Review of NASA Plans for the International Space Station

Review of NASA Strategic Roadmaps: Space Station Panel, National Research Council

ISBN: 0-309-65619-2, 60 pages, 8 1/2 x 11, (2006)

Review of NASA Plans for the International Space Station

Review of NASA Strategic Roadmaps: Space Station Panel
Space Studies Board
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS   500 Fifth Street, N.W.   Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract NASW-01001 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number 0-309-10085-2

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
500 Fifth Street, N.W.
Washington, DC 20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, <http://www.nap.edu>.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

Other Reports of the Space Studies Board

The Astrophysical Context of Life (SSB with the Board on Life Sciences, 2005)
Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation (2005)
Extending the Effective Lifetimes of Earth Observing Research Missions (2005)
Principal-Investigator-Led Missions in the Space Sciences (2005)
Preventing the Forward Contamination of Mars (2005)
Priorities in Space Science Enabled by Nuclear Power and Propulsion (SSB with the Aeronautics and Space Engineering Board [ASEB], 2005)
Review of Goals and Plans for NASA's Space and Earth Sciences (2005)
Science in NASA's Vision for Space Exploration (2005)

Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report (SSB with ASEB, 2004)
Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report (2004)
Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy (SSB with ASEB, 2004)
Plasma Physics of the Local Cosmos (2004)
Review of Science Requirements for the Terrestrial Planet Finder: Letter Report (2004)
Solar and Space Physics and Its Role in Space Exploration (2004)
Understanding the Sun and Solar System Plasmas: Future Directions in Solar and Space Physics (2004)
Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond (SSB with ASEB and the Board on Atmospheric Sciences and Climate [BASC], 2004)

Assessment of NASA's Draft 2003 Earth Science Enterprise Strategy: Letter Report (2003)
Assessment of NASA's Draft 2003 Space Science Enterprise Strategy: Letter Report (2003)
Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations (SSB with ASEB and BASC, 2003)
Steps to Facilitate Principal-Investigator-Led Earth Science Missions (2003)
The Sun to the Earth—and Beyond: Panel Reports (2003)

Assessment of Directions in Microgravity and Physical Sciences Research at NASA (2002)
New Frontiers in the Solar System: An Integrated Exploration Strategy (2002)
The Sun to Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics (2002)

Limited copies of these reports are available free of charge from:

Space Studies Board
National Research Council
The Keck Center of the National Academies
500 Fifth Street, N.W., Washington, DC 20001
(202) 334-3477/ssb@nas.edu
www.nationalacademies.org/ssb/ssb.html

NOTE: Listed according to year of approval for release.

REVIEW OF NASA STRATEGIC ROADMAPS: SPACE STATION PANEL

MARY JANE OSBORN, University of Connecticut Health Center, *Chair*
PORTONOVO S. AYYASWAMY, University of Pennsylvania
JAMES P. BAGIAN, Veterans Administration National Center for Patient Safety
ELIZABETH CANTWELL, Los Alamos National Laboratory
MICHAEL J. ECONS, Indiana University School of Medicine
TOMMY W. HOLLOWAY, NASA (retired)
HERMAN J. MERTE, JR., University of Michigan (professor emeritus)
JAMES PAWELCZYK, Pennsylvania State University
JAMES G. QUINTIERE, University of Maryland
DENNIS W. READEY, Colorado School of Mines
DANNY A. RILEY, Medical College of Wisconsin
CAROL E.H. SCOTT-CONNER, University of Iowa College of Medicine
PETER SUEDFELD, University of British Columbia (professor emeritus)
KENNETH T. WHEELER, JR., Wheeler Scientific Consultants, Inc.

Staff

SANDRA J. GRAHAM, Study Director
CATHERINE A. GRUBER, Assistant Editor
CELESTE NAYLOR, Senior Program Assistant

SPACE STUDIES BOARD

LENNARD A. FISK, University of Michigan, *Chair*
GEORGE A. PAULIKAS, The Aerospace Corporation (retired), *Vice Chair*
SPIROS K. ANTIOCHOS,† Naval Research Laboratory
DANIEL N. BAKER, University of Colorado
ANA P. BARROS,* Duke University
RETA F. BEEBE, New Mexico State University
ROGER D. BLANDFORD, Stanford University
RADFORD BYERLY, JR., University of Colorado
JUDITH A. CURRY, Georgia Institute of Technology
JACK D. FARMER, Arizona State University
JACQUELINE N. HEWITT, Massachusetts Institute of Technology
DONALD INGBER, Harvard Medical Center
RALPH H. JACOBSON, The Charles Stark Draper Laboratory (retired)
TAMARA E. JERNIGAN, Lawrence Livermore National Laboratory
KLAUS KEIL,† University of Hawaii
MARGARET G. KIVELSON,* University of California, Los Angeles
DEBRA S. KNOPMAN,† RAND
CALVIN W. LOWE, Bowie State University
HARRY Y. McSWEEN, JR.,* University of Tennessee
BERRIEN MOORE III, University of New Hampshire
NORMAN NEUREITER, American Association for the Advancement of Science
SUZANNE OPARIL, University of Alabama, Birmingham
RONALD F. PROBSTEIN, Massachusetts Institute of Technology
DENNIS W. READEY, Colorado School of Mines
ANNA-LOUISE REYSENBACH,* Portland State University
ROALD S. SAGDEEV,* University of Maryland
CAROLUS J. SCHRIJVER,* Lockheed Martin Solar and Astrophysics Laboratory
HARVEY D. TANANBAUM, Smithsonian Astrophysical Observatory
RICHARD H. TRULY,† National Renewable Energy Laboratory (retired)
J. CRAIG WHEELER, University of Texas, Austin
A. THOMAS YOUNG, Lockheed Martin Corporation (retired)
GARY P. ZANK,† University of California, Riverside

MARCIA SMITH, Director (from March 2006)
JOSEPH K. ALEXANDER, Director (through October 2005)

---
*Member until June 30, 2005.
†Member starting July 1, 2005.

Preface

In January 2004 President George W. Bush announced that the U.S. space program would undertake "a renewed period of discovery," and he charged the National Aeronautics and Space Administration (NASA) with focusing its efforts on exploration.[a] Subsequently referred to as the vision for space exploration, this policy included human and robotic missions to the Moon, Mars, and beyond. The group appointed by President Bush to recommend how to best implement the new policy—the Commission on Implementation of United States Space Exploration Policy—issued its report in June 2004.[b] The commission endorsed the objectives and actions specified in the president's vision for space exploration and recommended that NASA address certain new technology capabilities that it would need in its various endeavors over the next several decades. The commission also recommended that NASA "ask the National Academy of Sciences to engage its constituent scientific community in a re-evaluation of priorities to exploit opportunities created by the space exploration vision."[c]

Then-NASA Administrator Sean O'Keefe subsequently wrote to the presidents of the National Academy of Sciences and the National Academy of Engineering proposing that the National Research Council (NRC) and NASA consider how to "collectively address the commission's recommendations."[d] He also announced a new strategic planning process in which NASA would develop a set of strategic roadmaps for each of the major exploration objectives. Finally, Congress in its FY 2005 appropriations bill for NASA directed the "Space Studies Board to conduct a thorough review of the science that NASA is proposing to undertake under the space exploration initiative, and to develop a strategy by which all of NASA science disciplines . . . can make adequate progress toward their established goals as well as providing balanced scientific research in addition to support to the new initiative."[e]

The NRC's initial, partial response to the recommendations of the president's commission and the requests from NASA and the Congress was provided in the Space Studies Board's February 2005 report *Science in NASA's Vision for Space Exploration*.[f]

Contemporaneously with the preparation of that report and in response to the president's direction, NASA created two complementary roadmapping efforts: a capabilities roadmapping effort and a strategy roadmapping effort. These were to be melded to produce an integrated space exploration architecture for the agency. To further assist NASA, and in response to the various requests, the NRC

---

[a] "President Bush Announces New Vision for Space Exploration Program, Remarks by the President on U.S. Space Policy, NASA Headquarters, Washington, D.C.," January 14, 2004. Available at <www.whitehouse.gov/news/releases/2004/01/20040114-3.html>.

[b] President's Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate, and Discover*, 2004.

[c] *A Journey to Inspire, Innovate, and Discover,* p. 9.

[d] Letter dated July 12, 2004, from NASA Administrator Sean O'Keefe to National Academy of Sciences President Bruce Alberts. See Appendix A.

[e] Conference Report (House Report 108-792) to Accompany H.R. 4818 FY 2005 Consolidated Appropriations Bill, Division I—Department of Veterans Affairs, Housing and Urban Development, and Independent Agencies, "National Aeronautics and Space Administration," p. 1.

[f] NRC, *Science in NASA's Vision for Space Exploration*, The National Academies Press, Washington, D.C., 2005.

organized separate, independent reviews of the expected NASA roadmaps, including a review of an anticipated roadmap for the completion and use of the International Space Station (ISS).

However, when Michael Griffin became NASA's administrator in mid-April 2005, he directed that the agency accelerate the completion of some of the ongoing strategic roadmaps and deferred or redirected other portions of NASA's strategic planning activities. The NRC review efforts were changed accordingly. The Space Studies Board, in collaboration with the Aeronautics and Space Engineering Board, was redirected to conduct two reviews (instead of five), the first to assess NASA's six strategy roadmaps in space and Earth sciences and the second to review a NASA plan for the ISS. In this connection it formed two panels: the Panel on Review of NASA Science Strategy Roadmaps and the Review of NASA Strategic Roadmaps: Space Station Panel.

The two NRC panels were given the following charge:

1. Assess the intrinsic merit of the proposed roadmap objectives and of their proposed implementing programs, especially with respect to relevant NRC or other external advisory reports. Assess whether clear arguments are made for their potential for contributing decisive or transformational technological or scientific advancements.

2. Ascertain whether there are any significant gaps or if there are important crosscutting opportunities or scientific infrastructure issues that are not identified and adequately developed.

To the extent feasible, within the constraints of the schedule and the availability of NASA material for review, [the panel will] also consider the following:

- Initial priorities and decision rules for making prioritization decisions;
- Relationships between program elements;
- Schedule, resource, and technology realism; and
- Relationships between NASA and non-NASA participants from the perspective of whether the roadmaps can make adequate progress toward their established goals as well as providing scientific research support of the vision for space exploration.

The review of six science strategy roadmaps in Earth and space sciences was conducted by the Panel on Review of NASA Science Strategy Roadmaps under an expedited schedule in June and July of 2005, and the report was released in prepublication form in August 2005.[g] The Space Station Panel's review of the plan for the ISS was deferred to the fall of 2005 so that NASA could complete a 60-day study of the "configuration options for the ISS in the context of potential future flight rates for the Space Shuttle Program, and within the Presidential constraint to cease flights of the Shuttle fleet no later than the end of fiscal year 2010."[h] The findings of that 60-day study were to be integrated into NASA's ISS research and use plan before the NRC Space Station Panel reviewed it.

On September 22, 2005, the NRC Space Station Panel received viewgraph materials providing review context and background on recent NASA studies bearing on ISS utilization; the results of the analysis by the Exploration Systems Mission Directorate of ISS utilization requirements; ISS mission objectives for exploration; descriptions of the payloads currently manifested on ISS mission Increments 12 to 15; and a white paper describing the history of peer-reviewed science objectives for the ISS. The panel met once, October 3-5, 2005, to hear briefings on several NASA studies relevant to ISS planning and use, including the 60-day study of the configuration options for the ISS.

[g] NRC, *Review of Goals and Plans for NASA's Space and Earth Sciences*, The National Academies Press, Washington, D.C., 2005 [prepublication].

[h] Letter dated May 23, 2004, from NASA Deputy Administrator Frederick Gregory to Space Studies Board Chair Lennard Fisk. The 60-day study was called the Shuttle/Station Configuration Options Team study, and its scope included ISS assembly, operations, and use.

Acknowledgment of Reviewers

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

Eleanor Blakely, Lawrence Berkeley National Laboratory,
Carlos Fernandez-Pello, University of California, Berkeley,
Andrew Hoffman, East Windsor Associates,
Suzanne Oparil, University of Alabama, Birmingham,
Lawrence A. Palinkas, University of Southern California,
George A. Paulikas, The Aerospace Corporation (retired),
Ronald F. Probstein, Massachusetts Institute of Technology (emeritus professor), and
Joseph H. Rothenberg, Universal Space Network.

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 Louis J. Lanzerotti, New Jersey Institute of Technology. Appointed by the NRC, 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 panel and the institution.

Contents

APPENDIXES

Executive Summary

This report of the National Research Council's (NRC's) Space Station Panel reviews NASA plans for the completion of the International Space Station (ISS) and its utilization in support of the human exploration of the solar system. At the time this report was written, no single integrated plan for the ISS was available for the panel's review. Instead, from the information made available to it from several recent NASA planning activities relevant to ISS utilization for the new exploration missions, the panel developed broad advice on programmatic issues that NASA is likely to face as it attempts to develop an updated utilization plan for the ISS. The panel also discussed some potentially important research and testbed activities to support exploration objectives that may have to be carried out on the ISS to be successful.

CURRENT STATUS OF ISS PLANS

According to the information presented to the panel, the ISS today is approximately 50 percent completed. NASA plans 18 or 19 more flights to finish construction of the ISS but hopes to reduce that number. The shuttle, currently the only transportation system capable of deploying the large ISS structural components and research modules, is planned to be decommissioned at the end of 2010. The panel's understanding is that NASA still plans to deploy all previously planned rack-level research facilities except for those associated with the centrifuge accommodation module (i.e., the life sciences glove box and animal holding racks). However, it appears that much of the racks' supporting equipment has been eliminated in concert with the NASA research programs that would have utilized the racks. The ISS currently carries a reduced crew of two, and NASA is considering scenarios for increasing it to six in 2009 or 2015, with 2008 being the earliest date that the ISS might be capable of sustaining a crew of six.

NASA currently defines the mission objectives for the ISS in support of extended crewed exploration of space as follows:

- Develop and test technologies for exploration spacecraft systems,
- Develop techniques to maintain crew health and performance on missions beyond low Earth orbit, and
- Gain operational experience that can be applied to exploration missions.

The panel agrees that these are appropriate and necessary roles for the ISS. However, the panel noted with concern that these objectives no longer include the fundamental biological and physical research that had been a major focus of ISS planning since its inception. In addition to increasing fundamental scientific understanding, much of that research was intended to have eventual terrestrial applications in medicine and industry. Previous reports[1-3] also emphasized the importance of fundamental biological and microgravity research for the development of new technologies and the mitigation of space-induced risks to human health and performance both during and after long-term spaceflight. The loss of these programs is likely to limit or impede the development of such technologies and of physiological and psychological countermeasures, and the panel notes that once lost, neither the necessary research infrastructure nor the necessary communities of scientific investigators can survive or be easily replaced.

BIOMEDICAL AND TECHNOLOGY RESEARCH

Although it seems unlikely that the ISS will have to play a critical research role in support of lunar sorties (because of their short duration and capability for rapid return), the panel concluded that the ISS provides an essential platform for research and technology testing in support of long-term human exploration, including lunar outpost missions and, most especially, the human exploration of Mars. Indeed, it is uncertain whether the risks involved in sending humans on long-term exploration missions can be mitigated to acceptable levels without precursor experimentation and testing aboard the ISS. Understanding cumulative biological and psychological effects in long-term space environments and the impact of microgravity on the physical phenomena on which spacecraft systems depend, as well as long-term verification of hardware and biological countermeasures and life-cycle testing, will all require the ISS as the only capability available to allow tended experiments in a free-fall environment for periods of time that approximate the duration of a Mars outpost mission.

Given the lack of a single defined research plan for the ISS, the panel could not verify that specific areas it had identified as critical to exploration were in fact gaps in NASA's current planning. A number of broad areas of research important to exploration have been identified in past studies, and this report discusses several of these as examples of research and testing that may prove critical to fulfilling NASA exploration goals. As described in the report, these priority areas of research on the ISS include:

- Effects of radiation on biological systems,
- Loss of bone and muscle mass during spaceflight,
- Psychosocial and behavioral risks of long-term space missions,
- Individual variability in mitigating a medical/biological risk,
- Fire safety aboard spacecraft, and
- Multiphase flow and heat transfer issues in space technology operations.

This list is by no means comprehensive and includes at least some areas that have been considered, if not necessarily implemented, in one more of the NASA ISS planning studies reviewed by the panel.

PROGRAMMATIC ISSUES

Incomplete Information in Decision Support Tools

The panel noted that risk-based criteria[a] are conspicuously missing from the decision support tools presented to the panel. This weakness is particularly troubling in light of the need to prioritize what work can and must be done with respect to time limitations and other resource limitations such as cost, crew time, and so forth.

Recommendation: As has been discussed elsewhere,[4] the characterization of risk should be clearly communicated, along with concrete go/no-go criteria for missions, so as to achieve a rational and supportable allocation of ISS resources.

[a] See the 2006 Institute of Medicine and National Research Council report *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap* for a clear assessment of how risks should be analyzed and how R&D should be utilized to reduce risks.

Using the ISS to Support Exploration Missions

The panel saw no evidence of an integrated resource utilization plan for use of the ISS in support of the exploration missions. Presentations that covered some elements of criteria and processes for determining priorities for utilization of the ISS for different exploration missions demonstrated poor definition of those criteria and processes. In particular, the materials presented to the panel did not seem to take into account the effects that assigning high priority to one mission would have on factors such as the ability to complete another, perhaps later mission, because of depletion of necessary resources or limitations imposed by necessary lead times.

Recommendation: NASA should develop an agency-wide, integrated utilization plan for all ISS activities as soon as possible. Such a planning effort should explicitly encompass the full development of the Exploration Systems Architecture Study technology requirements, migration of current ISS payloads to meet those requirements, identification of remaining gaps unfilled by current ISS payloads, and the R&D and technology or operations payloads needed to fill those gaps. An iterative process that includes Exploration Systems Mission Directorate stakeholders and the external scientific and technical community should be employed to ensure that the as-flown experiments closely match the integrated ISS utilization plan.

Recommendation: Scheduled periodic reviews of the ISS utilization plan with the participation of a broad group of stakeholders (internal and external, scientific and operations) are needed to ensure that the plan remains appropriate and that it continues to promote an integrated approach to attaining the ultimate program goals.

Including Research and Development as an Objective for ISS Utilization

The ISS represents a unique platform for conducting enabling R&D for exploration missions, particularly a Mars mission. Enabling research was not noted as an objective of ISS support for exploration missions. The panel noted with concern this apparent gap in understanding the value of the ISS for exploration missions. Even in an era of extremely limited resources, the ISS may well represent the only timely opportunity to conduct the R&D that is necessary to solve exploration problems and reduce crew and mission risks prior to a Mars mission.

Recommendation: NASA should state that the objective for ISS utilization in support of exploration missions is to conduct enabling research for (1) technologies for exploration, (2) ways to maintain crew health and performance for missions beyond low Earth orbit, and (3) development of an operational capability for long-distance flights beyond low Earth orbit.

Recommendation: Based on the involvement of a broad base of experts and a rigorous and transparent prioritization process, NASA should develop and maintain a set of research experiments to be conducted aboard the ISS that would enable the full suite of exploration missions. These experiments should be fully integrated into the ISS utilization process.

Planning ISS Utilization to Support the Demonstration of Operations for Exploration

The ISS represents a unique platform with which to conduct operations demonstrations in microgravity. For a Mars mission, where significant periods of the mission will occur in microgravity because of the long travel times en route to and returning from Mars, the ISS may prove the only facility with which to conduct critical operations demonstrations needed to reduce risks and certify advanced systems. The panel is concerned that no evidence of definition of operations demonstrations requirements for exploration missions was shown, and such requirements do not appear to be a part of the plans for utilization of the ISS for exploration missions.

Recommendation: Using a rigorous process based on formal prioritization and involvement of the operations community, NASA should develop and maintain a set of operations demonstrations that need to be conducted on the ISS to validate operational protocols and procedures for long-duration and long-distance missions such as the ones to Mars. These demonstrations should be integrated into utilization of the ISS to support exploration.

Crew Size

As discussed in previous NRC and IOM reports,[5-9] no three-person crew (let alone the current two-person crew) will have time to do the necessary research and testing, nor will they be able to serve for human experimentation. Six astronauts will be needed to devote adequate time and effort to the research and testing essential for human missions to Mars and beyond.

Recommendation: NASA should give top priority to restoring the crew size of the ISS to at least six members at the earliest possible time, preferably by 2008.

Completion and Support of ISS Research Capability

Given that shuttle flights are being delayed and that no future shuttle flight schedule is certain, it is possible that the planned ISS configuration will not have been completed by 2010, putting the ISS contribution to exploration research at risk. It appears that there are no plans to provide a backup alternative for delivering ISS structural components and research modules if the shuttle does not complete this process by 2010.

Recommendation: NASA should plan options and decision points for obtaining a post-shuttle logistics capability for maintaining the ISS facility, for supporting the flight crew and research, and for demonstrating the technology and operations that will enable exploration missions. NASA should establish priorities and develop back-up plans to enable the post-2010 deployment of large ISS structural components and the research facilities required to accomplish exploration mission objectives.

REFERENCES

1. Institute of Medicine (IOM). 2001. *Safe Passage: Astronaut Care for Exploration Missions.* National Academy Press, Washington, D.C.
2. National Research Council (NRC). 1998. *A Strategy for Research in Space Biology and Medicine in the New Century.* National Academy Press, Washington, D.C.
3. NRC. 2003. *Assessment of Directions in Microgravity and Physical Sciences Research at NASA.* The National Academies Press, Washington, D.C.
4. IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap*. The National Academies Press, Washington, D.C.
5. NRC. 2003. *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences.* The National Academies Press, Washington, D.C.
6. NRC. 1998. *A Strategy for Research in Space Biology and Medicine in the New Century.*

7. NRC. 2000. *Review of NASA's Biomedical Research Program.* National Academy Press, Washington, D.C.
8. IOM. 2001. *Safe Passage: Astronaut Care for Exploration Missions.*
9. IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space.*

1
Introduction

As detailed in the Preface, the Space Station Panel was one of several subpanels originally charged by Congress to review NASA's strategic roadmaps for achieving the vision and goals of long-range human exploration of space. Because development of an International Space Station (ISS) roadmap (later the plan for ISS utilization) was repeatedly delayed, it became necessary to complete the panel's activities prior to the availability of a defined ISS plan in order to meet the stringent deadline for completion of the overall study. Accordingly, the panel necessarily modified its task to focus on the following aspects of the original task:

- Review and evaluation of projected goals for ISS research;
- Development of processes by which NASA will define the roadmap and its implementation strategies, including the criteria for prioritizing overall mission objectives as well as specific programmatic elements;
- Review of currently available plans for completion of the ISS and restoration of a full crew size;
- Identification of research and technology testing for which the ISS may provide a uniquely suitable platform and consideration of the ISS-based facilities essential for such research and testing; and
- Identification of potential gaps in projected programs and facilities for utilization of the ISS.

The panel met once, for 3 days, October 3-5, 2005, to hear presentations summarizing the development of an architecture for post-shuttle transport and life support and recent and ongoing planning activities in support of roadmap development and to draft its report. The panel was briefed on three recent, separate studies related to roadmap definition: the Exploration Systems Architecture Study (ESAS) Technology Assessment, the Station/Shuttle Configuration Options Team analysis, and the Zero-Base Review of NASA's Office of Human Systems Research and Technology's ISS research. The three had different goals and methodologies, and the panel's review and evaluation were based on its best understanding of how the different plans might fit together. In addition, the panel had access to a substantial number of NASA documents related to the briefings and the overall task of roadmap development. Finally, it relied heavily on previous NRC and IOM reports in evaluating projected ISS research and utilization programs (see Appendix C).

PLANNED PURPOSE OF THE ISS

In its presentations, NASA stated that the new objectives of the ISS utilization plan were to

1. Develop and test technologies for exploration spacecraft systems,
2. Develop techniques to maintain crew health and performance on missions beyond low Earth orbit, and
3. Gain operational experience that can be applied to exploration missions.

It should be noted that these objectives represent a major shift in research goals compared to earlier versions of ISS plans. It has always been an ISS objective to study and develop countermeasures for the detrimental effects of spaceflight on astronauts. However, ISS plans had also previously included a major focus on basic research in a number of diverse fields of biological and physical sciences, with research projects directed at increasing fundamental scientific understanding as well as eventual terrestrial applications such as understanding disease or improving industrial technologies. NASA confirmed that it plans to focus future research strictly on the ISS to support human exploration goals, and this shift in emphasis is consistent with major organizational changes carried out at NASA in recent years.

SCOPE AND LIMITATIONS OF THIS STUDY

Certain caveats concerning the panel's findings should be noted. The short time allotted for this study precluded any rigorous attempt to identify, assess, or prioritize the numerous kinds of in-flight research and testbed activities that may be needed to support NASA's space exploration objectives. Thus the research areas highlighted in this report, many of which are drawn from older studies, must be considered to exemplify the ISS research that can support exploration rather than to constitute a comprehensive list of such research. In addition, the diverse materials presented to the panel indicated that NASA is still in a relatively early stage of its planning for future ISS use and operation. The many uncertainties in these plans, as well as the limited detail available at this stage, mean that in most cases the panel could draw only broad conclusions about the plans and offer general recommendations for moving forward with ISS research and operations. These conclusions and recommendations are based on the panel's best understanding of the materials presented by NASA. It is possible that NASA planning materials exist that were not reviewed by the panel but that would appear to address some of the gaps identified in this report. However, given the rapidly changing planning landscape at NASA, it is unlikely that any such additional materials would have a high level of detail that both is based on rigorous analysis and has been validated. Thus the panel believes that most of its broad findings will remain valid and useful even as NASA develops more detailed plans for the ISS.

The following chapters summarize the panel's deliberations, conclusions, and recommendations with respect to ISS use for exploration (Chapter 2), plans for completion of ISS construction (Chapter 3), biomedical objectives supported by the ISS (Chapter 4), technology capability objectives supported by the ISS (Chapter 5), and some additional overarching issues (Chapter 6).

2
Process for Defining ISS Utilization

NASA gave the panel background materials and briefings that explained at varying levels of detail how the International Space Station (ISS) would or should be utilized in support of the exploration initiative. A number of common terms were used in these materials that had specialized meanings to NASA within the context of these programs. For the sake of clarity, the panel defines in Box 2.1 its understanding and use of these terms: enabling research, operational experience, operations demonstrations, technology demonstrations, utilization, and utilization planning.

The ISS utilization roadmapping effort sought to integrate several separate analyses that bear on ISS utilization in the context of the current exploration systems architecture. These studies include, in roughly chronological order:

- Research Maximization and Prioritization Task Force study, an external review of the established ISS research portfolio, conducted in 2002.
- Zero-Base Review of the Human System Research and Technology Office, an internal study that preceded definition of the exploration systems architecture. The findings of this review and earlier realignments of the role of the former Office of Biological and Physical Research resulted in reductions in non-exploration-related elements of the NASA research portfolio, including fluid physics, materials science, combustion, atomic physics, and animal/cell biotechnology.
- Exploration Systems Architecture Study (ESAS) Technology Assessment, an internal study utilizing a formalized decision analysis methodology, whose goal was to identify and enable key technologies required for the exploration systems architecture.
- Exploration Systems Mission Directorate (ESMD) Analysis of ISS Utilization Requirements, an internal analysis that used a decision support methodology with quality function deployment and analytical hierarchy process, and whose purpose was to establish the priorities for ESMD utilization of the ISS.
- Station/Shuttle Configuration Options Team analysis, a recent internal study that recommends deletion of the Russian science power module and the Japanese-built centrifuge accommodation module.

Although these reports had not been integrated to produce a complete roadmap at the time of this panel's review, it was clear that a great deal had been accomplished in a fairly short time. Unfortunately, time pressure led to a more superficial treatment of some issues than would normally be desirable, and several areas of concern were noted by the panel.

First, the results presented from the various decision support tools did not seem to contain any weightings associated with relative or absolute risk. There are numerous relevant risks, for everything from human health to small team dynamics to system operations to organizational risks.[1] The panel is concerned that these tools will therefore provide unreliable guidance to decision makers as they trade off risks and resources.

Second, the requirements for use of the ISS to support the exploration missions (out to and including a Mars mission) do not appear to be fully identified, even though the ISS might prove to be a *necessary* facility to address these requirements (irrespective of its current set of manifests and payloads). This is particularly troubling because if the ISS is shown to be the only facility where specific risk-

BOX 2.1
Definitions of Terms as Understood by the Panel

Enabling research: R&D that enables technology techniques to enhance crew health and performance and new operations concepts and procedures for exploration missions.

Operational experience: Experience in operating the system under discussion.

Operations demonstrations: Demonstrations of new operating concepts and procedures. Although these may use demonstration hardware or software as support, the focus is on the operating concept or procedure rather than on the new technology. This contributes to operational experience for future space systems since the demonstrations are focused on the planned operating concept.

Technology demonstrations: The testing of new technologies and associated procedures either in piece parts or in full systems to demonstrate new technologies and or new systems.

Utilization: A formal NASA program approach to determining how the ISS will be used that includes such elements as R&T planning, experimental facilities, and resource planning.

Utilization planning: The analysis of the needs of approved (funded or committed) payloads for operational resources, leading to a set of firm flight schedules and cargo manifests.[a]

[a] From the NASA Academy of Program and Project Leadership Terms and Acronyms Web site. Available at <http://appl.nasa.gov/resources/lexicon/terms_u.html>.

reducing R&D or operations demonstrations can be conducted, these tasks must be migrated to a new ISS utilization plan as soon as possible if there is to be any chance of carrying them out.

Third, none of the planning, prioritization, or utilization studies that the panel was shown appeared to have fully and thoroughly aligned ISS utilization with the needs of the exploration missions as expressed in the ESAS Technology Assessment. While this issue is similar to the one raised above, the point here is that the panel did not see evidence that even current ISS payloads have been aligned thoroughly with exploration mission needs.

Finally, the panel believes it is highly likely that a limited number of new research experiments and operations demonstrations will be identified as necessary to enable the full suite of exploration missions if NASA's process for realigning ISS utilization rigorously reassesses needs without regard for current ISS utilization planning. In the information presented to it, the panel saw no place within the planning process for inserting new research experiments or operations demonstrations.

INCOMPLETE INFORMATION IN DECISION SUPPORT TOOLS

The ESAS Technology Assessment presented to the panel showed that the decisions leading to the selected exploration architecture[a] had relied heavily on a computerized decision support tool (for use in prioritizing technologies and ISS experiments, for instance). This tool was able to produce detailed tables and data summaries that created the impression they were supported by validated data.

[a] This architecture included a design for the crew exploration vehicle and architecture for exploration missions, principally for use of the ISS in connection with a lunar sortie.

Unfortunately, the panel found that many of the weighting factors (such as for risk) had been based, at best, on expert opinion and not on hard data. While this may have been a consequence of time pressures, it means that the prioritization decisions were not based on any standardized evaluation of risk to the mission or crew as compared to a defined acceptable level of risk. Absent a means to compare the relative risks in this way, the data from any decision support tool will incompletely inform NASA's decision-making process and may well provide unreliable information to those who must make the final decisions that trade off risks and resources.

Finding: A widespread lack of explicit risk-based go/no-go criteria is notable in the evaluations presented to the panel. This weakness is manifest in many areas but is particularly critical when it comes to prioritizing what work needs to be done with respect to time and other limited resources such as cost, crew time, and so on.

Recommendation: As has been discussed elsewhere,[2] the characterization of risk should be clearly communicated, along with concrete go/no-go criteria for missions, so as to achieve a rational and supportable allocation of ISS resources.

USING THE ISS TO SUPPORT EXPLORATION MISSIONS

In all the presentations it was clear that the overarching goal was support of exploration missions: a crew exploration vehicle to low Earth orbit (LEO)/ISS, a lunar sortie, a lunar outpost, and a Mars mission. However, it was not clear which criteria and procedures were used to set priorities for utilization of the ISS in support of these quite different missions, nor do the requirements for use of the ISS to support the exploration missions (out to and including a Mars mission) appear to be fully identified, even though the ISS, irrespective of its current set of manifests and payloads, might turn out to be a *necessary* facility to address those requirements.

Efforts to align the current ISS payload portfolio with the ESMD ISS utilization requirements can best be described as nascent. The ESMD utilization team specifically recommended that its results should *not* be used to prioritize individual payloads or experiments, saying "more work would be required to refine data at the project level." In response to follow-up questions, briefers stated explicitly that *no activity was complete that attempted to prioritize individual experiments in the current payload portfolio in relation to ESMD requirements for research and technology (R&T).* The ESMD utilization team used assessments by subgroups in each R&T area reflecting the subgroups' perceptions of the value of each ISS facility toward accomplishing their R&T requirements. In these assessments, lunar missions were emphasized. The current portfolio of funded payloads (many of which had been designed, proposed, and reviewed in the mid- to late-1990s) was then used to populate the facilities deemed most valuable, without consideration as to how specific data or results obtained by that experiment would meet exploration goals.

In addition, in the ESMD Analysis of ISS Utilization Requirements a weighting factor for relevance was employed that assigned the lunar outpost a priority of 0.44 as compared to 0.27 for the Mars mission, 0.23 for a lunar sortie, and 0.05 for a crew exploration vehicle to LEO/ISS (Figure 2.1). These relative weights reflected internal stakeholder opinions about what needed to be improved to meet the exploration objectives, but the criteria on which the opinions were based were not clear to the panel.

In particular, this prioritization method did not seem to take into account the possibility that weight factors are cross-correlated. For example, assigning a high priority to one mission could have a significant effect on the ability to complete another, later mission. Other issues include the possibility that earlier missions might use up the resources needed by later missions, or that long lead-time items that are part of the critical path for later missions will be ignored until it is too late to make scheduled milestones. NASA's decision analysis results using uncorrelated weighting factors are shown in Figure 2.2.

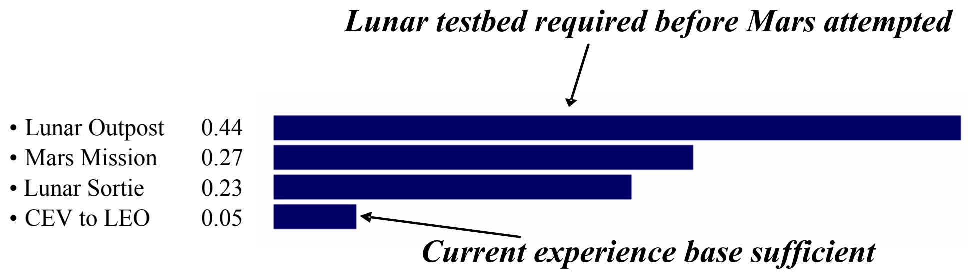

FIGURE 2.1 Design reference missions as ranked by NASA's Exploration Systems Mission Directorate for relevance to overall exploration objectives. SOURCE: Peter Ahlf, Exploration Systems Mission Directorate, NASA, "ESMD ISS Utilization Requirements Analysis Processes and Results," presentation to the Review of NASA Strategic Roadmaps: Space Station Panel, October 3, 2005, National Research Council, Washington, D.C.

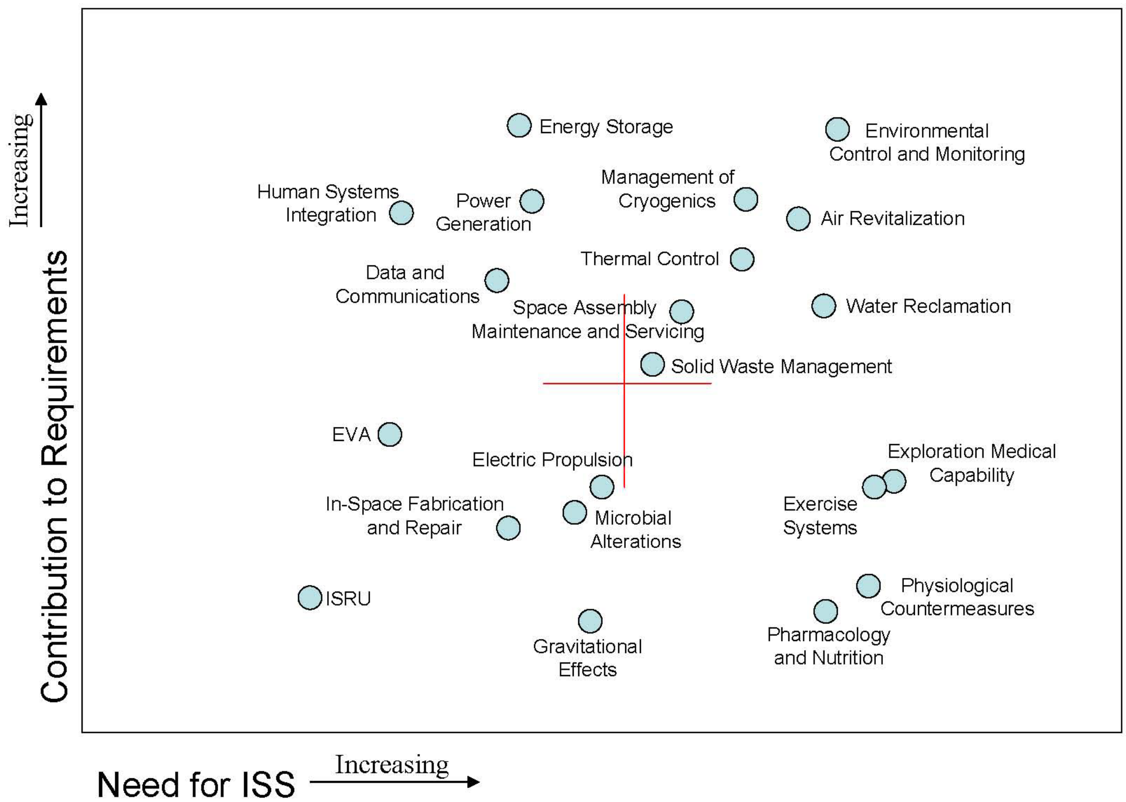

FIGURE 2.2 Comparison of the degree to which an R&T area contributes to meeting exploration requirements versus the need for ISS utilization for that R&T area. Those research and technology areas that are most relevant to a lunar outpost mission lie in the upper-right quadrant. Because this mission was assigned the highest-weight factor in the Exploration Systems Mission Directorate (ESMD) assessment, these topics are given the highest priority for the ISS. The R&T areas in the lower-right quadrant are those important for a Mars mission, which has a lower-weight factor in the ESMD assessment. These relative priority assignments of weight factors raise concerns as to whether the ultimate goal of a crewed Mars mission will be supported through the most prudent use of scarce resources with sufficient lead time. SOURCE: Peter Ahlf, Exploration Systems Mission Directorate, NASA, "ESMD ISS Utilization Requirements Analysis Processes and Results," presentation to the Review of NASA Strategic Roadmaps: Space Station Panel, October 3, 2005, National Research Council, Washington, D.C.

Finding: The criteria and processes used to examine priorities for utilization of the ISS are poorly defined with respect to allocation of ISS-based resources for different exploration missions. In particular, the materials presented to the panel did not seem to take into account the effects that high priorities assigned to one mission would have on factors such as the ability to complete another, perhaps later mission, through depletion of necessary resources or limitation of necessary lead times.

None of the variety of plans provided to the panel appear to have fully and thoroughly aligned ISS utilization with the needs of the exploration missions as expressed in the ESAS Technology Assessment. The panel did not see evidence that even current ISS payloads have been aligned completely with the needs of exploration missions. (This explained NASA's failure to present any overview of an integrated plan describing how the various requirements for a successful exploration program would be achieved, especially with respect to an optimal utilization of the ISS.) This is cause for concern due to the limited time left for utilization of the ISS, the complex relationship between the components of any single exploration mission and the components of other missions in the exploration initiative, and the possibility that, for a Mars mission, the ISS may be the only facility capable of conducting some crucial studies.

Finding: No evidence of an integrated resource utilization plan for use of the ISS in support of the exploration missions was presented to the panel, and indeed it appears that no such integrated plan exists.

Recommendation: NASA should develop an agency-wide, integrated utilization plan for all ISS activities as soon as possible. Such a planning effort should explicitly encompass the full development of the Exploration Systems Architecture Study technology requirements, migration of current ISS payloads to meet those requirements, identification of remaining gaps unfilled by current ISS payloads, and the R&D and technology or operations payloads needed to fill those gaps. An iterative process that includes Exploration Systems Mission Directorate stakeholders and the external scientific and technical community should be employed to ensure that the as-flown experiments closely match the integrated ISS utilization plan.

INCLUDING RESEARCH AND DEVELOPMENT AS AN OBJECTIVE OF ISS UTILIZATION

There is a complete absence of consideration for enabling research that may be necessary to solve exploration problems or to reduce crew and mission risk. For example, the panel expected to see such R&D gaps identified in the ESAS Technology Assessment, but they were not. The ISS offers a unique opportunity to conduct such research and may well represent the only timely opportunity before a Mars mission.

Finding: Enabling research is not a clearly stated objective for use of the ISS in support of exploration missions. Even in an era of extremely limited resources, for R&D that is necessary to solve exploration problems and reduce crew and missions risks, the ISS may well represent the only timely opportunity to conduct such R&D prior to a Mars mission.

Recommendation: NASA should state that the objective for ISS utilization in support of exploration missions is to conduct enabling research for (1) technologies for exploration, (2) ways to maintain crew health and performance for missions beyond low Earth orbit, and (3) development of an operational capability for long-distance flights beyond low Earth orbit.

Recommendation: Based on the involvement of a broad base of experts and a rigorous and transparent prioritization process, NASA should develop and maintain a set of research experiments to be conducted aboard the ISS that would enable the full suite of exploration missions. These experiments should be fully integrated into the ISS utilization process.

PLANNING ISS UTILIZATION TO SUPPORT OPERATIONS DEMONSTRATIONS FOR EXPLORATION

Although one of the objectives for ISS utilization for exploration missions is to "gain operational experience that can be applied to exploration," it appears that operations demonstrations have not been included in the current planning for ISS. The ISS environment offers a unique and timely opportunity to demonstrate operations protocols and procedures such as autonomous crew operations and protocols for communications between the crew and the ground.

Finding: A rigorous definition of operations demonstrations requirements for exploration missions has not been done, and such requirements are not a part of the exploration utilization plan.

Recommendation: Using a rigorous process based on formal prioritization and involvement of the operations community, NASA should develop and maintain a set of operations demonstrations that need to be conducted on the ISS to validate operational protocols and procedures for long-duration and long-distance missions such as the ones to Mars. These demonstrations should be integrated into utilization of the ISS to support exploration.

LIFE SUPPORT CONSIDERATIONS

The stated goal of the ESMD Analysis of ISS Utilization Requirements was to establish priorities for ESMD use of the ISS for research purposes. Life support technologies and environmental controls and monitoring were accorded the highest priority with respect to both "need for ISS" and "contribution to requirements." The panel agrees with this assessment.

The recent IOM and NRC review of NASA's bioastronautics roadmap emphasized as follows:[3]

> In the context of long-duration missions, ensuring highly reliable performance of technologies will depend on two principal means of verification: stress testing and full-duration life testing. In the former approach, relevant environmental factors are made more stressful (e.g., hotter or colder than normal) to permit evaluation of long-term performance in a short period of time. The "full-duration" approach is to build the apparatus and operate it within normal limits for an extended period of time, preferably several times the actual requirement. (As mentioned previously, in order to achieve a TRL [technology readiness level] of 7, this testing should be performed in a relevant environment.) Coupled with failure analysis and remediation, the full-duration approach gives the greatest confidence. To accomplish this sort of qualification with advanced life support systems, accumulated operational experience with such systems or their immediate predecessors is necessary.*
>
> ______________
>
> *The Russian-built Elektron oxygen generator is a case in point. A U.S.-designed and U.S.-built system using more advanced technology awaits launch in mid-2008. The United States is engaged in adapting the Russian system rather than using the intervening time to qualify the U.S. apparatus.

It is troubling, therefore, that the information presented to the panel suggests use only of advanced environmental control and life support systems currently under development. What appears to be missing is an analysis of risk and a consequent risk reduction program to drive the next generation of effective and efficient life support system technologies that will be needed for long-duration, long-distance missions to Mars. For these lengthy, low-gravity, no-abort transit missions, life support equipment that functions and can be maintained in microgravity for prolonged periods will be needed in some form. It is highly unlikely that the ISS advanced environmental control and life support systems currently under development will meet these needs. However, any new concepts for such equipment will have to be tested in a relevant environment.

Finding: Next-generation life support system and environmental control technology demonstration requirements for long-duration, long-distance exploration missions have not been defined and are not included in ISS exploration utilization planning.

Recommendation: Using a well-defined risk-based prioritization scheme and including broad-based expertise, NASA should develop and maintain a set of requirements for ISS technology demonstrations for next-generation life support and environmental control systems for long-duration, long-distance missions.

KEEPING THE ISS UTILIZATION PLAN EFFECTIVE AND CURRENT

The failure to thoroughly scrutinize the results generated by evaluation tools can be attributed to the short time NASA had to formulate ISS plans and to the state of flux in many areas at NASA. However, the panel strongly believes that some form of ongoing external review would improve NASA's ability to produce an actionable plan for ISS utilization that addresses and solves gaps in knowledge and understanding necessary to successfully complete exploration missions.

Recommendation: Scheduled periodic reviews of the ISS utilization plan with the participation of a broad group of stakeholders (internal and external, scientific and operations) are needed to ensure that the plan remains appropriate and it continues to promote an integrated approach to attaining the ultimate program goals.

REFERENCES

1. Institute of Medicine (IOM) and National Research Council (NRC). 2006. *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap*. The National Academies Press, Washington, D.C.
2. IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space.*
3. IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space*, pp. 82-83.

3
Plans for ISS Construction

According to the materials presented to the panel,[a] the ISS today is approximately 50 percent completed. Issues surrounding the ISS as a facility for research, technology demonstration, operations demonstration to support exploration appear to fall into three categories: the completion of construction, the post-shuttle logistical support, and crew deployment.

COMPLETION OF ISS CONSTRUCTION

While the panel did not receive substantive information about completing construction of the ISS in NASA briefings, nearly all of them referred to it. The rest of this chapter is based on what the panel inferred about NASA's plans from those briefings and other information provided to it. The shuttle will be decommissioned at the end of 2010. The current goal is 19 shuttle flights, which will allow deployment of most of the major planned facilities. Currently, the shuttle is the only transportation system capable of deploying the large ISS structural components and research modules. The ISS external configuration remains as previously planned, with the exception of the deletion of the centrifuge accommodation module (CAM) and the Russian science power module (SPM). Animal holding facilities and the life sciences glove box (both would have been internal components of the CAM) were also deleted.[b]

Otherwise all major facilities are planned to be deployed by the shuttle. Examination of documentation provided to the panel indicates that several research support facilities have been deleted in concert with cancellation of the research program that would have utilized them.[c] In addition to the deletion of the CAM and the Russian SPM, some logistics flights were deleted, reducing the number of planned shuttle flights from 28 to 19. To build schedule margin, the program will endeavor to fly extra flights in some years. Given that shuttle flights are being delayed and that all future flight schedules are unsure, the planned ISS configuration might not be completed by 2010, which puts ISS exploration mission objectives at risk. It appears that there are no plans to provide an alternative to the launch-by-

---

[a] Mark Uhran, assistant associate administrator, International Space Station, Space Operations Mission Directorate, NASA Headquarters, "International Space Station: First Steps to Exploration," presentation to the Review of NASA Strategic Roadmaps: Space Station Panel, dated October 3, 2005, National Research Council, Washington, D.C.

[b] Habitat holding racks would have supported up to four habitats optimized for plant culture, cell culture, invertebrates, or small mammals. Each mammalian habitat can house up to 6 adult rats or 12 mice in microgravity conditions for up to 90 days or longer if husbandry supplies are changed out by the crew. The life sciences glove box would have provided a containment facility for these changeouts and other experiments requiring crew intervention. Such capabilities would allow researchers to use animal surrogates to quantify the long-term effects of the space environment on model organisms, including mammalian species, and to test the safety and efficacy of proposed countermeasures before their use in humans. Neither a quantitative nor a qualitative assessment of the additional risks posed for human spaceflight by the deletion of these facilities was presented to the committee.

[c] Trinh, Eugene, NASA Headquarters, "Human Systems Research and Technology. Summary of Zero Base Review (ZBR). Process and Results," presentation dated September 12, 2005.

shuttle of ISS structural components and research modules if the shuttle does not complete this task by 2010.

POST-SHUTTLE ISS LOGISTICS SUPPORT

A robust logistics capability not only will maintain the basic functioning of the ISS facility but also will be paramount in accomplishing ISS exploration mission objectives. Logistics flights to the ISS will deploy crew supplies; maintenance equipment, including replacement spares; specific research experiments and associated equipment and samples; and, finally, technology demonstration hardware and associated provisions.

Logistics requirements can be categorized as either pressurized logistics for internal use or unpressurized logistics for external use. The size and shape of unpressurized logistics are such as to prevent them from being handled internally. NASA suggested that logistics requirements after 2010 over and above those provided by the current baseline Progress flights, the European Space Agency's automated transfer vehicle (ATV) flights, and the Japanese H-II transfer vehicle (HTV) flights will be provided by a combination of a yet-to-be-procured U.S. commercial cargo vehicle, the crew exploration vehicle (CEV) pressurized cargo system, the cargo delivery vehicle (an unpressurized CEV derivative), and additional Progress, HTV, and ATV flights. The capabilities of each element in the combination, the acquisition schedules, and the funding requirements have not been specified in enough detail to give the panel confidence that ISS exploration mission objectives have a high likelihood of being fulfilled. This suggests that there would be significant value in developing a detailed plan to provide the post-shuttle logistics system.

CREW DEPLOYMENT

Although no clear data were provided on the amount of crew time required to accomplish the planned ISS research, technology demonstrations, and operations demonstrations, it is unlikely that a team of three will be sufficient. Nor were plans for increasing the crew size to six discussed in detail. A discussion and review of other NASA materials suggested several options for crew deployment. NASA described Notional Scenario 1,[1] which provided for a crew of six in 2015. Notional Scenario 2 provided for a crew of six in 2009. In response to questions, NASA indicated that the ISS might be capable of sustaining a crew of six in 2008 at the earliest, depending on deployment of the advanced environmental control and life support systems. The panel believes that in order to accomplish ISS exploration mission objectives, the crew complement has to be increased as soon as practicable.

RECOMMENDATIONS

The following steps are needed to make possible the research, technology demonstrations, and operations demonstrations required to enable plans for human exploration of the Moon and Mars:

1. NASA should plan options and decision points for obtaining a post-shuttle logistics capability for maintaining the ISS facility, for supporting the flight crew and research, and for demonstrating the technology and operations that will enable exploration missions.
2. NASA should establish priorities and develop back-up plans to enable the post-2010 deployment of large ISS structural components and the research facilities required to accomplish exploration mission objectives.
3. NASA should develop plans to deploy six persons to the ISS as soon as practicable, preferably in 2008.

REFERENCE

1. National Aeronautics and Space Administration (NASA). 2004. *Bioastronautics Critical Path Roadmap*. NASA, Washington, D.C.

4
Biomedical Research Issues

NASA's biomedical program has been reviewed in a number of past NRC reports.[1,2] A 2001 IOM review noted that "the three most important health issues that have been identified for long-duration missions are late effects of radiation, loss of bone mineral density, and behavioral adaptation."[3] More recently, the Bioastronautics roadmap, described by NASA as "the framework used to identify and assess the risks of crew exposure to the hazardous environments of space," was reviewed.[4] The review of that document reiterated the importance of the three areas cited in the 2001 IOM report and identified additional concerns, including food and nutrition and advanced life support. The relevance of ISS research to some of these critical research areas is discussed below.

RADIATION

The radiation encountered once one leaves Earth's atmosphere consists of a mix of high-energy gamma rays, protons, electrons, neutrons, and high-Z charged particles that cannot be simulated on the ground. Positioned as it is in low Earth orbit, the ISS is exposed to all of these types of radiation, but the proportion of total exposure accounted for by exposure to high-Z particles is less than that expected on the lunar surface or in transit to Mars. Although a direct extrapolation of the radiation hazard from long-term animal experiments on the ISS to the radiation hazards encountered by humans during exploration missions in free space is problematic due to the differences in energy and mass spectrum of the galactic and solar cosmic rays, data obtained from animal experiments on the ISS are important because the mixed radiation field cannot be simulated on the ground, and adequately shielding the occupants in an exploration spacecraft is currently prohibitive due to the large upmass required.

For the proposed lunar sortie missions, present estimates of the radiation risk are likely valid because the total exposure is relatively low.[5] The predominant risk is probably the induction of hematologic and solid malignancies, and no acute effects are expected. However, during 6-month stays at a lunar outpost on a 3-year round trip to Mars, the exposure to radiation has the potential to produce significant long-term effects that may not be limited to cancer induction.[6,7]

Classically, the radiation risk was predominantly thought to be associated with damage to the proliferating cells in organs whose function relied heavily on cell renewal systems to replace their damaged components.[8,9] Recently, this concept has been called into question by a number of human and rodent studies.[10-12] For example, 20 to 50 percent of brain tumor patients who receive fractionated large-field or whole brain irradiation and survive longer than 6 months have measurable cognitive deficits;[13-15] of these, 10 to 15 percent progress to a condition similar to that seen in Alzheimer's patients. In rodents, the late radiation effects produced by single dose or short fractionation schemes are not predictive of the late effects produced by prolonged fractionation schemes in brain, kidney, lung, and heart, where the functionality is predominantly the nondividing cells.[16-19]

Mechanistic studies have demonstrated that ionizing radiation produces a chronic increase in the intracellular reactive oxygen species, which leads to a chronic inflammatory response.[20] Importantly, the level of reactive oxygen species and inflammation in nondividing cells never returns to its original level after irradiation, and so these cells, which do not die, function abnormally for months or years after irradiation.[21] In nearly all the cases studied so far, these radiation-induced deficits occur with no gross histopathological evidence of disease.[22-24]

Given that (1) the dose, dose rate, and composition of a radiation field can drastically alter the biological outcome of exposure,[25-28] (2) the results of short-term exposures do not predict the results of long-term exposures,[29-32] (3) the biological effects of mixed-field radiation are generally worse than the sum of the biological effects of the individual types of radiation,[33-35] and (4) microgravity and other environmental factors in the space vehicle are likely to have some influence on the final biological response, it would appear that experiments to assess the risk of prolonged exposure to space radiation can only be performed in the ISS or on the Moon. This would require both restoration of the capacity to perform long-term rodent experiments on the ISS or on the Moon and initiation of preflight and long-term postflight testing of humans for kidney, lung, heart, and brain function.

Importantly, the low linear energy transfer (LET) radiation damage to the kidney and the brain, including cognitive impairment, appears to be modifiable in both humans and rodents using pharmacological interventions.[36,37] Although there are no data on mitigating the late effects in liver, kidney, lung, and brain produced by high-LET radiation or mixed radiation fields, there are suitable pharmacological agents that could be tested on the ISS or on the Moon now.[38,39]

Finding: There is insufficient information about the mixed-beam radiation effects on biological systems to confidently derive risk estimates for a Mars mission. Based on current knowledge, it is dangerous to assume that carcinogenesis is the only long-term risk of extended-duration spaceflight.

Recommendation: A high priority should be given to assessing the noncarcinogenic late effects of exposure to space radiation on the ISS or the Moon and to testing pharmacological interventions for ameliorating these late effects, because the results are critical for designing a Mars mission.

BONE AND MUSCLE

Existing countermeasures have failed to prevent deterioration of bone and muscle in astronauts during spaceflight. Current data based on 4- to 6-month spaceflights indicate that there is impressive bone loss at both the spine and hip.[40] Observed losses at the spine and hip average 0.9 percent and 1.5 percent per month, respectively. Quantitative computer tomography studies indicate that loss of trabecular bone at the femoral neck (a frequent hip fracture site) is 2.7 percent per month.[41] Although there is a wide spectrum of individual variation, linear extrapolation of these data suggests that approximately two-thirds (64 percent) of astronauts would experience more than a 25 percent loss of bone mineral at the hip during a 30-month Mars outpost-class mission. A 21 percent decline in peak force of slow muscle fibers has been observed after a 17-day spaceflight, and a 20 to 48 percent reduction in maximal voluntary contraction of the plantar flexors has been observed after 6 months in space.[42] This level of deterioration will compromise motor performance and increase susceptibility to injury, changes unlikely to be acceptable for an outpost-class mission to Mars. Moreover, reversibility of tissue deterioration is unclear for long-duration flights, particularly in an environment of radiation exposure and suboptimal nutrition. The ability of fractional gravity environments (such as the 0.16-*g* and 0.38-*g* fields of the Moon and Mars, respectively) to maintain bone and muscle integrity has not been determined, and recent data indicate that bone density does not return to baseline within 12 months of returning to Earth.[43,44] Muscle function appears to return to preflight levels within weeks. However, studies of long-term recovery have not been conducted to ascertain whether the deterioration involved nonpathological muscle cell shrinkage and postflight cell enlargement or a process of pathological cell degeneration followed by cell regeneration. Pathology is a concern, because tissue regeneration may be compromised by exposure to radiation in spaceflight.[45,46]

NASA has some human experiments planned and in progress to address the issue of bone loss. However, space-based clinical trials of antiosteoporotic therapies lag behind terrestrial applications by more than 10 years.[47] Animal experiments could test whether antiresorptive drugs with or without other interventions would mitigate these risks. Animal studies would also allow for biomechanical studies (e.g., stress/strain curves) and bone histomorphometry, which would allow for better estimation of risks to astronauts and provide information to test maintenance of bone strength as well as bone density. Finally, an animal centrifuge (currently deleted because the JAXA-supplied centrifuge accommodation module has been removed from the flight manifest) would allow investigators to test (1) the potential bone-sparing effect of a fractional gravity environment such as that encountered on the Moon (0.16 *g*) or Mars (0.38 *g*), and (2) the effect of an intermittent centrifugal loading as a potential countermeasure.

Finding: Current countermeasures have failed to mitigate significant progressive loss of bone and muscle mass during spaceflight.

Recommendation: Long-duration experiments to characterize temporal muscle atrophy and bone loss in the spacecraft environment should be designed and conducted on the ISS. Restoration of the animal habitat and glove box are essential for these studies, and the probable utility of the animal centrifuge as a unique fractional gravity research tool and a potential countermeasure should be reevaluated in the context of a martian outpost scenario.

BEHAVIOR

The 2001 *Safe Passage* report noted that "human interactions aboard a spacecraft, isolated in time and space from Earth, may well be one of the more serious challenges to exploratory missions by humans."[48] Every recent examination of long-duration spaceflight has identified psychosocial (including cultural) issues as among the most likely, and potentially most damaging, inherent problems.[49-53] Highly probable sources of adjustment difficulties include prolonged separation from one's customary physical and social environment—in fact, from one's home planet—under conditions of danger, dependence on complex life support technologies, noise, hygienic shortcomings, confinement, reduced privacy and personal space, significant changes to one's body and physiological processes, difficulty of leaving in an emergency, enforced and monotonous closeness (both psychological and physical) with people of possibly very different, and possibly aversive, backgrounds and personalities, and the disorienting aspects of microgravity or reduced gravity. Previous reports have identified problems of adaptation to capsule living such as anxiety, depression, withdrawal, interpersonal hostility directed against crewmates and/or mission controllers and the home organization, sleep disturbances, psychosomatic symptoms, and counterdependence.[54] A 2006 IOM and NRC report commented on the added difficulties of communicating and establishing positive relationships within groups that are diverse (with respect to ethnicity, gender, education, organizational norms, and general culture) and between spacefarers and their home organizations, and the tendency of these difficulties to exacerbate other problems.[55]

Although there is a sufficiency of data from spaceflight to establish the psychosocial realm as one that must be seriously considered, considerable corroborative evidence has been derived from research in simulated and analog environments.[a] Many of these environments involve isolation, confinement, and remoteness from "normal" social networks and accustomed sites; some are in locations where the outside environment is dangerous, life support systems are crucial, and access is limited. It is clear that both analog and simulated environments can be, and have been, useful in identifying many of the psychosocial problems that are likely to plague the crews of Moon outposts and Mars explorations. However, these terrestrial environmental approximations cannot duplicate the extreme physical conditions that space

[a] Simulated environments include bed-rest laboratories and mock-ups of a space vehicle or station in which volunteers live for weeks or months. Analog environments include small polar research stations, undersea habitats, and submersible vessels.

explorers will face, particularly the loss of gravity and resultant physiological changes and disruptions of basic functions such as spatial perception and locomotion.[56] The effects of these psychosocial and environmental factors are interactive. Further, unlike almost all analogs and simulations, spaceflight—especially Mars flight—poses the problem that crew members who experience serious psychological or psychiatric dysfunction cannot be spared from their job assignments. There will be no one who could administer psychotherapy, no facilities for providing sedation or other restraints until the end of the mission (unless it is imminent), and no chance of returning affected crew members immediately to Earth. Thus, such breakdowns are very likely to be dangerous to the mission and to the lives of the crew.

Finding: Simulation and analog environments do not fully mimic the psychosocial and behavioral risks of long-term human spaceflight, especially those posed by a prolonged Mars mission, and are not adequate as testbeds for development and validation of effective countermeasures against these risks.

Recommendation: Research should be carried out on the ISS (and/or the Moon) to establish how specific factors of the space environment might impair behavior, performance, interpersonal relationships, and psychological well-being and to develop effective countermeasures against potential adverse effects.

DATA

Life Sciences Data Archive and the Longitudinal Study of Astronaut Health

The end points of all research are new knowledge, technologies, and products. In the realm of medical operations and biological responses to spaceflight, this information is codified in the Life Sciences Data Archive and the Longitudinal Study of Astronaut Health.[57] These data will never be re-created and therefore constitute unique resources for future mission planners. The importance of these resources and issues related to their availability to investigators have been discussed in detail in previous reports.[58,59] These resources are not mentioned in the ISS roadmap exercises.

Recommendation: NASA should provide mechanisms to retain and readily access the scientific knowledge and data already obtained from previous space missions. Such information should be in a form (e.g., Internet-based) that is usable by members of the scientific and medical communities both within NASA and outside it.

Individual Variability

When deciding what amount of ISS resources should be directed to mitigate a medical/biological risk, individual differences (biological, psychological, cultural, social) pose a particular challenge. For example, preliminary data provided to the panel indicate that bone and muscle loss varied by a factor of 3 or more, and in many individuals these parameters had not returned to baseline. Although it has made considerable progress in representing biological variability in the permissible levels of exposure to radiation, NASA lacks a similar approach for musculoskeletal and cardiovascular deconditioning standards. Defining the probability that any crew members will exceed the proposed standard is a necessary part of safety decisions. If insufficient data exist to make medical and safety decisions (both go/no-go and mission modifying) in a probabilistic fashion, additional data collection or alternative statistical treatment is warranted.[60]

The panel concurs with a recent report recommending that NASA incorporate quality-of-evidence measurements and use standard-of-uncertainty analysis techniques to assess medical risk, particularly for human exploration missions.[61] Reliance on expert opinion without an adequate evidence base is not an acceptable method for making decisions related to crew health and safety. The tacit assumption that risk values and associated medical decision making can be extrapolated from current data obtained from limited sources, such as anecdotal reports from previous crew members and short-duration animal and human studies in the actual space environment, raises concerns.

Recommendation: NASA should critically analyze both disaggregated and aggregated data (such as that in the Longitudinal Study of Astronaut Health and the Life Sciences Data Archive) to derive confidence bands for medical risks. The quality of the data and the difference between best-case and worst-case scenarios should be assessed and analyzed.

- Additional, hypothesis-driven, long-duration research on the ISS may be necessary to refine confidence bands such that there is a reasonable statistical likelihood that the adaptation of crew members during a long-duration mission will fall within a clinically acceptable range.
- Research into predictors of individual responses to conditions on the ISS or during extended-duration spaceflight is needed to allow tailoring of individual countermeasures.

Recommendation: NASA should utilize previous recommendations (e.g., those of the IOM and NRC bioastronautics roadmap review committee) to select and sequence additional needed experiments and address in a timely fashion those critical issues that could affect important decisions on the design of architecture for future missions.

REFERENCES

1. National Research Council (NRC). 1987. *A Strategy for Space Biology and Medical Science.* National Academy Press, Washington, D.C.
2. NRC. 1998. *A Strategy for Research in Space Biology and Medicine in the New Century.* National Academy Press, Washington, D.C.
3. Institute of Medicine (IOM). 2001. *Safe Passage: Astronaut Care for Exploration Missions*. National Academy Press, Washington, D.C., p. 3.
4. IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap*. The National Academies Press, Washington, D.C.
5. Brenner, D.J., and E.J. Hall. 1992. Commentary 2 on Cox and Little: Radiation-induced oncogenic transformation: The interplay between dose, dose protraction, and radiation quality. *Adv. Radiat. Biol.* 16: 167-179.
6. Curtis, S.B. 1994. Importance of dose rate and cell proliferation in the evaluation of biological experimental results. *Adv. Space Res.* 14: 989-996.
7. Curtis, S.B. 1996. Possible effects of protracted exposure to the additivity risks from space radiations. *Adv. Space Res.* 18: 41-44.
8. Withers, H.R., L.J. Peters, and H.S. Kogelnik. 1980. The pathobiology of late effects in irradiation. Pp. 439-448 in *Radiation Biology in Cancer Research* (R.E. Meyn and H.R. Withers, eds.). Raven Press, New York, N.Y.
9. Rubin, P., and G.W. Casarett. 1968. Clinical radiation pathology as applied to curative radiotherapy. *Cancer* 22: 767-778.
10. Denham, J.W., and M. Hauer-Jensen. 2002. The radiotherapeutic injury—A complex "wound." *Radiother. Oncol.* 63: 129-145.
11. Coleman, C.N., H.B. Stone, J.E. Moulder, and T.C. Pellmar. 2004. Modulation of radiation injury. *Science* 304: 693-694.
12. Stone, H.B., C.N. Coleman, M.S. Anscher, and W.H. McBride. 2003. Effects of radiation on normal tissue: Consequences and mechanisms. *Lancet Oncol.* 4: 529-536.

13. Roman, D.D., and P.W. Sperduto. 1995. Neuropsychological effects of cranial radiation: Current knowledge and future directions. *Int. J. Radiat. Oncol. Biol. Phys.* 31: 983-998.

14. Surma-aho, O., M. Niemalä, J. Vilkki, M. Kouri, A. Brander, O. Salonen, A. Paetau, M. Kallio, J. Pyykkönen, and J. Jääskeläinen. 2001. Adverse long-term effects of brain radiotherapy in adult low-grade glioma patients. *Neurology* 56: 1285-1290.

15. Shaw, E.G., and M.E. Robbins. 2005. Central nervous system. In *Radiation Toxicity: A Practical Guide* (W. Small and G.E. Woloschak, eds.). Kluwer Academic Publishers, New York, N.Y.

16. Tofilon, P.J., and J.R. Fike. 2000. The radioresponse of the central nervous system: A dynamic process. *Radiat. Res.* 153: 357-370.

17. Gaber, M.W., O.M. Sabek, K. Fukatsu, H.G. Wilcox, M.F. Kiani, and T.E. Merchant. 2003. Differences in ICAM-1 and TNF-α expression between large single fraction and fractionated irradiation in mouse brain. *Int. J. Radiat. Biol.* 79: 359-366.

18. Jaenke, R.S., M.E.C. Robbins, T. Bywaters, E. Whitehouse, M. Rezvani, and J.W. Hopewell. 1993. Capillary endothelium: Target site of renal radiation injury. *Lab. Invest.* 57: 551-565.

19. Rubin, P., J. Finkelstein, and D. Shapiro. 1992. Molecular biology mechanisms in the radiation induction of pulmonary injury syndromes: Interrelationship between the alveolar macrophages and the septal fibroblast. *Int. J. Radiat. Oncol. Biol. Phys.* 24: 93-101.

20. Robbins, M.E.C., and W. Zhao. 2004. Chronic oxidative stress and radiation-induced late normal tissue injury: A review. *Int. J. Radiat. Biol.* 80: 251-259.

21. Robbins, M.E.C., and W. Zhao. 2004. Chronic oxidative stress and radiation-induced late normal tissue injury: A review.

22. Yoneoka, Y., M. Satoh, K. Akiyama, K. Sano, Y. Fujii, and R. Tanaka. 1999. An experimental study of radiation-induced cognitive dysfunction in an adult rat model. *Br. J. Radiol.* 72: 1196-1201.

23. Hodges, H., N. Katzung, P. Sowinski, J.W. Hopewell, J.H. Wilkinson, T. Bywaters, and M. Rezvani. 1998. Late behavioral and neuropathological effects of local brain irradiation in the rat. *Behav. Brain Res.* 91: 99-114.

24. Brown, W.R., C.R. Thore, D.M. Moody, M.E. Robbins, and K.T. Wheeler. 2005. Vascular damage after fractionated whole-brain irradiation in rats. *Radiat. Res.* 164(5): 662-668.

25. Brenner, D.J., and E.J. Hall. 1992. Commentary 2 on Cox and Little: Radiation-induced oncogenic transformation: The interplay between dose, dose protraction, and radiation quality. *Adv. Radiat. Biol.* 16: 167-179.

26. Curtis, S.B. 1994. Importance of dose rate and cell proliferation in the evaluation of biological experimental results.

27. Curtis, S.B. 1996. Possible effects of protracted exposure to the additivity risks from space radiations.

28. Hall, E.J. 1994. *Radiobiology for the Radiologist,* 4th Edition. J.B. Lippincott Co., Philadelphia, Pa.

29. Tofilon, P.J., and J.R. Fike. 2000. The radioresponse of the central nervous system: A dynamic process. *Radiat. Res.* 153: 357-370.

30. Gaber, M.W., O.M. Sabek, K. Fukatsu, H.G. Wilcox, M.F. Kiani, and T.E. Merchant. 2003. Differences in ICAM-1 and TNF-α expression between large single fraction and fractionated irradiation in mouse brain. *Int. J. Radiat. Biol.* 79: 359-366.

31. Jaenke, R.S., M.E.C. Robbins, T. Bywaters, E. Whitehouse, M. Rezvani, and J.W. Hopewell. 1993. Capillary endothelium: Target site of renal radiation injury. *Lab. Invest.* 57: 551-565.

32. Rubin, P., J. Finkelstein, and D. Shapiro. 1992. Molecular biology mechanisms in the radiation induction of pulmonary injury syndromes: Interrelationship between the alveolar macrophages and the septal fibroblast.

33. Ngo, F.Q., E.A. Blakely, and C.A. Tobias. 1981. Sequential exposures of mammalian cells to low- and high-LET radiations: I. Lethal effects following X-rays and neon-ion irradiation. *Radiat. Res.* 87: 59-78.

34. Iliakis, G., F.Q. Ngo, W.K. Roberts, and K. Youngman. 1985. Evidence for similarities between radiation damage expressed by beta-ara-A and damage involved in the interaction effect observed after exposure of V-79 cells to mixed neutrons and gamma irradiation. *Radiat. Res.* 104: 303-316.

35. Ngo, F.Q., E.A. Blakely, C.A. Tobias, P.Y. Chang, and L. Lommel. 1988. Sequential exposures of mammalian cells to low- and high-LET radiations. II. As a function of cell cycle stage. *Radiat. Res.* 115: 54-69.

36. Coleman, C.N., H.B. Stone, J.E. Moulder, and T.C. Pellmar. 2004. Modulation of radiation injury. *Science* 304: 693-694.

37. Moulder, J., M.E.C. Robbins, E.P. Cohen, J.W. Hopewell, and W.F. Ward. 1998. Pharmacologic modification of radiation-induced late normal tissue injury. Pp. 129-151 in *Radiation Therapy* (B.B. Mittal, J.A. Purdy, and K.K. Ang, eds.). Kluwer, Norwell, Mass.

38. Coleman, C.N., H.B. Stone, J.E. Moulder, and T.C. Pellmar. 2004. Modulation of radiation injury.

39. Moulder, J., M.E.C. Robbins, E.P. Cohen, J.W. Hopewell, and W.F. Ward. 1998. Pharmacologic modification of radiation-induced late normal tissue injury.

40. Lang, T., A. LeBlanc, H. Evans, Y. Lu, H. Genant, and A. Yu. 2004. Cortical and trabecular bone mineral loss from the spine and hip in long-duration spaceflight. *J. Bone Miner. Res.* 19: 1006-1012.

41. Lang, T., A. LeBlanc, H. Evans, Y. Lu, H. Genant, and A. Yu. 2004. Cortical and trabecular bone mineral loss from the spine and hip in long-duration spaceflight.

42. Fitts, R.H., D.R. Riley, and J.J. Widrick. 2001. Functional and structural adaptations of skeletal muscle to microgravity. *J. Exp. Biol.* 204: 3201-3208.

43. Sibonga, J.D., H.J. Evans, H. Sung, E.R. Spector, V.S. Oganov, A.V. Bakulin, L.C. Shackelford, and A.D. LeBlanc. 2005. Skeletal recovery following long-duration spaceflight missions as predicted by preflight and postflight dual x-ray absorptiometry (DXA): Scans of 49 crewmembers. *J. Bone Miner. Res.* 20: S44.

44. Lang, T.F., A. LeBlanc, H. Evans, and Y. Lu. 2005. Recovery of proximal femoral density and geometry after long-duration spaceflight. *J. Bone Miner. Res*. 20: S44.

45. Mozdziak, P.E., Q. Truong, A. Macius, and E. Schultz. 1998. Hindlimb suspension reduces muscle regeneration. *Eur. J. Appl. Physiol. Occup. Physiol.* 78: 136-140.

46. Kirchen, M.E., K.M. O'Connor, H.E. Gruber, J.R. Sweeney, I.A. Fras, S.J. Stover, A. Sarmiento, and G.J. Marshall. 1995. Effects of microgravity on bone healing in a rat fibular osteotomy model. *Clin. Orthop. Relat. Res.* 318: 231-242.

47. Strewler, G.J. 2004. Decimal point—Osteoporosis therapy at the 10-year mark. *N. Engl. J. Med.* 350(12): 1172-1174.

48. IOM. 2001. *Safe Passage: Astronaut Care for Exploration Missions*, p. 3.

49. Harrison, A.A. 2001. *Spacefaring: The Human Dimension*. University of California Press, Berkeley, Calif.

50. IOM. 2001. *Safe Passage: Astronaut Care for Exploration Missions*, p. 3.

51. Kanas, N., and D. Manzey. 2003. *Space Psychology and Psychiatry*. Kluwer, Dordrecht, and Microcosm Press, El Segundo, Calif.

52. National Aeronautics and Space Administration (NASA). 2004. *Bioastronautics Critical Path Roadmap*. NASA, Washington, D.C.

53. NRC. 1998. *A Strategy for Research in Space Biology and Medicine in the New Century.*

54. Suedfeld, P., and G.D. Steel. 2001. The environmental psychology of capsule habitats. *Annual Review of Psychology* 51: 227-253.

55. IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space.*

56. NRC. 1998. *A Strategy for Research in Space Biology and Medicine in the New Century,* p. 198.

57. IOM. 2001. *Safe Passage: Astronaut Care for Exploration Missions*, p. 3.

58. NRC. 1998. *A Strategy for Research in Space Biology and Medicine in the New Century.*

59. IOM. 2001. *Safe Passage: Astronaut Care for Exploration Missions*.

60. IOM. 2001. *Small Clinical Trials: Issues and Challenges.* National Academy Press, Washington, D.C.

61. IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space.*

5
Technology Capability Objectives Supported by the ISS

The panel's review of technology capabilities supported by the ISS was restricted to aspects of the ISS research plan that pertain to the physical sciences. This discussion is based primarily on presentations and documentation provided by NASA.[a] As noted in Chapter 1, the panel had little time in which to attempt a rigorous identification, assessment, and prioritization of the research and operational studies associated with the physical sciences that may be needed to support NASA's space exploration objectives. The areas highlighted in this chapter represent the best efforts of the panel at this juncture to point NASA to topics that do not appear to have been thoroughly considered.

One of the significant issues for the panel's evaluation of the ISS focus on physical science was the lack of a consistent set of technology issues and proposed approaches to satisfying these. For example, the Zero-Base Review appears to show that all materials science, combustion, and fluid physics funding will be (or has been) eliminated.[b] Yet some information provided to the panel implies that several ISS facilities and modules constructed for research in these disciplines would still be delivered to the ISS—for example, the fluids integrated rack and the combustion integrated rack. The panel also notes that the microgravity sciences glove box is already on the ISS.[c] This made it difficult to comment on the efficacy and appropriateness of the intended ISS research, since it was unclear what research is to be, or can be, carried out on the ISS. In this context, the panel has chosen to identify potential gaps in a number of broad areas, and examples of these are discussed below. Owing to the limitations of this study, this list cannot be considered comprehensive by any means, but the panel thinks that the issues identified are important in the context of both risk reduction and the design and testing of advanced technologies for exploration missions.

FIRE SAFETY

Fire in the constricted areas of a spacecraft can be devastating. It has been documented that five incidents with ignition potential have occurred during the 12 years of shuttle operations,[1] and two fire incidents involving oxygen generators occurred on the Mir.[2] When the operational durations of these vehicles are compared with the time needed for a voyage to Mars, it can be seen that fire would be a very serious risk in the Mars program. Past NRC studies have repeatedly called for research on fire mitigation, detection, and suppression.[3,4]

Fundamental research on combustion phenomena in microgravity has elucidated many fire issues peculiar to microgravity, yet there is still relatively little known about flame behavior that relates to fire

[a] NASA, "Pre-Brief Materials for the NRC Review of NASA Strategic Roadmaps: ISS Panel. Review Context and Background," presentation dated September 19, 2005.

[b] E. Trinh, NASA Headquarters, "Human Systems Research and Technology. Summary of Zero Base Review (ZBR). Process and Results," presentation dated September 12, 2005.

[c] P. Ahlf, Exploration Systems Mission Directorate, NASA, "ESMD ISS Utilization Requirements Analysis Processes and Results," presentation to the Review of NASA Strategic Roadmaps: Space Station Panel, October 3, 2005, National Research Council, Washington, D.C.

safety issues in spacecraft. Indeed, our scientific understanding of fire on Earth is still emerging, and specialized studies in microgravity have been invaluable to that effort. In this context, the ISS is unique in providing sufficient time in a microgravity environment to achieve definitive evaluation of spacecraft fire phenomena—unachievable by short-duration microgravity facilities such as drop towers and unrealizable by computation that lacks sufficient spatial resolution. Thus, should fire safety gaps be identified that must be filled in order to reduce the fire risks on exploration missions to acceptable levels, the ISS is the only facility that could be used to conduct the studies. Such risk-reducing studies might include the effects of fire on humans and equipment and the design implications for suppressing, escaping, or correcting the damage of fire.

The presentations by NASA to the panel were ambiguous in describing the projects in the proposed continuation of the ISS program that are deemed essential for human space exploration (Mars).[d] Fire safety prioritization appears to have focused on fire detection and fire suppression without evidence that these are the most critical fire safety areas for future missions.[e] In addition, the two areas that appear to have been retained in ISS research planning—detection and suppression—were not presented in sufficient detail to allow the panel to assess whether NASA's plans to address them are adequate**.** NASA needs to set design performance objectives for fire detection, suppression, and prevention and then demonstrate the certainty of achieving them. Fire poses an uncertain risk for the success of long-term spaceflight. Some of the areas of importance that were reduced or eliminated from the ISS program include these:

- *Tests for flammability and material screening*. NASA currently has several tests for flammability.[f] However, these fire tests may not provide the proper levels of risk reduction for the new exploration program. For example, it has been noted that NASA-STD-6001 Test 1 results do not map quantitatively to results in the low- or partial-gravity environments of an exploration vehicle or habitat.[5] Although NASA has performed extensive research to establish a replacement for the upward flammability test in a 1-*g* environment, it is not clear to the panel that this has been accomplished. NASA appears to be canceling the FEANICS program that is designed to verify the new test with ISS experiments.

Previous reviews have stated the need for achieving prediction of surface flame spread in microgravity and fractional gravity.[6] In order to rationally choose construction materials for spacecraft interiors that minimize the risk of, and danger from, fire and combustion, risk programs that include a better understanding of flame spread in microgravity are a primary consideration.[7]

- *Oxygen system safety.* Combustion involving pure oxygen sources is a particular hazard in spacecraft and can result in temperatures capable of turning most materials into fuels. It was noted in a previous NRC report that the aspects of ignition, flame spread, and extinguishment that are unique to oxygen fires are critical research areas for human exploration.[8] Thus, the use of oxygen generators and high-O_2 atmospheres are matters of special concern.
- *Smoldering and pyrolysis.* Smoldering and transition to flaming combustion are significantly different processes in microgravity than on Earth.[9] The mechanisms that could enhance smoldering

---

[d] The projects indicated for continued funding appear to be smoke detection (DAFT and SAME) and smoke suppression (FLEX), the latter using the combustion integrated rack. The project related to material flammability and development of a new NASA test method (FEANICS) appears to have been dropped from the ISS but might be carried out on a limited basis on the ground.

[e] *Assessment of Directions in Microgravity and Physical Sciences Research at NASA* (NRC, 2003, p. 87) lists a number of fire-related issues that are at the level of critical impact on technology needed for human space exploration.

[f] For example, NASA-STD-6001 Test 1 looks at upward flame propagation. Other tests include the cone calorimeter (ASTM E 1254) for materials that fail the upward flame propagation test, ASTM D 93 for the flashpoint of liquids, and a special test for electrical wire flammability, containers, and metal flammability, which uses a version of the upward flame propagation test in pure oxygen.

combustion ignition and propagation, transport of the combustion products, and the mechanism of detector response in zero gravity are not fully understood, especially with respect to design parameters for fire detection systems.

NASA's combustion research program has laid a good foundation for understanding spacecraft fire issues. However, it is not clear to the panel that NASA has fully addressed the fire research knowledge gaps whose filling in is crucial to reducing risks on long-term exploration missions. Fire safety is grounded in the fundamentals of combustion, and gaps in understanding of the fundamentals of microgravity combustion must be assessed in terms of the additional risks they pose to crew and vehicles in the exploration missions program.

Finding: The history of spacecraft fire incidents suggests that the risk of a fire incident on a long-term mission such as a trip to Mars is high.

Recommendation: NASA should develop fire safety design performance criteria for long-term exploration missions as soon as possible. These criteria should be used to drive an analysis of additional research or testing necessary to ensure fire safety at the design level, an endeavor for which the ISS is the only viable research facility.

Finding: If risk mitigation and technology requirements studies indicate that there are fire safety gaps for exploration missions, the ISS may well prove an essential facility for further studies. In particular, drop tower duration is too short for viable fire safety studies, and computational prowess is unlikely to be sufficient to solve these problems via modeling in any relevant time frame.

Recommendation: NASA should convene a panel of internal and external experts to conduct a complete review of the potential risks associated with fire safety issues in the exploration missions. The panel should be asked to comment specifically and technically on adequate and appropriate research programs needed to mitigate the risks associated with fire safety for exploration missions. The panel should also be asked to comment on risk that would be added to the total risk picture for exploration missions by not updating current NASA fire safety tests.

MULTIPHASE FLOW AND HEAT TRANSFER ISSUES

Multiphase flow and heat transfer (MFH) processes involve a fluid of two or more phases (typically two—liquid and vapor). Such processes rely on the latent heat of liquid-vapor phase change and are highly efficient in transferring large amounts of heat. Systems that demand high efficiency for heat transfer and require high power- to-weight ratios operate under multiphase flow conditions. In the past, NASA almost exclusively employed single-phase systems in space exploration, but it has now given research in MFH a high priority.[g] For achieving the space exploration goals envisioned in ESAS,[h] issues and concerns related to MFH processes in microgravity environments are not understood adequately to mitigate risks.[10] The ISS may be the only testbed suitable for achieving this understanding.

[g] E. Trinh, NASA Headquarters, "International Space Station Research Plan: Implementing the Vision for Space Exploration," presentation to the Review of NASA Strategic Roadmaps: Space Station Panel, October 3, 2005, National Research Council, Washington, D.C.

[h] John Connolly, NASA, "ESAS: Exploration Systems Architecture Study. ESAS Study Summary," presentation to the Review of NASA Strategic Roadmaps: Space Station Panel, October 3, 2005, National Research Council, Washington, D.C.

An example of the potential criticality of MFH is in environmental management, where the chemical composition of the atmosphere and properties such as relative humidity and temperature must be rapidly and accurately measured and controlled. Such control has a high likelihood of being achieved by employing MFH processes. Since capillary forces become strong in the absence of gravity, thermocapillarity, together with the use of suitable geometries of the solid heated (for humidification) or cooled (for dehumidification) surfaces, can be used to facilitate a flow of liquid, whether in the form of drops or thin films. NASA's current ISS research plans[i] do not appear to include an examination of the combined effect of solid surface geometries and thermocapillarity in long-term microgravity. If an examination of technology needs for long-term exploration missions such as a mission to Mars were to identify MFH processes as strong candidates for meeting those needs, studies aboard the ISS of the flow and stability of drops and thin films on variable wetting surfaces in the presence of phase changes might be the only way to develop design parameters for a reliable optimized (in terms of mass and energy consumption) system.

Another example of the potential need for greater understanding of MFH processes is thermal control. An active thermal control mechanism based on MFH might consist of a heat pump/refrigerant unit with the attendant evaporation and condensation components. Passive systems for thermal control include the use of heat pipes—conventional and loop systems—where thermocapillarity provides the driving force needed for liquid motion in microgravity. Operating either of these multiphase systems in an exploration mission would require understanding the phase separation processes well enough to design systems that can operate reliably for long periods of time in microgravity. Again, the ISS may prove to be the only facility that can be used to improve understanding of microgravity thermocapillarity to the levels needed to provide design parameters that will enable risk mitigation.

Related to thermal control, the panel notes that two pool boiling experiments have been proposed for the ISS.[j] It has been demonstrated with pool boiling, but not yet with flow boiling, that heat transfer rates are greater in microgravity than on Earth. Although the critical heat flux with pool boiling is known to be reduced in microgravity, the critical heat flux with flow boiling in microgravity remains undetermined. The panel believes that flow boiling may be more relevant to the thermal control needs for exploration missions. As such, studies involving heat fluxes, subcooling parameters, and a range of Reynolds numbers would be important to enable system optimization.

Previous NRC reports, including one in 2003,[11] have pointed out that in the past, because of risk and reliability considerations, NASA has chosen not to use active, high-power-density systems that involve heat transfer by phase change (e.g., condensation and boiling). This panel was presented with material that current and future technology developments of space power are in the hundreds of kilowatts (electric) range and thus may require a nuclear reactor as a high-temperature heat source[12-14] whatever the thermal-to-electric conversion system may be. The high efficiency and high power-to-weight ratio of closed-cycle multiphase systems, based on the use of the latent heat of phase change (i.e., condensation and evaporation) to transfer energy, will thus be significantly more attractive to NASA in these future systems. (For example, alkali metal heat pipes have been considered as an efficient way of supplying high-temperature heat energy to a power conversion engine at its hot end.[15,16]) This is another critical example in which use of multiphase systems in an exploration mission scenario would require understanding the phase change processes well enough to design systems that could operate reliably for long periods of time in microgravity.

---

[i] E. Trinh, NASA Headquarters, "International Space Station Research Plan: Implementing the Vision for Space Exploration"; NASA, "Pre-Brief Materials for the NRC Review of NASA Strategic Roadmaps: ISS Panel. Current Working Manifest for ISS/Shuttle: Payload Descriptions," presentation dated September 19, 2005.

[j] NASA, "Pre-Brief Materials for the NRC Review of NASA Strategic Roadmaps: ISS Panel. Current Working Manifest for ISS/Shuttle: Payload Descriptions," presentation dated September 19, 2005.

A final example of what may be anticipated with exploratory missions such as those to Mars is the management of cryogenic liquids such as oxygen. The importance of technologies to manage cryogenic liquids in microgravity has been recognized in previous NRC studies[17] and in some NASA exploration planning studies.[k] Management of a cryogenic liquid involves its storage and transport via ducts. It may be anticipated that the non-venting mode of storage will be used for the long periods of time with exploratory missions. This may require refrigeration to condense the vapor formed if inward heat leaks are sufficiently large. Proper temperature gradients on the condensing surfaces together with their geometry can provide the motion by thermocapillary effects to move the liquid to the inlet of a suitable pump. The necessary temperature gradients can be provided by the refrigeration device. Successful cryo management under such circumstances will require an understanding of multiphase flow and heat transfer issues, and the ISS could serve as a unique testbed if appropriate engineering studies are planned and carried out.

Finding: Multiphase flow and heat transfer systems operating in microgravity environments are profoundly influenced by thermocapillarity effects and may be significant components of exploration missions. Studies aboard the ISS may be the only way to obtain information on temperature and geometry effects on the motion of films and fluid particles at interfaces (with emphasis on thermocapillary effects).

MATERIALS RESEARCH

One of the primary justifications for construction of the ISS was that it would allow unique materials to be developed and processed in microgravity. To that end, NASA encouraged and supported a significant research effort in microgravity materials research with the intent of better understanding the effects of gravity on materials processing. With the new vision for the ISS, NASA no longer supports microgravity materials research. The panel is concerned that this wholesale elimination of materials science research has also eliminated consideration of materials processes that might be quite important to exploration missions, such as welding, soldering, and brazing—processes that rely on poorly understood interfacial effects and thermocapillarity.

REFERENCES

1. Friedman, R. 1992-1993. Fire safety practices and needs in human-crew spacecraft. *J. Appl. Fire Sci.* 2(3): 243-250.
2. Zimmerman, R. 2003. *Leaving Earth.* Joseph Henry Press, Washington, D.C.
3. National Research Council (NRC). 2003. *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences*. The National Academies Press, Washington, D.C.
4. NRC. 2000. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies.* National Academy Press, Washington, D.C.
5. Ruff, G.A., D.L. Urban, and M.K. King. 2005. A research plan for fire prevention, detection and suppression in crew exploration systems. 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., January 10-13.

[k] NASA, "Pre-Brief Materials for the NRC Review of NASA Strategic Roadmaps: ISS Panel. Review Context and Background," presentation dated September 19, 2005, p. 22.

6. NRC. 2000. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies.*

7. NRC. 2003. *Assessment of Directions in Microgravity and Physical Sciences Research at NASA*. The National Academies Press, Washington, D.C.

8. NRC. 2003. *Assessment of Directions in Microgravity and Physical Sciences Research at NASA,* pp. 36 and 87.

9. NRC. 2003. *Assessment of Directions in Microgravity and Physical Sciences Research at NASA.*

10. NRC. 2000. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies.*

11. NRC. 2003. *Assessment of Directions in Microgravity and Physical Sciences Research at NASA.*

12. Martin, J., O. Mireles, and R. Reid. 2005. Multiple restart testing of a stainless steel sodium heat pipe module. Pp. 150-157 in *Space Technology and Applications International Forum - STAIF 2005* (M. El-Genk, ed.). AIP Conference Proceedings 746. American Institute of Physics, Melville, N.Y.

13. Satter, C.M. 2005. JIMO follow-on mission studies. Pp. 249-257 in *Space Technology and Applications International Forum - STAIF 2005* (M. El-Genk, ed.). AIP Conference Proceedings 746. American Institute of Physics, Melville, N.Y.

14. Wright, S.A., R.J. Lipinski, T. Pandya, and C. Peters. 2005. Proposed design and operation of a heat pipe reactor using the Sandia National Laboratories annular core test facility and existing UZrH fuel pins. Pp. 449-460 in *Space Technology and Applications International Forum - STAIF 2005* (M. El-Genk, ed.). AIP Conference Proceedings 746. American Institute of Physics, Melville, N.Y.

15. Martin, J., O. Mireles, and R. Reid. 2005. Multiple restart testing of a stainless steel sodium heat pipe module.

16. Wright, S.A., R.J. Lipinski, T. Pandya, and C. Peters. 2005. Proposed design and operation of a heat pipe reactor using the Sandia National Laboratories annular core test facility and existing UZrH fuel pins.

17. NRC. 2000. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies.*

6
Additional and Overarching Issues

UTILIZATION OF THE ISS FOR LONG-RANGE HUMAN EXPLORATION OF SPACE

NASA currently defines the mission objectives for the ISS in support of extended crewed exploration of space as follows:

- Develop and test technologies for exploration spacecraft systems,
- Develop techniques to maintain crew health and performance on missions beyond low Earth orbit, and
- Gain operational experience that can be applied to exploration missions.

The panel agrees that these are appropriate and necessary roles for the ISS, although it has concerns (discussed below) about the areas omitted from this list. Although it seems unlikely that the ISS will have to play a critical research role in support of lunar sorties (because of their short duration and capability for rapid return), the panel concluded that the ISS provides an essential platform for research and technology testing in support of long-term human exploration, including lunar outpost missions and, most especially, the human exploration of Mars. Indeed, it is not certain that the risks involved in sending humans on long-range exploration can be mitigated to acceptable levels without precursor experimentation and testing aboard the ISS. Understanding the risks of radiation exposure and interactions, cumulative biological effects in long-term microgravity environments, and effects on human behavior and performance, as well as long-term verification of hardware and biological countermeasures and life-cycle testing, will all require the ISS as the only available capability for tended experiments in a free-fall environment for periods of time that approximate a Mars outpost mission.

As noted previously, the panel lacked both the time and the necessary data to attempt a comprehensive assessment of the diverse research issues that have to be addressed to enable NASA's human exploration plans. A number of broad areas important to exploration were identified in past studies, and this report discusses several of them to show the kinds of research and testing that are needed and could be performed on the ISS. However, a successful exploration program will require a much better understanding of the improved technologies and capabilities needed to support a reliable and affordable exploration program, and the research and operations demonstrations needed to support their development, than NASA has at present or appears to be in the process of developing.[a]

Recommendation: NASA should give priority to full use of ISS capabilities for research, technology, and countermeasure testing and operations demonstrations in preparation for human exploration of the Moon, Mars, and beyond.

Recommendation: NASA would benefit from, and should consider, a comprehensive study that would rigorously review the wide range of biomedical and technological issues relevant to exploration, identify

---

[a] See the discussion in "Using the ISS to Support Exploration Missions" in Chapter 2.

specific research projects and testbed experiments needed to support biomedical countermeasures and exploration technology development, and prioritize these in terms of such factors as mission importance, range of use, timelines, and probability of success.

UTILIZATION OF THE ISS FOR FUNDAMENTAL RESEARCH

The panel noted with special concern the potential long-term impact of recent decisions to eliminate delivery of certain ISS research facilities, specifically the centrifuge accommodation module and the planned animal habitats and holding racks and the life sciences glove box, and to eliminate or severely downgrade fundamental research in previously funded areas of physical and life sciences. Previous reports have emphasized the importance of areas of fundamental biological and microgravity research in the development of new technologies and the mitigation of space-induced risks to human health and performance both during and after long-term spaceflight.[1-3] Chapters 4 and 5 of the present report summarize several priority areas of fundamental biomedical and physical science research that are crucial to achieving acceptable levels of risk in spaceflight beyond low Earth orbit. The panel fears that loss of these programs may limit or impede development of such technologies and biological countermeasures and it notes that, once lost, neither the necessary research infrastructures nor the necessary communities of scientific investigators can survive or be easily replaced.

Recommendation: NASA should reconsider the role of the ISS in fundamental research in microgravity and biological sciences and the facilities essential for this research, with the aim of acquiring new knowledge critical to mitigating the multiple risks of long-term spaceflight beyond low Earth orbit.

CREW SIZE

As discussed in earlier reports, neither sufficient time for research and testing nor a sufficient number of volunteers for human experimentation can be afforded by a three-person crew,[4-8] much less the current reduced number of two. Completion of ISS research and testing essential for human missions to Mars and beyond will require a full six-person crew to enable astronauts to give adequate time and effort to these activities.

Recommendation: NASA should give top priority to restoring the crew size of the ISS to at least six members at the earliest possible time, preferably by 2008.

REFERENCES

1. Institute of Medicine (IOM). 2001. *Safe Passage: Astronaut Care for Exploration Missions.* National Academy Press, Washington, D.C.
2. National Research Council (NRC). 1998. *A Strategy for Research in Space Biology and Medicine in the New Century.* National Academy Press, Washington, D.C.
3. NRC. 2003. *Assessment of Directions in Microgravity and Physical Sciences Research at NASA*. The National Academies Press, Washington, D.C.
4. NRC. 2003. *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences*. The National Academies Press, Washington, D.C.
5. NRC. 1998. *A Strategy for Research in Space Biology and Medicine in the New Century.*
6. NRC. 2000. *Review of NASA's Biomedical Research Program.* National Academy Press, Washington, D.C.

7. IOM. 2001. *Safe Passage: Astronaut Care for Exploration Missions.*
8. IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap*. The National Academies Press, Washington, D.C.

Appendixes

A
Letters from NASA

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

July 12, 2004

The Honorable Bruce Alberts
President
National Academy of Sciences
500 Fifth St., NW
Washington, DC 20001

Dear Dr. Alberts:

The recently completed Report of the President's Commission on Implementation of United States Space Exploration Policy ". . . recommends that NASA ask the National Academy of Sciences to engage its constituent scientific community in a re-evaluation of priorities to exploit opportunities created by the space exploration vision. In particular, the community should consider how machines and humans, used separately and in combination, can maximize scientific returns." NASA believes that such engagement would be beneficial and continue a rich tradition of cooperative endeavor between our Agency and the Academy.

As a consequence, I propose that a NASA senior leadership team meet with the National Academy of Sciences and the National Academy of Engineering to consider how we might collectively address the Commission's recommendations. Dr. Charles Elachi, Director of NASA's Jet Propulsion Laboratory, will lead the team for NASA.

I look forward to our discussions regarding this exciting aspect of implementing the President's Vision.

Cordially,

Sean O'Keefe
Administrator

National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

Science Mission Directorate

December 21,2004

Dr. Lennard Fisk
Chair
Space Studies Board
National Research Council
500 5th Street, NW
Washington, DC 20001

Dear Dr. Fisk:

In January 2004, President Bush directed NASA to pursue a broad but focused program of space exploration. In response to this direction, and subsequent guidance from the Aldridge Commission, NASA has laid out a planning framework that will culminate in an agency-wide Integrated Space Architecture implementing this Vision for Space Exploration. This Architecture will be constructed from Strategic Roadmaps and Capability Roadmaps prepared over the next six months. The Architecture will be used to guide agency-wide programmatic and budget decisions.

The Strategic Roadmaps to be developed in support of this integrated planning process will refine top-level Agency Objectives flowing from the Vision for Space Exploration and propose implementation options, pathways, and decision processes for achieving these strategic objectives. Thirteen advisory committees have been chartered under the Federal Advisory Committee Act to develop these Roadmaps. Each committee includes representatives from industry, academia, NASA, and other Government agencies. The schedule for completion of these roadmaps varies, but most are projected for completion by the end of July.

Because of the critical importance of the Architecture, and, therefore, of the Roadmaps upon which it is based, NASA would like to request that the Space Studies Board, working together with the Aeronautics and Space Engineering Board as appropriate, conduct a critical review of drafts of eleven of these roadmaps as they reach a mature state. A review of the other two roadmaps, on aeronautical technologies and space shuttle, will be undertaken separately. The schedule and terms of reference of the review requested here are delineated in the enclosed Statement of Work.

We look forward to working with you and your colleagues to ensure the success of NASA's planning activity and the resulting exciting program of exploration.

Cordially,

Bernard Seery
Director
Advanced Planning and Integration Office

Enclosure

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

April 28,2005

The Honorable Shenvood L. Boehlert
Chairman
Committee on Science
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

As NASA implements the Vision for Space Exploration, we recognize the magnitude of the task ahead and the importance of engaging the best and the brightest the country has to offer in developing the requisite details for an effective implementation.

In two letters dated December 10,2004 and December 23,2004, NASA notified the Committee of the establishment of 13 Strategic Roadmap Committees chartered to advise the NASA Administrator on a range of areas related to the Vision for Space Exploration and the Mission of the Agency. These Committees were chartered under the Federal Advisory Committee Act (FACA) (5 U.S.C. App.). NASA also established 15 Capability Roadmap Teams that have worked to identify key capabilities needed to support the Agency's investment portfolio as we strive to reach our science and exploration goals.

For many months, teams of outstanding individuals have played an important role in helping craft roadmaps for NASA. Recognizing that broad participation in the process that informs critical space program decision-making is extremely important, NASA structured the roadmap teams to include individuals who are considered experts in their fields from within NASA, other government agencies, academia, and the private sector. We appreciate their hard work and support and value their contributions to this critical endeavor.

To best use these roadmaps to inform our fiscal year 2005 Operating Plans, fiscal year 2006 budget plans, and fiscal year 2007 budget development, NASA is accelerating the completion of roadmap development and creating a strategic architecture. This decision-making framework must be available to NASA leadership by mid-summer 2005 to influence major programmatic decisions as part of the fiscal year 2007 budget development and ensure that current budget plans are aligned with the new direction.

The roadmaps developed by these experts will provide an excellent foundation for NASA integration of these roadmaps into a decision-making framework. We will give full consideration to their thoughtful contributions as we finalize the NASA architecture to support our future missions, programs, and budget requests.

Given our decision to accelerate the schedule, NASA will complete all roadmap efforts – strategic and capability – by May *22, 2005.* This revised schedule, with an architecture development effort beginning immediately, impacts the National Research Council (NRC) review of individual roadmaps, which will not take place as originally planned. The NRC, in response to separate congressional direction to review NASA science, will receive the science strategic roadmaps and will provide a report or other input to NASA by August 1, *2005.* We look forward to receiving the NRC's recommendations on the science roadmaps and to a continuing dialogue on science priorities and related issues.

To support immediate decision-making, NASA is initiating an internal Exploration Systems Architecture Study (ESAS) to determine how to accelerate development of the Crew Exploration Vehicle (CEV) and reduce the gap between Shuttle retirement and CEV operations. NASA will select a preferred architecture approach this summer for lunar exploration, including CEV launch, in-space transportation, and surface operations, and develop associated requirements and budgets for implementation. This architecture study is to support the Agency's science and exploration objectives.

We would be pleased to discuss these planning efforts and the new schedule in more detail at your convenience. Questions may be directed to the Acting Assistant Administrator for Legislative Affairs, Angela Phillips Diaz, at *(202)* 358-1948.

Cordially,

Michael D. Griffin
Administrator

B
Acronyms and Abbreviations

CAM	centrifuge accommodation module
CEV	crew exploration vehicle
ESAS	Exploration Systems Architecture Study
ESMD	Exploration Systems Mission Directorate
EVA	extravehicular activity
IOM	Institute of Medicine
ISRU	in situ resource utilization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
LEO	low Earth orbit
LET	linear energy transfer
MFH	multiphase flow and heat transfer
NASA	National Aeronautics and Space Administration
NRC	National Research Council
R&D	research and development
R&T	research and technology
SPM	science power module (Russian)

C
National Academies' Reports Relevant to This Study

National Research Council (NRC). 1998. *A Strategy for Research in Space Biology and Medicine in the New Century.* National Academy Press, Washington, D.C.

NRC. 2000. *Engineering Challenges to the Long-Term Operation of the International Space Station*. National Academy Press, Washington, D.C.

NRC. 2000. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies.* National Academy Press, Washington, D.C.

Institute of Medicine (IOM). 2001. *Safe Passage: Astronaut Care for Exploration Missions*. National Academy Press, Washington, D.C.

NRC. 2003. *Assessment of Directions in Microgravity and Physical Sciences Research at NASA*. The National Academies Press, Washington, D.C.

NRC. 2003. *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences*. The National Academies Press, Washington, D.C.

IOM. 2004. *Preliminary Considerations Regarding NASA's Bioastronautics Critical Path Roadmap*. The National Academies Press, Washington, D.C.

IOM and NRC. 2006. *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap*. The National Academies Press, Washington, D.C.

D
Biographies of Panel Members and Staff

MARY JANE OSBORN, *Chair*, is professor of molecular, microbial, and structural biology at the University of Connecticut Health Center. Her fields of specialization are microbial biochemistry, microbiology, and molecular biology. Current research interests include mechanisms of cell division in *Escherichia coli*. Dr. Osborn is a member of the National Academy of Sciences. She has served on numerous distinguished committees, including the National Science Board, the President's Committee on the National Medal of Sciences, the Advisory Council of the National Institutes of Health's Division of Research Grants (chair, 1992-1994), the Advisory Council of the Max Planck Institute of Immunobiology, the Board of Scientific Advisors for the Roche Institute for Molecular Biology (chair, 1983-1985), and the NAS Council. In addition, Dr. Osborn has served on numerous NRC committees, including the Committee on Space Biology and Medicine (chair, 1994-2000), and the Space Studies Board (1994-2000).

PORTONOVO S. AYYASWAMY is the Asa Whitney Professor of Dynamical Engineering at the University of Pennsylvania. His current research projects focus on direct-contact heat and mass transfer, cell culturing in simulated microgravity conditions, transport in biological systems on macroscopic and microscopic levels, plasma arc heat transfer and applications in semi-conductor integrated chip technology, and non-Newtonian flows in die bonding. Dr. Ayyaswamy received the 2001 American Society of Mechanical Engineers International Heat Transfer Memorial Award in the science category "for many seminal contributions to such diverse fields of heat transfer as phase-change, plasma, bio, and natural convection, in particular to transport processes with the moving droplets and the thermal design of advanced industrial equipment." He is also the recipient of the American Institute of Aeronautics and Astronautics Award–Aerospace Professional of the Year in 1997 "for outstanding contributions to the advancement of the Arts and Sciences of Aeronautics and Astronautics." As a professor of mechanical engineering and applied mechanics, he has conducted extensive research on phase-change transport phenomena and has co-authored the monograph *Transport Phenomena with Drops and Bubbles*. He is a fellow of the American Society of Mechanical Engineers.

JAMES P. BAGIAN is the chief patient safety officer and the director of the Veterans Administration National Center for Patient Safety. Dr. Bagian has expertise in the development and implementation of interdisciplinary programs and projects involving engineering, medical sciences, and human factors disciplines. Dr. Bagian served as a NASA astronaut from 1980 to 1995 and is a veteran of two space shuttle missions. He also was an investigator for both the Challenger and Columbia missions. Dr. Bagian focuses on applications in aerospace systems, environmental technology, and patient safety—notably crew survival and physiological adaptation issues that impact aviation and spaceflight operations. He also investigates how systems-based solutions can be implemented and the role of leadership in ensuring patient safety and the quality of care. Dr. Bagian is a member of the National Academy of Engineering and the Institute of Medicine (IOM). He currently serves on the IOM Committee on NASA's Bioastronautics Critical Path Roadmap and previously served as chair of the Committee on Space Biology and Medicine and member of the Space Studies Board (1995-1997 and 2000-2003), and as chair of the Task Group on Research on the International Space Station (2001-2003).

ELIZABETH CANTWELL is the deputy division leader for science and technology in the International, Space and Response Division at the Los Alamos National Laboratory. She previously served as section leader for the Micro and Nanotechnology Center, Lawrence Livermore's engineering research center for fabricating small sensors and devices. She earned an undergraduate degree in psychology from the University of Chicago and an M.S. and a Ph.D. in mechanical engineering from the University of California, Berkeley. She also holds an M.B.A. from the University of Pennsylvania's Wharton School of Business. Dr. Cantwell began her career building life support systems for crewed space missions with the National Aeronautics and Space Administration. She was a member of the NRC Committee on Advanced Technology for Human Support in Space (1996-1997) and of the IOM Committee on Review of NASA's Bioastronautics Critical Path Roadmap (2004-2005).

MICHAEL J. ECONS directs the Division of Endocrinology and Metabolism at Indiana University. Dr. Econs has used a combination of clinical and molecular research to substantially advance the field of metabolic bone disease. His contributions to this effort include the identification of the genes responsible for X-linked hypophosphatemic rickets and autosomal dominant hypophosphatemic rickets. He has also made contributions to the understanding of the genetics of osteoporosis and autosomal dominant osteopetrosis. He is a member of the Central Society for Clinical Investigation and the American Society for Clinical Investigation and has lectured on various topics in metabolic bone disease at numerous academic institutions and medical/scientific meetings.

TOMMY W. HOLLOWAY retired in 2002 as manager of the International Space Station Program Office for NASA's Johnson Space Center. Mr. Holloway was named space station manager in April 1999 after serving as manager of the space shuttle program for nearly 4 years. He began his career with NASA in 1963, planning activities for Gemini and Apollo flights at what was then known as the Manned Spacecraft Center. He was a flight director in Mission Control for early space shuttle flights and became chief of the office in 1985. In 1989, he was named assistant director for the Space Shuttle Program for the Mission Operations Directorate. He served as deputy manager for program integration with the Space Shuttle Program and director of the Phase I Program of Shuttle-Mir dockings before being named space shuttle program manager in August 1995. He served on the NRC Committee on Assessment of Options for Extending the Life of the Hubble Space Telescope (2004-2005).

HERMAN J. MERTE, JR., is professor emeritus in the Mechanical Engineering Department at the University of Michigan. His research interests involve heat transfer, including dynamics of phase change, boiling, and condensation; study of boiling heat transfer (pool and flow) in microgravity; and heat transfer in wire bundles. Dr. Merte has been involved in heat transfer research related to phase changes of boiling and condensation under reduced- and high-gravity fields since 1957. This included boiling (pool) of water and liquid nitrogen at up to 20 *g*, of water at up to 300 *g*, of mercury at 300 psi and up to 15 *g*, of liquid hydrogen in a 1.4-second drop tower; and dropwise and film condensation of water at up to 1,000 *g*. Since 1984 this included flow boiling of R-113 at various levels of heat flux and liquid subcooling, at various flow velocities, and various orientations relative to Earth's gravity field; and pool boiling of R-113 at various levels of heat flux and subcooling in long-term microgravity (2 minutes per condition) in the GAS on the space shuttle, for 5 flights, and a total of 45 experiments.

JAMES PAWELCZYK is a physiologist at Pennsylvania State University. He was a payload specialist on Space Transportation System-90 (Neurolab) and flew in 1998 with a focus on neuroscience. Dr. Pawelczyk was a member of the NASA Life Sciences Advisory Subcommittee in the Office of Biological and Physical Research. He was a member of the ReMaP Task Force (2002), charged with reprioritizing research on the International Space Station. He has received NASA funding as an individual principal investigator, as a project leader on center grants, and in contracts (including international collaboration) since 1993. Dr. Pawelczyk's research areas include central neural control of the cardiovascular system and compensatory mechanisms for conditioning and deconditioning. He is knowledgeable about NASA and spaceflight operations and has medical expertise in the effects of space travel on human systems. He is currently a member of the IOM Committee on NASA's Bioastronautics Critical Path Roadmap.

JAMES G. QUINTIERE is the John L. Bryan Professor of Fire Protection Engineering at the University of Maryland, College Park. He has more than 35 years' experience in fire research. Dr. Quintiere has conducted research in the study of fire growth in structures and on materials, developed test methods for ignition and flame spread, studied smoke movement in full-scale and scale model systems, and has developed theoretical solutions and simulation models for fire behavior and material response to fire. He has more than 100 publications in the field and is a former chair and founding member of the International Association for Fire Safety Science. He received the U.S. Department of Commerce Bronze Medal (1976) and Silver Medal (1982) as well as the Howard W. Emmons Lecture Award from the IAFSS in 1986. He is a fellow of the Society of Fire Prevention Engineers and the American Society of Mechanical Engineers. He is author of *Principles of Fire Behavior* and co-author of *Enclosure Fire Dynamics*, and he has completed a draft *Fundamentals of Fire Phenomenon* for John Wiley.

DENNIS W. READEY is the Herman F. Coors Distinguished Professor of Ceramic Engineering in the Metallurgical and Materials Engineering Department and director of the Colorado Center for Advanced Ceramics at the Colorado School of Mines. Previously he served as chair of the Department of Ceramic Engineering at Ohio State University and as a program manager in the Division of Physical Research of what is now the Department of Energy, where he was responsible for funding research on ceramic materials in universities and national laboratories. He was also group leader of the basic ceramics group at Argonne National Laboratory and a group leader in the research division of the Raytheon Company. He is a fellow and past-president of the American Ceramic Society and a fellow of the American Society of Metals International, has served on the board of directors of the Minerals, Metals, and Materials Society, and currently is on the board of directors of the Accreditation Board for Engineering and Technology. Dr. Readey's current research interests include gaseous and aqueous corrosion of ceramics, the effect of atmospheres on sintering, the properties of porous ceramics, processing and properties of ceramic-metal composites, fuel cell materials, and electronic properties of oxide compounds. Dr. Readey is chair of the NRC Committee on Microgravity Research and is a member of the Space Studies Board.

DANNY A. RILEY is a professor of cellular biology and anatomy in the Department of Cell Biology, Neurobiology, and Anatomy at the Medical College of Wisconsin. Dr. Riley's primary projects involve the skeletal muscle weakness and injury experienced by astronauts returning to Earth and the loss of sensation and blood flow to the human hand following prolonged use of power tools. He served in a postdoctoral training position at the National Institutes of Health where he investigated various aspects of nerve generation. From there he went to the University of California, San Francisco, as a faculty member for 8 years prior to his accepting his current position. Dr. Riley served on the NRC Committee on Space Biology and Medicine (1997-2000) and was a member of the NSF Graduate Panel on Biomedical Sciences (1982).

CAROL E.H. SCOTT-CONNER is a professor in the Department of Surgery at the University of Iowa's College of Medicine. For 9 years, she served as head of that department. She is widely known for her contributions to the fields of minimally invasive and oncologic surgery. Dr. Scott-Conner was a professor of surgery at the University of Mississippi's School of Medicine prior to her appointment at the University of Iowa. She currently serves on the IOM's Committee on Aerospace Medicine and Medicine of Extreme Environments and the Committee on Review of NASA's Bioastronautics Critical Path Roadmap. Dr. Scott-Conner formerly served on the Committee on Longitudinal Study of Astronaut Health (2003-2004) and the Committee on Creating a Vision for Space Medicine During Travel Beyond Earth Orbit (1999-2001).

PETER SUEDFELD is a professor and dean emeritus in the Department of Psychology at the University of British Columbia (UBC). Dr. Suedfeld taught at the University of Illinois and at University College, Rutgers-The State University of New Jersey before moving to UBC. His research focuses on how human beings adapt to and cope with novelty, challenge, stress, and danger. The research has three major aspects: laboratory and clinical studies on restricted environmental stimulation, field research on psychological and psychophysiological concomitants of working in extreme and unusual environments such as space and polar stations, and the archival and experimental study of information processing and decision making under uncertainty and stress. Dr. Suedfeld is a fellow of the Royal Society of Canada. He served on the NRC Panel on Human Behavior (1997-1998) and is chair of the Life Sciences Advisory Committee of the Canadian Space Agency.

KENNETH T. WHEELER, JR., is professor emeritus of radiologic sciences at the Wake Forest University School of Medicine and president of Wheeler Scientific Consultants, Inc. Dr. Wheeler received his B.A. from Harvard College in 1962, an MAT in education (biological sciences) from Wesleyan University in 1963, and a Ph.D. in radiation biophysics from Kansas University in 1970. After a postdoctoral fellowship at Colorado State University (1970-1972), and prior to joining the faculty at Wake Forest, Dr. Wheeler previously served on the faculties of the University of California, San Francisco (1972-1976), University of Rochester School of Medicine (1976-1981), Brown University (1981-1983), and Kansas University (1983-1986). He served as a reviewer for the 2001 NRC report *The Impact of Low-Level Radioactive Waste Management Policy on Biomedical Research in the United States*.

Staff

SANDRA J. GRAHAM, study director, 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, many of them focused in the areas of space life sciences and microgravity sciences.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board. She joined SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has also worked as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

CELESTE NAYLOR joined the Space Studies Board in June 2002 as a senior project assistant. She has worked with the Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope and also 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 more than 7 years of experience in event management.