spent meets the experiment requirements documentation. In addition, NASA should carefully consider what steps could be taken to reduce demands on on-orbit crew time. For example, any reduction in the time needed for ISS maintenance would have a large positive impact, in percentage terms, on the small amount of crew time now available for science.

International Partners

The transition of the ISS from Rev. F to Core Complete has severely limited the facilities available to accomplish U.S.-based scientific research. Increased collaboration with international partners to share facilities and crew time could enable research that the U.S. science community cannot accomplish alone.

Recommendation: To maximize ISS facility usage NASA should promote further collaborative interactions between the ISS science programs of the United States and those of its international partners in all disciplines.

Experiment Equipment and Facilities

The elimination or postponement of ISS experiment racks, modules, and equipment has greatly reduced the potential scientific yield of the ISS. Once a science prioritization on a cross-disciplinary basis is accomplished and the number of crew members available for scientific activities is finalized, the decisions about which experimental modules and experimental equipment are needed can be addressed intelligently. A rational plan that is consistent with stated scientific priorities is critical to assuring the scientific community that the ISS has a scientific future.

Recommendation: NASA should develop a plan providing for ISS experiment racks, modules, and equipment that is consistent with the scientific priorities of NASA and the ISS and is achievable within fiscal and schedule constraints.

The development cost to the United States of the ISS as currently planned is approximately $26 billion. The additional cost to increase the crew number to seven has been estimated at approximately $5 billion (IMCE, 2001).[3] This 20 percent increase in development cost would yield a 900 percent increase in the crew time available for research (4.5 versus 0.5 crew available for scientific activities). If the primary objective of the ISS is indeed to be a world-class laboratory in space, then the cost-benefit of taking this course of action is obvious. Not to do so would be akin to building a million-dollar home but stopping short of running electrical and water services to it. Without plans and decisions based on cross-disciplinary priorities that are clearly articulated and supported by corresponding allocations of resources, the ISS can never achieve the status of a world-class research laboratory.

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[3] While the numbers are the latest public numbers provided by NASA, they are currently being reviewed and updated by NASA, and may be revised in the future.

1
Introduction

TASK DESCRIPTION AND HISTORY

This report represents phase II of a study requested by Congress and conducted by the Task Group on Research on the International Space Station to examine factors affecting the utilization of the International Space Station (ISS) for research. The phase I report, released in September of 2001, looked at the readiness of the scientific community to utilize the ISS[1] and the benefits and costs of flying additional shuttle missions dedicated to science during the station build-up[2] (NRC, 2001). During the course of that study, the National Aeronautics and Space Administration (NASA) announced that it would make major changes in the final ISS configuration in order to address construction cost overruns. These design changes (discussed below) would reduce considerably the research capabilities of the ISS and therefore had to be taken into account when the task group made its phase I recommendations. While the task group concluded in that report that the research community was in fact ready to utilize the ISS, it also pointed out that the uncertainty resulting from years of schedule delays, funding fluctuations, and lack of flight opportunities seriously threatened the continued viability of the ISS research community in many disciplines. The task group also noted that the planned reductions in ISS capabilities would exacerbate this problem considerably.

An implication of the conclusions of the phase I report is that, given the research capabilities of the redesigned ISS, the planned science would be best supported by flying additional annual shuttle missions dedicated to science even if the cost of such missions slowed ISS development. However, implementation of the task group's recommendation now appears extremely unlikely—in fact, since the release of the phase I study, NASA has effectively canceled one[3] of its two remaining shuttle missions dedicated to science and has reduced the total number of shuttle flights per year.

For phase II of the overall study, the original charge[4] to the task group was as follows:

> (3) Assess the current and projected factors that may limit the U.S. scientific community's ability to maximize the research potential of the ISS, and
> (4) Make recommendations for improving the community's ability to maximize the research potential of the ISS.

While these tasks remained unchanged as the task group began its work, concerns about the impact of the ISS redesign prompted Congress[5] to ask that the task group attempt to address additional issues during its phase II study. The task group was unable to accommodate that request fully, given the time available for the study, but it did agree that the following requested analysis fell within the scope of its current task: "compare and evaluate the research programs of the ISS which can be accomplished with a crew of three and a crew of six [or seven]."

Though the task group had addressed in its phase I report the overall impact on research of the changes to the ISS design, in order to address the above issues it needed to perform a more detailed analysis of that impact. In the chapters that follow the report looks at the impact of the redesign on a discipline-by-discipline basis, compares within each discipline the types and levels of research that could be supported by the previous and current designs for the ISS, and attempts to provide specific suggestions

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[1] Task (1) in the phase I report.
[2] Task (2) in the phase I report.
[3] NASA is no longer funding the R-2 mission, a SpaceHab shuttle mission dedicated to science.
[4] Tasks (1) and (2) were addressed in the phase I report.
[5] House-Senate Conference Committee report on FY 02 appropriations for NASA.

for steps that NASA and the research community could take to maximize the research potential of the ISS.

CHANGES TO THE ISS CONFIGURATION

When a major redesign of the ISS was announced in the spring of 2001, the new ISS configuration was initially referred to as the Rev. G design (the previous design had been Rev. F). Many aspects of the Rev. G design,[6] which is now called "Core Complete," are still highly fluid, and NASA has left open the possibility that it might eventually be able to restore some of the deleted elements of the Rev. F design in the eventuality that cost and schedule problems are resolved and money becomes available. Despite this possibility of restoration, in the past year NASA has moved forward rapidly with plans to adopt the Core Complete design, including extensive changes in shuttle schedules and facility funding. Tables 1.1 and 1.2 illustrate the task group's understanding of many of the current differences between the Rev. F and Core Complete designs for ISS.

The most critical difference between the Rev. F design and the Core Complete design resulted from the deletion of the crew return vehicle, which reduced the number of crew that could live aboard the completed ISS, from six or seven to three. Since NASA has estimated that 2.5 crew members will be needed to maintain and operate the ISS, the number of crew available to perform scientific research drops from 3.5 or 4.5, to 0.5, a decrease of at least 85 percent. Of this remaining research time, the U.S. share is currently 50 percent[7] and will drop to 38 percent once the laboratories of the international partners are brought into orbit.[8] Based on NASA's planned work week of 40 hours per crew member, a total of 20 hours would be devoted to research each week, with about 7.5 hours of this going to U.S. research. NASA data indicate that early ISS crews have chosen to work considerably longer than 40 hours per week, and some of that time has been devoted to performing additional experiment runs and procedures. However, this additional effort is unplanned and so the amount of supplementary science that can be obtained in this way is likely to be modest. NASA guidelines require that payload planning must be based on the assumption of a 40 hour week as this most accurately describes what can be accomplished on orbit. This assumption is further supported by the fact that NASA anticipates that crew time required for ISS maintenance and repair will rise on future missions as more elements are added to the ISS and the original elements accumulate hours of operation.

Since the release of the phase I report, NASA has reduced the number of planned shuttle flights for ISS to four flights per year. This may be an even more serious constraint on ISS science than the reduction in crew size. The task group has learned that NASA's current analysis predicts that by the time the centrifuge accommodations module is launched,[9] the entire upmass capacity of the four flights per year will be needed for the ISS logistics and maintenance hardware, leaving only limited capability for research outfitting and resupply. NASA is currently studying this issue, and few details are available at this time.

Also affecting the science capabilities of the completed ISS is the elimination of a number of research facilities from Rev. F, as shown in Table 1.2. Note that the loss of racks shown here does not capture the additional impact of deleted experiment modules, which are the functional experiment units that go into these racks. Most of these facilities and modules supported research in specific scientific fields and, as noted in the phase I report and discussed in detail in the chapters that follow, the impact of their elimination will vary by discipline. While the centrifuge, a key facility for life sciences research, is

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[6] An official Rev. G design has not been released to date and the name Rev. G is not currently used.

[7] The Russians have the other 50 percent.

[8] These percentages are averages over time, so the percentage of U.S. research time may be higher or lower on a given mission.

[9] Currently planned for 2007.

TABLE 1.1 Comparison of Research Support Capabilities Provided by the Rev. F and Core Complete Designs of the ISS

Research Support Capability	Rev. F	Core Complete
Number of crew	6 or 7	3
Number of crew available to perform research[a]	3.5 or 4.5	0.5
Shuttle flight rate to the ISS	6 to 9 per year[b]	4 per year[c]
Total shuttle flights to the ISS (2002-2006)	37[b]	21[c]
Rack volume for research[d,e]	34.4 m^3	23.2 m^3
Number of research racks[d,f]	27	20

NOTE: Data taken from various NASA briefings.
[a] NASA currently estimates a minimum of 2.5 crew required for maintaining the ISS, exclusive of any science-related duties.
[b] From final FY 01 budget.
[c] From the Administration's proposed FY 03 budget and NASA planning charts.
[d] U.S. share.
[e] Numbers based on NASA estimates of 0.5 m^3 of research volume for each EXPRESS rack and 1.6 m^3 of research volume for international standard payload racks (ISPRs). EXPRESS rack volume is less than the volume in ISPRs because of the space needed for mid-deck locker hardware.
[f] Does not include data on the experiment modules also eliminated in plans for Core Complete.

currently still included in the Core Complete design, it has experienced numerous development delays and is not expected to be launched prior to 2007 at the earliest.

Ironically, it is the capabilities that were most unique to the ISS that are most threatened by the changes in the configuration. The complex, dedicated scientific facilities and the availability of astronaut scientists with time to perform experiments, analyze results, and then design successive series of experiments based on those results were intended to enable sophisticated research studies to be carried out in space much as they would be on the ground. This opportunity to perform iterative experiments and to replicate results—particularly unexpected results—was a key advantage of the ISS as compared to Spacelab. Also important were the advanced scientific facilities that required too much volume, power, or other resources to be feasible on a Spacelab mission. Under current planning scenarios, the ISS will now provide less crew time dedicated to science annually than did Spacelab, and many facilities that were to perform world-class science are threatened with cancellation or downgrading to smaller, less capable equipment. While the ability to run experiments that require more than 10 to 14 days for completion is an advantage that Core Complete still retains over Spacelab, this capability may not be useful without adequate crew time and other resources.

REPORT ASSUMPTIONS AND ORGANIZATION

In comparing the science capabilities of Rev. F and Core Complete, the task group considered the possibility that facilities provided by international partners—such as those planned for the European Space Agency's (ESA's) Columbus module—could replace capabilities that would have been provided by canceled U.S. facilities. Current ISS partner agreements allocate an overall percentage of time on these facilities to U.S. investigators. It should be noted, however, that the time available to the task group did not allow for a thorough exploration of this option. Furthermore, since the choice of international partner facilities was made with the intent of complementing rather than duplicating U.S. capabilities, the task group did not expect to find numerous instances where partner facilities could actually replace U.S. capabilities. In addition, because ISS design changes have created uncertainty about the eventual level of

TABLE 1.2 Comparison of the Number of Internal Racks in the Baseline (Rev. F) and Core Complete Designs

	Rev. F Baseline, 27 Racks[a]	Core Complete, 20 Racks[b]	Facility Status[c]
	Human research facility 1	Human research facility 1	On orbit
	EXPRESS rack 1	EXPRESS rack 1	On orbit
	EXPRESS rack 2	EXPRESS rack 2	On orbit
	EXPRESS rack 3	EXPRESS rack 3	On orbit
	EXPRESS rack 4	EXPRESS rack 4	On orbit
	EXPRESS rack 5	EXPRESS rack 5	On orbit
IP[d]	Microgravity science glove box	Microgravity science glove box	On orbit
	Window observational facility	Window observational facility	To fly in 2003
	Human research facility 2	Human research facility 2	To fly in 2003
	EXPRESS rack 6	EXPRESS rack 6	Construction complete
	Habitat holding rack 1	Habitat holding rack 1	In development
	Fluids Integrated Rack	Fluids Integrated Rack	In development
	Materials science research facility 1	Materials science research facility 1	In development
IP[d]	Life sciences glove box	Life sciences glove box	In development
	EXPRESS rack 7	EXPRESS rack 7	
	Habitat holding rack 2	Habitat holding rack 2	In development
	Combustion Integrated Rack	Combustion Integrated Rack	Under construction
	EXPRESS rack 8	EXPRESS rack 8	Construction complete
	Shared Accommodations Rack	~~Shared Accommodations Rack~~	No longer funded
	Materials science research facility 2	~~Materials science research facility 2~~	No longer funded
	Materials science research facility 3	~~Materials science research facility 3~~	No longer funded
	Commercial materials	~~Commercial materials~~	No longer funded
	Biotechnology facility	~~Biotechnology facility~~	No longer funded[e]
	X-ray diffraction system	~~X-ray diffraction system~~	No longer funded
	Advanced human support technology	~~Advanced human support technology~~	No longer funded[e]
IP[d]	Minus-eighty-degree freezer	Minus-eighty-degree freezer	To fly in 2003
IP[d]	Cryofreezer	Cryofreezer	In development

NOTE: This list does not include the various modules, habitats, and other experiment equipment also deleted from the ISS. Details on these can be found in the discipline chapters. A flight date is shown for facilities that have already been built and are scheduled to fly in the near term. Facilities that have not been built are shown as in development.

[a] Based on Rev. F assembly sequence and August 1, 2001, MPOM (multilateral payload outfitting model).

[b] Racks shown with shading are not in the current budget guidelines and would be eliminated under Core Complete.

[c] Dates after 2003 are preliminary planning dates.

[d] International partner (IP) provides rack (the materials science research facility is partially IP-provided).

[e] Some hardware from this facility may go into EXPRESS racks.

SOURCE: Adapted and updated from NASA briefing charts originally dated February 8, 2002.

participation by international partners, the task group considered it problematic to assume that these facilities would be available on the ISS and thus to U.S. investigators.

The manner in which scientific disciplines in the biological and physical sciences have been categorized and labeled in NASA programs has varied considerably during the past decade. To consider separately every discipline or subdiscipline that is, or has been, defined in NASA programs was not practical in this brief study. However the task group has analyzed a representative sampling of the scientific disciplines that have been supported by the Office of Biological and Physical Research (OBPR), and most of the disciplines that were expected to be heavily dependent on the ISS as a vehicle for future space research are discussed specifically in the chapters that follow.

For the benefit of general readers, the research areas covered in this report are organized into the broad categories of physical sciences, fundamental biology, and bioastronautics (human physiology and performance). It should be noted that these categories do not necessarily align with current OBPR organizational charts, some of which have been considerably altered in recent years. For each discipline examined within those categories, a separate and independent assessment was made of:

- The impact of ISS changes on the discipline,
- The factors limiting the utilization of the ISS by that discipline community, and
- Possible steps for maximizing the research potential of the ISS for that discipline community.

This discipline-by-discipline examination was intended to ensure that the task group understood both the differences and similarities of ISS utilization by the discipline communities in more detail than would have been possible with a more global analysis. Each discipline section of the report, therefore, has a similar structure, and issues common to multiple disciplines appear repeatedly in different sections of the report. The findings and recommendations that are common to many disciplines are summarized in Chapter 5. For issues and recommendations specific to a limited number of disciplines the reader is referred back to the individual chapters.

2

Impact of ISS Changes on Physical Sciences Research

INTRODUCTION

The physical sciences research sponsored by NASA's Office of Biological and Physical Research (OBPR) has typically come under four disciplines—materials science, combustion science, fluids science, and fundamental physics—although some overlap occurs between these disciplines. OBPR has a Physical Sciences Division that also supports areas of biology-related or non-gravitational research, such as biotechnology and nanotechnology, that are not discussed in this chapter.[1] In the sections that follow, the research sponsored by NASA in these four areas is described, and the task questions relating to implementation of the research on the ISS are considered.

Specialized research racks for physical sciences experiments on the ISS are designed to hold several modules. Each module contains one or more experiments, and in some cases the equipment can be shared. Large projects, such as the-low temperature facility, will be installed in special carriers mounted on the outside of the ISS.

Overall, the cuts made in the NASA/ISS research capability budget since Rev. F were absorbed primarily by the physical sciences research program, whose budget went from $980 million to $576 million, a 41 percent reduction.[2] This reduction resulted in the cancellation (or deselection) of 26 of 77 flight experiments, a 34 percent reduction. Most of the deselected experiments, although not yet under construction, were chosen for deletion because the necessary facilities would require near-term expenditures. Scientific merit was not a criterion.

In addition, significant reductions in the scope of the remaining experiments retained have been imposed. In large part the physical science experiments are designed for remote operation and require relatively little crew intervention, so they could in theory be carried out with the smaller three-person crew. However, just the time needed to load an experiment, let alone intervene in an ongoing experiment, might exceed the allotted U.S. crew time (7.5 hours/week). NASA also is planning fewer shuttle flights to the ISS; four per year were recommended in the Young report (IMCE, 2001), greatly constraining the ability to transport materials to be used in the experiments. Finally, the uncertainty surrounding the budget and funding levels is having a negative impact on the scientific community, as principle investigator (PI) funding for scheduled flight experiments is reduced. Given these uncertainties, PIs may seek opportunities elsewhere, thereby jeopardizing the future of ISS science.

MATERIALS SCIENCE

Program Description

The overall goal of the OBPR materials science program is to use microgravity to establish and improve the quantitative and predictive relationships among the processing, structures, and properties of materials used for making products. Materials are inherent in all branches of engineering and have influenced social change profoundly over the course of history. Because gravity plays a critical role in materials formation, it is necessary to understand and control the effect of gravity on the processes used to produce materials, and also to resolve fundamental scientific questions about materials phenomena by

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[1] The cell biology research carried out in the biotechnology program is discussed in other sections of this report. Protein crystal growth, also part of the biotechnology program, is not among the subdisciplines covered in this report, although it has been reviewed recently by the NRC (2000a).

[2] From FY 01 budget to Administration's FY 03 proposed budget.

testing them in an environment free of contamination by fluid convection, sedimentation, and hydrostatic pressure.

In particular, experiments in this program have been directed at producing benchmark data sets or testing fundamental theories. Examples of OBPR-funded research in materials science include studies of the role of liquid convection in crystal growth, including its influence on impurities and crystal perfection; isothermal dendritic growth; directional solidification; gravitational effects on distortion during sintering; the accurate measurement of thermophysical properties needed for the computer-aided modeling of manufacturing processes; the formation of metallic glasses (amorphous metals); and the exploration of new and innovative ways to process materials (Sekerka, 2001a). To date, fundamental knowledge of the role of convection in crystal growth has been applied to the production of melt-grown silicon crystals (as a source of substrates for integrated circuits), with an increase in yield approaching two orders of magnitude (Sekerka, 2001b). Scientific research on isothermal dendritic growth in microgravity has established a basis for assessing the validity of competing theories of dendrite growth. Liquid-phase sintering studies in microgravity are expected to provide design parameters for the low-cost fabrication of parts, for example, automobile connecting rods.

The quality of the materials science research funded through the physical sciences program is uniformly high. This is reflected, for example, in the scientific stature of current and previous NASA principal investigators (PIs).[3]

Impact of ISS Changes

In the Rev. E (June 1999) Assembly Sequence and Research Outfitting design, the dedicated Materials Science Research Rack 1 (MSRR1) was scheduled for delivery to the ISS in February 2003. In Rev. E, the second and third dedicated materials science research racks (MSRR2 and MSRR3) were deferred to 2005 or later. In Rev. F (August 2000), MSRR1 was scheduled for September 2004, a slippage of 19 months. In Rev. F, MSRR2 and MSRR3 were deferred to 2006 or later. Subsequently, in the Core Complete design, MSRR1 is scheduled for January 2005 with an attendant slippage of 4 months, while MSRR2 and MSRR3 are canceled.

The microgravity research program selected 26 materials science flight investigations for execution through 2008 (Wargo, 2002). Eighteen of these flight investigations were to utilize MSRR1, MSRR2, or MSRR3; three investigations were to be carried out in the Microgravity Science Glovebox (MSG) facility, two investigations in the European Electromagnetic Levitation (EML) facility, two in the Japanese Electrostatic Levitation (ESL) facility, and one in the French DECLIC apparatus.

In terms of materials science, the reduction in the NASA ISS research capability budget translated into the elimination of MSSR2 and MSSR3, with attendant cancellation of equipment. The one remaining piece of NASA-provided equipment for MSRR1 is the Quench Module Insert, which will be inserted into the Materials Science Laboratory planned to be built by the European Space Agency (ESA). NASA's rationale for the elimination of MSRR2, MSRR3, and 10 experimental modules (Robey, 2001) is that substantial funding is associated with these facilities, coupled with the fact that each facility was scheduled far enough into the future to avoid the lay-off of current employees. In addition, the resource analysis from the ISS program office at the Johnson Spaceflight Center (JSC) indicated that activities in the materials science research racks were more crew-intensive than those in the other physical sciences flight research programs (Trinh, 2002a).

NASA reports that as of April 10, 2002, 12 flight investigations remained in the OBPR materials science program (Wargo, 2002) (see Appendix A). Nevertheless, only part of the original proposed scope of work can be conducted in each investigation. This limit on scope will adversely affect the level of meaningful research that can be performed in materials science. Seven flight investigations will use the

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[3] Seven are members of the National Academy of Engineering, two are members of the National Academy of Sciences, and five are fellows of the Metals, Minerals, and Materials Society.

MSRR1 facility, three will be performed in the MSG facility, and two will make use of the EML facility to be fabricated by the ESA and installed in the European Columbus Orbital Facility (COF).

The 14 flight investigations that have been eliminated from the materials science program are listed alphabetically in Table 2.1. These investigations were designed to enhance the materials processing science base, thereby allowing improvements in metal casting technology; process modeling of casting and welding; design of alloys for automotive, aerospace, and computer applications; fabrication of new microporous materials for application in detergents and petroleum cracking; fabrication of alloys compatible with high-temperature applications; the manufacture of improved electro-optical materials; and the commercial production of bulk metallic glasses.

As shown in Appendix A, seven flight investigations in materials science are planned for MSRR1 over the time frame 2005-2008. Of the three flight investigations to be carried out in the MSG facility, one is scheduled for 2002 and the remaining two for 2007. The two flight investigations in the EML facility are scheduled for 2005.

The severe reduction in the scope and number of flight investigations in materials science from 26 to 12 (54 percent) comes from the elimination of MSRR2 with its complement of experiment modules and the elimination of planned experiment modules from MSRR1. MSRR3 was to have accommodated modules for future experiments, international hardware, and equipment for new initiatives and multidisiciplinary utilization (Robey, 2001).

Consideration is being given to restoring the two investigations by Beckermann and one each by Koss and Glicksman (Wargo, 2002). A funding wedge (a research reserve mandated by OBPR to enforce prioritization of OBPR science) has been set aside in the research budget of the OBPR programs to cover the cost of experiments identified as having a high priority. It may also be possible to reinstate Trivedi's investigation by using the French DECLIC apparatus through a collaborative agreement. With the reorientation of the research to emphasize the use of specific facilities across disciplines, it may be possible to use the Combustion Integrated Rack (CIR), should it be built, for a limited number of materials science experiments.

The overall impact of restructuring and downsizing the ISS research program in materials science is that much of the basic science integral to key areas of materials processing is deferred indefinitely. In particular, all U.S. space research on the ISS involving thermophysical property measurements, dendritic solidification, and the evolution of microstructure on a local scale using transparent model systems—research that is important to both space- and ground-based manufacturing—will be terminated. There will also be a significant reduction in the amount of research on semiconductor crystal growth, optoelectronic materials, and microstructure development and pattern formation in metal casting. No new starts in nascent areas (such as biomaterials) will be possible, unless these areas are given a higher priority.

With the restructured research program for the ISS, it becomes difficult to claim that materials scientists will have a state-of-the-art laboratory for pursuing cutting-edge research in materials processing in a microgravity environment. In its phase I report (NRC, 2001), the task group cautioned that investigator readiness is beginning to deteriorate, and that it will continue to do so as the date of completion for the ISS slips—an opinion shared widely in the ISS user community (Sekerka, 2001b; Fettman, 2001; Katovich, 2001). The restructuring and downsizing of the materials science component of the ISS research program will have a negative impact on PI readiness in this discipline. Only one flight experiment in materials science is scheduled prior to 2005.

Factors Limiting Utilization of the ISS

A major factor limiting utilization of the ISS by the materials science community is the elimination of MSRR2 and the experiment modules associated with nine experiments in MSRR1 and MSRR2 collectively (Robey, 2001). The only remaining experimental capability is that associated with the Low Gradient Furnace (LGF) and the Quench Module Insert (QMI) in the Materials Science Laboratory (MSL). This has imposed a limit of seven experiments in MSRR1 (Appendix A) but it

TABLE 2.1 Flight Investigations Eliminated in the Core Complete ISS—Materials Science

Investigation	Principal Investigator	Affiliation
Self diffusion in liquid elements	R.M. Banish	University of Alabama, Huntsville
Thermophysical property measurements: Te-based II-VI semiconductor compounds	R.M. Banish	University of Alabama, Huntsville
Equiaxed dendritic solidification experiment	C. Beckermann	University of Iowa
Dendritic alloy solidification experiment	C. Beckermann	University of Iowa
Fundamental study of crystal growth in microporous materials	P. Dutta	Ohio State University
Evolution of local microstructures: spatial instabilities of coarsening clusters	M. Glicksman	Rensselaer Polytechnic Institute
Physical properties and processing of undercooled metallic glass-forming liquids	W.L. Johnson	California Institute of Technology
Transient dendritic solidification experiment	M. Koss	College of the Holy Cross
Diffusion processes in molten semiconductors	D.H. Matthiesen	Case Western Reserve University
Space- and ground-based crystal growth using a baffle	A. Ostrogorsky	University of Alabama, Huntsville
Dynamical selection of three-dimensional interfacial patterns in directional solidification	R. Trivedi	Iowa State University
Crystal growth of ZnSe and related ternary compound semiconductors by vapor transport	C.H. Su	Marshall Space Flight Center
Microgravity studies of liquid-liquid phase transitions in undercooled alumina-yttria melts	R. Weber	Containerless Research, Inc.
Defect formation during melt growth of electro-optical single crystals	A.F. Witt	Massachusetts Institute of Technology

SOURCE: Wargo (2002).

probably represents optimal restructuring for the ISS materials science program given the overall budget cuts in ISS research.

This drastic curtailment is having a negative effect on the materials community, since the restructured ISS is not able to accommodate current and future PIs of approved proposals.
In the absence of a modern laboratory for cutting-edge materials research in an extraterrestrial environment, the ISS will fail to fulfill one of its primary objectives in the materials research field. In turn, materials researchers will have little or no alternative but to abandon NASA and fields of study dependent on flight opportunities and pursue careers elsewhere.

Note also that NASA's Commercial Furnace Module cannot be used for those materials science experiments currently selected, as its capabilities do not satisfy space and power requirements.

All the experiments in the MSRR1 are fully automated and can be run from the ground. Sample exchange is accomplished manually and is projected to take 1-1.5 hours per exchange (Wargo, 2002). Similarly, in the MSG, the experiments are semiautomated once the samples are in the facility and instructions are preprogrammed into the apparatus. The EML will be run from the ground, but sample exchange, pumping, and the replacement of gas bottles will be manual, with a projected time of 1-1.5 hours per event. Thus, while the materials research experiments require modest crew intervention, the reduction in crew size from seven (or six) to three may impact the program adversely. With the U.S. allotment of 7.5 hours/week, insufficient time will be available for a crew of three to load or exchange experiments.

Maximizing ISS Research Potential

The most effective option for maximizing the remaining research potential of the ISS in materials science would be to make resources available for the development of experimental modules for MSRR1. The projected final cost of MSSR1 ($124 million) is about 0.5 percent of the $31 billion projected cost to complete the construction of the ISS (IMCE, 2001). MSRR1 was designed to accommodate PIs who have entered the program over the last 5 years, as well as future PIs. In this context, it will be critical to the future of the materials science program on the ISS to establish priorities. As noted in the preceding section, to increase ISS research potential in materials science, allocation of resources to restore some or all of the experimental modules is essential. These modules can be accommodated in MSRR1.

It is important to appreciate that space is available in MSRR1. The MSL within MSRR1 leaves room for several experimental modules. Reinstating some (or all) of the experimental modules in the materials science program would take advantage of dead (wasted) space in the one dedicated research rack.

A limited class of materials science research, that is, experiments compatible with low power and small volume, could be executed on the EXPRESS rack. For example, the two investigations proposed by Banish (see Table 2.1) might be compatible if sufficient power is available. However, no money has been allocated to build the equipment required for these investigations.

While in principle the utilization of the ISS might be increased by speeding up the preparation of investigations for flight, the materials science program is “too ready,” with PIs awaiting a launch date. The rate-limiting element is access to capability (research facilities), which is tied to the launch schedule, upmass (and downmass), and budget.

COMBUSTION SCIENCE AND FIRE SAFETY

Program Description

NASA’s highest-priority goal for the Human Exploration and Development of Space (HEDS) program is safety. One of the most feared, potentially catastrophic safety hazards in spacecraft is fire. At least six prefire, on-orbit incidents have occurred involving the space shuttle, and two serious fires erupted during the Russian space station program. In support of these concerns, a panel of combustion experts (Law, 2001) has stated as follows:

> We can say with near-certainty that the probability of the initiation of an accidental fire event during the lifetime of ISS is unity—whether the fire transitions into a serious problem or not will depend on our collective knowledge of low-gravity fire prevention, detection, and suppression. NASA’s ongoing research program has made encouraging progress to minimize the frequency and consequences of such an event, but future progress—both for ISS and exploration—depends critically on the use of the Combustion Facility as planned for the ISS.

Fire safety can be implemented at three stages: fire prevention, fire detection, and fire suppression. Recommended methods and procedures developed for fire safety under normal-gravity environments do not necessarily apply to microgravity environments since gravity plays a dominant and frequently controlling role during combustion on Earth. Heat released in flames on Earth leads to a rapid and dramatic (factor of seven) decrease in density and creation of buoyancy-induced flows. Virtual elimination of buoyancy in microgravity allows other mechanisms to control flame characteristics (Ross, 2001). Not only can fire safety issues be examined on the ISS, but microgravity also provides opportunities to measure phenomena otherwise masked or complicated by gravitational forces. The likelihood of success and of benefits for ground-based energy production is sufficiently great that in 1999 a NASA advisory group for combustion science (Law, 1999) proposed a major, focused activity in the flight research program that would obtain fundamental data and practical information for industrial applications. Clearly, funding issues now preclude such an expansion, but the interest and need for such studies remain. NASA has sought to encourage research in the microgravity combustion program that is relevant to energy use, global warming, air pollution, and industrial manufacturing.

Combustion research issues that would be pursued on the ISS by investigators now in the ground and flight program include flammability limits and flame propagation of various solid and liquid fuels under microgravity conditions, combustion around single fuel droplets and internal droplet circulation, radiative quenching in flames, the character of soot/particle formation in microgravity, and the transition between smoldering fires and flames. Collectively, these fundamental investigations would contribute to spacecraft and building fire safety, reduced pollutant formation, increased engine efficiency, and education. Numerous highly distinguished investigators have been attracted to this program.[4]

Impact of ISS Changes

The principal facility for combustion research on the ISS is the CIR. The unique software structure of the CIR (which has won federal, NASA, and private sector awards) was designed to minimize the need for crew. Its design enables tool-free, rapid change-out of PI-specific modular components (windows, diagnostics, and experimental hardware). The storage and processing capabilities are 100 times greater than those of an EXPRESS rack, which minimizes communication needs and maximizes flexibility in operations. The CIR is planned for construction within an international standard payload rack containing its own isolation, avionics, power, software, and environmental subsystems. In addition, it includes an optics bench, a combustion chamber for low- and high-pressure operation, fuel and oxidizer management, exhaust treatment, and related diagnostics. This multiuser facility is uniquely capable of providing a reusable on-orbit capability for combustion science research on the ISS. Additional details of the CIR and its capabilities are provided by O'Malley and Weiland (2001).

The CIR will provide 90 percent of the flight hardware needed to perform most of the microgravity combustion experiments. (Some early experiments will be performed in the MSG.) The remaining hardware will be PI-specific and will be provided by the PI hardware development teams. This PI-specific hardware will be launched separately from the CIR and installed into the CIR in orbit and may be shared with other PIs. In Rev. F, the CIR was to be housed in the Fluids and Combustion Facility (FCF) (NASA, 2002a), which contained the CIR and the Fluids Integrated Rack (FIR), together with the Shared Accommodations Rack (SAR). The SAR was to house common capabilities, including power control and distribution, environmental controls, command and data management, communications, and stowage. In addition to the CIR/FCF, the MSG was, and still is, available for limited combustion-related experiments.

In the initial description of the ISS Core Complete design, the CIR and the SAR were eliminated, which would have prevented further research on fire safety on the ISS. The CIR facility was temporarily added back into the ISS plan, following a substantial and rapid response to NASA headquarters and to Congress by the combustion and industrial communities (U.S. Sections, Combustion Institute, letter to D. Goldin dated March 29, 2001; also see, for example, Syed, 2001; Pearlman, 2001; T'ien, 2001; Edelman, 2001; Egolfopoulos, 2001; Schowengerdt, 2001; and Bellan, 2001). With the elimination of the SAR, all operational components must be self-contained within the CIR, and the repackaged CIR has limited

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[4] Four are members of the National Academy of Engineering, 19 are fellows of scientific and engineering societies, and 2 are among the most highly cited 100 engineers according to the ISI (Voorhees, 2002).

optical and diagnostic access. In addition, numerous advanced diagnostics have been eliminated owing to insufficient space without the SAR (D.L. Urban, personal communication, 2002).

Despite its temporary reinstatement, the CIR is still in jeopardy as a result of continuing budgetary concerns. Without it, six of the ten combustion investigations on spacecraft fire safety, combustion fundamentals, and pollutant formation (see Appendix B) cannot be performed.

The ISS resources reduced in the Core Complete design are crew time, upmass, and stowage volumes, all key to the combustion program. Assessing the impact of these reductions on the CIR experiments is difficult, since a prioritization for use of resources was not provided by NASA management. Nevertheless, as described in the following paragraphs, the reduction in station size and in the number of shuttle flights will significantly decrease the resources available for combustion science on the ISS.

Even at the completion of Core Complete, crew time available for experiments will be significantly constrained, with only three crew members present on the ISS. This constraint will have an impact on planned combustion research but should not cripple the research effort, as the CIR was designed to minimize the need for crew interactions. Originally, NASA estimated that a minimum of 100 hours of crew time per year would be required to support experiments in the CIR. With Core Complete, the allocated time has been reduced to about 30 hours per year. This reduction is accommodated by decreasing the number of scheduled runs for each PI. Since time is typically consumed in calibration and demonstration of technique, the 70 percent reduction in crew time is expected to result in greater than 70 percent reduction in the quantity of science returned.

Communication rates are limited to the existing maximum ISS pipeline bandwidth of 50 megabits per second. Since bandwidths sufficient for real-time control (3 megabits per second) cannot be dedicated to an experiment, combustion investigations will utilize a low-resolution video transmitted with a time delay of many seconds or minutes followed by transmission of a set of high-resolution still pictures in the hours following an experiment. Dedicated communications were planned in an earlier ISS configuration. Without this capability (and in the absence of compensatory crew time) and despite careful preplanning of experiments, it will be challenging to make effective use of the limited fuel and oxidizer samples and maximize scientific return.

The smaller ISS and reduction of the shuttle flights to four per year have also necessitated reductions in the stowage and upmass allocated per experiment. Typical material required for an experiment includes gas cylinders, fuel samples, extra cameras, and redundant (back-up) equipment. To accommodate facility changes in Core Complete, stowage per experiment has been reduced from about 0.2 cubic meters to an estimated 0.1 cubic meters. The result is that each set of experiments has been replanned and will be constrained to fewer tests over a smaller range of conditions, thus reducing their scientific value. Given that the first set of experiments are performed for calibration and demonstration of technique and that some of the stowage volume is required for hardware, the decrease by a factor of two in allocated stowage will lead to a greater than twofold decrease in returned scientific results. Solid fuel experiments have been reduced by as much as a factor of four. Hence, the combustible (fire safety) characteristics of some materials cannot be evaluated, and there will be a smaller range of conditions examined for other fuels.

In addition to reductions in ISS facilities, budgets for ground-based activities have been decreased. All PI projects were reduced by 5 percent in FY 01, and all ground-based and selected flight projects are being reduced by another 10 percent or more in FY 02. Furthermore, the employment of summer students at NASA sites has been reduced dramatically (by 80 percent); this program is recognized as having provided excellent training experience for the next generation of the nation’s scientists and engineers. In addition, the selection of new combustion experiments that would fly after 2008 has been curtailed due to the lack of funds for flight reviews.

Of the experiments already selected for flight on the ISS, three have been eliminated in the Core Complete plan. These experiments were originally planned as ISS glove box investigations. The eliminated projects are shown in Table 2.2.

TABLE 2.2 Flight Investigations Eliminated in the Core Complete ISS—Combustion Science

Investigation	Principal Investigator	Affiliation
Low stretch diffusion flames over solid fuels	S. Olson	NASA Glenn Research Center
Surface smoldering spread and evolved products	T. Kashiwagi	National Institute of Standards and Technology
Front interaction with vortex experiment	P. Ronney	University of Southern California

Together these glove box investigations were to have provided supplemental information in support of other flight- or ground-based investigations on fire safety and pollutant formation.

The planned list of ISS experiments in combustion science that will be flown through 2006 is given in Appendix B. The CIR experiments through 2005 include only combustion experiments on fuel droplets. In 2006, alternative CIR inserts will be provided for examination of flames with solid and gaseous fuels.[5]

Except for the glove box investigations cited above, NASA has not eliminated any other combustion investigations, in the hope of maximizing both scientific return and community involvement. Instead, each of the experiments that will be flown has new limitations to the range of experimental conditions and the number of materials that can be evaluated. These limitations are an important and undesirable constraint on the fire safety investigations. Nevertheless, if the CIR is flown on the ISS, if adequate crew time is available, and if sufficient upmass is provided, benefits are anticipated to accrue in the areas of spacecraft fire safety, education, engine efficiencies, and pollutant emission.

Factors Limiting Utilization of the ISS

The CIR is a critical component for the majority of the combustion experiments planned through 2010, yet its existence on the ISS is threatened by budgetary concerns. Without this facility, the ISS cannot be effectively utilized for a program of combustion research. The EXPRESS racks cannot be easily modified into a substitute CIR owing to substantial requirements for flow control, diagnostics, automated exhaust treatment, safety, and high data acquisition and data storage. Assuming that the CIR is available, other factors limiting the use of the ISS for research in combustion science include crew time, stowage volume, upmass, and bandwidth for communications. Initial (Rev. F) estimates (D.L. Urban, personal communication, 2002) of crew time required to support combustion research were approximately 100 hours per year. Crew time that will be available for combustion research has now been reduced to about 30 hours per year. Desired stowage volume for several of the combustion experiments exceeds the imposed allocation of 0.1 cubic meter for consumables and other related materials by at least a factor of two.

Enhancements of international collaborations have the potential to increase the value of the scientific research in this area, and limited interactions already exist. In combustion research, collaborations include the European development of a high-pressure chamber to be placed into the CIR for European-sponsored experiments of combustion processes at high pressure, as well as construction of a disk laser by the Europeans to use as a high-powered light source (diagnostic) in the CIR during combustion experiments. In addition, NASA has recently initiated a coordinated International Announcement of Opportunities, similar to a NASA Research Announcement, but only the Japanese have

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[5] As of the final printing of this report, full funding is available for the development of the insert for solid fuels, and funding is being sought for the gaseous fuel insert.

acted by funding some recent proposals. Generally, the coordination of international activities is challenging due to cumbersome negotiations, but it is expected that science will benefit through increased international interactions and sharing of facilities, and perhaps co-planning of experiments and/or inserts for the CIR.

Maximizing ISS Research Potential

A strong ground-based research program is the most important factor for maximizing the potential of the ISS for scientific research in general, including combustion research. The ground-based efforts create a critical mass of scientists and engineers who identify the creative, world-class experiments for flight investigations. This pool of scientists also reviews, examines, and carefully revises experiments proposed by individual PIs to maximize the potential benefit and impact of each experiment. At present, NASA's microgravity program in combustion science is attracting most of the leading combustion researchers in the United States and their students. Continuation of the ground-based program will maintain strong interest in related science issues and help to attract students to the field.

Perhaps the most important constraint of Core Complete on combustion research comes from the limitation on consumables. Relaxation of newly imposed volumetric and weight limitations on consumables (i.e., the combustible materials) would have a direct impact on the quantity and quality of science that can be performed once experimental hardware is in space. This issue is particularly important for fire safety investigations, in which flammability limits for a range of materials need to be determined. If materials are not flown, then their combustible characteristics cannot be determined. Thus, relaxing upmass constraints would have a direct benefit in reducing fire safety hazards for future manned flights.

The constraints of crew time and training could be mitigated partially by allocating higher-bandwidth communications to the experiments. Safety issues, occasional unexpected events, and event times measured in fractions of a second call for real-time monitoring of combustion experiments. High data acquisition and storage rates are provided within the CIR to collect data for postprocessing and for downloading in the hours following an experiment. Active monitoring is desired during each experiment in case unusual or unanticipated events occur. At present, it is expected that support from the crew and time for appropriate training will be minimal. Hence, it must be presumed that the outcome of an experiment can be well enough known that the sampling rates, the duration of the experiment, the control of oxidizer or fuel flows, etc. can be preprogrammed via software. Time scales can vary dramatically in combustion experiments, and predictive models or ground-based experiments provide only a guide to ideal sampling conditions for optimum scientific return. Bandwidths of 2-3.5 megabits per second dedicated to the combustion investigations at the time of the experiments could enable (compressed) real-time video monitoring from the ground, with a ground-based scientist then able to intervene and adjust the experiments as appropriate. Increased science return would be anticipated, due to more effective use of the equipment and consumables. However, crew time would still be required to change fuel and oxidizer samples or make facility changes.

Another possibility, perhaps unique to combustion research, for increasing the utility of the ISS is to investigate effects of partial gravity (0 to 1 *g*) on flame spread rates and flammability. The centrifuge module would enable simulation of partial gravity conditions for extended times; the longest test time available for examination of fire safety issues on Earth through aircraft-based tests approaches 1 minute for partial gravity (0.6 *g*) conditions and much shorter for lower gravity levels. A separate rack for such studies would have to be designed and built to perform such investigations, and the possible effect of coriolis forces would have to be addressed. It should be noted that such an approach is not part of existing NASA plans; however, the importance of the proposed studies is based on the nonlinear dependencies between phenomena driving combustion. As gravity (and buoyancy) increases above microgravity conditions, natural convection adds fresh air to the flame and thus increases flame spread rates; but at higher gravity levels, the higher levels of buoyancy-driven air cool and dilute the combustion products, thus slowing the transfer of heat to the flame and reducing resultant flame propagation rates. It has been shown that flame spread and flammability characteristics are most adverse under partial gravity conditions, such as those on the Moon or Mars (Sacksteder and T'ien, 1994). Hence, it is strongly recommended by the task group that the centrifuge, if flown, be utilized also for fire safety investigations in anticipation of human flights to Mars.

FLUID PHYSICS

Program Description

The goal of the OBPR fluid physics program is to comprehend the fundamental physical phenomena underlying flows observed in nature and to aid the space program in its effort to develop new technologies or to adapt existing technologies to space applications. The fluid physics program encompasses five major research areas: interfacial phenomena, biological fluid dynamics, dynamics and instabilities, complex fluids, and multiphase flows and phase change. Research on interfacial phenomena includes studies directed at understanding capillary phenomena and the dynamics of fluid-fluid and fluid-solid interfaces. Biological fluid dynamics focuses on the underlying fluid physics and transport phenomena in biological and physiological systems. The study of dynamics and instabilities encompasses research topics ranging from the fluid mechanics of star formation and Earth's interior to the dynamics of electrically charged fluids. Complex fluids currently under investigation include fluids as diverse as colloids, foams, and granular aggregates, with applications ranging from sensors to smart materials. Multiphase flows and phase change involve investigations in two-phase flows, such as gas-liquid systems, in which gravity has a controlling influence on the flows owing to the large density difference between the phases. The research in many of these areas is relevant to the HEDS program. For example, multiphase fluid flow experiments performed in microgravity are important for applications such as spacecraft thermal management, environment control, human life support, and advanced power and propulsion systems (NRC, 1995).

It is worth noting here that the quality of the investigators attracted by the NASA fluids program has been very high.[6]

Impact of ISS Changes

The facilities planned in Rev. F for the ISS for use in fluid physics research were the Fluids Integrated Rack, the Microgravity Sciences Glovebox, the Shared Accommodations Rack, and an EXPRESS rack. A total of 32 experiments had been selected for flight using these facilities through 2008.

The recent cut in NASA's OPBR budget for ISS research was absorbed in large part by the physical sciences research program, and a significant part of that was in fluid physics, where the SAR was eliminated and several modules were lost. In fluid physics, NASA cut a number of experiments still in the development stage, resulting in the elimination of nine experiments slated to fly in the 2003-2005 time frame. The remaining 23 experiments are now expected to fly in 2005-2008 if funds become available for the development of the experimental modules. Further budget cuts being considered in this program could either eliminate some of these selected experiments or greatly reduce future experiments in 2008 and onward. For example, 7 of the existing 23 experiments counted in the fluid physics total are still

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[6] As evidenced by the fact that of the 110 PIs in the program in FY 01, 8 were members of the National Academy of Engineering, 4 were members of the National Academy of Sciences, 37 were fellows of the American Physical Society, 12 were fellows of the American Institute of Aeronautics and Astronautics, and 5 were fellows of the American Society of Mechanical Engineers (Voorhees, 2002).

uncertain because their funding depends on the budget wedge—a research reserve mandated by OBPR in order to enforce prioritization of OBPR science (Trinh, 2002b).

The principal reduction in fluid physics capability on the ISS is that due to the elimination of the SAR, a resource to have been shared between fluid physics and combustion research. According to information provided by NASA, experiments were selected for elimination based on their proximity to flight (thus reducing near-term budgets) rather than on scientific priorities. It is hard to determine the exact number of experiments eliminated by the loss of this facility, because several of the proposed experiments might be accommodated in the FIR or the MSG or in facilities provided by international partners. The loss of this facility affects the number rather than the type of experiments that can be performed aboard the ISS. The nine eliminated experiments are shown in Table 2.3.

The experimental modules currently planned for flight research are the Light Microscope Module, the Granular Flow Module, and the Ultraviolet-Visible-Infrared Spectrophotometer (UVIS), all of which are intended for use in the FIR. Two instruments for fluid physics research are also being planned for use in facilities provided by the international partners, the Fluid Science Laboratory (FSL) and DECLIC. The FSL is a multiuser research facility dedicated to investigations in fluid physics under microgravity conditions. It can be operated in fully automatic or semiautomatic mode on the station by the flight crew or remotely controlled from ground in the so-called telescience mode. DECLIC is dedicated to the physics of transparent media in general and to model material sciences and near-critical and supercritical research in particular. The Pool Boiling Module is no longer planned. The racks are outfitted to be operated remotely from the ground. The crew is needed primarily for sample change-out and instrument repair as needed.

According to NASA the U.S. fluid physics research currently remaining on the schedule (listed in Appendix C), while considered to be of very high quality, was retained principally because these experiments were to be flown at a late date, and therefore the cost for module development could be deferred. Whether there will be resources in the future for module development is critical for the success of the fluid physics program. (For example, the CIR was initially cut, but it has been restored by Congress. The restoration of this facility comes with a potentially significant future cost to the physical sciences research program, because the funding provided was insufficient to complete the facility and the remaining cost may be borne by the research program in future years.)

While most of the fluid physics research experiments are designed to be operated by ground personnel and therefore require only modest crew intervention, the reduction of the crew from seven (or six) to three may nevertheless adversely impact the program. With a crew of only three, so little time is available (given the U.S. allotment of 7.5 hours/week) that simply loading or exchanging experiments can consume all of it. Compared with some other disciplines, however, the fluid physics program is well positioned to operate on the Core Complete ISS, although suboptimally in terms of numbers of experiments that can be performed. The loss of the SAR and associated resources for module development limits the type and number of experiments that can be performed. The SAR could accommodate a greater number and variety of experiments than the FIR and MSG. Completing the SAR as originally planned would greatly enhance the fluid physics research program.

The principal impact of the budget cuts and restructuring of the ISS on PI readiness has been a reduction in the number of new investigations funded in the latest call for proposals and an across-the-board 15 percent cut in all funded investigations. There is still an active complement of researchers in the program, but there is growing concern in the fluids community that the program is in jeopardy. If this concern is not addressed and the funding picture deteriorates further, many excellent PIs may leave the program.

TABLE 2.3 Experiments Eliminated in the Core Complete ISS—Fluid Physics

Investigation	Principal Investigator	Affiliation
Microscale Hydrodynamics Near Moving Contact Lines (fundamentals of wetting and spreading of fluids)	Steve Garoff	Carnegie Mellon University
Passive and Active Stabilization of Liquid Bridges in Low Gravity (important for drop dynamics, wetting, and growth of molten materials)	Phil Marston	Washington State University
Microgravity Experiments to Evaluate Electrostatic Forces in Controlling Cohesion and Adhesion of Granular Materials (applications in the processing and transport of granular particulates, e.g., pharmaceuticals)	John Marshall	NASA Ames
Diffusing Light Photography of Containerless Ripple Turbulence (fundamentals of two-dimensional turbulent fluid flows)	Seth Putterman	University of California, Los Angeles
Acoustic Study of Critical Phenomena in Microgravity (fundamentals of material phase transitions)	Mike Moldover	NIST
Using Surfactants to Control Bubble Growth Coalescence in Nucleate Pool Boiling (boiling is a widespread natural and industrial process used, for example, in steam production in power plants)	Kate Stebe	Johns Hopkins University
Structure and Dynamics of Freely Suspended Liquid Crystals (containerless processing of liquid crystals, which are used in flat panel displays, for example)	Noel Clark	University of Colorado
Gradient Driven Fluctuations (fundamental fluid physics)	David Cannell	University of California, Santa Barbara
Investigations of Mechanisms Associated with Nucleate Boiling under Microgravity Conditions (boiling is a widespread natural and industrial process used, for example, in steam production in power plants)	Vijay Dhir	University of California, Los Angeles

Factors Limiting Utilization of the ISS

Two main factors keep the fluid physics community from maximizing the remaining research potential of the ISS. The first is the development of experiment modules to be used in the facilities. These modules are tailored to a specific set of requirements and can be used for several related investigations (e.g., colloidal physics, granular flow research). A broad range of research areas could be covered with use of the SAR, as discussed above. Furthermore, had development of the SAR continued, it would have provided advanced data handling capabilities, science accommodations, and upgrade possibilities that could significantly increase science utilization on the ISS for fluid physics and combustion science. Since the SAR design was to be patterned after that of the FIR, its development cost is much less than either the FIR or CIR, which are first-unit builds.

The second main factor limiting the utilization of the ISS is the research and technology infrastructure (number and level of PIs supported). Only a few areas of research are being pursued on the

ISS. This is having a very negative impact on the community at large, as many investigators are being turned away from ISS research because there are not enough resources to accommodate their areas of study. As mentioned before, many of the flight-selected experiments require experiment module development, and resources for that development must be assured, while at the same time not jeopardizing future experiments.

Maximizing ISS Research Potential

As noted above, the principal factor limiting the fluid physics community from maximizing the research potential of the ISS is resources for module development. The expected crew utilization, the availability of power, the data up-link capacity, etc. are adequate to carry out the currently selected suite of experiments. Restoring the SAR to the ISS would greatly expand the available experimental platform and allow a more vigorous program. Stable funding for module development and for ground-based research from which future flight experiments will be selected is necessary. The fluid physics program offers a tremendous scientific return for a relatively modest investment.

FUNDAMENTAL PHYSICS

Program Description

There are three principal research areas in the fundamental physics microgravity program: gravitational and relativistic physics, laser cooling and atomic physics, and low-temperature and condensed matter physics. The fundamental physics program began about 15 years ago as an outgrowth of the low-temperature part of the fluid physics program. The original emphasis was on liquid helium critical point experiments; since the early 1990s, the program has grown considerably and now includes laser cooling and trapping of atoms, high-energy physics (cosmic ray studies), gravitational relativistic physics (tests of the equivalence principle), and atomic clock experiments. It can be fairly stated that the overall quality of research funded through this program has been very high. Many of the most highly regarded scientists in the country working in these fields have participated in the program, including 6 Nobel laureates, 9 members of the National Academy of Sciences, and 25 fellows of the American Physical Society (Voorhees, 2002).

The basic thrust of the fundamental physics program has been the investigation of phenomena that are not accessible, or only partially accessible, on Earth, as a consequence of either gravity or the atmosphere. Most of the experiments in this program depend on the absence of gravity to enable measurements not possible on Earth. One such area is the preparation and study of unique samples, such as a uniform fluid free from gravity-induced density gradients. This uniformity is of crucial importance for the study of critical phenomena. An early successful experiment in this area was the Lambda Point Experiment that was flown on the space shuttle in October 1992. Heat capacity data were obtained approaching a few nanokelvin of the lambda point (NRC, 1995). Similarly, while then considered as part of the fluid physics program, a space shuttle study of the critical point (T_c) of xenon by Berg, Moldover, and Zimmerli (1999) obtained viscosity data two orders of magnitude closer to the critical point than was possible on Earth and found an unexpected frequency-dependence close to T_c, signaling the onset of viscoelastic behavior. Among the critical point studies planned for the ISS program are studies of the equation of state of helium, accurate tests of scaling hypotheses and crossover models, finite-size scaling effects, and critical phenomena in out-of-equilibrium systems.

A second research area that is enabled by the microgravity environment is high-resolution laser cooling and atomic clock studies. The anticipated development of highly accurate clocks in space would be of major benefit for navigation and guidance systems. Because gravity is absent, laser-cooled beams of atoms can interact with radiation fields for extended times, providing extremely accurate measurements of frequency. This capability will be exploited both to test very-high-precision atomic clocks and to carry out highly sensitive tests of Einstein's equivalence principle and of other predictions of relativity theory. The satellite test of the equivalence principle (STEP) experiment, in which Galileo's famous Pisa experiment will be repeated in the microgravity environment, will advance by five orders of magnitude the precision with which the equivalence principle has been tested (Ashby, 2002). Additional tests of relativity will be conducted with a new superconducting microwave oscillator (SUMO), which will also provide a calibration for atomic clocks.

One class of experiments requires use of the ISS not for the absence of gravity, but rather for the absence of the atmosphere. Antiprotons are elementary particles that are strongly absorbed by the atmosphere. The Alpha Magnetic Spectrometer (AMS) experiment will measure the flux of antiprotons impinging on Earth, providing a sensitive test of some current cosmological theories that predict a proton-antiproton asymmetry.

Impact of ISS Changes

Under the Rev. F model, one major fundamental physics facility was planned for the fundamental physics program on the ISS, and this facility has been retained under the Core Complete model. The Low Temperature Microgravity Physics Experiments Facility (LTMPEF)[7] will be mounted on the outside of the ISS. Its liquid helium cryostat can simultaneously accommodate two experiments. While the LTMPEF will support the planned experiments in low-temperature physics, those investigations classed as laser cooling and atomic physics experiments will be attached at a second external site on the ISS. The latter experiments are expected to utilize experiment-unique hardware and will not be housed in a common facility. In addition, the large instrument for the AMS experiment[8] requires its own external attachment site. In 2001 it was decided to eliminate the LTMPEF, although the decision was subsequently reversed. The cancellation of this facility not only would have eliminated low-temperature physics from the ISS but also would have compromised the Primary Atomic Reference Clock in Space (PARCS) project, which requires the low-temperature facility for an independent frequency standard, and with it the atomic physics program. Currently, all of the fundamental physics experiments that were planned for Rev. F are still on the ISS flight schedule. These are listed in Appendix D.

The resources to have experiments developed, launched, and mounted in place are all essential for advancing to launch. The fundamental physics experiments are all either contained in an external facility or attached at separate external sites (Robey, 2002). The special carriers in which the experiments must be mounted for transport to the ISS, via either the shuttle or another launch vehicle, are a critical resource. As a result of the shift from the Rev. F to the Core Complete design for the ISS, the development of these carriers is now uncertain—clearly, budget constraints will make it difficult for NASA to complete them in a timely fashion.

Fundamental physics experiments generally do not require active participation by the crew. However, they do require crew time for external installation of the facilities. The LTMPEF and the laser cooling and atomic physics experiments must each be mounted on the exterior of the ISS by robotic arms operated by the crew. The AMS must be manually mounted by the crew and will require crew extravehicular activities. In addition, any delay after launch in mounting and initiating experiments in the LTMPEF will mean that helium is being lost, reducing the time available for conducting the experiments.

In assessing PI readiness to utilize the ISS, it has been difficult to separate the impact of the problems attributable to differences between Rev. F and Core Complete from the impact of existing funding and schedule issues. However, in general PIs have reported that delays in scheduling and uncertainty about the availability of resources have limited their ability to keep their projects operating

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[7] Also known as LTMPF.

[8] This experiment does not officially fall under the Physical Sciences Division at NASA but is included here with other fundamental physics experiments for completeness.

optimally. Involving graduate students and junior faculty members without jeopardizing their careers requires a reasonable degree of certainty that projects can be completed in a predictable time. The changes made to the ISS program have directly affected these projects and prevented the PIs from giving them the priority that they would otherwise have had.

Factors Limiting Utilization of the ISS

There are two major problems limiting ISS utilization by the fundamental physics community: lack of resources and funding instability. The latter problem has been extremely serious. When ISS funding problems have arisen, NASA has tended to cut instrument budgets. The most serious example (for fundamental physics) was the (temporary, as it turns out) cancellation of the LTMPEF in 2001. Furthermore, while no fundamental physics experiments have been canceled, reductions in instrument budgets have forced some PIs to fabricate sections of instruments (e.g., some of the cryostat components for the low-temperature experiments) that could have been purchased, causing further delays.

While there are multiple external attachment points for external modules, some of which will be used for the NASA EXPRESS pallet, most of them are too small to accommodate the LTMPEF. It will therefore have to be mounted on the Japanese Experimental Module–Exposed Facility (JEM-EF), which will have the only large carrier attachment points. The JEM-EF is scheduled for installation on the ISS in 2004-2005 (Gregory, 2002) and is a critical requirement for the low-temperature and atomic physics programs. But the reductions in Core Complete have placed the international partner agreements in question, and there is some risk that the JEM-EF may not be completed, which will effectively eliminate the low-temperature research program on the ISS. Finally, the task group wishes to note the impact of flight delays on PI readiness. Two experiments on the heat capacity of helium near the lambda point were performed on shuttle flights in 1992 and 1997. The next experiment will be on the ISS. However, the launch date has been moved back repeatedly, and the time gap between the 1997 experiment and the ISS experiment, currently scheduled for 2005, has become extremely long. The result of this constant slippage of the schedule is that PIs cannot take launch dates seriously and are hesitant to commit the necessary personnel to perfecting the apparatus.

Both the lack of resources to complete and fly experiments and overall funding instability have led to the development and launch delays discussed above. As noted previously, this has created considerable uncertainty among fundamental investigators. Given the timing of academic promotion and tenure decisions, it may be problematic for PIs to commit themselves to experiments with unpredictable delays. Also, maintaining a viable research team in the face of such delays is a serious concern. Graduate students and postdoctoral researchers cannot be expected to work indefinitely on the preparation of a spaceflight experiment when launch dates continue to recede into the future, and will most certainly therefore turn to other projects.

Maximizing ISS Research Potential

The problems preventing the physics community from maximizing the ISS potential come mainly from budgetary decisions that in turn resulted from ISS construction cost overruns. However, some decisions that have had a particularly damaging effect on the viability of the ISS for fundamental physics seem to have been made without considering the scientific implications. To maximize the science return of the ISS in fundamental physics it is important that NASA managers who understand the science and its needs be much more intimately involved in the ISS budget process. It is unlikely, for example, that the initial decision to cancel the LTMPEF would have been made by someone who was aware that it would severely compromise the ability to perform atomic physics experiments on the ISS, as well as eliminate the low-temperature physics experiments on the ISS.

Finally, the most critical step in maximizing the ISS research potential for fundamental physics is to restore the confidence of the research community. That step will require serious NASA commitments to preventing further slippage of experiment launch schedules, and maintaining adequate funding for those experiments selected for the ISS.

3
Impact of ISS Changes on Bioastronautics

INTRODUCTION

Bioastronautics is the discipline that encompasses the knowledge needed to maintain the health, safety, and well-being of astronauts. It includes the research that might lead to countermeasures for the adverse effects on astronauts of the spacecraft environment. The Bioastronautics Research Division within NASA's Office of Biological and Physical Research sponsors research in a large number of areas, including bone and muscle studies in animals and humans, radiation biology, and behavioral research. There is clearly some overlap with fundamental biological research in such areas as mammalian muscle and bone development, but the task group has generally chosen to use NASA's categorization for individual experiments. Here, as in the other chapters, the task group has not attempted to discuss individually every program of research carried out in bioastronautics, but it does consider—either individually or in aggregate (such as in systems physiology)—most of the programs that had been expected to make significant use of the ISS. In the sections that follow, the research sponsored by NASA in several major areas is described, and the task questions relating to their implementation on the ISS are considered.

Delays or cancellations of the on-board installation of the animal habitats[1] means that there will be no non-human vertebrate research on the ISS until they are available. Delay of the life sciences glovebox, most recently scheduled for launch in 2005, would eliminate many critical cell culture experiments.

The absence of the 1 *g* centrifuge and the reduction of crew size have severely affected each of the bioastronautics disciplines. The reduction in crew size has a twofold impact on bioastronautics research. In addition to the loss of crew to perform the research, the number of crew available to serve as human subjects in the observation of physiological deficits caused by spaceflight, and in the development of countermeasures, is also reduced. While the relative significance of crew and facility reductions varies by discipline, the net result is a limit on the variety and quality of the science that can be performed on the ISS.

SYSTEMS PHYSIOLOGY

Program Description

Systems physiology encompasses musculoskeletal, cardiovascular, neurovestibular, and immunological research directed toward maintaining humans for longer durations in space. There are two main goals of systems physiology research. The first is to understand the basic physiological mechanisms underlying astronauts' adaptation to weightlessness and readaptation to 1 *g* . The other is to develop scientifically based countermeasures for the effects of weightlessness. These countermeasures should help maintain crew safety, optimize their performance, and allow for longer-duration missions. Systems physiology research is vital since maintaining humans for long durations in weightlessness will be critical to accomplishing NASA's long-term goals in space. In addition, studies in this area add to the base of knowledge that can be used for understanding and treating similar problems on Earth, such as osteoporosis, muscle wasting, and low-blood pressure occurring with standing.

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[1] These are to be provided by international partners.

This section provides an overview of the problems facing all areas of systems physiology on the ISS, and the subsequent sections provide information on specific disciplines (cardiopulmonary physiology, muscle and bone physiology, radiation biology, and behavior and performance).

Several programs at NASA and at other agencies administer efforts relevant to systems physiology:

- *NASA Research Announcement (NRA) program*, a NASA program of competitive peer reviewed research that funds both intramural and extramural investigators;
- *National Space Biomedical Research Institute* (NSBRI), an extramural independent program focused on countermeasure development;
- *Countermeasure Evaluation and Validation Program* (CEVP), a NASA program for validating new countermeasures;
- *Flight medicine*, an intramural NASA program that prescribes countermeasures and makes ongoing measurements; in addition, flight medicine programs for individual nations can specify countermeasure programs for their astronauts (Ohshima et al., 2002);
- *Russian biomedical research program*, an independent Russian effort to study physiology and develop countermeasures;
- *European Space Agency projects*, ESA-sponsored experiments participated in by European astronauts who fly on the Soyuz to the ISS on taxi flights; and
- *Individually sponsored projects*. Mark Shuttleworth, who flew as a space tourist, brought along his own suite of experiments from South African researchers. This approach would appear to be open to others who fly via this route.

NASA's NRA program tends to focus on studies of basic mechanisms but includes countermeasure studies as well. The NSBRI program is chartered to develop countermeasures, and the CEVP is designed to validate countermeasures. The flight medicine program provides the ongoing monitoring of crew members and prescribes countermeasures. A summary of the current efforts in system physiology appears in Appendix F.

Impact of ISS Changes

Hardware Changes

Table 3.1, taken from the NASA Flight Equipment Experiments Information Package, shows what equipment was offered to potential investigators for use on the ISS (ISLSWG, 2001). The ESA-supplied equipment will be available on the ISS when the Columbus module arrives at the ISS. The U.S.-supplied equipment will be in place once both racks of the Human Research Facility (HRF) are installed. The first rack is already installed; the second, and final, rack of the HRF is scheduled for installation in January 2003. When the Columbus module and HRF are installed, the hardware that had been promised to human investigators will be in place. But it represents only a subset of what was available in the past on Spacelab flights, which contained not only the basic equipment for human physiology research (blood-pressure devices, gas analyzers, etc.) but also an animal habitat that is not present on the ISS. The main piece of equipment that would represent a major advance over Spacelab, the 1-*g* centrifuge, has been significantly delayed, and its future is uncertain.

TABLE 3.1. Summary of Available Hardware to Support Human Subject Research on the ISS

	Shuttle-Based	ISS-Based	Agency	Web Site
Physiological monitoring				
Manual blood pressure device	X	X	NASA	http://lslife.jsc.nasa.gov/hardware/mbpd.html
Automatic blood pressure system	X		NASA	http://lslife.jsc.nasa.gov/hardware/abps.html
Continuous blood pressure device		X	NASA	http;//lslife.jsc.nasa.gov/hardware/ebpd.html
Combined blood pressure monitoring		X	NASA	
Percutaneous electrical muscle stimulator	X	X	NASA/ESA	http://www.estec.esa.nl/spaceflight/pems.html
Pulmonary function system		X	NASA/ESA	
Gas analyzer mass spectrometer		X	NASA	http://lslife.jsc.nasa.gov/hardware/gasmap.html
ECG/EMG/EEG	X	X	NASA	
Holter monitor	X	X	NASA	http://lslife.jsc.nasa.gov/hardware/holter.html
Pulse oximeter	X	X	NASA	http://lslife.jsc.nasa.gov/hardware/pulseseox.html
Respiratory impedance plethysmograph	X	X	NASA	
Ultrasound doppler		X	NASA	http://lslife.jsc.nasa.gov/hardware/ultra.html
Venous occlusion cuff and controller	X			
Sample collection and stowage		X		
Human sample collection kits	X			http://lslife.jsc.nasa.gov/hardware/sample.html
Exercise				
Bicycle ergometer	X	X	NASA	http://lslife.jsc.nasa.gov/hardware/cevis.html
Treadmill	X	X	NASA	http://lslife.jsc.nasa.gov/hardware/tvis.html
Interim resistive exercise device		X	NASA	
Muscle strength torque and joint angle			NASA	
Muscle atrophy research and exercise system		X	NASA/ESA	http://www.estec.esa.nl/spaceflight/mares.html
Resistive exercise device		X	NASA	
Hand grip/pinch force dynamometer	X	X	NASA/ESA	http://www.estec.esa.nl/spaceflight/hd.html
Cardiovascular loading				
Lower-body negative pressure	X	X	DLR	http://lslife.jsc.nasa.gov/hardware/lbnp.html
Posture				
Foot-ground interface				http://lslife.jsc.nasa.gov/hardware/fgi.html

TABLE 3.1 Continued

	Shuttle-Based	ISS-Based	Agency	Web Site
Activity monitoring				
Activity monitor		X		http://lslife.jsc.nasa.gov/hardware/actmonitor.html
Medical procedures injection and infusion system	X	X		
Eye movements	X	X		
3D eye-tracking device				http://www.dlr.de/struktur_strategie/raumfahrtmanagement/RD-JW/projekte-uebersicht
European physiology modules			ESA	http://www.estec.esa.int/spaceflight/epm/epmintro.html
Multielectrode EG mapping module		X	ESA	http://www.estec.esa.int/spaceflight/epm/epmintro.html
Bone analysis module		X	ESA	http://www.estec.esa.int/spaceflight/epm/epmintro.html
Body movement analysis instrument		X	ESA	http://www.estec.esa.int/spaceflight/epm/epmintro.html
CARDIOLAB		X	ESA	http://www.estec.esa.int/spaceflight/epm/epmintro.html
Physiological pressure measurement instrument		X	ESA	http://www.estec.esa.int/spaceflight/epm/epmintro.html
Xenon skin blood flow measurement instrument		X	ESA	http://www.estec.esa.int/spaceflight/epm/epmintro.html

NOTE: This list, from the Space Life Sciences and Space Sciences Flight Experiments Information Package, indicates the equipment that was planned for research use on the ISS at the time of its publication (ISLSWG, 2001). Most of the equipment will be in place as part of either the Human Research Facility (HRF) or the European Columbus module.

Crew Resources

For bioastronautics research the crew not only perform the experiments but also are often the key source of data on the adaptation to weightlessness. One major benefit of the ISS was to have been the ability to fly large crews so that adaptations could be documented, mechanisms determined, and countermeasures developed. The Rev. F ISS plan called for a crew of six to seven, with three to four of those devoted to scientific activities. A crew of six flying every 3 months would have provided the possibility of collecting data on 24 people in 1 year. Assuming that three crew members would have been devoted to scientific research full-time (40 hours/week), then about 120 hours a week would have been available for science.

The current Core Complete plan calls for a long-duration crew of three for flights that will be extended to 4-6 rather than 3 months. The maximum number of crew members who could be studied in 1 year in this scenario is approximately nine. This amounts to a 63 percent reduction in crew members available. This number is further reduced by the fact that not all crew members may participate in a given experiment. American crew members participate mainly in the U.S. research program, and Russians may participate to some extent in the NASA program, and the converse will probably also be true. An experiment that requires a significant number of participants (more than six or seven) to produce meaningful results could take years to complete, even assuming that all crew members agree to participate.

About 20 hours a week will be available in-flight for science, which is approximately an 80 percent reduction in the time available under Rev. F. Another important component of crew time is the time available for training and for data collection before and after a flight. The original (Rev. F and earlier) plans allowed for some crew members to be dedicated to scientific activities, while others could focus on station operations. In this way, the time available for scientific training could be expanded for those crew members carrying out the experiments. This is no longer the case.

In the current Core Complete plan, a total of an hour and a half per crew member is available on landing day for all scientific measurements on the crew. Separate time is allocated for flight medicine measurements, but these are not considered research data by NASA.[2] More time is available on subsequent days. Compared with what had been available in prior programs (Skylab, Spacelab), time for crew training and pre- and post-testing are very limited (Table 3.2). These limitations indicate that only the simplest experiments requiring minimal crew training, time, and other resources could be performed.

Work can still be done on the ISS in the flight medicine and the Russian biomedical research programs. The work currently ongoing on the ISS in the area of countermeasures and physiology is mainly part of these programs. As has been outlined in various reports (NRC, 1998, 2001; IOM, 2001), these data are considered private medical data and so are not routinely available to researchers.

The Value of the Remaining Research Capability

Several factors have to be considered to assess the value of the research capability in systems physiology. Among them are these:

- Availability of the crew for testing during the mission, since systems physiology research involves measurements on the crew.
- Availability of the crew for testing before and after the mission. Premission testing provides the baseline for comparison, and postflight testing shows the nature of the changes that have taken place and how long they last.
- Availability of the crew for training, since the complexity of the experiments is limited by how much time the crew members have to learn the equipment and procedures.

Table 3.2 provides a qualitative comparison of the ISS with other space research capabilities that have existed in the past

In its current form, the ISS program appears to be less capable than Skylab or Spacelab of supporting research. Studies on humans can be performed, but at a decreased rate, because of time and resource considerations. Studies of laboratory animals, e.g., rats, mice, and quail, will not be possible until the animal and avian habitats are available on the ISS. Without the 1-g centrifuge, the animal studies will not have appropriate controls.

Factors Limiting Utilization of the ISS

When resources are critically limited, as with the ISS, it is vital to use them efficiently. Yet the several independent programs for research in systems physiology on the ISS are not well coordinated. In fact, they sometimes work in opposition or duplicate efforts. For example, the NRA program tends to focus on studies of basic mechanisms but has countermeasure studies as well. The Russian biomedical

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[2] Work is ongoing to make these data available to researchers.

TABLE 3.2 Research Capabilities of Past and Present Space Research Platforms

	Skylab	Spacelab	Mir	ISS
In-flight crew testing	Extensive	Extensive	Moderate	Limited
Pre-/postmission/ flight crew testing	Extensive	Extensive	Moderate	Limited
Crew training	Extensive	Extensive	Moderate	Limited
Long duration?	Yes	No	Yes	Yes

NOTE: The Skylab flights and dedicated Spacelab missions involved extensive testing on the crew before, during, and after the flights. The Mir program usually had one person of the three-person crew who was mainly involved in research. During the Shuttle-Mir program this was not always the case due to logistical problems in getting the research program to the crew members and the increased operational load as Mir aged.

program appears to measure the same kinds of parameters as the flight medicine program and other NASA programs (NASA, Public Affairs, 2002).

The connection between the CEVP and the other efforts is not firmly established. The NSBRI program is chartered to develop countermeasures. If a countermeasure is shown to be promising, the NSBRI investigator must wait for a research announcement from the NRA program and then submit a proposal and have it reviewed and approved before proceeding to flight. This process can typically take several years. There is no direct link to the CEVP. Flight surgeons can prescribe countermeasures that have not been evaluated by the CEVP. Moreover, NRA or NSBRI projects that lead to a countermeasure do not automatically get reviewed for the CEVP. When the CEVP was first proposed, it included a set of measurements that could be used to meet both clinical and research needs. This set of tests, known as the integrated testing regime, was not fully implemented, and ongoing monitoring of crew members is performed using requirements set by the flight medicine program. The flight medicine program, however, collects data that are classified as private medical data and so are not routinely shared, although a method is being developed to share grouped data. The Russian program collects data on both cosmonauts and astronauts, but this information is also not readily available. With the exception of the flight medicine program measurements and, possibly, the Russian program, participation in biomedical measurements pre-, in-, and postflight is voluntary, even though these measurements were cited in a recent review of the ISS as being one of the most important products of the ISS (IMCE, 2001).

The disjointed nature of the program detracts from its ability to achieve research goals that require measurements on many people or consistent measurements over time. These kinds of measurements are the essence of systems physiology research. Data collected for experiments that study human physiology or countermeasures clearly overlap with the measurements that are being taken by NASA's flight medicine program. Despite this, no systematic way exists to integrate experiments with the measurement program that is already under way. Individual investigators need to negotiate this on their own—there is no NASA program in place to facilitate or enforce this integration. Funded investigators in the NASA program need to contact the flight medicine program or the CEVP to arrange sharing agreements. While this has worked successfully in many cases, it provides an advantage to those with the most knowledge about and experience with the system.

While the physiologic measurements made in the flight medicine program are mandatory, investigators with an approved countermeasure project need to "sell" their experiment to the crew members to encourage their participation. This arrangement could give rise to some confusing experiences for the investigators and flight surgeons. At present it is possible for an investigator to propose an investigation, pass peer and technical review, pass the institutional review boards at NASA and the investigator's home institution, and be funded and manifested, but be unable to complete the project because of difficulties enrolling participants. Also, any experiment involving testing the validation of a countermeasure will probably overlap with ongoing flight medicine program efforts.

Limitation on Scope of Experiments

Resource limitations clearly affect the ability to complete currently manifested experiments, but they also affect the kinds of experiments that are proposed and selected. At present, to be selected, a flight experiment must have only minimal requirements for crew training, crew time, equipment (i.e., equipment that is not already in the inventory) or other resources. Box 3.1 lists the restrictions that were placed on flight experiments in the latest flight experiment announcement of opportunity from NASA. As a result of such restrictions, the current program screens out demanding experiments. Because investigators must review these restrictions in advance, many important experiments may not even be proposed to NASA. The restrictions listed in Box 3.1 refer to the assembly phase of the ISS, but due to the reductions in crew time on Core Complete it is unlikely that these restrictions could be relaxed after assembly has ended.

For instance, since most countermeasure validation experiments would, by their very nature, require collection of baseline data shortly before flight and immediately after landing, the restrictions placed by NASA on pre- and postflight testing (see Box 3.1)—limited baseline crew data collection on the two days after landing (R + 0 to R + 2) and limited baseline crew data collection during the 30 days prior to launch (L–30 to launch)—would inhibit investigators from proposing experiments that required these resources. If such experiments were proposed, they would seem to require too many resources to be selected.

Maximizing ISS Research Potential

There are a number of ways to mitigate, to some degree, a few of the problems identified in the preceding discussion and to maximize the remaining research potential of the ISS. For example, the different research programs (NRA, NSBRI, flight medicine, ESA, the Russian program, independent research) should be coordinated to eliminate duplication and maximize the use of available resources.

NASA's research objectives are often stated in general terms (i.e., develop countermeasures) rather than in a specific form (i.e., ensure that there is no significant change in bone mineral density in all crew members). As a result, there is no way to establish clear priorities or assess the effectiveness of the program. Without clear priorities, the limited station resources cannot be used effectively. The research objectives for systems physiology need to be stated in a specific way to help set priorities and measure progress. The Critical Path Roadmap process that has been established by NASA has been an excellent start in this direction and should be continued.

If a core goal of the ISS is to study the physiology of weightlessness and develop countermeasures, then crews should be selected on the basis of their willingness to participate in research studies. To date, participation by U.S. crew members in the research program has been very good. The involvement of Russian crew members also should be worked out in advance. An approach to this issue is outlined in a report by the Institute of Medicine (IOM, 2001).

Most of the data needed for countermeasure development and validation are collected by NASA's flight medicine program and are not routinely available to other researchers. Participation in the flight medicine program is mandatory, and controversy exists over whether this program has a significant research component since it provides most of the ongoing monitoring data. As has been stated in several other reports (NRC, 1998, 2000b; IOM, 2001), a mechanism to share and review these data needs to be developed. The current effort to provide group data from the flight medicine program tests should be continued and supported.

Crew time is the major limiting factor for research activity in systems physiology. Without an expansion of the time available for pre- and post-training and testing, it will be difficult to accomplish

BOX 3.1 Limitations on the ISS Experiments Imposed by the OBPR Budget for FY 03

1. The need for a large allocation of in-flight crew time (experiment procedures that will take more than 3 hours per week).
2. Measurements to be made on long-duration crew members within their first days on-orbit, which implies that the measurements have to be made on the shuttle before docking with the ISS or on the return trip.
3. Intensive early flight activities (Flight Day 0 to Flight Day 15). Operations that require more than 1 hour per subject per day for more than 2 days during this period are considered intensive operations.
4. Baseline crew data collection on the 2 days after landing (R + 0 to R + 2).
5. Baseline crew data collection during the 30 days prior to launch (L–30 to launch).
6. Excessive crew training (more than 10 hours to familiarize a novice with the procedure).
7. A large number of crew subjects (more than 6).
8. Complex or invasive in-flight procedures on the crew, such as indwelling catheters, multiple hardware items that must be integrated or synchronized, precise requirements for when an experiment must be performed, complex skills required (e.g., in-flight biopsies, microneurography, etc.).
9. Large upmass/volume. Volume on the space shuttle is usually measured in “middeck locker equivalents.” A middeck locker can hold a volume with dimensions of 44.0 x 25.3 x 51.6 cm (17.337 x 9.969 x 20.320 in.) and can hold a total of 27.2 kg (60 lb). A request that involved more than three of these dedicated to a single experiment on a single mission would be difficult to accommodate.
10. Procedures on nonhuman specimens on the day of launch (unless automated).
11. Procedures that require crew time prior to docking on the ISS or on the day of landing.
12. Complex in flight procedures on nonhuman specimens, such as surgeries or dissections.
13. Experiments that require more than one flight to meet objectives.

SOURCE: This material is taken from the 2001 NASA research announcement soliciting flight experiments for the ISS.

significant work. Time for pre- and post-training and testing should thus be increased to allow for meaningful experiments to be performed and proposed.

Conclusions

The ISS research program as initially proposed (Rev. F and earlier configurations) provided several crew members and a considerable amount of research time. The cuts in the program, however, make meaningful systems physiology work very difficult to accomplish. Programs should be coordinated and duplication eliminated, and long-standing issues surrounding data privacy and participation should be resolved.

CARDIOPULMONARY PHYSIOLOGY

Program Description

The cardiopulmonary research program supported by NASA is a mix of studies on humans and animals that address the major effects of weightlessness on cardiopulmonary systems. A ground-based program exists to study these areas, along with a program for flight experiments. An ongoing program of cardiovascular monitoring and assessment of astronauts is also in place. In this report, just the flight portion of the cardiopulmonary program is discussed.

One significant cardiovascular effect of spaceflight is the reduction in blood pressure that can occur while standing postflight or during reentry after exposure to weightlessness (known as orthostatic intolerance). In addition to postflight orthostatic intolerance, other cardiovascular issues of importance for spaceflight include in-flight aerobic deconditioning, cardiac atrophy, and cardiac arrhythmias. The important pulmonary physiology concerns, and the main foci of pulmonary research, are adequate denitrogenation prior to extravehicular activities (EVAs), increased aerosol deposition in spaceflight, and changes in pulmonary perfusion.

Programs with Efforts in Cardiopulmonary Physiology

Several programs administer efforts that lead to flight measurements relating to cardiopulmonary physiology:

- *NASA NRA program*, a competitive Headquarters-based research program that funds intramural and extramural research, has three flight experiments in this area. A pulmonary experiment (PUFF) and a cardiovascular experiment (XENON) are both currently on the ISS. The third cardiovascular experiment is in the definition phase.
- *NSBRI program,* an extramural independent program focused on countermeasure development, includes cardiovascular efforts but has no flight projects.
- *Countermeasure Evaluation and Validation Program,* a program for validating new countermeasures, has one experiment that is studying midodrine as a countermeasure for orthostatic intolerance and also includes cardiovascular monitoring during reentry on the shuttle.
- *Flight medicine program,* an intramural program that prescribes countermeasures and makes ongoing measurements, makes a series of cardiovascular measurements, pre-, in-, and postflight. The AMERD document (NASA, 1998b) describes the components of this program, which include exercise tests, EKGs, and stand tests.
- *Russian biomedical research program,* an independent Russian effort to study physiology and develop countermeasures, includes two ongoing flight experiments (cardio-lower body negative pressure (LBNP and pulse). Monitoring is also done during reentry in the Soyuz capsule.
- *European Space Agency projects.* European astronauts who fly on the Soyuz to the ISS on taxi flights participate in ESA-sponsored experiments. One such experiment is the evaluation of a blood pressure monitoring device.
- *Individually sponsored projects*. Mark Shuttleworth, who flew as a space tourist, solicited research from South African investigators and participated in a cardiovascular study during his flight.

Impact of ISS Changes

Resources

The initial equipment plans in Rev. F called for the HRF to provide the main equipment for U.S.-sponsored cardiovascular research, and the specific cardiovascular equipment promised is still expected to be in place on Core Complete. In addition, more equipment will be available when the Columbus module arrives at the ISS (see preceding section, “Systems Physiology”). The Russian program also includes cardiovascular research equipment, but whether Russian equipment could be shared to do U.S.-sponsored research is not clear.

Crew time, as well as crew to serve as subjects, however, are limiting resources. Cardiopulmonary research competes with every other discipline studying human physiology for its share of the limited amount of time available for training, preflight data collection, in-flight data collection, and postflight assessment. At present, the NASA program supports two experiments in this area, with one additional experiment in the definition phase. The flight medicine program and the Russian biomedical program have ongoing monitoring and assessment efforts.

Since the data collected in the flight medicine program are considered private medical data, however, they are not routinely shared. This is a problem that has been identified in other National Academies reports (NRC, 2000b; IOM, 2001).

With the limitations on in-flight crew time, training time, and pre- and postflight data collection, it is unlikely that any further NASA-sponsored research could be performed until the three currently planned experiments are completed. These limitations are also delaying the manifesting of peer-reviewed experiments still in the definition phase. The Soyuz taxi flights still offer the potential for short-duration experiments for the European Space Agency astronauts and private individuals.

Research Program

A recent review of NASA's biomedical research program (NRC, 2000b) listed four key areas for research in the cardiopulmonary area: orthostatic intolerance, cardiac atrophy, arrhythmias, and pulmonary changes. The research currently manifested is summarized in Appendix F. One ongoing NASA research project is studying midodrine as a countermeasure for orthostatic intolerance. Given the limited number of crew members to study and the constraints on crew time, it is unlikely that any other countermeasure validation studies could or should be supported. The flight medicine program makes ongoing orthostatic intolerance assessments, but their results are not available to the research community (although they are used to assess the effectiveness of the countermeasure program). The Russian cardio-LBNP experiment continues, as does the Russian pulse experiment. Whether these measurements are integrated into other measurements being made is not clear.

Cardiac atrophy will be addressed in the one pending flight experiment. At present, it is not clear if this experiment will be approved for flight. Cardiac arrhythmias could be detected using the equipment on the ISS, but there does not appear to be a formal program in place to monitor for these. Pulmonary measurements are ongoing with the one pulmonary flight experiment.

Overall, NASA has not deleted any cardiopulmonary experiments, but, as noted above, few experiments have been selected for flight. One approved experiment from the last announcement of opportunity for flight experiments (in 1999) is still not manifested.

Factors Limiting Utilization of the ISS

For a potential investigator several factors limit utilization of the ISS for studies of cardiopulmonary physiology. These limitations can be divided into those that exist prior to submitting an experiment, and those that exist once an experiment has been approved for flight.

As discussed in the section "Systems Physiology" above, an investigator who did submit a research proposal in response to the Announcement of Opportunity in 1999 would have noted that there were many limitations on the type of flight experiments that could be submitted. Experiments that required a significant time commitment at any point (pre-, in-, or postflight) were discouraged by the language of the announcement. This meant that experiments that required measurements during recovery and rehabilitation would be difficult or impossible to perform. As a result, only the simplest cardiovascular experiments were likely to be submitted. One experiment that is currently approved for flight but not manifested remains in the definition phase because of its demands for pre-and postflight testing.

Maximizing ISS Research Potential

Several steps could be taken to maximize the research potential on the ISS. In the area of human physiology, the most critical resource is the number of crew members who can participate and the time they have available for training, baseline measurements, and postflight data collection. Any increase in crew size, crew time (pre-, in-, or postflight), or operational efficiency would benefit research.

The research efforts of the NRA, NSBRI, CEVP, and flight medicine and Russian programs could be coordinated to eliminate conflicts, overlaps, and duplication of effort. Using different protocols and equipment to measure essentially the same set of cardiovascular parameters does not make the best use of the limited number of people who can participate in these studies.

Many worthwhile recommendations have been made in the past about spaceflight research that are of particular importance now in a time of tight budgets and limited resources. The guidelines outlined in three National Academies reports (NRC, 1998, 2000b; IOM, 2001) IOM should be used to focus the research program, set priorities, and establish guidelines for crew involvement.

MUSCLE AND BONE PHYSIOLOGY

Program Description

This program deals with bone and muscle loss—major pathophysiological changes associated with microgravity and the spaceflight environment (NRC, 1995, 1998, 2000c; Schneider et al., 1995; Turner, 2000a). Reductions in bone mass and bone density, loss of muscle mass, and failure to repair these tissues after reentry put space travelers at risk for fractures and prolonged loss of neuromuscular activity, including muscle weakness, fatigue, lack of coordination, and muscle soreness. Bone and muscle loss is listed as a top-priority area in NASA's Critical Path Roadmap, and the biotechnology research done as part of this program has implications for both NASA and human health.

Three types of studies were discussed throughout the 1990s in connection with preventing the bone and muscle loss encountered by astronauts and cosmonauts on short- as well as long-term spaceflights. These studies, which also addressed fundamental questions in bone and muscle physiology, were planned for the whole organism (humans and animals) and for individual tissues and cells. In 1998, the NRC Committee on Space Biology and Medicine provided a series of essential questions to be answered to understand bone loss in space (NRC, 1998). The committee suggested that a determination be made as to whether animals sustain bone loss comparable to the loss in humans. When and if an animal model showed changes similar to those in humans, the committee suggested that it be evaluated in ground-based experiments to see if that environment could be used to mimic bone loss in space. Muscle physiology studies were suggested that would determine how muscle alterations and atrophy could be minimized by understanding the hormonal and nutritional aspects of muscle change in weightlessness. Determination of how skeletal muscle deficits are reflected in other organ systems was also suggested. Concurrent muscle, bone, and blood flow studies were recommended. These are but a few of the recommended studies, many of which were included subsequently by NASA in its portfolio of bone and muscle physiology research on the ground and in flight. The ISS experiments in this area are listed in Appendix G.

The experiments needed to carry out these studies involve analysis of bone and muscle loss after short- and long-term exposure of humans, animals, and cells to altered gravity environments, with studies done in both simulated and actual hypogravity. The efficacy of a wide range of countermeasures hypothesized to prevent bone and muscle loss problems would also need to be analyzed in detail. Possible countermeasures include exercise regimes and pharmacological interventions. Another recommended countermeasure is exposure to 1 *g* in a centrifuge. Based on studies showing that intact rats and isolated bone and muscle cells exposed to hypergravity did not show the muscle and bone loss associated with weightlessness (Guignandon et al., 1997, 2001; Vasques et al., 1998), it was hypothesized that in the future exposing astronauts to 1 *g* while on the ISS would be a more effective countermeasure against bone and muscle wasting than defined exercise programs in low gravity (Wade et al., 1997; Kreitenberg et al., 1998). Exercise programs and evaluations of bone mineral density and urinary calcium are also being conducted as part of the flight medicine program studies, but as noted above, these data are not accessible.

Impact of ISS Changes

The Rev. F design for the ISS included resources that would support bone and muscle research: six EXPRESS racks, six crew members, and a 1-*g* centrifuge for animals. Direct computer-based interaction between investigator and crew and new sensors for in-flight measurement of metabolism were also promised. Core Complete plans reflect extensive restructuring from the original Rev. F. Cell science and biotechnology research (which includes research on bone and muscle cells) will now be limited to two EXPRESS racks (in place of six). While cuts in the bone and muscle research program cannot be isolated from the list of bioastronautics microgravity research program cuts made by NASA, as discussed below, there will be significant reductions in equipment as well as in manifested experiments (Table 3.3) by 2004. The reductions in science equipment are compounded further by the decrease in crew size.

The list of items of equipment that were promised in Rev. F and are now delayed or deleted in Core Complete includes the "next-generation rotating wall perfused bioreactor system," the advanced animal habitat, the avian habitat, the aquatic habitat, and the 1 *g* centrifuge. Loss of the animal habitat and the lengthy delays in the 1 *g* centrifuge are disastrous, as bone and muscle loss in nonhuman models cannot be evaluated without this equipment. NASA also indicated that cuts are planned for PI-unique hardware for looking at macromolecular biotechnology (which includes tissue engineering of bone, muscle, and cartilage). These cuts will have a major negative impact on bone and muscle cell biology studies, and on animal studies once the animal habitats are on board because, in order to do procedures on animals, the habitats must be linked to the life sciences glovebox. It should be noted that no vertebrate research can be accomplished on the ISS until the habitats are available. Table 3.3 indicates experiments deleted by NASA because of lack of availability of this equipment. The loss of these experiments will retard the accumulation of basic biology data on how bone and muscle loss occurs in microgravity, delaying the development of the most effective countermeasures.

The list of future studies in bone and muscle physiology manifested for flight on the ISS provided by NASA in early 2002 is given in Appendix G. Specific equipment available on the ISS for bone and muscle studies is discussed below.

ISS Facilities for Bone and Muscle Research

The following equipment and facilities for bone and muscle research will be available on the ISS (NASA, OBPR, 2002):

- The advanced thermoelectric refrigerator freezer (ARTIC) is a permanent refrigerator freezer that fits in an EXPRESS rack and can store samples at –80°C . It will be the main storage freezer/refrigerator for large and complex experiments. The unit was installed on the ISS in April 2002.
- The cellular biotechnology operations support system is on-station hardware dedicated to cultivating cells. It contains a biotechnology specimen temperature controller (BSTC), a biotechnology refrigerator, a gas supply module, and two biotechnology cell science stowage units. The BSTC's chamber will act as a non-rotating bioreactor, in which the cells will be cultivated. The experimental tissues grown will be used for the study of human diseases. The rotating wall vessel was used for the establishment of cartilage and bone cultures on the shuttle; thus it is likely that this unit may be available for similar studies on the ISS. The unit was installed in August of 2001, and the first frozen set of cultures were returned on STS 108.
- Two EXPRESS racks provide a standardized refrigerated system for experiments. Each EXPRESS rack is housed in an international standard payload rack, which is a refrigerator-size container that acts as the EXPRESS rack's exterior shell. Each rack can be divided into segments. The EXPRESS racks on the ISS have eight middeck locker locations and two drawer locations each. Experiments

TABLE 3.3 Deleted OBPR-Sponsored Bone and Muscle Experiments on the ISS

Project Title	Principal Investigator	Institution
Effect of space travel on skeletal myofibers	H. Vandenburgh	Brown University
Spaceflight and bone metabolism: age effects and development of animal model for human bone loss	B. Halloran	Veterans Administration Medical Center
Skeletal development in embryonic quail on the ISS[a]	S.B. Doty	Hospital for Special Surgery
Relationship of morphogenesis and mineralization to gravitaxis	P.J. Duke	University of Texas Health Science Center
Differentiation of bone marrow macrophages in space	S.K. Chapes	Kansas State University
Effects of resistance training using flywheel technology on size and function of skeletal muscle in crew stationed in space	P. Tesch	Karolinska Institute

NOTE: Six of 12 peer-reviewed experiments that were originally scheduled for the ISS were deleted due to resource limitations.
[a] This experiment flew on the shuttle (UF-1) in December 2001, but according to Stephon B. Doty (personal communication, September 13, 2002) and documentation provided recently by NASA (Fundamental Space Biology, ISS Flight Experiment Queue, Code UF, 2002), repeats are not planned, thus reducing the value of this study.

contained within EXPRESS racks are controlled either by the crew or remotely from the ground by the payload rack officer on duty at the Payload Operations Center at NASA's Marshall Space Flight Center in Huntsville, Alabama.

- The Human Research Facility (HRF) Rack 1 houses a computer workstation and portable laptop computer for crew members to command and test the rack's equipment, collect and store experiment data, send data to and from scientists on Earth, provide a place for the crew to store notes, and for human life sciences experiments. Beginning with Expedition Two, the ISS crew will use the computers to transmit, among other things, the H-Reflex life sciences physiological experiments. Also housed in the rack is equipment for the gas analyzer system for metabolic analysis physiology and ultrasound human life sciences experiments. The Ultrasound Imaging System has the capacity with appropriate attachments to be used in the bone and muscle research programs to generate three-dimensional images of muscles, tendons, and blood vessels.

There are three pieces of equipment for exercise studies: a leg cycle ergometer, a treadmill, and an interim resistance-training device. The equipment is used extensively for a prescribed crew exercise program (NASA, OBPR, 2001); however, data are not accessible to outside researchers to evaluate the efficacy of these programs.

ESA has a bone analysis module for ultrasound measurements of bone density, a bone physiology module as part of the European physiology modules, a percutaneous muscle stimulator, and a muscle atrophy and exercise system, all of which are available to U.S. investigators on the ISS (ESA, 1999). All of these will be essential for conducting those human studies that are already approved for flight.

Animal studies cannot commence until the habitats are available. The original hope was that the ISS would enable long-term experiments, some initiated in microgravity, that could address hypotheses and interventions related to the effects of long-term spaceflight on musculoskeletal loss. These long-term experiments were designed to minimize physiologic changes known to occur as a result of launch and reentry either by starting cultures or embryonic growth after launch, or by maximizing the time in microgravity. The great advantage of these studies was their expected use of the promised centrifuge, which would have allowed the effects of changes in gravitational force to be separated from other effects.

Delay of the large 1-*g* centrifuge and the life sciences glovebox, and deletion of the advanced animal habitat, will have a major effect on the quality of the science, as ground controls are not subject to the other environmental challenges that ISS occupants and future space explorers face.

Feasible Experiments in Core Complete

The research in bone and muscle physiology that can be done on Core Complete is limited, both in terms of the time available for experimentation and the reduced numbers of human subjects for study. However, some important investigations in bone and muscle physiology could still be initiated, recognizing that it will take a longer time for them to be completed. Noninvasive measurements of bone turnover, e.g., bone mineral density measurements made pre- and postflight, urine samples (excretion of calcium or collagen cross links) collected during flight for testing on the ground, and in-flight muscle force measurements, could in principle eventually be accomplished, even with a crew of three per mission. However, the number of years required to complete the studies with the Core Complete configuration may be much greater than originally planned by investigators because of the reduction in crew size. The three-person crew is likely to have less time available for collection of data on humans, let alone for running experiments. Since the crew of three also includes the international partners, it is not clear how participation in NASA-sponsored experiments is assigned, as other partners appear to be running similar experiments. Because flights currently alternate between two Americans and one Russian, or one American and two Russians, based on previous experience with joint missions, it can be estimated that it will take more than 6 months to collect 3 months worth of NASA data on six crew members.

Inclusion of exercise equipment for crewmembers, and its regulated use, was proposed to prevent bone loss (Keller et al., 1992) and is now in use in the flight medicine program. The data from Skylab, Mir, and NASDA studies (LeBlanc et al.,1998; Vico et al., 2000; Miyamoto et al., 1998) demonstrate that exercise diminishes bone and muscle loss but does not prevent it. Data on the long-term efficacy of exercise as a countermeasure are not available. Information from the flight medicine program studies using the treadmill, cycle ergometer, and resistance-training device, although lacking a no-exercise control, should provide a baseline for additional countermeasures. However, the data are not available to NASA investigators. Formal studies of drug-based interventions such as the use of bisphosphonates (Apseloff et al., 1993; Grigoriev et al., 1992; NewsRx.com, 2001), parathyroid hormone (Canadian Space Agency press release, 2001), or osteoprotegerin (Amgen, 2001; Bateman et al., 2000, 2001) could be accomplished were crew available and willing to participate. Unfortunately, these potential countermeasures can sometimes be prescribed by astronauts' and cosmonauts' physicians without being part of a study and without plans for formal evaluation.

Animal studies could be performed if the animal habitat on the Core Complete ISS (along with the 1-*g* centrifuge and the life sciences glove box) were available. Cell culture studies could then also be done if sufficient crew time were available for maintenance of long-term cultures. Without this and the other nonvertebrate habitats, the basic biological understanding needed to translate cell and organ culture information to human studies will be not be forthcoming.

Factors Limiting Utilization of the ISS

Perhaps the biggest obstacle for investigators planning bone and muscle experiments for the ISS and recruiting student participants for these studies is uncertainty. There is uncertainty about whether the equipment for the planned ISS experiment will ever be available, uncertainty about when the experiment will be manifested and flown, and uncertainty about whether replicate experiments will be possible. Another major obstacle, caused by schedule delays related to ISS construction, is the extensive amount of time between selection of a project for flight definition and actual flight. During these long delays, the science has often progressed so much that the entire study should be redesigned. These obstacles discourage students from building an interest in space science, and new investigators from becoming involved in ISS-based projects; cause concerns about promotions among non-tenured faculty; and are leading some long-time NASA investigators to question their continued commitment, as well as that of their students.

If there are not appropriate controls, such as that to be provided by the 1-*g* centrifuge, or if an experiment is postponed for so long that the graduate students who were scheduled to work on it have since finished their PhDs, or if the new and better measurement equipment exists but is not approved for ISS experiments, it will be difficult to retain existing investigators, let alone attract new ones.

Maximizing ISS Research Potential

As noted throughout this section, the ISS research potential for studies on bone and muscle physiology on Core Complete is particularly limited by the absence of three resources: the animal habitat (for vertebrate animal studies), the 1-*g* centrifuge (for in-flight control studies) ,[3] and crew (both as volunteer subjects and as scientists performing the experiments). The life sciences glovebox is also a critical resource that is not expected to be flown until 2005 or later. While it would be preferable to have more EXPRESS racks available for cell culturing and other biotechnology experiments supporting bone and muscle research, and more importantly, for replicate experiments, the electrical power, stationary equipment, and refrigeration in Core Complete are acceptable for the studies currently proposed in muscle and bone physiology. With the current number of EXPRESS racks, however, and the difficulty of doing the number of studies required based on statistical considerations, it may be impossible to recruit new scientists into the discipline. There are currently investigators with proposed and planned experiments who, if they have reliable information as to when their experiments will fly and a commitment that they will be able to repeat these experiments, might consider remaining in the field.

To help maximize bone and muscle physiology research, the requirement for volunteer participants for human experiments might be met with a plan for recruitment, education, and training of crew members before they are scheduled for flight. Human studies that require a small number of subjects[4] should be selected in preference to those requiring larger numbers until a larger crew is available. Of course, increasing the crew size would enable studies on the crew to be completed more rapidly and with less experimental variation. The sharing of data between bone and muscle researchers and with researchers in other areas of physiology, as stated in the section "Systems Physiology," is essential and must be seamless and guaranteed. This should hold for both clinical data and data from basic science research.

Reestablishment of the animal habitat and its 1-*g* centrifuge as early as possible is essential for understanding the mechanisms of bone and muscle loss and developing methods to prevent such changes in these tissues. Animal studies cannot be manifested until the habitat is available, and should not be scheduled until NASA can guarantee that replicate experiments will be performed. Research on the ground to refine concepts based on animal models should continue until the habitat becomes available. Proposals for research on the ISS utilizing vertebrate animals in space should not be reviewed until then.

In conclusion, bone and muscle research is a top priority for maintaining astronaut health and is a promising area for microgravity research. However, the lack of crew time, equipment, and appropriate controls must be addressed in order to make progress in this area.

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[3] Absent from the ISS until 2007 or later.

[4] Even these smaller studies will likely have to be carried out over a number of missions in order to obtain a statistically significant sample.

RADIATION BIOLOGY

Program Description

Ionizing radiation from the Sun and from galactic cosmic rays is not a significant health hazard on the surface of Earth. However, for long-term occupants of the ISS (~250 miles above Earth) and, for example, astronauts traveling to Mars, the hazards may be significant. The diminished shielding by Earth's atmosphere and decreased diversion of charged particles by Earth's magnetic field result in increased dose rates of ionizing radiation. Hence, it is important to know not only the radiation dose levels on the ISS and how they vary with time, but also the dose levels beyond low Earth orbit (i.e., at interplanetary distances). At such distances galactic cosmic radiation, including high-atomic-number (Z), high-energy (HZE) nuclei, takes on greater significance because the particles lose large amounts of energy per micrometer (and so are known as high linear energy transfer (LET) particles). It is important to know not only the health effects of LET particles, but also the countermeasures—shielding and potential biochemical modifiers—to reduce the health effects. It should be noted that radiation hazards, such as mutations and increases in cancer incidence after return to Earth, are estimated from data on reasonably large populations exposed to short-duration doses of low-LET radiation (Japanese survivors of the nuclear bombs and groups exposed to therapeutic doses of x rays). It is from these data that the effects of chronic exposures are inferred (NRC, 1990). The biological effects of HZE cosmic-ray nuclei are the subject of ongoing, ground-based research because, although doses received on the ISS are measurable, these doses are too low to result in observable acute or chronic effects on cells or animals.

NASA's research is aimed at understanding and ameliorating both the physical and biological concerns raised by travel or residence in space. The physical concerns are (1) the radiation levels at the ISS as a function of location on the station at solar maximum/minimum and at times in between and (2) real-time monitoring of and shielding against the high radiation levels associated with solar flares. The biological challenges are to estimate mutagenic and cancer risks and risks to the integrity and functioning of the central nervous system from cosmic-ray nuclei and to determine if microgravity alters the radiation responses of cells in vitro and in vivo (NRC, 2000a) and whether radiation and microgravity stresses might affect the immune system synergistically (NRC, 2000b). It has been estimated that the probability that radiation will affect the immune system might be equal to or greater than the probability for its inducing mutations (Todd et al., 1999).

NASA has supported and continues to support ground-based ionizing radiation research of relevance to space travel. These experiments are essential for determinations of the relative biological effectiveness, compared to gamma rays, of the high-energy particles encountered in space. The 2001 task book for NASA life sciences describes 29 projects covering many different biological end points (NASA, 2001c). The experiments include determinations of the biological effects of energetic protons at Loma Linda University and the effects of HZE nuclei at an accelerator at the Brookhaven National Laboratory. The accelerator has been available for only ~10 days per year, but its availability will increase to an appreciable fraction of the year in 2003 and beyond, when the construction, supported by NASA, of a new accelerator (the Booster Applications Facility) is completed. NASA has also supported dose measurements, using tissue-equivalent proportional counters, on space shuttle flights at the ISS inclination (51.65 degrees) (Badhwar, 2002). The data showed that "given a shielding distribution for a location inside the Space Shuttle or inside an ISS module, this [radiation measurement] approach can be used to predict the combined GCR and trapped dose rate to better than ±15 percent for quiet solar conditions" (Badhwar, 2002, p. 69). The dose measurements in air must be converted to dose equivalents in tissue using estimated quality factors and actual doses in tissue. These tissue doses have been obtained by use of thermoluminescent dosimeters inserted into a human phantom (a dummy) (Badhwar et al., 2002). The dosimeter data were compared with those calculated from theoretical radiation transport models. The dose-rate prediction of the models at the level of the blood-forming organs was ~20 percent lower than the measured dose rates.

Impact of ISS Changes

The physical measurements of radiation doses to astronauts can be performed with existing equipment, already on the ISS, and with existing data storage and transmission capabilities, and so will not be affected by the changes in research capability in going from Rev. F to the Core Complete ISS design. The determination of the doses received by astronauts is not an experiment but a continuous environmental monitoring effort. There are, at present, two radiation investigations planned for the ISS (see Appendix H). However, it should be noted that the determinations made in the experiment "Chromosome Aberrations in Blood Lymphocytes of Astronauts" on Increment 8 (scheduled for May-September, 2003) will have less statistical significance because of the reduction in crew (sample) size from six or seven members to three. There have been no cuts in existing dosimetric equipment, but the installation of the advanced animal habitat (accommodating 6-8 rats or 20-30 mice) and the centrifuge has been delayed for a number of years. Although the majority of the radiation-response experiments on biological systems can continue to be done on Earth (NRC, 2000b), the delays will eliminate important experiments that should be carried out on the ISS and cannot be done on Earth. The purpose of such experiments would be to determine whether the effects of radiation delivered in microgravity will be similar, qualitatively and quantitatively, to those observed on Earth. If they are, the extensive ground-based data on the effects of HZE nuclei may be extrapolated to microgravity. If they are not, more extensive experiments on-orbit would be necessary to determine the molecular/cellular explanations for the differences, and how to extrapolate radiation effects from ground to orbit. The deletion of the habitat (advanced animal habitat) for mice and rats, unless restored in the 2003 NASA budget, and the delay of the centrifuge module until 2007 or later mean that there can be no serious planning for animal experiments on the ISS that would measure the effects of radiation in microgravity on biological responses. Such responses include the effects of ionizing radiation on the killing or mutation of cells in vivo or the effects of radiation on the immune system. The centrifuge is needed to provide a 1-*g* control in the environment of the ISS. The relevant experiments are not listed in the ISS research plans through 2006, nor do preliminary ground studies on the effects of radiation on the immune system appear to have been planned (NRC, 2000b).

Factors Limiting Utilization of the ISS

Among the biomedical research countermeasure goals listed by NASA (Fogleman, 2001) are "Radiation and Immunodeficient Correction." These were estimated to be at Countermeasures Readiness Level 1-4.[5] However, neither the radiation nor the immunodeficiency countermeasures can be evaluated without extensive experiments on the ground and in orbit, using the centrifuge module to supply a 1-*g* control. Ionizing radiation is mutagenic, and mutations at the DNA sequence level are best studied using known genes. A simple, suitable model system could be transgenic mice in which multiple copies of a known gene of a bacterial virus are inserted into each cell of the body. Following exposure to radiation, the gene may be isolated from different tissues and analyzed in bacteria infected with the viruses to determine the frequency and nature of mutations and their repair versus time following exposure (Swiger, 2001). Mice are also suitable for the detection of immune system changes. A radiation source, probably a compact source of x rays, is necessary and is envisaged on the ISS (Olsen, 2001). The minimum requirement for such experiments would be a small mouse colony, a source of x rays, appropriate dosimetry, and a centrifuge so as to repeat, on-orbit, the experiments at 1 *g*. Several doses would be needed at microgravity and at 1 *g,* Several repair times (times between exposure and assay) would also be required, and two end points (mutation and immunosuppression) would have to be assessed. Hence,

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[5] These levels are defined as follows: 1. Phenomenon observed and reported, problem defined; 2. Hypothesis formed, preliminary studies done to define parameters, demonstrate feasibility; 3. Validated hypothesis, understanding of scientific processes underlying problem; 4. Formulation of countermeasures concept, based on understanding of phenomenon.

the task group estimates that the minimum colony size would be 50-100 mice in space. (The mutation assays could be done on Earth on frozen tissues transported from orbit, but the immunosuppression assays would probably have to be done on the ISS.) Such experiments, on-orbit, are labor-intensive and probably could not be carried out if there were only a three-member crew. Moreover, the lack of the advanced animal habitat and the centrifuge module eliminates the possibility of doing any such controlled vertebrate experiments relating biological effects of radiation with microgravity.

Maximizing ISS Research Potential

The principal radiation biology experiments that should be carried out on the ISS are the relative radiation effects on vertebrates at microgravity compared with 1 *g* , of a known source of radiation, say x rays, on (1) mutation induction and (2) the immune system. Extensive and relevant experiments have been carried out on Earth, but this is not the case for studies of radiation effects on the immune system. Similar results from immune system investigations on Earth are needed before designing immunosuppression experiments to be carried out on the ISS. The experiments on the ISS not only would require the specialized equipment described above but are labor-intensive as well. It is not conceivable that the experiments could be carried out by a crew of three. The task force estimates that a crew of six or seven, two of whom should have biological expertise, would be needed. When such experiments have been selected following peer review, and when the experiments are approved for flight, crew members or mission specialists will have to be trained to carry out the necessary procedures.

BEHAVIOR AND PERFORMANCE

Program Description

NASA's research efforts in the area of behavior and performance fall under two multidisciplinary approaches that encompass diverse areas of investigation: neurobiological-psychosocial aspects and human factors engineering. The first approach includes research on the characteristics of sleep and circadian rhythms and changes in cognitive and perceptual performance associated with long-duration missions. It also covers the psychosocial aspects of living in a confined and isolated environment and how individuals, groups, and organizations respond to the environmental stressors associated with these environments. Human factors engineering addresses the design of the interfaces or systems with which astronauts interact in space. In 1998 NASA's research agenda for behavior and performance on the ISS focused on two questions: (1) How do microgravity and the space environment affect human behavior and performance? and (2) How can we enhance human performance in spaceflight? To answer these questions, a strategy report (NRC, 1998) recommended that NASA develop noninvasive qualitative and quantitative techniques for assessing pre-, in-, and postflight behavior and performance. The report also placed a high priority on investigating the neurobiological and psychosocial mechanisms underlying the effects of physical and psychosocial stressors on cognitive, affective, and psychophysiological measures of behavior and performance. A final area in which research was recommended was the evaluation of existing countermeasures and the development of new countermeasures that effectively contribute to optimal levels of crew performance, individual well-being, and mission success.

Impact of ISS Changes

The equipment necessary to conduct investigations involving human behavior and performance are provided by the two HRF racks on the ISS. Rack 1 of the HRF was deployed in May 2001 and rack 2 is scheduled for deployment on ULF-1 in January 2003. The HRF provides equipment for studies of physiological, chemical, and behavioral changes in astronauts that are associated with spaceflight. Rack 1 includes an ultrasound imager, gas analyzer, computer workstation, and portable laptop computer that crew members can use to access various experimental protocols and to collect, store, and transmit experimental data (NASA, 2001a). No elements of the HRF have been deleted in response to the ISS restructuring in 2001, and there are no changes to planned flight hardware through 2005. However, rack 1 of the HRF was scheduled for deployment in March 2000 and rack 2 in December 2001. As a consequence of these delays in launch dates, 11 experiments (3 U.S. and 8 international) have been deselected from the ISS since October 2000 by the Bioastronautics Research Division. However, none of the deselected experiments are in the behavior and performance area.

The Bioastronautics Research Division has approved 21 experiments for the ISS that run through calendar year 2004. Beyond that, additional experiments will be manifested from those studies now undergoing definition and from new projects selected through future NASA research solicitations. At present, a single study in the behavior and performance area on the ISS is being conducted continuously from ISS flight increments 2-6. No other studies are scheduled for the ISS in the behavior and performance area. The objective of the current study is to identify and define interpersonal factors that can affect the performance of the crew and ground support personnel during ISS missions. Questionnaires are completed weekly by crew members using the workstation and personal computer. Data are also being obtained from ground control personnel supporting the missions in the United States and Russia.

The reduction in crew size from six to three will have a profound impact on the study of human behavior and performance on the ISS. This will be most evident in the limited data collected on each flight owing to the small number of subjects available for study, and this will be compounded by the limited time available for this three-person crew to participate in scientific studies. For many of the high-priority areas of research that have been identified for the behavior and performance subdiscipline, a large number of subjects is essential in order to derive meaningful conclusions from experimental data, owing to the inherent variability between subjects. This intersubject variability is likely to be an even more important issue in long-duration missions, in which time and the responses of subjects to prolonged habitation in space are now added factors in data analyses. These human performance data are essential to NASA's development of reliable screening and selection procedures that consider individual personality characteristics and assess crew compatibility (NRC, 1998). Because the reduction in crew size also limits the number of experiments that can be conducted on the ISS, it impacts the scientific community's readiness and willingness to participate in space research. With only a single experiment in behavior and performance scheduled over the next 4 years, it will be difficult to maintain the commitment of the scientific community to this area of study.

Factors Limiting Utilization of the ISS

The factors limiting utilization of the ISS for research in human behavior and performance are clearly those that affect all discipline areas: the low rates of selection for funding, the shortage of flight opportunities, deselection of flight experiments, and across-the-board cuts in funding levels. The combined effect of all these factors serves to discourage new investigators from entering the field and alienates established researchers. Plans call for both HRF racks to be deployed by January 2003, so the physical resources are available on the ISS to conduct numerous studies of human behavior and performance; the primary physical factor limiting utilization of the ISS in this research area is crew time.

In addition to the paucity of research, no funding exists at all for advanced human support technology experiments on the ISS. This means that one of the two elements of NASA's research agenda (NASA, 1998a) for the ISS in the behavior and performance area—namely, how human performance in spaceflight can be enhanced—will not be addressed in the foreseeable future. If, as the ISS IMCE Task Force recommended (IMCE, 2001 p. 9), "the highest research priority should be solving problems associated with long-duration human spaceflight, including the engineering required for human support mechanisms," then there will have to be a significant increase in funding for research activities on the ISS for the behavior and performance research program to answer this question.

Maximizing ISS Research Potential

As detailed above, the main factors limiting utilization of the ISS in the Behavior and Performance area are the absence of any significant research program for the ISS, which primarily reflects budgetary constraints, and the small crew size and limited crew time. The development of a research program on the ISS in the Behavior and Performance area will require stable and predictable funding for research. Since the crew size will be limited to three people for at least the next 6 years, information that is available on crew performance aboard the ISS from other sources should be used for scientific study. Information collected as part of the flight medicine program, for instance, on medication use, sleep-wake cycles, and cognitive assessments, could be used to provide further information on crew performance.

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Impact of ISS Changes on Fundamental Biology

INTRODUCTION

NASA research in fundamental biology seeks to understand the changes that occur in the physiology and function of living organisms in a spaceflight environment. Research sponsored by the NASA Office of Biological and Physical Research (OBPR) includes such areas as cell and molecular biology, developmental biology, and gravitational ecology. More recently NASA has begun to bring evolutionary biology into the program. Discussed in this chapter are areas of fundamental biological research in which NASA has developed a substantial program and that are likely to have a significant presence on the ISS, and task questions 3 and 4, which relate to its implementation on the ISS, are considered. It is shown that the downgrading of the ISS from Rev. F to Core Complete and the limitation of crew size to three seriously jeopardize the ability to carry out meaningful science in these fields. The loss or lengthy delay of critical facilities such as the centrifuge and the animal habitats makes some experiments in fundamental biology impossible, while other experiments will be seriously compromised by the lack of crew time.

CELL AND DEVELOPMENTAL BIOLOGY

Program Description

Cell biology studies biological processes at the level of the basic unit of biology, the cell. As such, cell biology underpins the other biomedical disciplines relevant to space biology. Developmental biology focuses on the processes and mechanisms responsible for the development of the zygote into a primordial set of cell types and on subsequent developmental events that produce the mature organism.

The past decade has seen major technical developments in the study of eukaryotic cells, including the application of molecular genetics and molecular biology, advanced imaging technology, cell culture methodologies, protein chemistry, and macromolecular structural determination. These developments have led to dramatic progress in our understanding of fundamental biological processes at the cellular and developmental levels. Fundamental questions that are now within the reach of experimental investigation include those surrounding the mechanisms by which cells replicate and maintain their genomes, regulate survival, generate and maintain a complicated internal cytoarchitecture and organellar substructure, respond to changes in the extracellular environment, and differentiate into specialized tissues and multicellular organisms.

The Space Studies Board report *A Strategy for Research in Space Biology and Medicine in the New Century* (NRC, 1998) pointed out that, with only a few exceptions, cells are considered incapable of perceiving gravity directly. However, cells in tissues respond indirectly to gravity as a result of changes occurring in the cellular environment, and the report recommended investigating several specific areas of fundamental cell biology in space. Among these areas were the mechanisms of cellular mechanoreception and cellular responses to environmental stresses encountered in spaceflight (e.g., anoxia, temperature shock, vibration). It was also recommended that NASA, in cooperation with the scientific community and industry, should work to develop advanced instrumentation and methodologies for space-based studies at the cellular level. A further recommendation was to evaluate carefully experiments with cells in culture prior to flight, looking at their theoretical and practical justification, the availability of fully tested hardware, the capacity to carry out appropriate controls, adequacy of sample sizes, and the potential for repeating the experiments. In addition, the problems associated with alterations of sedimentation and fluid and gas convection in weightlessness should be considered.

Finally, the report concluded that investigations involving single cells and cell culture models should be analyzed in ground-based studies.

The *Strategy* report (NRC, 1998) also reviewed the current state of the field of developmental biology and the potential for meaningful investigations of development processes in microgravity. It stressed two main questions relevant to future investigations conducted in space: Can organisms undergo normal development in microgravity? Are there developmental phenomena that can be studied better in microgravity than on Earth? It was concluded that the space environment may indeed be useful for understanding certain biological phenomena in developing systems. Specific systems in which gravity was considered likely to play a critical role in development and/or maintenance include the vestibular system and the multiple sensory systems that interact with the vestibular system. The answers to these questions could have profound effects on the performance of astronauts in space and their postflight recovery on Earth. Gravity was also expected to influence topographical neural space maps that exist throughout the brain, with attendant effects on neuroplasticity, i.e., long-term changes in neuron structure and function in response to changes in their activity. Finally, the report concluded that analyses of complete life cycles in space could determine if some developmental events are affected by reduced gravity, and that high priority should be given to testing vertebrate models, including avian systems. If developmental effects are detected, control experiments must be performed on the ground and in space with the latter, including the use of a space-based 1-*g* centrifuge. Important issues related to these goals should be investigated in ground-based studies as preludes for investigation in space. Controls for the effect of non-gravitational stresses likely to be encountered in space, such as loud noise and vibration, must also be performed on the ground so that space experiments can be designed to isolate the effects of microgravity from the effects of other stresses.

A number of experiments under way within current NASA fundamental biology and biotechnology programs in cell and developmental biology are asking questions pertinent to the recommendations made in the *Strategy* report (NRC, 1998). An examination of the NASA task book relevant to fundamental biology (NASA, 2001c) found 102 entries, nearly all of them ground-based studies. Emphasis is being placed on the development and function of the vestibular system, otoliths and hair cells, bone, smooth and skeletal muscle, adrenal cells, endothelial cells, and lymphocytes. Studies are under way in the areas of proprioreception, hormone response, signal transduction, immune response, neuronal development and plasticity, early embryonic development and stem cell migration, aging, neurosecretion, cytoskeleton and motility, cell survival, circadian rhythms, and homeostasis and energy metabolism. Some use is being made of "simpler" eukaryotic, multicellular organisms such as fruit flies and zebra fish, as well as unicellular prokaryotes. Overall, these studies stress the potential importance of cell and developmental biology for both basic research and countermeasure research in bioastronautics.

Note that the assessment in the next subsection largely ignores the cell and developmental biology of plant systems, which are discussed in a separate section.

Impact of ISS Changes

In terms of cell and developmental biology research, the critical resources of the Rev. F configuration included a crew of six or seven members, habitat holding racks for mice and rats (including special inserts for animal biotelemetry systems), a 2.5-m, 1-*g* centrifuge, a life sciences glove box, a cryofreezer, an insect habitat, an aquatic habitat, an avian research facility, an avian development facility, and a budget commensurate with the needs of world-class cell and developmental biology research.

A number of these critical resources have been considerably delayed or eliminated (Liskowski, 2002a). For example, the advanced animal habitat has been eliminated along with the avian research facility, essentially precluding the ability to characterize the genetic and developmental response of nonhuman vertebrates such as rats and mice to long-term exposure to space. Deployment of the centrifuge accommodation module and the 2.5-m, 1-*g* centrifuge and associated software (by NASDA), a critical element of control experiment design, has been delayed until at least 2008. Other facilities are currently planned, but the implementation of most has been delayed. These include (see also the section in Chapter 3 on ISS facilities for bone and muscle research) the general-purpose incubator, the ARTIC −80 °C freezer (installed in 2002), the −80 °C freezer (MELFI, in 2003), the cell culture unit (2005/2006), the insect habitat (Canadian Space Agency, in 2006) and its included small internal centrifuge, two core facility habitat holding racks (2004/2005) for the first, followed by the second approximately 2 years later), and the life sciences glovebox (2005/2006). The avian research facility will be only on the shuttle and not available on the ISS. The aquatic habitat is being built by the Japanese Space Agency (NASDA) but apparently will not be available until after 2008. Dramatic cuts have been announced in the budget for fundamental space biology (Liskowski, 2002b), of which developmental biology is a part. The task group noted that ISS restructuring is under way, with consideration of how to reinstate some of these eliminated facilities.

It is difficult to predict exactly the time needed to carry out research in cell and developmental biology, but experience shows the importance of significant direct intervention by trained crew members and suggests that requirements for crew time tend to be greater than initially anticipated. The reduction from a six- or seven-member to a three-member crew suggests that sufficient time will simply not be available, since the skeleton crew will have to focus on space station operation rather than research activities. In addition, there appear to be few opportunities for adequate preflight crew training in the requisite research techniques. Thus, most experiments will need to be largely self-contained and highly automated.

Planned Experiments That Have Been Eliminated

From the information provided by NASA (e.g., Ostrach, 2002), it is noted that two scheduled ISS experiments in developmental biology had been deselected as of December 2001. These are experiments 96-01-207, “Relationship of morphogenesis and mineralization to gravitaxis,” by P.J. Duke, University of Texas, and 99-02/03-026, “Effect of microgravity during the critical period of Zebrafish vestibular development,” by S. Moorman, Case Western Reserve University.

Effect on Cell and Developmental Biology

The projected reductions and delays in the deployment of research facilities on the ISS pose major challenges to the vitality of research in cell and developmental biology. For example, the elimination of the advanced animal habitat and plant research unit will make it difficult to carry out a comprehensive program in developmental biology aimed at understanding the manner in which complex organisms, especially eukaryotes, respond to long periods in space. Included in this impact will be difficulties in fully applying a number of elegant genetic systems pertinent to the study of cell and developmental biology. While this loss could potentially be offset in part by using insect and avian systems, it would still severely limit, and probably eliminate, some of the most important vertebrate models.

The loss of crew time poses further problems. The impact is not only on the performance of experimental procedures during a flight interval but also on the preparation of material for further analysis upon reentry. Further, a shuttle flight rate of only four per year will severely limit the ability to transport research material to and from the ISS. Finally, the delay of deployment of the 2.5-m, 1-*g* centrifuge critically limits the design of necessary control experiments. An important capability of the ISS was expected to be its provision of an environment in which studies could be carried out in space, eliminating the confounding variables associated with launch and reentry. Without the centrifuge, critical control experiments in which organisms are maintained at 1 *g* at the same time and place as they are maintained in microgravity are not possible, critically compromising the interpretation of results.

Impact on Readiness of Principal Investigators

The important studies in cell and developmental biology in space involve long-term commitments on the part of investigators. With continued losses of funding and the associated uncertainties in the availability of facilities, crew time, and the 2.5-m, 1-*g* centrifuge, the developmental biology community may become unwilling to be involved in the microgravity research program. Even when funds and technical capacity are available, there are often long delays from selection to flight, and the possibility of having an experiment removed from the queue downstream remains an important consideration. These are serious problems that not only stifle enthusiasm within groups of colleagues, but also become an important factor in academic career decisions, especially for young investigators and students. Without confidence that high-quality science can be accomplished, these investigators will have no practical choice but to seek other opportunities to which to apply their talents.

Research That Can Still Be Done on the ISS

Five experiments in cell and developmental biology have been identified that were flown in 2001 under the cellular biotechnology program on UF-1 and ISS 7A.1 (Trinh, 2002b). They involved the production of growth factor and antigen synthesis by cells in culture; tumor cell gene expression; and renal differentiation and hormone production. An encouraging number of additional ground-based studies are identified in the NASA task book that included analyses of stress, neuronal plasticity, vestibular function, bone and muscle physiology signal transduction, and immune response(NASA, 2001c). On the other hand, only five experiments in cell and molecular biology and one in developmental biology are currently on the list of those selected for definition in 2001[1] (Appendix I), perhaps accurately reflecting the extent of the remaining research capacity on the ISS. As discussed above, the absence of the 2.5-m, 1-*g* centrifuge and the limited crew time negatively impact cell and developmental research in a general and pervasive manner. The avian development and insect units can provide some relief when they become available, but even there, uncertainties surrounding crew time for research and hardware lead to a less-than-positive sense of potential. The expanded use of lower organisms such as the fruit fly and *C. elegans* may be worth considering in the present climate in view of their small size and the potential for genetic analysis. The *Strategy* report (NRC, 1998) noted that engineering demands and expense, and the difficulty of repeating experiments in space in sufficient number for analysis, place substantial burdens on the testing of hypotheses about the role of gravity in normal developmental events. These issues are highly relevant to cell and developmental biology and are exacerbated in the current climate of ISS cutbacks, as is reflected in the minimal level of research in cell and developmental biology that is currently being carried out on or planned for the ISS.

The question for the present evaluation, then, is whether the ISS can, in its expected Core Complete configuration, carry out high-quality research aimed at answering basic questions in cell and developmental biology. Without proper resolution of the issues raised above, it may be necessary to further delay studies of this nature in cell and developmental biology on the ISS, emphasizing in the interim basic ground-based research. In fact, as stated in the guidelines in the *Strategy* report (NRC, 1998), there are substantial issues that can, and must, be settled first by ground-based research, including most prominently the testing of protocols and equipment. However, for this approach to be effective, it will be essential to provide sufficient funds to perform the recommended research.

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[1] Experiment list was provided by NASA and contains experiments already selected, as of February 2002, for future flight on the ISS.

Factors Limiting Utilization of the ISS

As outlined throughout the previous sections, many factors limit utilization of the ISS for fundamental biological research in cell and developmental biology. They include the elimination of key facilities and equipment or uncertain delays in their installation, inadequate crew time for research, and the absence of a concrete set of research priorities within which to plan. Limitations on funding for developing experiments are an additional concern; for example, funding for fundamental biology in OBPR has remained at a plateau level for several years.

Overlying these important specific issues, however, is a pervasive uncertainty as to if and when relief from these problems can reasonably be expected. At the level of prudent experimental planning, there is a discomfortingly long time line from initial conceptualization to actualization of a study, bringing further uncertainties about whether a study will still be state of the art in concept and approach by the time it can be flown. These uncertainties negatively impact not only the ability to develop scientific strategies but also investigator morale and commitment.

Maximizing ISS Research Potential

It is clear that many opportunities originally envisioned for research in cell and developmental biology have been dramatically curtailed. There is concern as to whether the current Core Complete stage of the ISS can truly support the highest-quality cutting-edge research in cell and developmental biology. Nevertheless, it appears that some possibilities may exist. A workshop titled "Space Biology in the Early International Space Station," held at NASA Ames Research Center on March 14-15, 2002, and chaired by B.S. Blumberg and K.M. Baldwin, was convened to explore the type, scope, and value of biological research that could be best accomplished on the ISS, given the constraints of the present realities.

To carry out high-quality science is difficult under the best of conditions. The challenge for ISS research is to identify, within current vehicle constraints, high-priority, high-quality, hypothesis-driven experiments that can be sufficiently replicated and validated with adequate controls, including in-flight gravitational controls. Careful ground-based evaluation of facilities and experiments in advance flight, always important, becomes even more critical now in order to ensure that meager opportunities are not wasted. Care must be taken not to succumb to the temptation to carry out a particular experiment simply because it is possible, especially if the research will be weak, uncontrolled, and of low priority.

One way to maximize the potential for research in cell and developmental biology would, of course, be to resurrect the missing funding and facilities, including a proposed buyback of rodent and plant research capability. In the absence of such facilities, meaningful studies of vertebrates will be difficult, but a carefully chosen small set of insects and simpler multicellular eukaryotic organisms, such as drosophila and *C. elegans,* could be selected for initial investigations, in the hope that more complex vertebrate organisms can be worked with in the future. Organisms for which the entire genome has been sequenced should be given priority. The European Biolab offers an excellent model that should be investigated in this regard (ESA, 2002); this unit, which will include two 60-cm centrifuges, is designed for experiments involving cell culture, microorganisms, and small invertebrates. NASA should encourage the development and deployment of this unit and work to ensure that it will be available for use by U.S. investigators.

The admonition of the *Strategy* report (NRC, 1998)—to carefully evaluate experiments with cells in culture prior to flight with regard to their theoretical and practical justification—remains a timely recommendation and should be included in the planning of all future experiments. Vigilance will have to be continued to discriminate between effects directly related to microgravity from those arising secondarily from environmental variables such as perturbations in diffusion, turbulence, and radiation, for example. Adequate funding should be provided to encourage this ground-based preparation and to help maintain the scientific community for the future.

Even when specific questions and appropriate systems can be identified, experiments will have to be planned that require a minimum of crew time. Advances in biotechnology, in-flight automation, telecommunication, miniaturization of systems, and bioinformatics for online data offer some hope.

The concept of sending up material at low temperature for study at physiological temperatures on the ISS also offers potential. At the other end of the experimental time line, facilities for cryo-storage of selected biological material prior to return must be developed and placed on the ISS in order to optimize options for postflight sample analysis on Earth.

PLANT BIOLOGY

Program Description

The study of plants in space is driven by two objectives (NRC, 1998). The first is to determine how best to grow plants in a spacecraft environment. A goal of NASA is to mount missions, sometime in the future, to remote areas of our solar system and to set up and maintain a human presence on the Moon and/or on Mars. These long-duration stays by humans in space, cut off from constant resupply from Earth, will require that the astronauts be able to produce at least some of their own food. Therefore the farming of plants in space, as part of an advanced life support (ALS) system, will be a necessity.

Growing plants efficiently and successfully in space has proven to be difficult. There are practical problems to overcome, such as how best to get water to the roots without subjecting them to anaerobic conditions, or how best to handle the elevated levels of carbon dioxide and ethylene that are commonly found in human-occupied spacecraft. For each potential crop, the optimal light intensity and quality and the maximal crop density must be known. Most of the important problems have been identified, and solutions have been proposed. Tests of these solutions have thus far produced promising results (WCSAR, 2001), but there are still significant technical barriers to overcome.

The second objective of space research on plants is to obtain fundamental knowledge about the extent to which gravity is required for and/or influences plant development and physiology. A few responses to gravity, such as gravitropism and circumnutation, are already well known and have been studied extensively on Earth. The pivotal question requiring experiments with plants in space, as explained in the *Strategy* report (NRC, 1998), had been whether a plant can successfully go through its complete life cycle in microgravity. The repeated failure of the Russians to grow any plant through a full generation in space had increased the importance of performing a definitive experiment to answer this question. In fact, it has been recognized by the plant gravitational biology community that a plant should be grown through at least two successive generations in space, in order to answer this question (NRC, 1998). Ideally the experiment should have an on-board 1-*g* centrifuge control, but despite the lack of a centrifuge control and less than optimal conditions, this question has now been answered. An experiment on Mir, using *Brassica rapa*, succeeded in growing the plants through more than two complete generations, despite many technical difficulties (Musgrave et al., 2000). More recently, *Arabidopsis* plants have been grown through a single generation on the ISS (University of Wisconsin-Madison, 2001).

These experiments effectively eliminate the possibility that gravity is a requirement at some stage for the survival of plants, but there is still a real possibility that a lack of gravity might alter some aspect of plant development or physiology. Spaceflight experiments to date have shown some minor effects of the microgravity environment on plant development. However, the lack of a 1-*g* on-board control has made it impossible to separate responses caused by a lack of gravity from responses to other parameters of spaceflight, such as vibration, enhanced carbon dioxide, or lack of air circulation. Moreover, many plant processes, such as photosynthesis, have never been studied in a microgravity environment.

Impact of ISS Changes

Since the early days of ISS planning it has been envisioned that the ISS would contain two facilities essential for plant science experiments. The first is a plant research unit (PRU) in which to grow plants and conduct long-term experiments on plants under conditions of controlled light intensity, temperature, carbon dioxide, and humidity. This unit would not contain a centrifuge, but it would be capable of being attached to a large-diameter centrifuge (see below). The PRU, in the absence of a centrifuge, would be suitable for the range of ALS experiments whose goal is to learn how to grow plants in space but not for the experiments in fundamental biology, whose goal is to understand the mechanisms by which plants respond to gravity. The second facility is a 2.5-m centrifuge, to which the PRU (and comparable animal modules) could be attached. It would provide the 1-*g* conditions needed as controls for microgravity experiments on the ISS. The combination of the PRU and the centrifuge would provide a suitable facility for experiments in fundamental plant biology.

Two PRUs have already been built in the United States, and both have been or are being flight tested. The units differ with respect to the size of the plants that can be accommodated and the parameters that are controlled; each unit would be of particular value for a specific set of plant experiments. The first to fly on the ISS is the advanced astroculture (ADVASC) unit, produced by the Wisconsin Center for Space Automation and Robotics (WCSAR), which has been flown on two missions (6A to 7A.1 and UF-1 to 8A). Its development was funded by the Space Product Development (SPD) Program in Code UM. This unit is a two-middeck-locker-equivalent unit and will not fit on the large centrifuge in its present state but could be modified to fit the centrifuge. It will accommodate plants up to 12 inches high. WCSAR is also developing a commercial plant biotechnology facility (CPBF) with a chamber that will permit the use of larger plants (up to 19 inches). It uses half an EXPRESS rack and will not be suitable for use on the centrifuge. It is anticipated that the CPBF will be completed by FY 03. It will be available for both commercial and fundamental plant research aboard the ISS. The second unit was produced by ORBITEC (NASA, 2001b) (funded by Code UF) as a prototype for the plant research unit (PRU). This biomass production system (BPS) will not fit on the centrifuge in its current configuration. It was expected that the BPS would be developed into a PRU that could be attached to the centrifuge. However, funds to continue this work have been eliminated, and the current BPS unit is probably not suitable for future use on the ISS.

The status of the 2.5-m centrifuge is not certain, but it will not be part of the ISS at Core Complete. The current plans are for deployment of the centrifuge in 2008 at the earliest. The lack of a suitable PRU and of an on-board centrifuge in going from Rev. F to the Core Complete design will have a severe negative impact on what can be accomplished on the ISS in fundamental plant science.

On the other hand, the Europeans are planning to deploy two facilities that will significantly improve the situation. The first is their European Modular Cultivation System (EMCS), which will fit in an Express Rack on the U.S. Destiny lab (ESA, 2001) and is scheduled to be deployed on the ISS in July 2004. The EMCS will contain two 60-cm-diameter centrifuges, capable of *g* forces between 0.001 and 2 *g* and holding four experimental containers (ECs). Each EC will be illuminated and will have controlled humidity, temperature, and gases. Since an EC is only 60 x 60 x 120 mm, only small plants such as *Arabidopsis* can be grown in it. Nevertheless, almost all of the fundamental plant biology research questions likely to be proposed for study in space (as outlined in the NRC's 1998 *Strategy* report) could be addressed with this facility, since it will provide both controlled conditions at microgravity and the necessary on-board 1-*g* controls.

In addition to the EMCS, the European Columbus module will contain the Biolab (ESA, 2002). It, too, will have two 60-cm-diameter centrifuges and will have illuminated ECs that will accommodate small plants. While the Biolab is planned primarily for experiments involving cell cultures, microorganisms, and small invertebrates, it can be used for plant experiments as well.

At present, no plant experiments have been deselected. Seven plant experiments, supported by Code UF, are currently under definition and/or development. These are listed in Appendix J. Four of these experiments fall into the area of advanced life support, while three are directed toward fundamental biology problems. In addition, the ADVASC experiments, already flown in Increment 2 and 4, are manifested for Increments 5, 6, and 7 as well. These experiments are a combination of apparatus testing and experiments supported by commercial partners.

As discussed, the change in the ISS from Rev. F to Core Complete is expected to result in a reduction in crew size from six or seven to three. The effect of this change on the plant science experiments is difficult to assess. Most of the currently planned experiments will require some involvement by the crew, and experience from Mir indicates that the crew time requirements could be considerable. In some experiments, for example, crew must be involved almost every day to plant seeds, make the physiological measurements, and harvest the material at specific times. In addition, before flight the crew will have to be trained extensively in many of the procedures that must be carried out. As one of a crew with only three members, it is difficult to see how a crew member would have the time to undergo the necessary training. Further time-line planning for the ISS could therefore lead to the deselection of some of these plant experiments.

To sum up, the impact on the plant science program of the changes in facilities on the ISS could be limited, or it could be severe. Until the EMCS and Biolab arrive at the ISS, the only plant growth units would be the two commercial WCSAR units-the ADVASC and the CPBF. They should be suitable for the ALS experiments. As soon as the EMCS or Biolab is on the ISS and available for general use, meaningful fundamental plant biology experiments can be undertaken. However, if the crew size remains at three, it may severly limit the types of experiments that can be carried out.

Factors Limiting Utilization of the ISS

Three factors limit utilization of the ISS by the plant science community. The first is the availability of the needed facilities. Although two plant growth units are currently under development in the United States, only the WCSAR units are likely to be available on the ISS at Core Complete. These units are suitable only for ALS experiments. There will be no U.S.-produced facilities suitable for fundamental plant biology studies. In the absence of a PRU and the 2.5-m centrifuge, the EMCS and Biolab facilities that are being developed in Europe are essential for plant experiments, especially in fundamental plant sciences.

The second limiting factor is funds for the development of plant experiments. It is essential that the ground-based background experiments be completed and the equipment and protocols for flight experiments be thoroughly tested on Earth before any experiment is carried out on the ISS. There has, unfortunately, been a lack of sufficient funds for this precursor ground-based research—indeed, the funds available for fundamental biology in OBPR have remained flat for several years. If funds for this type of work are diverted to cover other areas of need, there will not be opportunities for PIs to develop new experiments. The shortness of the list of currently funded plant experiments for the ISS means that the community of plant researchers willing and able to utilize the ISS at some future date is in danger of dropping below a critical mass.

Finally, the lack of crew time, both for training for the experiments on the ground and then, when onboard, for running the experiments, may limit the ALS experiments, even if the facilities for this type of experiment are aboard the ISS.

Maximizing ISS Research Potential

There are four prerequisites for maximizing the research potential of the ISS in the plant science area:

- *Continued development of suitable experimental facilities.* First, funds should be restored to permit the BPS to be developed into a PRU that can be utilized on the large-diameter centrifuge.

Although the Europeans are developing two facilities that should be ideal for experiments involving small plants such as *Arabidopsis* a PRU, is needed that can handle larger plants, such as would be grown in a spacecraft on a long-duration mission. The date on which the centrifuge will be deployed on the ISS needs to be firmed up and made available to researchers, so that they do not have unrealistic expectations about when they will be able to do valid fundamental plant biology experiments on the ISS. The development of the WCSAR units needs to continue so that ALS experiments can take place on the ISS in the period before the PRU/centrifuge facility is available. Agreements need to be reached between SPD and Code UF to make these units available to all researchers.

- *Availability and accessibility of the EMCS and Biolab.* NASA needs to encourage the Europeans to continue with the development of the EMCS and Biolab modules and to ensure that they are deployed on the ISS. Agreements need to be reached with ESA about the availability of the EMCS and Biolab for use by U.S. investigators.
- *Adequate funding for the preparation of plant experiments for future increments.* Because of the many delays and uncertainties surrounding flight experiments, the community of plant scientists interested in making use of the ISS is small. This community must be nurtured by providing enough funding to complete all the preliminary, ground-based experiments. Certainty about funding for preliminary studies, coupled with firm plans for flight opportunities, will significantly expand plant scientists' interest in conducting experiments on the ISS.
- *Sufficient crew time.* There is a sense of discouragement about the possibility that there will be only three crew members on the ISS at Core Complete. Those scientists who have already completed flight experiments know that the requirements for crew time are always more, rather than less, than the amount initially anticipated. There is no point in proposing experiments that involve a significant amount of crew time, even if the facilities for the experiments are available. If the ISS is to be a major research facility, it is essential that the number of crew be increased beyond three.

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Conclusions and Recommendations

OVERVIEW

Preceding chapters analyze on a discipline-by-discipline basis the factors limiting the scientific community's ability to maximize the research potential of the ISS were. Based on that analysis the task group concluded that NASA's revision of the ISS to the Core Complete configuration has drastically reduced the ability of the ISS's to support science. Reduction of upmass capability, facilities and equipment, and available crew time for science operation singly or in combination severely limits or forecloses the scientific community's ability to utilize the research potential of the ISS. The decision not to proceed with the initial capabilities as originally planned in Rev. F, combined with the absence of any well-articulated cross-disciplinary goal to unify or guide the process, has exacerbated an already significantly diminished capability of the ISS. The impact on the various scientific disciplines of the ISS revision to the Core Complete configuration varies, but it is in all cases substantial. Although the stated goal of NASA for its ISS program is to create a world-class laboratory, it is the opinion of the task group that the actions taken with regard to crew time, equipment, facilities, and logistics make this unlikely.

LIMITING FACTORS

Discussed below are the specific factors that the task group found will create the most significant limitations on the ability of the science community to maximize the research potential of the ISS.

Interdisciplinary Priorities Not in Place

Many vital pieces of experimental equipment have been eliminated or indefinitely postponed. In many cases, such as in fluid physics, NASA has said that these decisions were made based primarily on what equipment had not yet been built, without any apparent weighting of the impact on overall scientific objectives. Since no cross-disciplinary priorities exist to act as a roadmap, these decisions appear to have been arbitrary. This inability on the part of NASA to provide cross-disciplinary priorities, as requested by the task group, during either phase I or the current phase II, was consistent with the demonstrated lack of scientific rationale used or provided to justify cuts made in manifested equipment and experiments. Lengthy delays or cancellation in equipment availability (e.g., the 2.5-m, 1-*g* centrifuge and advanced animal habitat) virtually eliminate the ability to achieve scientific objectives in disciplines such as radiation biology, systems physiology, countermeasure development, crew behavior and performance, fundamental biology, and bone and muscle physiology.

Crew Time

The most widespread and significant impact on the achievement of scientific objectives stems from the substantial reduction in crew time available for scientific activities. The original plans for the ISS specified a crew complement of six or seven persons. As the required housekeeping for the ISS was expected to, and has, occupied 2.5 crew persons, this would have left a 3.5- or 4.5-person crew available for scientific activities on the completed space station. The current plan for the ISS now includes only three crew members. This means that only 20 hours per week are available for scientific work, without taking into account the impact that unplanned activities may have. It should be noted that this 20-hour figure is used by NASA for mission planning, and although the time actually devoted on-orbit may differ, the end result is that the tasks that are planned on the ground for 20 hours represent one-half of the on-orbit available time for one crew member. A further complicating factor in deciding how to apportion the 20 hours per week available for science payload operations stems from the fact that, according to the agreements currently in place with the international partners, the 20 available hours will be allotted, on average, in the following manner: 10 hours for Russia, 7.5 hours for the United States, and 2.5 hours for all others. This arrangement makes the situation even bleaker for U.S. investigators. The dramatic reduction in available crew time results in a space station with less time available for research than was available 30 years ago on Skylab, and it will critically compromise the ability of the ISS to support a significant program of science research. This limitation has an impact on every discipline examined, from a potential total elimination of the ability to achieve even a modicum of meaningful work on the ISS in many areas of radiation biology, systems physiology, crew behavior and performance, and fundamental biology, to lesser impacts on disciplines such as plant science, materials science, fundamental physics, combustion science, and fluid physics. Even these potentially less-affected fields will probably sustain significant negative impacts when they are forced to compete with the remaining scientific complement for the minimal time available.

Distributing the 20 hours of available time among several crew members ensures that no crew member will have more than a small percentage of his or her time associated with science activities. This creates inefficiencies and a lack of continuity. Past spaceflight experience has shown that science is served best when crew members train in depth on experiments and have a substantial portion of their on-orbit time dedicated to science.

International Partner Participation

The numerous revisions to the ISS configuration have resulted in strong objections by international partners that NASA is no longer in compliance with agreements on ISS development and utilization. To date, these compliance issues have not been resolved. This raises questions about whether the international partners will continue to support the ISS at previously planned levels. Since the announcement of the Core Complete configuration for the ISS, a large portion of the ESA budget for ISS support has been frozen, and NASDA has also announced that it expects to make substantial cuts in its ISS budget. Loss of science facilities that were to be provided by partners could have serious consequences for an already hobbled science program. For example, if the Japanese experiment module exposed facility were not available, the fundamental physics program on the ISS would be all but eliminated.

Experiment Facilities, Equipment, and Upmass

As shown in Table 1.1, many experiment racks have been eliminated or delayed indefinitely in the redesign of the ISS. In addition, the modules containing the functional equipment that will go into the remaining racks have also been reduced significantly in number, worsening an already dramatically reduced capability. The disciplines that are affected most severely by these reductions are materials science, fluid physics, fundamental biology, and muscle and bone physiology. For instance, the deletion of the animal habitat and the lengthy delay in the 1-*g* centrifuge severely limits research in systems physiology, fundamental biology, radiation biology, and bone and muscle physiology. The animal habitat is essential for basic studies on rats and mice, and the 1-*g* centrifuge is critical for providing valid in-flight controls for animal and plant experiments. The 1-*g* centrifuge could also be used in the future to support combustion research. The absence of these facilities significantly limits what kind of research can be proposed and implemented on the ISS.

Facilities for materials science research have been reduced dramatically. The Rev. F plan called for a facility with three research racks, a rack-mounted materials science laboratory, 13 experiment modules, and two furnaces. Only one research rack, the materials science laboratory, one multiuser quench module insert, and a low-gradient furnace remain. With the limitations on upmass that will occur with a reduction in shuttle flights, it is unlikely that further modules can be provided. The return of samples and provision of supplies will also provide an ongoing logistics challenge. To accommodate fewer shuttle flights and facility changes in Core Complete, upmass and stowage volumes are expected to be reduced for many of the experiments. The quantity of scientific work is expected to be reduced accordingly.

The combustion research, fluid physics, and fundamental physics programs depend on instrumentation, and all have major pieces of equipment either at risk or canceled. The Shared Accommodations Rack supported both combustion and fluids physics work but has been deleted. Both the Combustion Integrated Rack and the Low Temperature Microgravity Physics Experiments Facility were deleted but subsequently restored; their future, however, is still uncertain.

Another unknown that affects all science operations on the ISS is logistics. It is being proposed to lengthen stays on the ISS and decrease the shuttle flight rate. Each shuttle flight would therefore need to have all the necessary supplies (food, water, clothes, parts) to support the longer stays, making it likely that operational needs will predominate on each shuttle flight, and thus making it more difficult to provide supplies and equipment for experiments.

The combined effects of reduced equipment and reduced logistical support will make a world-class research effort virtually impossible to initiate or sustain.

Research Community Readiness

The factors already cited, combined with the poor track record of NASA and the ISS for meeting schedule, budget, and scientific performance targets, further detract from the ability of the ISS to attract the scientific community or garner its support (see Figure 5.1).[1] The uncertainty and instability of the ISS program with regard to keeping promises made to the science community do little to attract or retain established and next-generation scientists, whose careers can be seriously damaged by the failure of the program to provide the scientific opportunities that were promised. The avowed goal of the ISS—to be a world-class scientific laboratory producing world-class science—is not tenable as the ISS currently stands.

MAXIMIZING RESEARCH POTENTIAL

In considering ways in which the research potential of the ISS could be maximized, the task group looked at the restoration of certain critical capabilities to the ISS, as well as options based only on the current Core Complete configuration. Described below are the steps that would have the greatest impact on the overall research potential of the ISS. Suggestions for additional steps that would maximize research in specific disciplines are contained in the discipline chapters of the report.

Scientific Priorities

Prioritization across and within scientific disciplines is the first step in deciding how the research potential for the ISS can be maximized. At the time of this writing NASA had charged an internal committee, the Research Maximization and Prioritization (ReMaP) Task Force, with developing priorities for its entire program of life and physical sciences research—and the task group is aware of ReMaP's

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[1] Note that this issue was reviewed in greater detail in the phase I report produced by this task group (NRC, 2001).

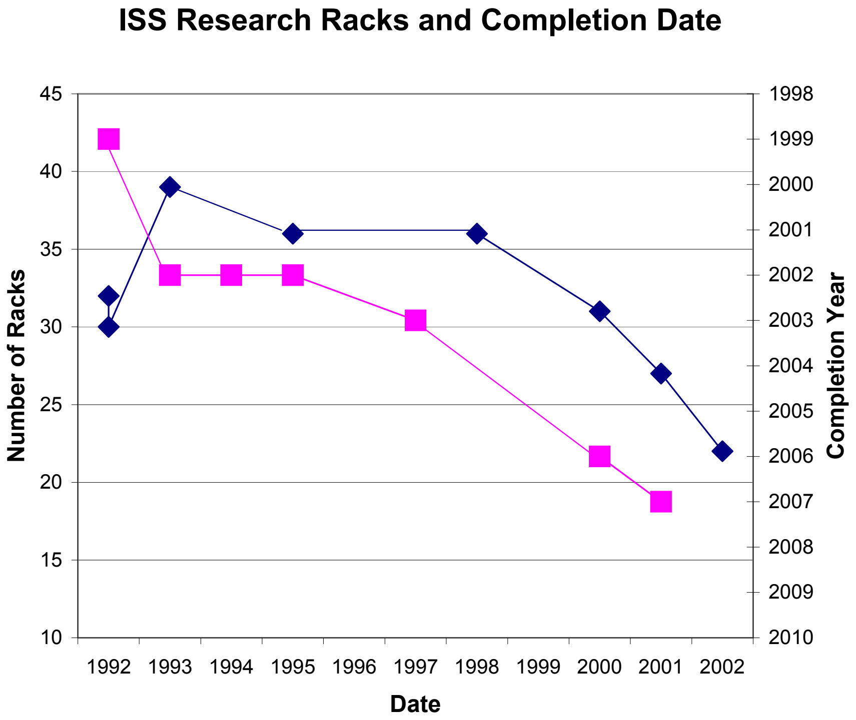

FIGURE 5.1 Changes over time in the planned ISS completion date (squares) and the total number of planned U.S. research racks (diamonds). For Core Complete, no completion date is available for comparison with previous dates, therefore no point is shown for 2002. SOURCE: Based on data from various NASA briefing charts and ISS documents. Since most older charts counted the centrifuge as three research racks, for purposes of comparison the 2002 total has been increased to reflect that assumption.

preliminary findings.[2] However, a detailed list of cross-disciplinary research priorities for the ISS has not yet been released, and numerous scheduling and other obstacles are faced by ReMaP in the development of such a list. Until such a prioritization is accomplished, however, it is virtually pointless to begin replanning, since without this prioritization there is no frame of reference or goal that can be used to guide or evaluate the success or efficacy of the research program.

The charge to this task group was to recommend ways of maximizing the research potential of the ISS. Effective utilization of these recommendations requires that NASA establish cross-disciplinary research priorities based on clear programmatic goals, since maximizing the potential involves making trade-offs. At present, the primary goal of the ISS is unclear. A tension seems to exist between enabling the human exploration of space and performing activities that have intrinsic scientific importance. These two categories are not mutually exclusive, but without a cross-disciplinary prioritization both within and across these two categories, intelligent use of the scarce and costly resources of the ISS is impossible. The following examples illustrate the range of possible primary goals that NASA might conceivably choose for the ISS:

- The primary goal could be to support long-duration human space exploration. In this scenario, priorities and rankings for use of scarce resources could be set based on how well the individual

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[2] National Research Council committees, including the Task Group on Research on the International Space Station, and the Committee on Microgravity Research, have provided ReMap with relevant past reports and data to assist it in its work.

projects support this specific objective, which would include addressing questions in both the biological and the physical sciences.

- The primary goal could be to have a world-class research laboratory, without any special emphasis on exploration, that serves a variety of disciplines. In this scenario, priorities might be set by providing each discipline with a budget and allowing each discipline to set its own priorities within that budget.
- The strategy could be a hybrid of the two strategies above. One goal might be primary—for example, human exploration of space—but in pursuing that goal NASA would not eliminate scientific activities that are not directly related to human exploration. In this case, a fixed baseline budget might be furnished for scientific activities not related to human exploration, with the remainder of the research budget being devoted to human exploration and dispersed based on priorities (such as those in NASA's Critical Path Roadmap.[3] Alternatively, the primary goal could be to perform research of intrinsic scientific importance. In pursuing this goal, NASA would not eliminate activities related to human exploration that are not directly related to these scientific pursuits. As above, a fixed baseline budget could be furnished for human exploration not directly related to scientific activities, with the remainder being devoted to activities with intrinsic scientific importance and allocated based on priorities.
- Finally, a salvage strategy could, in principle, be envisioned. The goal would be to get the maximum use out of the existing facilities. In this case, experiments would be selected principally because they are the easiest to perform and require the fewest resources (i.e., prioritization based on logistics). However, this arrangement has the potential to seriously compromise the quality of the science on the ISS. Even with a salvage strategy, care must be taken not to succumb to the temptation to carry out a given type of research simply because it is easy if in fact it yields little of real scientific value.

The best evidence available to the task group (such as that in IMCE (2001) and NASA testimony on a number of occasions before Congress) suggests that NASA wants to create a world-class laboratory in space that will provide the information needed to enable long-duration human exploration in the future, while maintaining a strong basic research program (the hybrid strategy described above). The recommendations that follow have been made with this goal in mind.

Finding: No cross-disciplinary prioritization plan exists for ISS research. This lack of cross-disciplinary prioritization exacerbates the uncertainty that is already undermining the confidence of the scientific community and that community's readiness to support the ISS program.

Recommendation: Based on overall program goals for the ISS, NASA should create a cross-disciplinary research prioritization plan with accompanying rationale that permits ranking and can be used to effectively manage the scientific program.

Research Coordination

In the life science disciplines, the research and operational medicine programs require crew activities that can influence or perturb the same physiologic parameters. These activities are not coordinated systematically in the flight program and can result in inadvertent corruption of scientific data as well as inefficient expenditure of resources.

Finding: Lack of effective coordination between operational medicine protocols and systems physiology research leads to conflicts and deleterious interactions during missions that result in the squandering of scarce crew resources.

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[3] See <http//criticalpath.jsc.nasa.gov/main.asp>.

Recommendation: NASA should establish systematic coordination between human physiology research and operational medicine on the ISS to ensure that crew care is not compromised and that coordinated acquisition of scientific data is facilitated.

Crew Time

As already noted, the time available for scientific activities on the Core Complete ISS is wholly inadequate and is the single biggest factor that is limiting achievement of scientific objectives. According to NASA, the reason for holding crew size to three is the inability to deorbit more than three crew members in the event of an onboard emergency, due to the limited capacity of the Soyuz and the indefinite postponement of a crew return vehicle.

Finding: NASA policy restricting crew size to that which can be returned immediately to Earth in the case of an emergency limits the crew size to three. This constraint means that little time is available for scientific activities since the time required for ISS housekeeping (this includes normal operation and maintenance exclusive of science) leaves only 0.5 crew available for science-related activities.

Recommendation: In view of the effect of crew return options on crew size, NASA should reevaluate its assumption that the crew return requirement in case of an emergency is the best approach to maintain crew safety and mission success. There may be other options—for example, safe haven concepts—that would maintain crew safety and permit a crew of seven. If it is determined that there is a requirement to ensure return of the ISS crew to Earth immediately, NASA should develop a plan whereby the original complement of seven crew members can be accommodated in a return vehicle so that the scientific objectives of the ISS can be met.

Finding: NASA currently has 20 hours of crew time per week identified for science-related activities on the ISS. Of this, only 7.5 hours will be allotted to the United States, which is not sufficient to take advantage of even the reduced scientific capabilities of the Core Complete ISS. Unplanned events, such as in-flight equipment repairs, even if they require a small amount of time (e.g., 30 minutes), can take a large slice out of the time for scientific activities performed if they are taken out of the science utilization time.

Recommendation: NASA should evaluate the adequacy of the time allotted to perform the science that is scheduled for the ISS, taking into account interdisciplinary priorities and the equipment and facilities that are available. Caution should be used when allocating the hours available for science investigations, since small allocations to individual crew members often involve overhead that may render the time operationally ineffective for research even though the total time spent meets the experiment requirements documentation. In addition, NASA should carefully consider what steps could be taken to reduce demands on on-orbit crew time. For example, any reduction in the time needed for ISS maintenance would have a large positive impact, in percentage terms, on the small amount of crew time now available for science.

International Partners

The transition from Rev. F to Core Complete has placed severe constraints on facilities to accomplish U.S.-based scientific research. There will be little redundancy between facilities available in the U.S., European, and Russian research modules. There will also be crew members from different countries on the ISS at all times. Therefore, in order to maximize the research on the ISS, it is essential to ensure coordination of the research, so that crew from one country will be able to conduct experiments in the modules of other countries and PIs from the U.S. will have access to facilities from other countries. Increased collaboration with international partners to share facilities and crew time could enable research that the U.S. science community cannot accomplish alone.

Finding: Looking at the facilities and equipment developed by the United States and its international partners, it can be seen that some research facilities are significantly delayed or missing from the Core Complete ISS, while some others appear to be redundant.

Recommendation: To maximize ISS facility usage, NASA should promote further collaborative interactions between the ISS science programs of the United States and those of its international partners in all disciplines.

Experiment Equipment and Facilities

Once the science prioritization on a cross-disciplinary basis is accomplished and the number of crew available for scientific activities is finalized, the decisions as to what experimental modules and experimental equipment are needed can be addressed intelligently. A rational plan that is consistent with stated scientific priorities is critical to assure and encourage the scientific community that the ISS has a scientific future.

Finding: The elimination or postponement of ISS experiment racks, modules, and equipment has greatly reduced the potential scientific yield of the ISS.

Recommendation: NASA should develop a plan providing for ISS experiment racks, modules, and equipment that is consistent with the scientific priorities of NASA and the ISS and is achievable within fiscal and schedule constraints.

The U.S. development cost of the ISS as currently planned has been estimated at approximately $26 billion. The additional cost to increase the crew number to seven is approximately $5 billion (IMCE, 2001).[4] This means that a 20 percent increase in development cost would yield a 900 percent increase in crew research availability (4.5 versus 0.5 crew available for scientific activities). If the primary objective of the ISS is indeed to be a world-class laboratory in space, then the cost-benefit of taking this course of action is obvious. Not to take action would be akin to building a million-dollar home but stopping short of running electrical and water services to it. Without plans and decisions based on cross-disciplinary priorities that are clearly articulated and supported by corresponding allocations of resources, the ISS can never achieve the status of a world-class research laboratory.

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[4] While the numbers are the latest public numbers provided by NASA, they are currently being reviewed and updated by NASA, and may be revised in the future.

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APPENDIXES

NOTE: Appendixes A though J contain lists of future ISS experiments provided by NASA in February 2002 that were current as of that date

Appendix A
Future Investigations in Materials Science Planned for the ISS

Investigation	Principal Investigator/Affiliation	Flight Hardware Availability/Carrier	Facility
Kinetics of Nucleation and Crystal Growth in Glass-Forming Melts in Microgravity	D. Day, University of Missouri at Rolla	2008	MSRR1 MSL[a]/LGF[b]
Gravitational Effects on Distortion in Sintering	R.M. German Pennsylvania State University	2007	MSRR1 MSL/LGF
Reduction of Defects in Germanium-Silicon	F. Szofran, Marshall Space Flight Center	2007	MSRR1 MSL/LGF
Particle Engulfment and Pushing by Solidifying Interfaces	D.M. Stefanescu University of Alabama	2005	MSRR-1 MSL/LGF/ QMI[c]
Coupled Growth in Hypermonotectics	J.B. Andrews, University of Alabama at Birmingham	2005	MSRR-1 MSL/LGF/ QMI
Interface Pattern Selection in Directional Solidification	R.K. Trivedi, Iowa State University	2006	MSRR-1 MSL/LGF/ QMI
Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Experiments	D.R. Poirier, University of Arizona	2006	MSRR-1 MSL/LGF/ QMI
Coarsening in Solid-Liquid Mixtures	P.W. Voorhees Northwestern University	2003	MSG[d]
Spaceflight Holography Investigation in a Virtual Apparatus	J. Trolinger, Metrolaser, Inc.	2007	MSG
Transient Interfacial Phenomena in Miscible Polymer Systems	J.A. Pojman, University of Southern Mississippi	2007	MSG
Role of Convection and Growth Competition in Phase Selection in Microgravity	M.C. Flemings Massachusetts Institute of Technology	2005	EML[e]
Quasicrystalline Undercooled Alloys for Space Investigation	K. Kelton, Washington University	2005	EML

[a] Materials Science Laboratory.
[b] Low Gradient Furnace.
[c] Quench Module Insert.
[d] Microgravity Science Glovebox.
[e] Electromagnetic Levitation Facility.

Appendix B
Planned ISS Combustion-Related Investigations Through 2006

Investigation and Principal Investigator	Hardware Availability	Flight Date	Facility Required	Target Application(s)
Fiber Supported Droplet Combustion (FSDC-3) Forman Williams et al., University of California, San Diego	May-03	May-03	MSG	Diesel and jet engine efficiencies
Smoke Point in Coflow Experiment (SPICE) Gerard Faeth Michigan State University	Sep-03	Oct-03	MSG	Pollution reduction
Candle Flames in Microgravity (CFM-2)[a] Daniel Dietrich NASA, Glenn Research Center	Feb-04	Feb-04	MSG	Fundamental study of microgravity flammability Educational value
Smoke David Urban NASA, Glenn Research Center	Sep-04	Oct-04	MSG	Spacecraft fire safety
Droplet Combustion Experiment (DCE-2) Forman Williams University of California, San Diego	Jan-03	Jul-04	CIR	Diesel and jet engine efficiencies Spacecraft fire safety Data key to validating combustion analytical codes
Bi-Component Droplet Combustion Experiment (BCDCE) Benjamin Shaw University of California, Davis	Jan-03	Jul-04	CIR	Diesel and jet engine efficiencies Practical fuels are multicomponent in nature Liquid motion strongly affects combustion and vaporization behavior.
Sooting and Radiation Effects in Droplet Combustion Experiment (SEDC) Mun Choi Drexel University	Oct-04	Jan-05	CIR	Diesel and jet engine efficiencies Pollution reduction Measurements benchmark evolving droplet combustion and soot models
Dynamics of Droplet Combustion and Extinction Experiment (DDCE) Vedha Nayagam National Center for Microgravity Research	Mar-05	Apr-05	CIR	Diesel and jet engine efficiencies Spacecraft fire safety Enhancement of spacecraft fire safety by establishing a detailed mapping of flammability limits of liquid fuels.
Flammability Diagrams of Combustible Materials in Microgravity (FIST) A.C. Fernandez-Pello University of California, Berkeley	Apr-06	Apr-06	CIR	Spacecraft fire safety Improve material screening Important implications for safety of future space missions
Smolder, Transition, and Flaming (STAF) A.C. Fernandez-Pello University of California, Berkeley	Apr-06	Apr-06	CIR	Spacecraft fire safety. Terrestrial (building) fire safety Long-duration smoldering and transition to flames

NOTE: The last two investigations may slip into 2007 owing to funding limitations. CIR, Combustion Integrated Rack; MSG, Microgravity Science Glovebox.

[a] The candle flame is an ideal example of a non-propagating, steady-state diffusion flame.

Appendix C
Future Flight Investigations in Fluid Physics Planned for the ISS

Principal Investigator	Institution	Experiment Title	Facility[a]
P. Wayner	Rensselaer Polytechnic	Constrained Vapor Bubble Experiment	FIR
P. Chaikin	Princeton	Physics of Hard Spheres Experiment-2	FIR
D. Weitz	Harvard	Physics of Colloids in Space-2	FIR
A. Yodh	University of Pennsylvania	Low Volume Fraction Entropically Driven Colloidal Assembly	FIR
A. Gast	MIT	Anisotropic Colloidal Self Assembly-2	FIR
J. Jenkins	Cornell	Particle Segregation in Collisional Shearing Flows	FIR
M. Louge	Cornell	Microgravity Apparatus	FIR
R. Behringer	Duke	Gravity and Granular Materials	FIR
M. Dreyer	University of Bremen, Germany	Capillary Channel Flows	FIR
A. Sangani	Syracuse	Microgravity Observations of Bubble Interactions	FIR
A. Gast	Stanford	Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions	MSG
P. Voorhees	Northwestern	Coarsening in Solid-Liquid Mixtures-2	MSG
G. McKinley	MIT	Shear History Extensional Rheology Experiment	MSG
J. Kim	University of Maryland	Microheater Array Boiling Experiment	MSG
V. Dhir	UCLA	Nucleate Boiling Experiment	MSG
A. Gast	Stanford	Chain Aggregation Investigation by Scattering	MSG
T. Matula	University of Washington	Buoyancy-Driven Instabilities in Single-Bubble Sonoluminescence	MSG
A. Yodh	University of Pennsylvania	Ultraviolet-Visible-Infrared Spectrophotometer	MSG
D. Weitz	Harvard	Physics of Colloids in Space	EXPRESS Rack
P. Chaikin	Princeton	Physics of Colloids in Space	EXPRESS rack

Principal Investigator	Institution	Experiment Title	Facility[a]
T. Maxworthy	USC	Dynamics of Miscible Interfaces	EXPRESS rack
D. Durian	UCLA	Foam Optics and Mechanics	Fluid Science Lab, ESA
R. Berg	NIST	Critical Viscosity of Xenon-2	STS-107/Freestar

[a] FIR, Fluids Integrated Rack; MSG, Microgravity Sciences Glovebox.

Appendix D
List of ISS Fundamental Physics Experiments, 2002-2008

There are currently nine fundamental physics experiments in three areas scheduled for the ISS between 2002 and 2007, and two more are under development that have yet to be scheduled (tbs). In addition, the STEP experiment (Francis Everitt, Stanford) will be conducted as a free-flyer project.

GRAVITATIONAL AND RELATIVISTIC PHYSICS

1. *Alpha Magnetic Spectrometer (AMS) (2004), Samuel Ting, MIT.* Because elementary particles such as the antiproton are absorbed by Earth's atmosphere, the flux of particles arriving from outer space can only be mesaured above the atmosphere. The AMS will measure the antiproton flux for an extended time in order to quantify the antiproton flux.
2. *Superconducting Microwave Oscillator (SUMO) (2007), John Lipa, Stanford*. The superconducting oscillator will provide an ultra-stable low-noise signal for the atomic clock experiments (RACE) on the ISS. It can provide new tests of Special and General Relativity and the Standard Model of Matter.

LASER COOLING AND ATOMIC PHYSICS

3. *Condensate Laboratory Aboard the Space Station (CLASS) (tbs), William Phillips, NIST.* Bose-Einstein condensation can be used to produce atom lasers, which are expected to lead to a new generation of quantum technologies.
4. *Primary Atomic Reference Clock in Space (PARCS) (2005), Donald Sullivan, NIST.* Atoms cooled to one-millionth of a degree in near-zero gravity can be measured for long times, providing an extremely accurate frequency measurement, e.g., an extremely precise clock. The frequency of the laser-cooled cesium clock of PARCS can be compared with clocks on Earth, providing a precise test of Einstein's prediction of the gravitational shift.
5. *Rubidium Atomic Clock Experiment (RACE) (2007), Kurt Gibble, Pennsylvania State University*. A laser-cooled atomic clock based on rubidium atomic beams is expected to be more stable than one based on cesium, allowing precision tests of the limits of relativity.
6. *Quantum Interferometric Test of the Equivalence Principle (QUITE) (was SMW-G) (tbs) Mark Kasevich, Yale.* Atom wave interferometry will allow exacting tests of Einstein's equivalence principle. Laser cooling will simultaneously cool and trap both rubidium and cesium atoms, which will then undergo free fall in space. Splitting and recombining the atom waves inside an interferometer will provide detailed tests of the equivalence principle.

LOW TEMPERATURE AND CONDENSED MATTER PHYSICS

7. *Boundary Effect near the Superfluid Transition(BEST) (2007), Guenter Ahlers, University of California, Santa Barbara.* Critical properties of fluids in confined geometries are modified by finite-size scaling effects, but these effects are smeared by gravity on Earth. In space, they can be studied with high resolution.
8. *Critical Dynamics in Microgravity (DYNAMX) (2005), Robert Duncan, University of New Mexico.* The superfluid transition in He-4 will be studies with a small heat flux present, i.e., out of equilibrium. The resulting dynamical transition will provide a high-precision test of theories of

dynamical critical phenomena, and should exhibit the onset of macroscopic quantum order, usually masked by gravity.

9. *Microgravity Scaling Theory Experiment (MISTE) (2005), Martin Barmatz, JPL.* High-precision equation of state, heat capacity, and compressibility measurements will be carried out on He-3 in the critical region. Asymptotic and crossover models can be tested much more carefully than on Earth because the usul density gradients induced by gravity will be absent on the ISS.

10. *Coexistence Curve Experiment (COEX) (2005), Inseob Hahn, JPL.* This experiment is an extension of the MISTE experiment. It is designed to accurately test the scaling hypothesis and equation-of state model predictions.

11. *Heat Capacity at Constant Heat Current (CQ) (2005), David Goodstein, Caltech.* This experiment, and extension of the DYNAMX experiment, will study the heat capacity of Helium just below the superfluid-normal transition. The presence of a heat-capacity anomaly cannot be studied on Earth because of the density-gradients induced by gravity.

Schedule by projected year of launch

2004: AMS
2005: CQ, DYNAMX, MISTE, PARCS, COEX
2007: BEST, SUMO
2008: RACE
tbs (in development, to be scheduled): CLASS, QUITE

Launch schedule data from International Space Station Research Program: Implementation for the Physical Sciences, presentation by E.H. Trinh to TGRISS, March 5, 2002.

Appendix E
Systems Physiology Experiments Planned for the ISS

Experiment Number	Experiment Title	Investigator	Target Mission (if known)
NASA-Sponsored ISS Flight Experiments into Calendar Year 2004			
96-01-507	Human Orientation and Sensory Motor Coordination in Microgravity	A. Berthoz	Incr. 8-10 (6 Sz)
98-02-120	Promoting Sensorimotor Response Generalizability During Inflight Treadmill Exercise: A Countermeasure to Mitigate Locomote Dysfunction After Long-Duration Space Flight	Jacob J. Bloomberg	Incr. 5-9 pre/post only, Incr. 10 in-flight
99-03-046/99-03-377	Human Cardiovascular Performance in the Space Flight Environment	Michael Bungo, Ben Levine	Not manifested
96-04-318	Foot Reaction Forces During Spaceflight	P.R. Cavanagh	Incr. 6 (launch ULF1)
96-04-400	Effect of Prolonged Spaceflight on Human Skeletal Muscle	R.H. Fitts	Incr. 5, 6, 7, 8, 9
96-04-290	Effects of Microgravity on the Peripheral Subcutaneous Veno-Arteriolar Reflex in Humans	A. Gabrielsen	Incr. 3-4 (7A.1)
96-01-096	Crew Member and Crew-Ground Interactions During International Space Station Missions	N. Kanas	Incr. 2-5, 7-10
96-04-343	Sub-regional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight	T.F. Lang	Incr. 4-8
99-03-370	Influence of Sensory Integration on the Neural Processing of Gravito-inertial Cues	Dan Merfeld	Inc. 14
99-03-010 DSO TBD	Chromosomal Aberrations in Blood Lymphocytes of Astronauts	Gunter Obe	Incr. 6-7
96-01-085	Human Orientation and Sensory Motor Coordination in Microgravity	C.M. Oman (co-I with Berthoz)	Incr. 10-12
99-03-049 DSO TBD	A Comprehensive Characterization of Microorganisms and Allergens in Spacecraft Environment	D.L. Pierson	TBD
96-04-094	Dosimetric Mapping	G.F. Reitz,	Incr. 2
98-02-497	Effects of Resistance Training, using Fly-Wheel Technology, on Size and Function of Skeletal Muscle in Crew Stationed in Space	Per A. Tesch	Not manifested
96-04-011	A Study of Radiation Doses Experienced by Astronauts in EVA	I. Thomson	Incr. 4, 5, 6
96-04-082	Effects of Altered Gravity on Spinal Cord Excitability	D.G.D. Watt	Incr. 2-4 (5A.1)
96-04-044	The Effects of EVA and Long-term Exposure to Microgravity on Pulmonary Function	J. West	Incr. 3-5, 7 (7A.1)

Experiment Number	Experiment Title	Investigator	Target Mission (if known)
96-01-057 DSO 633	Renal Stone Risk During Space Flight: Assessment and Countermeasure Validation	P.A. Whitson	Incr. 3-10 (7A.1), STS-107, STS-113, R-2
SMO 008	Entry Monitoring	Meck	Incr. 8
SMO 006	Test of Midodrine as Countermeasure against Postflight Orthostatic Hypotension	Meck	Incr. 5, STS-108, 110, 111, 112, 109
NASA-Sponsored ISS Flight Monitoring			
MR085L	Neurocognitive Assessment (SCAT)		All
MR077L	Physical Fitness Assessment		All
MR021L	Crew Microbiology		All
MR016L	Inflight weekly food frequency questionnaire		All
MR024L	Body Mass Measurement		All
MR018L	Inflight urinalysis/hematocrit		All
MR003L	Radiation Biodosimetry		All
NASA-Sponsored ISS Pre/Post Flight Testing			
MR035L	Bone Densitometry		All
MR001L	Operational Tilt Test		All
MR071L	Holter Monitoring		All
MR010L	Clinical Laboratory Assessment		All
MR077L	Isokinetic Dynamometry/FASTEX		All
MR042L	Functional Neurological Assessment		All
Russian Flight Experiments			
MBI-1	Study of human body fluids under conditions of long-duration spaceflight		
MBI-3	Study of peridontal tissue conditions under spaceflight conditions		
MBI-4	Study of pharmacological influences under long-duration space mission conditions		
MBI-5	Intergrated study of the dynamics of the primary parameters of cardiac activity and blood circulation, using a lower body negative pressure (LBNP) apparatus		
MBI-8	Study of the action mechanism and efficacy of various countermeasures aimed at preventing locomotion system disorders in weightlessness		
MBI-9	Study of autonomic regulation of the human cardiovascular system in weightlessness		
RBO-1	Development of a method for real-time prediction of dose loads on the crews of manned space missions		

Experiment Number	Experiment Title	Investigator	Target Mission (if known)
RBO-2	Bioradiation dosimetry during spaceflight		
Russian Pre/Post Flight Experiments			
Motor control	Study of hypo-gravitational ataxia syndrome		
MION	Impact of microgravity on muscular characteristics		
Isokinez	Microgravity impact on voluntary muscular contraction. Human motor system readaptation to gravitation		
Tendometria	Micrgravity impact on induced muscular contraction. Long-duration spaceflight impact on the muscular and peripheral nervous apparatus		
Ravonvesie	Sensory and motor mechanisms in vertical posture control after long-duration exposure to microgravity		
Sensory adaptation	Countermeasures and correction of adaptation to space syndrome and of motion sickness		
Lokomotsii	Kinematic and dynamic locomotion characteristics prior to and after spaceflight		
Peregruzki	*G*-forces on Soyuz and recommendations for anti-*G* force countermeasure development		
Polymorphism	Genotype parameters related to human individual tolerance to spaceflight conditions		
Thermographia	Human peripheral thermoregulation during readaptation after long-duration spaceflight		
Khemoluminomer	Spaceflight factors impact on free-radical oxidation level, as well as changes in human organism during readaptation to Earth conditions		

NOTE: Table includes experiments in all areas of systems physiology including cardiovascular studies and musculoskeletal studies, which are also broken out separately in Appendixes F and G.

Appendix F
Cardiovascular Physiology Experiments Planned for the ISS

Experiment Number	Experiment Title	Investigator	Target Mission (if known)
NASA-Sponsored ISS Flight Experiments into Calendar Year 2004			
99-03-046/99-03-377	Human Cardiovascular Performance in the Space Flight Environment	Michael Bungo, Ben Levine	Not Manifested
96-04-290	Effects of Microgravity on the Peripheral Subcutaneous Veno-Arteriolar Reflex in Humans	A. Gabrielsen	Incr. 3-4 (7A.1)
96-04-044	The Effects of EVA and Long-term Exposure to Microgravity on Pulmonary Function	J. West	Incr. 3-5, 7 (7A.1)
SMO 008	Entry Monitoring	Meck	Incr. 8
SMO 006	Test of Midodrine as Countermeasure Against Postflight Orthostatic Hypotension	Meck	Incr. 5, STS-108, 110, 111, 112, 109
NASA-Sponsored ISS Flight Monitoring			
MR071L	Holter Monitoring		All
MR077L	Physical Fitness Assessment		All
NASA-Sponsored ISS Pre/Post Flight Testing			
MR001L	Operational Tilt Test		All
Russian Flight Experiments			
MBI-5	Intergrated study of the dynamics of the primary parameters of cardiac activity and blood circulation, using a lower body negative pressure (LBNP) apparatus		
MBI-9	Study of autonomic regulation of the human cardiovascular system in weightlessness		
Russian Pre/Post Flight Experiments			
Peregruzki	*G*-forces on Soyuz and recommendations for anti-*G* force countermeasure development		
Thermographia	Human peripheral thermoregulation during readaptation after long-duration spaceflight		

Appendix G
Future Bone and Muscle Physiology Experiments for the ISS

Project Title	Principal Investigator	Institute
Renal Stone Risk During Space Flight: Assessment and Countermeasure Validation (96-01-057 DSO 633)	P. Whitson	NASA Johnson Space Center (JSC)
Promoting Sensorimotor Response: Generalizability During Inflight Treadmill Exercise: A Countermeasure to Mitigate Locomotion Dysfunction After Long-Duration Space Flight (98-02-120)	J.J. Bloomberg	NASA JSC
Foot Reaction Forces During Spaceflight (96-04-318)	P.R. Cavanaugh	Pennsylvania State University
Effect of Prolonged Spaceflight on Human Skeletal Muscle (96-04-400)	R.H. Fitts	Marquette University
Effect of Altered Gravity on Spinal Cord Excitability (96-04-082)	D.G.D. Watt	McGill University
Subregional Assessment of Bone Loss in the Axial Skeleton in Long-Term Space Flight (98-04-343)	T.F. Lang	University of California at San Francisco

SOURCE: Uri (2002); NASA (2001a,c).

Appendix H
Radiation Experiments Currently Planned for the ISS

1. Study of Radiation Doses Experienced by Astronauts in EVA (12/01-8/02), Principal Investigator: I. Thomson, Thomson Associates (Canada).
2. Chromosomal Aberrations in Blood Lymphocytes of Astronauts (5/03-9/03), Principal Investigator: Gunter Obe, University of Essen (Germany).

Appendix I
Future Investigations in Cell and Developmental Biology on the ISS

Experiment Number	Experiment Title	Investigator/ Affiliation	Target Mission/ Flight Duration	Estimated Crew Time	Comments
01-057	Drosophila Behavior and Gene Expression in Microgravity	K. Beckingham, Rice University	No earlier than 2004-2006	TBD	CSA is lead agency, insect habitat
01-061	Genetic and Developmental Stability in Response to Long-Term Exposure of Drosophila Melanogaster to a Space Station Environment	J. Thompson, University of Oklahoma	No earlier than 2004-2006	TBD	CSA is lead agency, insect habitat
01-062	Gravity and the Insect Circadian Timing System	T. Hoban-Higgins, University of California, Davis	No earlier than 2004-2006	TBD	NASA is lead agency; ARC is lead center for definition
01-063	Mechanisms and Functional Consequences of Protein Kinase C Isoform Translocation Inhibition in Monocytes Exposed to Microgravity	M.N. Hughes-Fulford, California Institute for Research and Education	No earlier than 2004-2006	TBD	ESA is lead agency
01-092	Effect of Spaceflight on Microbial Gene Expression and Virulence	C. Nickerson, Tulane University	No earlier than 2004-2006	TBD	NASA is lead agency; ARC is lead center for definition

Appendix J
Future Experiments in Plant Biology Currently Planned for the ISS

FUNDED BY CODE UF

M. Musgrave, University of Massachusetts. Biological and physical constraints on seed development in microgravity. 2004 or later. (01-019)

G.W. Stutte, Dynamac Corp. Photosynthesis and metabolism of superdwarf wheat in microgravity (PESTO). Launch 8A/42. (96-01-269-2)

G.W. Stutte, Dynamac Corp. Photosynthesis and metabolism of superdwarf wheat in microgravity (PASTA). 2003 or later. (96-01-269-1)

G.W. Stutte, Dynamac Corp. Growth and development of *Raphanus sativus* in microgravity (RASTA). TBD. (96-04-291)

R.J. Ferl, University of Florida. Transgenic plant biomonitors of spaceflight exposure. TBD. (98-02-299)

J. Kiss, Miami University. Analysis of a novel sensory mechanism in root phototropism. TBD. (99-02/03-079)

S.J. Roux, University of Texas. Early development of fern gametophytes. TBD. (99-02/03-140)

FUNDED BY CODE UM

W. Zhou, Wisconsin Center for Space Automation and Robotics, Madison. Advanced astroculture. 4 flights, increments 2, 4, 5, 6, and 7, 4/01-5/03. (ADVASC-GC-01/03)

Appendix K
Acronym List and Glossary

ADVASC	Advanced Astroculture Unit
ALS	Advanced Life Support System
AMS	Alpha Magnetic Spectrometer
Arabidopsis	member of the mustard family, a small flowering plant that is widely used as a model organism in plant biology
ARC	Ames Research Center
ARTIC	Advanced Thermoelectric Refrigerator Freezer
Astroculture	the growing of various plants in space
BEST	Boundary Effect near the Superfluid Transition
BPS	Biomass Production System
Brassica rapa	member of the turnip family
BSTC	Biotechnology Specimen Temperature Controller
centrifuge	large, rotating module whose rotational velocity can be varied, providing for differing levels of "gravity" under which to perform experiments
CEVP	Countermeasure Evaluation and Validation Program
CIR	Combustion Integrated Rack
circumnutation	cyclic growth movement common to many plant species
CLASS	Condensate Laboratory Aboard the Space Station
COEX	Coexistence Curve Experiment
CPBF	Commercial Plant Biotechnology Facility
critical point	temperature and pressure at which the liquid and gaseous phases of a pure, stable substance become identical
CQ	Heat Capacity at Constant Heat Current
cytoarchitecture	the general way neurons connect up in a given lump of neuroanatomy—many-to-many, many-to-one, and so on
DECLIC	Despositif pour l'Etude de la Croissance et des Liquides Critiques (CNES Directional Solidification Furnace)
dendrite	mineral crystallizing in another mineral in a branching or treelike form
dosimeter	instrument that measures and indicates the amount of x-rays or radiation absorbed in a given period
DYNAMX	Critical Dynamics in Microgravity
EC	experimental container
EMCS	European Modular Cultivation System

EML	Electromagnetic Levitation (facility)
ergometer	instrument for measuring the amount of work done by a muscle or group of muscles
ESA	European Space Agency
ESL	Electrostatic Levitation (facility)
eukaryote	cellular organism having a membrane-bound nucleus within which the genome of the cell is stored as chromosomes composed of DNA
EXPRESS rack	Expedite the Processing of Experiments to the Space Station-a standardized payload rack that transports, stores, and supports experiments aboard the ISS
FCF	Fluids and Combustion Facility
FIR	Fluids Integrated Rack
GCR	galactic cosmic ray
gravitaxis	directed locomotory response to gravity
gravitropism	natural tendency for biological organisms or specific cells or organs of an organism to respond to the stimulus of gravity
HEDS	Human Exploration and Development of Space
HRF	Human Research Facility
hypergravity	conditions where the force of gravity is stronger than 1 *g*
hypogravity	conditions where the force of gravity is weaker than 1 *g*
HZE	high Z, high energy
IMCE	ISS Management and Cost Evaluation
immunosuppression	lowering of the body's normal immune response to invasion by foreign substances
ISS	International Space Station
JEM-EF	Japanese Experimental Module-Exposed Facility
LBNP	lower body negative pressure
JSC	Johnson Space Center
LET	linear energy transfer
LGF	Low Gradient Furnace
LTMPEF	Low Temperature Microgravity Physics Experiments Facility
mechanoreception	response to a mechanical stimulus, as in detection of touch
microneurography	procedure involving insertion of a small needle in an accessible nerve just below the knee to directly measure the nerve signals traveling from the brain to the blood vessels
MISTE	Microgravity Scaling Theory Experiment
morphogenesis	formation of the structure of an organism or part; differentiation and growth of tissues and organs during development

MSG	Microgravity Science Glovebox
MSL	Materials Science Laboratory
MSRR	Materials Science Research Rack
musculoskeletal sytem	the system of muscles and bones in vertebrates
myofiber	a skeletal-muscle cell
NAPA	National Academy of Public Administration
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
neuroplasticity	a quality allowing creation, forming, shaping or sculpting of neural tissue
neurosecretion	agent released from neural tissues with actions on other tissues, often as hormone, transmitter, or neuromodulator
neurovestibular	interaction between the brain and the vestibular organ, which is located in the inner ear
NIST	National Institute of Standards and Technology
NRA	NASA Research Announcement
NRC	National Research Council
NSBRI	National Space Biomedical Research Institute
OBPR	Office of Biological and Physical Research
optoelectronic	blending of photonics and electronics—photons for transmitting data and electrons for switching
organelle	distinct, membrane-enclosed structure in eukaryotic cells that has a specific function
orthostatic	relating to or caused by standing upright
otolith	small dense crystalline structure, made up of calcium carbonate, that induces a shearing force on hair cells in response to linear acceleration
PARCS	Primary Atomic Reference Clock in Space
pathophysiology	functional changes associated with or resulting from disease or injury
PEMS	Percutaneous Muscle Stimulator
PI	principal investigator
prokaryote	cell or organism lacking a true nucleus
proprioreceptor	joint and muscle receptor that provide information about limb position and movement as well as muscle length and tension
PRU	plant research unit
psychophysiology	branch of physiology dealing with the relationship between physiological processes and thoughts, emotions, and behavior
QMI	Quench Module Insert

QUITE	Quantum Interferometric Test of the Equivalence Principle
RACE	Rubidium Atomic Clock Experiment
ReMap	Research Maximization and Prioritization Task Force
SAR	Shared Accommodations Rack
sinter	to cause to form a coherent mass by heating without melting
SPD	Space Product Development (program)
STEP	Satellite Test of the Equivalence Principle
SUMO	Superconducting Microwave Oscillator
thermal neutron	neutron with a kinetic energy of about 0.025 eV and in thermal equilibrium with the substance in which it exists
thermoluminescence	phenomenon in which certain minerals release previously absorbed radiation upon being moderately heated
UCLA	University of California at Los Angeles
ULF	Utilization Logistic Flight
upmass	mass of material to be lifted to the ISS
USC	University of Southern California
UVIS	Ultraviolet-Visible Infrared Spectrophotometer
viscoelastic	having viscous as well as elastic properties
WCSAR	Wisconsin Center for Space Automation and Robotics

Appendix L
Excerpt from NASA Authorization Act of FY 2001

SEC. 203. 42 USC 2451 RESEARCH ON INTERNATIONAL SPACE STATION.

(a) Study.--The Administrator shall enter into a contract with the National Research Council and the National Academy of Public Administration to jointly conduct a study of the status of life and microgravity research as it relates to the International Space Station. The study shall include--

(1) an assessment of the United States scientific community's readiness to use the International Space Station for life and microgravity research;

(2) an assessment of the current and projected factors limiting the United States scientific community's ability to maximize the research potential of the International Space Station, including, but not limited to, the past and present availability of resources in the life and microgravity research accounts within the Office of Human Spaceflight and the Office of Life and Microgravity Sciences and Applications and the past, present, and projected access to space of the scientific community; and

(3) recommendations for improving the United States scientific community's ability to maximize the research potential of the International Space Station, including an assessment of the relative costs and benefits of--

(A) dedicating an annual mission of the Space Shuttle to life and microgravity research during assembly of the International Space Station; and

(B) maintaining the schedule for assembly in place at the time of the enactment.

(b) <<NOTE: Deadline.>> Report.--Not later than 1 year after the date of the enactment of this Act, the Administrator shall transmit to the Committee on Science of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate a report on the results of the study conducted under this section.

Appendix M
Short Biographies

TASK GROUP

James P. Bagian, NAE, is the director of the Veterans Health Administration's National Center for Patient Safety (NCPS), which was established to develop and lead activities and programs concerned with improving patient safety. He is a diplomate of the American Board of Preventive Medicine with subspecialty certification in aerospace medicine and is a registered professional engineer. Dr. Bagian was a NASA astronaut for more than 15 years, has extensive experience in aviation-related safety systems and human factors, and served as one of the lead investigators of the Challenger accident. Dr. Bagian chairs the VA Expert Advisory Panel on Patient Safety System Design. He is a faculty member of the Department of Preventive Medicine and Community Health at the University of Texas; a faculty member of the Department of Military and Emergency Medicine at the Uniformed Services University of the Health Sciences' F. Edward Herbert School of Medicine; and a member of the board of directors of the Aerospace Human Factors Society. Dr. Bagian was a member of the NRC Steering Committee for the Workshop on Reducing Space Science Research Mission costs (1996-1997), a joint Space Studies Board and Aeronautics and Space Engineering Board study; was a member of the SSB's Steering Group for the Workshop on Bionics for Space Exploration (1997-1998); and was chair of the Aeronautics and Space Engineering Board's Committee on Advanced Technology for Human Support in Space (1996-1997). Dr. Bagian served on the SSB from 1995 to 1997 and is currently a member of the Board and chair of the Committee on Space Biology and Medicine.

Adele L. Boskey is the Starr Chair in Mineralized Tissue Research at the Hospital for Special Surgery, a professor of biochemistry at Weill Medical College of Cornell University, and an adjunct professor of bioengineering at the City College of New York. She was director of research at the Hospital for Special Surgery until July 1, 2002. Dr. Boskey investigates calcium phosphate crystal deposition within the extracellular matrices of bones, teeth, ligaments, and tendons in mammals using solution, cell culture and in vivo models. Dr. Boskey had experiments fly on the space shuttle in 1994 and 1996 and has served on NIH-NASA advisory panels. She is a past president of the Orthopedic Research Society and president of the International Conferences on the Chemistry and Biology of Mineralized Tissues, and she served on the NRC Task Group for the Evaluation of NASA's Biotechnology Facility for the International Space Station, 1999-2000.

John F. Brady, NAE, is the Chevron Professor of Chemical Engineering at the California Institute of Technology. His awards and honors include the Joliot-Curie Professor, E.S.P.C.I., Paris (1988 and 1996); Professional Progress Award, AICHE (1988); ASEE Curtis W. McGraw Research Award (1993); Corrsin Lecture in Fluid Mechanics, Johns Hopkins University (1995); J.M. Burgers Professor, Twente University, The Netherlands (1997); and the G.K. Batchelor Lecture in Fluid Mechanics, DAMTP, University of Cambridge, England (1997). Dr. Brady's research interests cover suspensions and colloids, applied mathematics and computational physics, and fluid mechanics and transport processes.

Jay C. Buckey, Jr., is a research associate professor of medicine at Dartmouth Medical School. He was coinvestigator on cardiovascular experiments on the SLS-1 space shuttle mission and was an alternate payload specialist for the SLS-2 space shuttle mission. In 1998 he flew as a payload specialist astronaut on the Neurolab space mission, STS-90, which focused on the effects of microgravity on the brain and nervous system. Dr. Buckey is immediate past president of the American Society of Gravitational and Space Biology and a member of the NRC Committee on Space Biology and Medicine.

Meredith B. Colket III is a fellow at United Technologies Research Center (UTRC). Dr. Colket has directed and/or participated in research in chemical kinetics, CVD processes, coal devolatilization, combustion of alternative fuels, measurement of nitric oxide, probe phenomena, fuels research, coking studies, soot formation (modeling and experiments), NO formation and control, catalytic combustion processes, and development of combustion models and pollutant submodels for CFD codes. He is a member of the American Chemical Society, the Combustion Institute, AAAS, and AIAA. He has served as a member of the Microgravity Combustion Science Discipline Working Group since 1999; as chair of the Eastern States Section of the Combustion Institute, 1999-2001; and as a member, Advisory Committee 21st Symposium on Combustion, 1986.

Herman Z. Cummins, NAS, is the Distinguished Professor of Physics at City College of the City University of New York, where he directs a program of laser light-scattering studies of liquids and solids. His major effort is in the study of phase transitions and critical phenomena, most recently involving the liquid-glass transition, using Raman and Brillouin scattering and photon correlation spectroscopy. He is noted as the coinventor of laser Doppler velocimetry and pioneered light-scattering techniques to study diffusion, size, and shape of particles in solution. His research has concerned primarily the application of light-scattering spectroscopy to a variety of problems in physics and materials science.

Lynette Jones is a principal research scientist in the Department of Mechanical Engineering at the Massachusetts Institute of Technology. Her primary research is on the human proprioceptive system and the role of muscle and cutaneous mechanoreceptors in sensory processes. This research has led to studies of haptic interfaces that are used to interact with computer-generated virtual environments and teleoperated robots. She also does research on the development of wearable health-monitoring devices and is involved in developing a portable system to evaluate the visual-vestibular system. Dr. Jones is a member of the Society for Neuroscience and the NRC Committee on Space Biology and Medicine.

Alan Lawley, NAE, is the Grosvenor Professor of Metallurgy in the Department of Materials Engineering at Drexel University. Dr. Lawley's professional interests and activities involve teaching and research in the areas of physical and mechanical metallurgy, powder metallurgy, composite materials, materials engineering design, and engineering education. The overall mission of his research is to develop and exploit the science base of powder technology and to identify the complex relationships that exist between processing, microstructure, and properties, with a strong emphasis on particulate processing science. His current research focuses on the press and sinter processing of new ferrous alloys, and spray forming. Dr. Lawley is a fellow of APMI International and ASM International, is a former president of the Metallurgical Society (1982) and of the AIME (1987), has consulted extensively for government and industry, and served as a member of the National Materials Advisory Board. He received the Distinguished Service to Powder Metallurgy Award of the Metal Powder Industries Federation (1991), the Jenkins Award of the Institute of Materials (1996), the ASM Gold Medal (1996), and the TMS Educator Award (2002). He is editor in chief of the *International Journal of Powder Metallurgy.*

Steven E. Pfeiffer, a professor of microbiology at the University of Connecticut Health Center, has interests in molecular, cell, and developmental biology of the nervous system and myelinogenesis. A recipient of the Javitz Neuroscience Investigator Award from the National Institutes of Health, he is a member of the American Association of Cell Biologists; the American Society for Neurochemistry; the International Society for Developmental Neuroscience, of which he is past president; and the Society for Neuroscience. Dr. Pfeiffer is a member of the NRC Committee on Space Biology and Medicine.

Richard Setlow, NAS, is a senior biophysicist in the Biology Department at Brookhaven National Laboratory. Dr. Setlow's research interests include studies in far-ultraviolet spectroscopy, molecular biophysics, and environmental carcinogenesis. He received the Finsen Medal in 1980 for "outstanding contributions to photobiology and repair of nucleic acids" and the Enrico Fermi Award in 1989 from the

U.S. Department of Energy for "pioneering and far-reaching contributions to the fields of radiation biophysics and molecular biology." He is a member of the AAAS, the Biophysical Society, the American Society for Photobiology, the Environmental Mutagen Society, and the American Association for Cancer Research. Dr. Setlow's previous NRC service includes membership on the Committee on Human Exploration (1998-2000) and the Committee on Space Biology and Medicine (1994-2000). He also served as chair of the Committee on Health Risks from Exposure to Low Levels of Ionizing Radiation (BEIR VII) (1996-1998).

SSB Liaison

Robert Cleland, Space Studies Board liaison, is professor emeritus of botany at the University of Washington. Dr. Cleland's research has focused on the mechanism of auxin action, cell extension, and gravitropism. Since moving to the Department of Botany at the University of Washington, Dr. Cleland has carried out sabbatical research at the Universities of Leeds and Edinburgh in the United Kingdom and at Yale University. He has been a president of the American Society of Plant Physiologists and is a fellow of the AAAS. Dr. Cleland served on NASA's Life Science Advisory Committee and on the NRC Committee on Space Biology and Medicine. He is currently a member of the NRC Space Studies Board.

NAPA Consultants

David J. Pine, a retired senior executive with a 34-year career with the NASA, is a consultant to the National Academy of Public Administration, the joint participant in this study. While at NASA, Mr. Pine's organizations in the Office of the Chief Financial Officer and later at the Langley Research Center were responsible for the conduct of major NASA program analysis and evaluation for the NASA administrator and deputy administrator. All major programs, including the International Space Station, were reviewed annually by his organization. In addition, he led NASA's cost-estimating function. His organization provided NASA senior management with independent cost estimates and assessments of project costs to ensure cost realism in the development of NASA budgets. From early 1988 through the end of 1990, Mr. Pine was the deputy program manager for the Hubble Space Telescope and was responsible for telescope operations and the science support aspects of the program.

Thomas E. Utsman, retired from NASA, is a consultant to the National Academy of Public Administration. While at NASA, Mr. Utsman served as the space shuttle program director, deputy director of the Office of Space Flight, deputy director of the Kennedy Space Center (KSC), and the director of Space Shuttle Operations at KSC. In these assignments he developed a clear programmatic and operational understanding of human spaceflight.

Staff

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

Celeste Naylor joined the NRC and the Space Studies Board in June 2002 as a senior project assistant. She works primarily with the Committee on Microgravity Research and the Task Group on Research on the International Space Station. Ms. Naylor is a member of the Society of Government Meeting Professionals and has over 5 years of experience in event management.