



Advanced Technology for Human Support in Space

Committee on Advanced Technology for Human Support in Space; National Research Council

ISBN: 0-309-52459-8, 150 pages, 6 x 9, (1997)

This PDF is available from the National Academies Press at:
<http://www.nap.edu/catalog/5826.html>

Visit the [National Academies Press](http://www.nap.edu) online, the authoritative source for all books from the [National Academy of Sciences](http://www.nap.edu), the [National Academy of Engineering](http://www.nap.edu), the [Institute of Medicine](http://www.nap.edu), and the [National Research Council](http://www.nap.edu):

- Download hundreds of free books in PDF
- Read thousands of books online for free
- Explore our innovative research tools – try the “[Research Dashboard](#)” now!
- [Sign up](#) to be notified when new books are published
- Purchase printed books and selected PDF files

Thank you for downloading this PDF. If you have comments, questions or just want more information about the books published by the National Academies Press, you may contact our customer service department toll-free at 888-624-8373, [visit us online](#), or send an email to feedback@nap.edu.

This book plus thousands more are available at <http://www.nap.edu>.

Copyright © National Academy of Sciences. All rights reserved.

Unless otherwise indicated, all materials in this PDF File are copyrighted by the National Academy of Sciences. Distribution, posting, or copying is strictly prohibited without written permission of the National Academies Press. [Request reprint permission for this book.](#)

ADVANCED TECHNOLOGY FOR HUMAN SUPPORT IN SPACE

Committee on Advanced Technology for Human Support in Space
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

NATIONAL ACADEMY PRESS • 2101 Constitution Avenue, N.W. • Washington, DC 20418

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 committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of 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. Bruce M. Alberts 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. William 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. Kenneth I. Shine 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. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice-chairman, respectively, of the National Research Council.

This study was supported by the National Aeronautics and Space Administration under contract number NASW-4938 Task Order 112. Any opinions, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for the project.

Library of Congress Catalog Card Number 97-68305
International Standard Book Number 0-309-05744-2

Available in limited supply from: Aeronautics and Space Engineering Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418. 202-334-2855

Additional copies are available for sale from National Academy Press, 2101 Constitution Avenue, N.W., Box 285, Washington, D.C. 20055. 1-800-624-6242 or 202-334-3313. <http://www.nap.edu>

Copyright 1997 by the National Academy of Sciences. All rights reserved.

Printed in the United States of America

**COMMITTEE ON ADVANCED TECHNOLOGY
FOR HUMAN SUPPORT IN SPACE**

JAMES BAGIAN (committee chair), Environmental Protection Agency, Ann Arbor, Michigan
NORMAN BADLER (chair, Space Human Factors Subcommittee), University of Pennsylvania, Philadelphia
BRUCE BUGBEE, Utah State University, Logan
HARRIET BURGE, Harvard University School of Public Health, Boston, Massachusetts
ELIZABETH CANTWELL (chair, Environmental Monitoring and Control Subcommittee), Lawrence Livermore National Laboratory, Livermore, California
SUSAN DOLL (chair, Advanced Life Support Subcommittee), Boeing Defense and Space, Huntsville, Alabama
DONALD GARDNER, Inhalation Toxicology Associates, Raleigh, North Carolina
ANDREW HOFFMAN, East Windsor Associates, Broad Brook, Connecticut
JOSEPH KERWIN (chair, Extravehicular Activities Subcommittee), Krug Life Sciences, Inc., Houston, Texas
ROBERT MOSER, Canyon Consulting Corporation, Chama, New Mexico
MARY MUSGRAVE, Louisiana State University, Baton Rouge
DAVA NEWMAN, Massachusetts Institute of Technology, Cambridge
FREDERICK G. POHLAND, University of Pittsburgh, Pittsburgh, Pennsylvania
GAVRIEL SALVENDY, Purdue University, West Lafayette, Indiana
ROBERT E. SMYLLIE, Smyllie Associates, Reston, Virginia

Aeronautics and Space Engineering Board Staff

JOANN CLAYTON-TOWNSEND, Director
NOEL ELDRIDGE, Study Director (November 1995–December 1996)
TED MORRISON, Senior Project Assistant and Report Manager

AERONAUTICS AND SPACE ENGINEERING BOARD

JOHN D. WARNER (chair), The Boeing Company, Seattle, Washington
STEVEN AFTERGOOD, Federation of American Scientists, Washington, D.C.
GEORGE A. BEKEY, University of Southern California, Los Angeles
GUION S. BLUFORD, JR., NYMA Incorporated, Brook Park, Ohio
RAYMOND S. COLLADAY, Lockheed Martin Astronautics, Denver,
Colorado
BARBARA C. CORN, B C Consulting Incorporated, Searcy, Arkansas
STEVEN D. DORFMAN, Hughes Telecommunications and Space,
Los Angeles, California
DONALD C. FRASER, Boston University, Boston, Massachusetts
DANIEL HASTINGS, Massachusetts Institute of Technology, Cambridge
FREDERICK HAUCK, International Technology Underwriters, Bethesda,
Maryland
WILLIAM H. HEISER, United States Air Force Academy, Colorado Springs,
Colorado
WILLIAM HOOVER, U.S. Air Force (retired), Williamsburg, Virginia
BENJAMIN HUBERMAN, Huberman Consulting Group, Washington, D.C.
FRANK E. MARBLE, California Institute of Technology, Pasadena
C. JULIAN MAY, Tech/Ops International Incorporated, Kennesaw, Georgia
GRACE M. ROBERTSON, Douglas Aircraft Company, Long Beach,
California
GEORGE SPRINGER, Stanford University, Stanford, California

Staff

JOANN CLAYTON-TOWNSEND, Director

Preface

This report was prepared in response to a NASA request for an evaluation of programs of the Office of Life and Microgravity Sciences and Applications that will apply to NASA's long-term goals and the eventual human exploration of space. The study committee first met on March 27 and 28, 1996, in Washington, D.C. For the next five months, the committee met at all relevant NASA centers to gather information. The last meeting was held in September 1996, but subsequent substantive organizational changes in NASA that became known to the committee during the final drafting and editing process are noted herein.

The committee would have been unable to produce this report without the cooperation and assistance of those individuals at NASA who are the heart of these programs. Their dedication and responsiveness were invaluable. I would also like to recognize the dedication of the committee members, who made time in their already busy schedules to carry out this study and to arrive at consensus on the contents of the report. They did this in the best tradition of voluntarism and tirelessly looked for ways to enhance the content and value of the report. Lastly, I would like to recognize Noel Eldridge and Ted Morrison of the National Research Council (NRC) for their outstanding work during all aspects of the study and report preparation. Without the tireless and superb efforts of the committee and the NRC staff this report could never have been completed. For me, it has been an extreme pleasure to have had the opportunity to work with these individuals during the preparation of this report.

Above all, it is my hope that the information contained herein will be of use to NASA and the nation as it contemplates the future human exploration of the solar system.

JAMES BAGIAN, M.D., P.E.
Chair, Committee on Advanced Technology
for Human Support in Space

Table of Contents

EXECUTIVE SUMMARY	1
1 INTRODUCTION	10
Background, 11	
Approach, 12	
Office of Life and Microgravity Sciences and Applications Advanced Human Support Technology Program, 14	
Office of Life and Microgravity Sciences and Applications Work at NASA Centers, 15	
Long-Term Plans for Human Exploration, 17	
References, 21	
2 ADVANCED LIFE SUPPORT SYSTEMS	22
Introduction, 22	
Technical and Scientific Topics Related to Advanced Life Support, 24	
Programmatic Topics Related to Advanced Life Support Systems, 40	
High Priority Areas for Advanced Life Support Technology Research and Development, 47	
Relationship between the Advanced Life Support Program and the Success of Future NASA Missions, 49	
Program Objectives and Milestones, 49	
Overall Scientific and Technical Quality, 51	
Program Requirements, 52	
Program Direction and Organization, 53	
Synergism with Other Programs, 56	
Dual-Use Technologies, 58	
References, 60	

3	ENVIRONMENTAL MONITORING AND CONTROL	61
	Introduction, 61	
	Technical and Scientific Topics Related to Environmental Monitoring and Control, 62	
	Current Status of the Environmental Monitoring and Control Program, 68	
	High Priority Areas for Environmental Monitoring and Control Technology Research and Development, 71	
	Relationship between the Environmental Monitoring and Control Program and the Success of Future NASA Missions, 73	
	Program Objectives and Milestones, 73	
	Overall Scientific and Technical Quality, 75	
	Program Requirements, 76	
	Program Direction and Organization, 77	
	Synergism with Other Programs, 79	
	Dual-Use Technologies, 80	
	References, 81	
4	EXTRAVEHICULAR ACTIVITY SYSTEMS	82
	Introduction, 82	
	Technical and Scientific Topics Related to Extravehicular Activity Systems, 84	
	Programmatic Topics Related to Extravehicular Activity, 87	
	High Priority Areas for Extravehicular Activity Technology Research and Development, 90	
	Relationship between the Extravehicular Activity Program and the Success of Future NASA Missions, 92	
	Program Objectives and Milestones, 92	
	Overall Scientific and Technical Quality, 93	
	Program Requirements, 93	
	Program Direction and Organization, 94	
	Synergism with Other Programs, 95	
	Dual-Use Technologies, 96	
	References, 96	
5	SPACE HUMAN FACTORS	97
	Introduction, 97	
	Technical and Scientific Topics Related to Space Human Factors, 98	
	Programmatic Topics Related to Space Human Factors, 101	
	High Priority Areas for Space Human Factors Technology Research and Development, 102	
	Relationship between the Space Human Factors Program and the Success of Future NASA Missions, 103	

Program Objectives and Milestones, 104	
Overall Scientific and Technical Quality, 105	
Program Requirements, 106	
Program Direction and Organization, 108	
Synergism with Other Programs, 110	
Dual-Use Technologies, 111	
References, 112	
6 GENERAL FINDINGS AND RECOMMENDATIONS	113
ACRONYMS AND ABBREVIATIONS	116
APPENDICES	
A STATEMENT OF TASK	121
B MEMORANDUM OF UNDERSTANDING CONSOLIDATING HUMAN SUPPORT RESEARCH IN THE OFFICE OF LIFE AND MICROGRAVITY SCIENCES AND APPLICATIONS	123
C SUBCOMMITTEE MEMBERS AND MEETINGS	127
D LETTER REQUESTING COMMENTS FROM INDUSTRY	129
E ANALYSIS OF ADVANCED LIFE SUPPORT TECHNOLOGY DEVELOPMENT PROJECTS	131
F BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS	133

Figures and Tables

FIGURES

- 1-1 Budgets for the advanced human support programs, 13
- 1-2 Long-term goals for the human exploration of space, 19
- 2-1 Principal relationships in a bioregenerative life support system, 31
- 2-2 Fully closed food loop, 33
- 2-3 Partially closed food loop, 34
- 2-4 FY96 NASA funding for advanced life support, 41
- 2-5 NASA headquarters technology development road map, 1995 to 2015, 43
- 2-6a JSC technology development and validation road map, 1995 to 2010, 44
- 2-6b JSC ALS road map, post-2010, 45
- 4-1 NASA EVA Project Office organization chart, 87
- 4-2 NASA funding for advanced EVA systems, 1985 to 1996, 89

TABLES

- 1-1 OLMSA-Sponsored Research in Human Support at NASA Centers, 16
- 2-1 Metabolic Values for Normal Spacecraft Operation of One Astronaut, 23
- 2-2 Summary of Advanced Life Support System Functions, 26
- 2-3 Comparison of Design Factors for the Development of Life Support Systems, 38
- 3-1 Major Categories of Contaminants, 62
- 3-2 Potential Sources for Some Major Contaminants, 63
- 3-3 Microbiological Monitoring and Control Prioritization, 65
- 3-4 Goals and Objectives of the EMC Program, 69
- 3-5 EMC Schedule and Program Deliverables, 70
- 3-6 Funded Technical Development Projects (1995–1996), 70

- 4-1 Current Evolutionary (or Zero-G EMU) Technology Projects, 90
- 4-2 Current Revolutionary (or Lunar/Mars) Technology Projects, 91
- 5-1 Topics of Interest to the SHF Program, 99
- E-1 Compilation of the Advanced Life Support Technology
Development Projects, 132

Executive Summary

Although no national policies at this time call for human missions beyond low Earth orbit (LEO), a part of the National Aeronautics and Space Administration (NASA) is responsible for long-term technology development that would be applicable to future human long-duration space missions. This part, the Life Sciences Division of the Office of Life and Microgravity Sciences and Applications (OLMSA), requested that the National Research Council (NRC) examine and make recommendations regarding the four programs that make up its Advanced Human Support Technology Program. These programs provide technologies for advanced life support systems, environmental monitoring and control, extravehicular activities, and space human factors engineering, and vary greatly in technology development, scheduling, and funding challenges. Together, these ground-based research and development programs received about \$17 million in fiscal year 1996 (FY96), approximately 0.1 percent of the total NASA budget.

In the absence of a policy mandate, the committee based its assumptions on the 1996 NASA Strategic Plan and the 1996 NASA Human Exploration and Development of Space Strategic Plan. These documents identified 2010 to 2020 as the time when new technologies for human missions beyond LEO will be required. In the meantime, from 1997 to 2002, the International Space Station (ISS) is scheduled to be assembled in LEO, about 250 miles above the surface of the Earth, and plans call for operating the ISS for at least 10 years after assembly has been completed.

The findings and recommendations of the NRC Committee on Advanced Technology for Human Support in Space in the four technical areas are briefly described below. General findings and recommendations follow.

ADVANCED LIFE SUPPORT

In space, life support systems provide the basic functions that sustain life: controlling pressure, temperature, and humidity; providing usable water and breathable air; supplying food; and managing wastes. Technology available today is capable of supporting human crews in space for missions in LEO of short or indefinite duration as long as resupply is readily available, as evidenced by the U.S. Shuttle and Russian Mir programs. All crewed space missions so far have relied on resupply from Earth for some or nearly all of the required consumable resources (oxygen, water, food), as will the International Space Station. Technology to be used on the ISS is capable of recovering water from humidity condensate, waste hygiene water, and crew urine with 80 to 90 percent efficiency. However, no space-qualified technologies are capable of recycling food or oxygen from waste materials, and wastes will have to be discarded or stored for return to Earth. Reducing the transportation cost of resupply, which is a function of crew size and mission duration, is the major incentive for developing advanced technologies that can recover resources from waste materials. Resupplying future missions beyond LEO, missions to Mars for example, will be even more difficult and expensive, if not impossible.

In addition to reducing dependence on resupply, advanced life support (ALS) systems must also be more reliable and self-sufficient enough to ensure crew health and safety. The technical challenge for ALS research and development (R&D) is to provide the designers of future missions with mature technologies and hardware designs, as well as extensive performance data justifying confidence that highly reliable ALS systems that meet mission constraints can be developed.

The current OLMSA program in ALS builds on more than 30 years of development and experience with the operational use of spacecraft life support systems, primarily by NASA and large companies. Research continues at NASA, universities, and in industry to advance recycling technologies for water and oxygen. For approximately 15 years, NASA also has sponsored research on bioregenerative systems that would grow plants in controlled environments to provide food and oxygen, remove carbon dioxide, and transpire clean water.

The physical/chemical (P/C) and bioregenerative life support programs have been successfully merged into a single program, but the current ALS program does not have an appropriate balance of funded projects to bridge the gap between current P/C life support system technology and advanced bioregenerative systems that will be necessary in the nearly closed environments envisioned for permanent planetary bases. Intermediate scenarios will undoubtedly employ hybrid systems that use both P/C and bioregenerative components, and P/C systems will still be required to maintain environmental conditions and to provide redundancy for advanced bioregenerative systems. There is a sense in some parts of NASA and the space community that P/C technologies for recovering oxygen

and water are fully mature technologies and that the only area for advancement is in the development of bioregenerative technologies, but this is not an accurate assessment. There are significant difficulties associated with the use of bioregenerative technologies, and determining the mission scenarios for which they are appropriate should be a major goal of system analyses. Efforts to push the envelope of existing technologies, to think innovatively about P/C technologies, and to address issues associated with hybrid systems should be among the top priorities for technology development.

The management of the OLMSA ALS program—which sponsors R&D at four NASA centers (Ames Research Center [ARC], Johnson Space Center [JSC], Kennedy Space Center [KSC], and Marshall Space Flight Center [MSFC]) and in universities and industry—was in flux throughout the period of this study, although it was informally indicated that JSC will assume responsibility for implementing the ALS program. As of the end of the committee's work, however, neither a program manager nor support structure had been identified by JSC management. This uncertainty has had an adverse effect on the planning and implementation of the program.¹

The technology development road map proposed by NASA headquarters has four major elements: science and technology R&D; low gravity research on the ISS; ground integrated testbeds; and zero-g integrated testbeds on the ISS. The current focus of the ALS program is on ground integrated testbeds. The committee agrees that testbeds play a critical role in the technology maturation process but believes they must be supported by the rigorous and productive development of new technologies and coordinated with systems engineering and analysis. To provide direction for technology development decisions in the absence of a defined target mission, it is essential that systems analysis and trade-off studies be conducted to support testbed-acquired data. The combination of computer-based systems and models and testbed-acquired data makes increasingly detailed system assessments possible through an iterative process involving testbed acquired data, increased understanding of technology, improved fidelity of system models, and trade-offs. Once gaps in data have been identified, they can guide the development of requirements for testbeds, as well as for the structure and format of testbed programs. The committee considers the ground testbeds important and valuable but is concerned about the current balance between testing and technology development.

At the beginning of this study, NASA urged the committee to focus on the development of revolutionary technologies, but there was consensus among the members of the ALS subcommittee that it would be best to investigate both evolutionary and revolutionary improvements concurrently. There is no consistently successful way to solicit, find, or fund proposals for revolutionary technologies

¹Since this study was completed, much of the transition of program control from NASA headquarters to NASA centers for the four human support programs has been accomplished.

that have a reasonable probability of achieving their objectives. The committee believes that the Small Business Innovative Research (SBIR) Program has provided a significant means for small companies to participate in the development of ALS technology, although closer coordination with OLMSA funded work is needed. The committee found no formal method in place for soliciting and supporting contributions from large industry. Most ongoing efforts and coordination with NASA are largely industry-initiated. Unless industry has a reasonable expectation of funding from NASA for advanced development as a follow-on to their investment, future industry funding will probably be directed to more promising business opportunities, which would erode industry's ability to support NASA's future goals.

The potential for synergy between the ALS program and other NASA and OLMSA programs, especially with the environmental monitoring and control (EMC) program, is significant. The EMC program ultimately validates, and participates in, the proper functioning of ALS systems. As control strategies become more sophisticated, the sensors and monitoring equipment developed for EMC will be integral to an automated life support system. Unfortunately, there appears to be little communication or coordination between the ALS program and the Space Shuttle or ISS programs, although both the Space Shuttle and the ISS are essential to ensuring the utility of ALS projects directed at near-term needs and for providing on-orbit facilities to support technology development. The ALS program should recognize the ISS Environmental Control and Life Support System as a baseline for technology initiatives and should address the evolution of the ISS in concert with the development of tools, processes, subsystems, and systems necessary to support space vehicles and planetary bases.

ENVIRONMENTAL MONITORING AND CONTROL

The EMC program was established in 1994 to develop technology for determining and managing the chemical, physical, and biological elements of a crewed living space in the unique environment of a pressurized spacecraft under conditions of microgravity. EMC must ensure that air and water conditions, including surfaces in contact with air and water, are maintained within acceptable limits. The research currently funded by the program primarily focuses on the detection of chemical compounds. Some work is also being done on detecting microorganisms.

Environmental monitoring entails the continuous oversight of all media (including air, water, and surfaces) via sensors. Environmental control entails feedback of data to the appropriate component(s) of the life support system responsible for maintaining a given parameter within the desired range. Feedback includes various responses, such as caution lights that can be seen by crew members or output to a control process that results in operational adjustments. Sources of physical, chemical, and microbiological contaminants include humans and other organisms, food, cabin surface materials, and experiment devices.

EMC technologies and systems, by their very nature, are closely tied to the components of the life support system over which control may be exerted. EMC development is driven by scientific research related to environmental health, which provides a basis for determining the requirements for monitoring and control. As mission duration increases, EMC will become both more difficult and more important to the safety of the crew.

The committee found that the EMC program has a well conceived strategic plan that provides the program with goals, objectives, deliverables, and metrics. The committee recommends that efforts to implement the goal of using risk prioritization to determine requirements should be stepped up. Risks should be evaluated based upon the potential health impact of exposure to hazardous compounds or microorganisms, the likelihood of exposure, the impact on the mission, and the ability to control exposure.

In many cases, other organizations (in both government and industry) will be advancing technologies that are relevant, but not unique, to NASA. Therefore, EMC work should focus on NASA's truly unique needs, such as the effect of microgravity on sensor function and placement and the need for sensors and systems that can function continuously over many years with little maintenance. The NASA EMC program is a small, focused program working on unique products for future crewed space missions. The committee endorses NASA's establishment of an EMC technology program separate from the life support and environmental health programs. Because the EMC program is envisioned as an enduring, though always modest, effort, the committee recommends that the program continue to be managed separately from programs responsible for current and near-term flight operations. Nevertheless, to ensure that relevant work is properly integrated, the EMC program must maintain close communication with the ALS program.

EXTRAVEHICULAR ACTIVITY SYSTEMS

Crewmembers will be called on to perform useful work outside the confines of their pressurized spacecraft or planetary base. These activities are referred to as extravehicular activities (EVA). EVA has been a vital part of the U.S. space program since the Gemini program in the early 1960s. The spacesuit worn outside a spacecraft with its integrated life support system is called an extravehicular mobility unit (EMU). It must protect a crewmember from harsh environments characterized by the vacuum of space and solar radiation (with its attendant thermal loads). The EMU also provides some protection from ionizing radiation² and micrometeoroids. The EMU presents unique design challenges in that it is a miniature spacecraft that must simultaneously sustain and protect human life and

²The potential effects of ionizing radiation on space crews were studied in a report by a task group of the NRC Committee on Space Biology and Medicine, *Radiation Hazards to Crews of Interplanetary Missions: Biological Issues and Research Strategies* (NRC, 1997).

maximize productivity. The early suits used in the Mercury and Gemini programs were adaptations of pressure suits already in use by military aviators. The EMUs used in the subsequent Apollo and Space Shuttle programs were designed and built with specific characteristics tailored to their intended use. Future spacefaring activities will require EMUs with improved performance, safety, reliability, and maintainability.

Programs involving planetary (lunar/Mars) EVAs, with their attendant gravitational effects, will require capabilities that are beyond the current EMUs, which are designed for use in a weightless environment. Sustained EVAs in planetary conditions, which will occur far from access to resupply or other material support, will require EMUs designed for greater mobility and dexterity; reduced use of consumables; high reliability over long periods of time; reduced need for servicing; easier maintenance; increased resistance to dust; increased interchangeability and versatility; and reduced time for “prebreathe” for tissue denitrogenation (required to prevent decompression sickness, often colloquially referred to as “the bends”) prior to performing an EVA. Research on advanced EMU technologies may also have present and near-term benefits.

Although the areas that require additional work are reasonably well understood, no specific, overarching technical objectives or milestones have been identified for the EVA program. The committee found a number of unprioritized projects being maintained at a basal level while awaiting a decision regarding the program’s future course. As the duration of these projects increases, so do total costs. The lack of management direction has had a significant impact on the effectiveness of EVA technology development. Although the staff at NASA responsible for the EVA technical development is technically strong and competent, projects are sometimes conducted without adequate communication with the external engineering and scientific communities. More interaction with researchers external to NASA could leverage resources and improve the effectiveness of the R&D program.

The EVA Project Office, which was established at JSC during this study, appears to be in a position to provide direction and leadership for establishing long-term, advanced technical objectives and milestones. This office has outlined plans to increase contacts with the external technical and scientific communities and thus reduce the present insularity of the program. However, the funding dedicated to advanced technologies is small (about \$2 million in FY96), and the committee was informed by program management that the first priority of the EVA Project Office is to enable present and near-term mission operations rather than to develop new technology for advanced EVA systems. This is understandable, especially considering the demands that will be associated with assembling the ISS. Nevertheless, both operational and research responsibilities will reside in the EVA Project Office, which will have to take particular care to ensure that near-term needs do not overwhelm the pursuit of a consistent, coordinated advanced EVA R&D program.

SPACE HUMAN FACTORS

Human factors engineering is an essential ingredient of any space program involving humans. The discipline seeks to provide a working and living environment that will result in the greatest productivity and the highest probability of mission and task success. Human factors engineering is based on understanding the relationships between an individual (on a physical, cognitive, and social level) and the systems and environment with which he or she interacts.

Human factors research is being conducted at several NASA centers, but the OLMSA space human factors (SHF) program sponsors projects at just two centers, JSC and ARC. The program is small; the FY96 budget was approximately \$1.5 million, and only about 8 to 10 peer-reviewed projects were funded by the program. Very little funding is available for NASA-led projects or initiatives based solely on the decisions of program management, which limits management's ability to respond in a timely manner to new issues as they arise. The stated goals of OLMSA's SHF program, as currently and vaguely defined, are to address human psychological and physiological capabilities and limitations, develop cost effective technologies that support human and system elements of space flight, and ensure that mission planners use the results of human factors research and technology developments to increase mission success and crew safety.

The nature of these goals makes it difficult to evaluate the success of the programs. Currently, SHF research at JSC is best characterized as mission-oriented and intended to address operational issues of immediate concern rather than issues related to long-duration space missions. Only a few formal priorities beyond support for current or near-term missions have been defined, and work is usually directly related to space operations. The projects at ARC are primarily related to aviation (especially cockpit issues) and more basic research. ARC also studies perception, workload, and cognition associated with aeronautical flight. Occasionally, specific crew-related problems serve as catalysts for investigations, and some interest was expressed in finding applications for ARC research beyond aeronautics in the field of space and elsewhere. There is little overlap in the research under way at the two centers, and there appears to be relatively little interaction among researchers from the two communities.

Current projects supported by the SHF program may prove to be helpful for future missions, but their benefit to long-duration missions seems more likely to be fortuitous than deliberate. At the time of the committee's review, no program requirements documents or detailed strategic or operational plans were in place, and no programmatic leadership was addressing the long-term issues.

Within OLMSA, the work related to human behavior and performance is managed separately from the SHF program. The committee believes that this separation creates an unnatural division between activities that should be integrated. The committee believes that the behavioral aspects of human space explo-

ration are crucial to the success of long-term missions but have not been thoroughly researched. This is important because behavioral issues related to long-term space exploration are not likely to be addressed outside of NASA. But, in areas where there is overlap, the SHF program should encourage interaction both within the agency and with outside academic, commercial, and government work in related areas. Effective interaction would leverage the results and would also help avoid the tendency to “reinvent the wheel.”

Better communication and integration with other projects related to long-duration missions (e.g., ALS, EVA, training, safety, behavior, and performance) will be essential to crew safety and compatibility for lunar or Mars missions. The ISS should be used to study aspects of SHF, such as habitability, that must be incorporated into the design of future space vehicles (especially a Mars transfer vehicle) or planetary bases. The quality of research on SHF varies widely, and NASA would benefit considerably from better internal evaluations and periodic external reviews. Focused priorities—especially in areas where NASA has unique interests that are unlikely to be pursued by others—with clearly identified objectives, strong leadership and management, timely examination of technologies being developed elsewhere, and critical evaluations appear to be the ingredients necessary for future success.

The SHF program requires strong leadership with a view of the entire SHF area. The top NASA manager for SHF should have the experience and authority to coordinate disparate disciplines and entities and should be placed at a high level in the organization. Increasing the focus of the program while broadening the research base will be a challenge and will require a well orchestrated team effort.

GENERAL RECOMMENDATIONS

Recommendation 1. During the period of the committee’s study, the NASA Advanced Human Support Technology Program suffered from a lack of clear direction. This situation seems to arise from two basic conditions: (1) NASA has not directed research and development to address specific long-term goals in human space exploration, and (2) NASA has not decided who will lead the programs. NASA should establish a well-defined management structure for the human support programs and forthrightly communicate the new structure to NASA personnel. OLMSA should then proceed with programs directed at the unique needs for advanced human support technologies for crewed missions beyond low Earth orbit.

Recommendation 2. Requirements for technology development should be predicated on carefully developed reference missions and systems analyses to determine functional requirements. Good design reference mission studies exist that can be adapted and used by all programs. OLMSA should not expend significant resources to develop new reference missions.

Recommendation 3. It is clear that not all technology required to support human space exploration can be developed within the present annual funding levels (less than \$20 million annually for all four OLMSA programs). As long as funding remains close to current levels, the committee believes programs must be narrowly focused and prioritized to address key technology needs. The roles and tasks of all groups (NASA and non-NASA) performing human support research and development sponsored by NASA should be clearly defined, and only projects that address the highest priority technology needs for future missions should be allocated program resources.

Recommendation 4. Systems analysis approaches should be included in ongoing and future processes to determine the highest priority technologies for human support in space.

Recommendation 5. Periodic NASA announcements calling for proposals from prospective researchers in topics related to human support in space should clearly identify the high priority areas in each program. The selection process should give added weight to proposals that are relevant to the high priority areas defined in the announcement.

Recommendation 6. Spin-off technologies should be transferred to applications outside of OLMSA as appropriate, but only as dividends from projects aimed at furthering NASA objectives. Technology transfer should not become a major emphasis of small technology development programs.

Recommendation 7. The International Space Station should be used as a site for research relevant to human support in space and for tests and demonstrations of new human support technologies.

Recommendation 8. The committee recognizes that NASA has unique technology needs, but technical insularity in the NASA human support programs is excessive. NASA should put more emphasis on finding technologies and knowledge relevant to human support outside of the NASA centers and the other locations where technology has been developed in the past. The human support programs should strive to include universities and large companies in their projects and should make special efforts to take advantage of the willingness of industry to use private funds for research and development projects relevant to NASA's long-term goals. Technical communication—inter-, intra-, and extra-NASA—including publication, should be expanded and actively supported.

REFERENCE

NRC (National Research Council). 1997. Radiation Hazards to Crews of Interplanetary Missions: Biological Issues and Research Strategies. Committee on Space Biology and Medicine, Space Studies Board. Washington, D.C.: National Academy Press.

1

Introduction

Many advances in space technology that have been made by the National Aeronautics and Space Administration (NASA), military and national security organizations, and commercial space projects have been applied to subsequent, unrelated missions. However, in the United States, the technologies unique to supporting humans in space are unlikely to be developed outside of NASA. For example, advances in computing, electric power production, energy storage, communications, guidance and navigation, and structural analysis are essential to virtually all types of spacecraft. But technologies for recycling oxygen from carbon dioxide, for example, are crucial only to long-duration, crewed space missions. This means that significant improvements in human support technologies are unlikely to be made in time to meet NASA's long-term goals unless they are nurtured and advanced by NASA.

The statement of task for the study is provided in Appendix A. The findings and recommendations in this report have been organized in the following way. The Executive Summary provides a summary of the most important recommendations. In Chapters 2 through 5, which deal with each of the four programs that comprise the Advanced Human Support Technology Program, the findings and recommendations are grouped into eight categories. They are:

- high-priority areas for technology research and development (R&D)
- relationships between the research program and the success of future NASA missions
- program objectives and milestones
- overall scientific and technical quality
- program requirements

- program direction and organization
- synergism with other programs
- dual-use technologies

Chapter 6 presents the general findings and recommendations of the report.

BACKGROUND

The Advanced Human Support Technology Program resides in the Life Sciences Division of the NASA Office of Life and Microgravity Sciences and Applications (OLMSA). The program includes advanced life support systems (ALS), advanced environmental monitoring and control (EMC), advanced extravehicular activity systems (EVA), and space human factors engineering (SHF). These four programs are loosely connected by the common thread of human support but vary greatly in their technology development, scheduling, and funding challenges.

OLMSA was created in March 1993 from three divisions (life sciences, microgravity sciences and applications, and flight systems) of the Office of Space Sciences and Applications (OSSA). The Life Sciences Division has selected and sponsored most of the ground- and space-based biomedical and biological research funded by NASA since scientific research was initially performed on the Space Shuttle in the mid-1980s. This division is also responsible for planning the life sciences research that will be carried out on the International Space Station (ISS) beginning in approximately 1999. Although it has funded the development of some new technologies to help enable biological and biomedical research in space (such as new sensors), the development of new technology was not a major emphasis of the program until the Advanced Human Support Technology Program was established.

The Advanced Human Support Technology Program is unusual in OLMSA because its primary emphasis is on developing technologies to support humans in space rather than on basic scientific findings. Until 1993, almost all of OLMSA's projects in technology development were directly related to conducting specific experiments or sets of experiments in space. In 1993, additional responsibilities for developing advanced technologies related to supporting humans in space were transferred from another NASA office, which was called the Office of Advanced Concepts and Technology (OACT). (This office was subsequently reorganized into a new unit called the Office of Space Access and Technology [OSAT], which was disbanded in 1996.) The Memorandum of Understanding spelling out the transfer of new responsibilities to OLMSA is included in Appendix B.

Unlike many other NASA technology development efforts, the OLMSA Advanced Human Support Technology Program is not tied to specific large NASA programs that have been approved for future development (such as a hypothetical new mission to the Moon or Mars). OLMSA is the smaller of two offices responsible for NASA's Human Exploration and Development of Space

(HEDS), one of NASA's four enterprises. The other is the Office of Space Flight (OSF). The HEDS Enterprise is briefly described in the 1996 NASA Strategic Plan (NASA, 1996b) and in more detail in the HEDS Strategic Plan (NASA, 1996a). Its goals are to:

- increase human knowledge of nature's processes using the space environment
- explore and settle the solar system
- achieve routine space travel
- enrich life on Earth through people living and working in space

The present systems and technologies that support human life on the Space Shuttle, as well as those being developed for the ISS, are the responsibility of the OSF. (The OSF is responsible for virtually all aspects of the Space Shuttle and ISS programs, with the exception of the selection of the scientific or other research that will be carried out on board.) One aspect that merits special mention is that OSF is responsible for operating and developing the life support, environmental monitoring, EVA suit, and SHF hardware and for applied research programs directly associated with the operation of the Space Shuttle and ISS programs. Thus, within NASA and the HEDS Enterprise, NASA's near-term program and operational needs in the area of human support are the responsibility of OSF. The long-term needs are the responsibility of OLMSA.

When this study began, the responsibility for advanced EVA suits had recently been transferred to the Johnson Space Center (JSC); management for the other three programs remained at NASA headquarters. This was the situation throughout the time of the study, despite indications that program management responsibilities for all four programs would be shifted to one or more NASA centers.¹

For fiscal year 1996 (FY96), the NASA Life Sciences Division budget is about \$140 million—about 1 percent of NASA's budget. The areas of interest to the committee within the Life Sciences Division budget were funded at about \$22 million in FY96. Of the \$22 million, about \$16 to \$17 million was allocated to ground-based research and development and about \$5 to \$6 million was allocated to flight (i.e., space-based) experiments dedicated to mitigating risk in the systems being developed for the ISS. A summary of recent funding of the ground-based projects of the four human support programs is shown in Figure 1-1.

APPROACH

In 1995, OLMSA requested that the National Research Council (NRC) undertake a study of the four areas of the Advanced Human Support Technology Program. The NRC Committee on Advanced Technology for Human Support in Space was chartered to assess the status of technologies in these areas as well as

¹Since this study was completed, much of the transition of program control from NASA headquarters to NASA centers for the four human support programs has been accomplished.

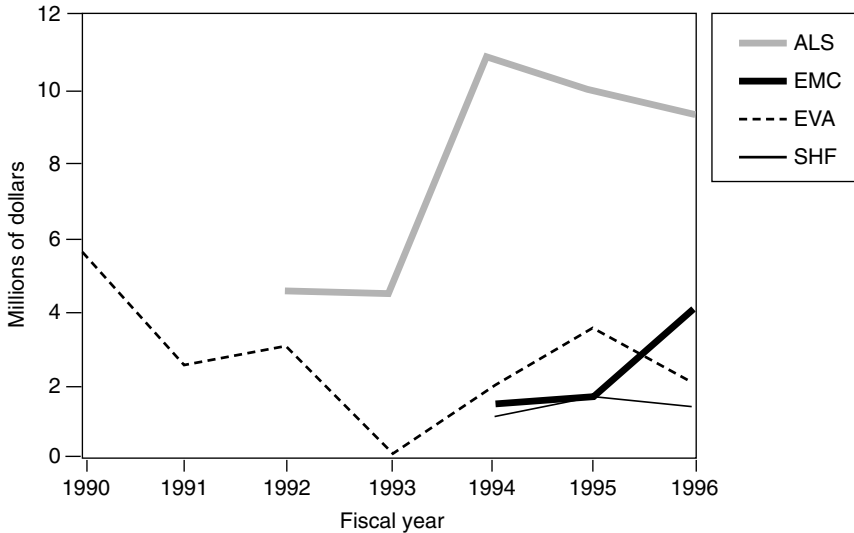


FIGURE 1-1 Budgets for the advanced human support programs. Source: NASA.

NASA's research and development (R&D) efforts that support human life in space on long-duration missions. The committee was also asked to make recommendations for potential improvements in the areas of concern (see Appendix A for the Statement of Task). The first meeting of the committee was held March 27 and 28, 1996. The meetings of the committee and its subcommittees are listed in Appendix C. Brief biographical sketches of the committee members are provided at the end of the report.

NASA and the nation currently have no formal plan to send people beyond low Earth orbit (LEO). Therefore, for purposes of this study, the committee drew on the 1996 NASA Strategic Plan and the 1996 NASA Human Exploration and Development of Space Strategic Plan in setting a time frame for technology preparedness. From 1997 to 2002, the ISS is scheduled to be assembled, and ISS partners anticipate operating the station for at least 10 years after assembly is completed. Thus, the committee identified 2010 to 2020 as an appropriate, approximate time when new technologies to meet the needs for human missions beyond LEO will be required.

The committee reviewed the findings and recommendations of a number of previous relevant reports during the course of the study, and these reports are listed in the bibliography. The committee also requested input from several companies that develop technology for human support in space and greatly appreciates the time and thought invested in their responses, which were very helpful to the committee in its deliberations. The letter sent to these companies is included in Appendix D.

OFFICE OF LIFE AND MICROGRAVITY SCIENCES AND APPLICATIONS ADVANCED HUMAN SUPPORT TECHNOLOGY PROGRAM

The stated purpose of the Advanced Human Support Technology Program is to “provide leadership and technologies to support humans in their exploration of the cosmos.” The four OLMSA human support programs are either new or have been recently reoriented based on earlier OSAT or OLMSA activities that predate the partial transfer of responsibilities from OSAT. The goals of these programs are briefly described below.

Advanced Life Support Program

The current ALS program is the result of combining the OLMSA Controlled Environment Life Support System (CELSS), which began in the late 1970s and focused on biological methods of life support, with OACT-funded research projects, which focused on physical/chemical methods of life support. Goals and objectives of the new program are based on using both biological and physical/chemical methods. The goal of the ALS program is to provide self-sufficiency in life support for productive research and exploration in space, for benefits on Earth, and to provide a basis for planetary exploration (Fogleman, 1996).

Advanced Environmental Monitoring and Control Program

The advanced EMC program was started by OLMSA in 1994 as a technology development program. OLMSA has a related environmental health program that focuses on scientific research. The goals of the EMC program are:

- to determine the requirements for EMC systems aboard future human spacecraft
- to obtain state-of-the-art, revolutionary technologies for spacecraft EMC
- to provide mature, tested environmental monitoring technologies for use in flight systems
- to provide the benefits of NASA-developed EMC technologies to U.S. industry and to improve human welfare (Schmidt, 1996)

Advanced Extravehicular Activity Systems

The OLMSA responsibility for advanced work in EVA systems was transferred from OACT and is currently managed by the Advanced EVA R&D branch of the OSF-led EVA Project Office at JSC. The responsibility of the program, as presented to the committee, is to “provide vision and leadership for advanced EVA R&D . . . manage R&D for advanced EVA systems, training, and support

equipment . . . manage [R&D for a] next generation spacesuit . . . and manage human physiology [and human factors] research needed for EVA” (Rouen, 1996).

Space Human Factors Program

The OLMSA SHF program is based on the 1993 merger of OLMSA and OACT responsibilities in this area. The current program consists almost entirely of projects selected from proposals submitted in response to NASA Research Announcements. OLMSA has a related program that funds scientific research on behavior and performance as part of OLMSA’s overall biomedical research program. The goals of the SHF program, as explained to the committee (Ellison, 1996), are:

- to expand knowledge of human psychological and physical capabilities and limitations in space through basic and applied research, tests, and evaluations
- to develop cost-effective technologies that support integrating the human and system elements of space flight
- to ensure that mission planners use human factors research results and technology developments to increase mission success and crew safety
- to make NASA technology available to the private sector for Earth applications or to use appropriate new technologies developed by private industry

OFFICE OF LIFE AND MICROGRAVITY SCIENCES AND APPLICATIONS WORK AT NASA CENTERS

Work is funded by the four human support programs at five NASA centers: JSC; Ames Research Center (ARC); Kennedy Space Center (KSC); Marshall Space Flight Center (MSFC); the Jet Propulsion Laboratory (JPL); as well as a number of non-NASA laboratories. The responsibilities of each NASA center are summarized in Table 1-1.

Johnson Space Center

According to the 1996 NASA Strategic Plan, JSC is the primary center for the HEDS Enterprise. Work performed at JSC is part of the OLMSA (long-term) and the OSF (current and near-term) sponsored programs. OLMSA-sponsored work at JSC includes major projects in ALS that feature the Early Human Testing Initiative as well as plans to test large, quasi-closed systems. OLMSA also funds advanced EVA work at JSC and projects in SHF. JSC manages the OLMSA-funded work in advanced EVA as part of its overall management of all NASA work on EVA systems. Work at JSC in the same general areas is also supported

TABLE 1-1 OLMESA-Sponsored Research in Human Support at NASA Centers

NASA Center	ALS	SHF Engineering	Advanced EMC	Advanced EVA Suits and Systems	Relevant Non-OLMSA Work
Johnson Space Center	primary center	primarily "operational" research and support	mostly OSF-sponsored	primary center	significant research and operations in ALS, EVA, EMC and SHF
Ames Research Center	bioregenerative and P/C research	primarily "fundamental" research	relevant work under the ALS program	most work ended in 1996	in aeronautics human factors
Kennedy Space Center	bioregenerative	no	no	no	very little
Marshall Space Flight Center	developing flight tests on the Space Shuttle	no	relevant work under the ALS program	no	in life support systems, including technology for ISS
Jet Propulsion Laboratory	no	no	yes	no	very little
Number of Projects at non-NASA Labs (FY96)	9	8	12	1	NA

by OSF as part of the Space Shuttle and ISS programs. This includes significant work in EMC, which is not directly supported by OLMSA.

Ames Research Center

Current work on human support at ARC is in the areas of ALS and SHF. The ALS work is wide-ranging, with more emphasis on waste recovery and waste management than at the other centers, and includes work on both physical/chemical (P/C) and bioregenerative systems. Work on SHF is associated with larger projects related to aviation human factors, and funding by OLMSA is based solely on the merit of individual proposals. ARC also has a significant history of developing technology for EVA suits and systems, but this work was being phased out at the time of the study.

Kennedy Space Center

Work at KSC includes the development of ALS systems and a long-term program to maximize the growth of plants in closed environments. KSC's work focuses on plant research and related technologies, such as nutrient delivery systems and lighting systems, that will be particularly applicable and relevant to growing plants in space.

Marshall Space Flight Center

MSFC performs OSF-sponsored work for the life support systems for the ISS. MSFC staff have also assisted in planning the flight programs sponsored by OLMSA's human support programs. OLMSA is also sponsoring MSFC-led work to perform risk reduction flight tests of ALS subsystem technologies on the Space Shuttle.

Jet Propulsion Laboratory

JPL is currently conducting OLMSA-sponsored R&D in EMC and is partially responsible for managing that program. Working with NASA headquarters and JSC staff, JPL staff have led the development of the EMC requirements document.

LONG-TERM PLANS FOR HUMAN EXPLORATION

NASA has no official plans to send humans beyond LEO in the near future. From approximately 1998 to 2002, the ISS will be assembled in LEO, about 250 miles above the surface of the Earth. NASA plans call for operating the ISS for 10 years after assembly has been completed, until at least 2012. The following

section discusses planned space activities that are relevant to current and anticipated activities of the Advanced Human Support Technology Program.

The Space Shuttle has been in operation since 1981 and is the only U.S. launch vehicle planned to be used in conjunction with the ISS. NASA currently plans to use the four Space Shuttle orbiters until at least 2012, and possibly longer. Other U.S. launch vehicles that could carry crews to orbit have been proposed, but so far none has been approved for development. NASA believes the next-generation launch vehicle will be developed by U.S. industry and will be based on NASA's current and near-term work on reusable launch vehicles.

Although the objective of many planned scientific missions is to improve our understanding of planetary science, these missions can also add to our knowledge of the Moon and Mars in ways that could be relevant to future human missions. For example, water is critical to the survival of humans. Information about the apparent presence of ice in a permanently shaded area at the lunar south pole or information about the presence of water, in the form of permafrost, below the surface layer of soil on Mars (water is known to exist on the polar ice caps of Mars) will affect future technology decisions.

For the next decade, NASA plans a series of robotic missions to the Moon, Mars, and selected asteroids. All of these missions will use smaller spacecraft than the large planetary spacecraft launched in the 1970s (e.g., Viking) or spacecraft begun in the 1980s (e.g., Galileo). The new spacecraft will be less expensive than their predecessors, will have new or unique capabilities, and will broaden the information base pertaining to future missions. The approved mission to orbit the Moon (Lunar Prospector) is scheduled for launch in 1997. But no new NASA spacecraft are currently in development to land on the Moon. NASA plans to send several spacecraft to Mars over the next few years. Some of these spacecraft will only orbit Mars, while others will actually land on the surface of Mars. The first two spacecraft are scheduled to arrive at Mars in the latter half of 1997. Mars Pathfinder is a lander with a rover, and Mars Global Surveyor is an orbiter that will carry six of the eight instruments flown on the Mars Observer spacecraft (which was lost en route to Mars in 1993).

A human mission to Mars may be facilitated by resources extracted from the Moon. The Moon could be a site for testing technologies for a Mars mission, as well as a site from which to stage a future mission to Mars. If hydrogen and oxygen are available in the form of water ice, both ingredients necessary for rocket propellants would be present on the Moon.

The 1996 NASA Strategic Plan describes NASA's long-term goals for the human exploration of space. Figure 1-2 is a summary chart from the 1996 Strategic Plan.

From 2003 to 2009, NASA will continue to focus its efforts in human space flight on operations in LEO, i.e., the Space Shuttle and the ISS. From 2010 to 2020 and beyond, NASA proposes to conduct international human missions to planetary bodies in our solar system. Presumably, the first destination beyond

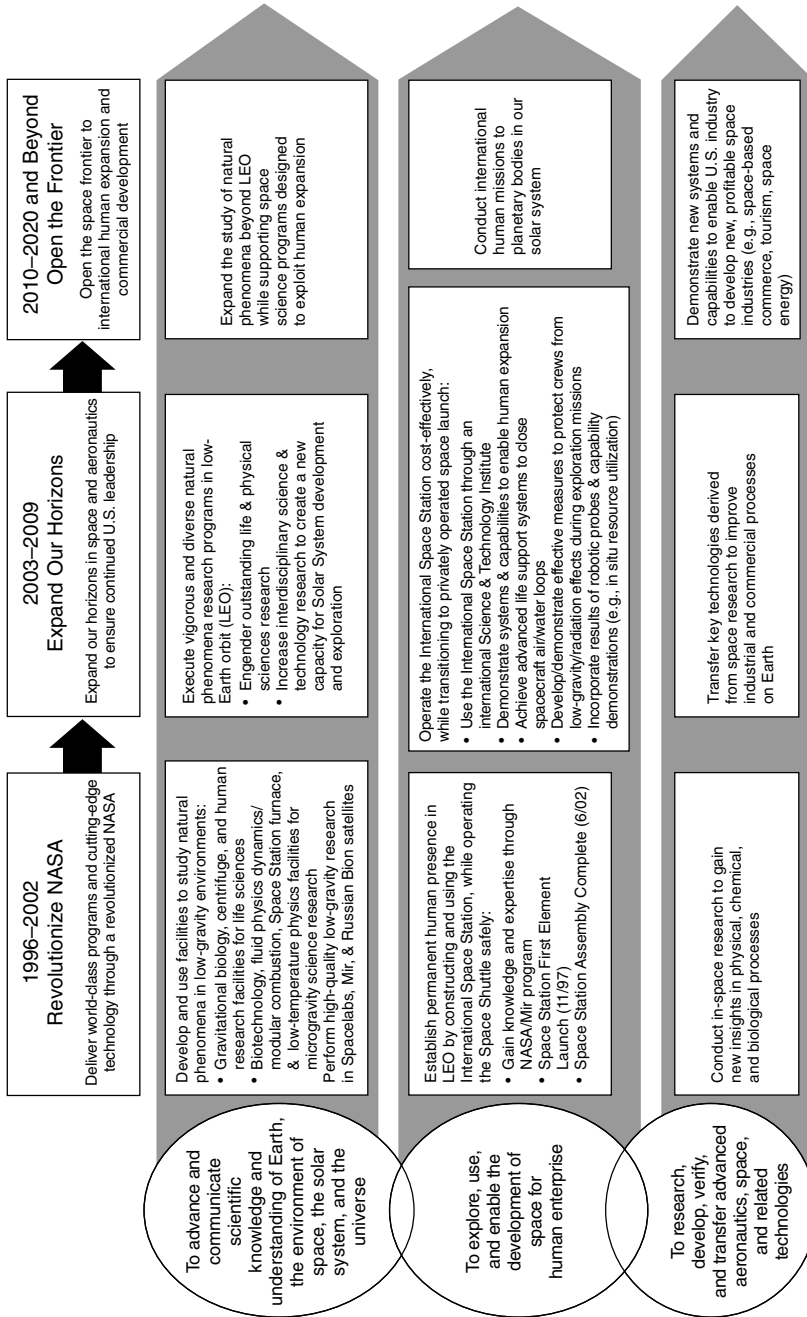


FIGURE 1-2 Long-term goals for the human exploration of space. Source: NASA 1996b.

LEO would be the Moon, and the next destination would be Mars, but this sequence is not certain. According to the 1996 NASA Strategic Plan (NASA, 1996b):

We will establish a lunar base for scientific research and the development of the Moon's resources. Scientists, engineers, and entrepreneurs from around the world will be able to use the Moon for research and to test new technologies not only for their commercial possibilities, but also for their application to Mars. As the enterprise progresses, we will eventually send the first international team to Mars and return them safely to Earth.

Some space enthusiasts have advocated going directly to Mars without revisiting the Moon. The argument against going directly to Mars is primarily that a short- or long-term stay on the Moon might provide insights into requirements for a mission to Mars. The Moon is about 250,000 miles away, a journey of four days from Earth. Mars, at its closest point, is almost 150 times more distant, about 35 million miles from Earth, a journey of at least several months in each direction. The Russian space program has shown that individual stays in space of more than 400 days are possible. However, missions with a minimum of about 600 days (which would be necessary for a round trip to Mars)² with a full crew and no rotation or resupply are well beyond today's technical capabilities.

The 1996 NASA HEDS Enterprise Strategic Plan is more explicit than the overall NASA Strategic Plan about the goals and objectives for exploration but not about the timing of future missions. The HEDS document states that closed life support systems might be validated on the ISS or on the Moon and that related technologies and systems will be "developed and tested to demonstrate long-term reliability and dramatically lower operating costs." On the basis of the information in these plans and for the purposes of this study, the committee has used 2010 to 2020 as the target time for using new technologies for human support beyond LEO. (The committee assumed that improved human support technologies for LEO missions would be useful at any time.)

In the absence of more explicit projections from NASA, the committee has taken 2010 to 2014 as the general time frame for the launch of a human mission to the Moon and 2015 to 2020 for a human mission to Mars. Both missions are assumed to be of indeterminate duration, i.e., the committee has not arbitrarily decided whether the mission will involve staying on the surface for a few days or if the first mission will be the start of a permanent, or near-permanent, stay on either body. However, in keeping with NASA plans, the committee recognizes the eventual need for technologies that can support long-term stays on the surface of the Moon or Mars.

²Sample scenarios for short-duration and long-duration human missions to Mars are provided in *America at the Threshold: America's Space Exploration Initiative* (Stafford et al., 1991).

REFERENCES

- Ellison, June. 1996. Space Human Factors (SHF) Program Mission Statement. Presented to the Committee on Advanced Technology for Human Support in Space, at the National Academy of Sciences, Washington, D.C., March 27, 1996.
- Fogleman, Guy. 1996. Presentation by NASA Life Sciences to the ASEB Advanced Human Support Committee. Presented to the Committee on Advanced Technology for Human Support in Space, at the National Academy of Sciences, Washington, D.C., March 27, 1996.
- NASA (National Aeronautics and Space Administration). 1996a. NASA's Enterprise for the Human Exploration and Development of Space – The Strategic Plan. Office of Life and Microgravity Sciences and Applications. Washington, D.C.: NASA.
- NASA. 1996b. NASA Strategic Plan. Washington, D.C.: NASA.
- Rouen, Michael. 1996. Proposed NASA EVA Organization and Management. Presented to the Committee on Advanced Technology for Human Support in Space, at the National Academy of Sciences, Washington, D.C., March 28, 1996.
- Schmidt, Gregory. 1996. Advanced Environmental Monitoring and Control Program. Presented to the Committee on Advanced Technology for Human Support in Space, at the National Academy of Sciences, Washington, D.C., March 27, 1996.
- Stafford, Thomas P., et al, 1991. America at the Threshold: America's Space Exploration Initiative. Washington, D.C.: White House Office of Science and Technology Policy.

2

Advanced Life Support Systems

INTRODUCTION

Life support systems, as addressed in this report, provide the following functions: temperature and humidity control; atmosphere control, supply, and revitalization; water recovery and management; waste management; and food management. NASA work in advanced life support (ALS) systems is directed toward scientific research and technology development related to physical/chemical (P/C) and bioregenerative processes needed to support humans in space, on the Moon, and on Mars. P/C processes use traditional engineering methods, such as filtration, distillation, and oxidation; bioregenerative processes are performed by living organisms.

Life support systems are described as “open-loop” or “closed-loop,” depending on the flow of material resources through, or within, the system. Open-loop life support systems provide all required resources, such as water, oxygen, and food, from storage or resupply, and store waste materials for disposal or return to Earth. In an open-loop system, the resources required increase proportionally as mission duration and crew size increase. Closed-loop life support systems require an initial supply of resources but then process waste products, such as carbon dioxide, urine, and wastewater, to recover useful resources, such as oxygen or water for reuse, thus reducing dependence on resupply. Both open- and closed-loop systems require energy from outside the system. The ultimate combination of technologies will be chosen based on results of system trade-offs to determine the optimal degree of closure, which is defined as the percentage of the total required resources provided by recycling. (Zero percent closure indicates that no resources are provided by recycling, and 100 percent closure implies that all resources are provided by recycling.)

The cost of recycling increases dramatically as closure approaches 100 percent. Table 2-1 shows the quantities of resources required for metabolism and hygiene activities for one crew member. If we assess the resupply reduction potential for water (hygiene and potable), oxygen, and food based on the magnitude of the mass of each resource, it appears that the recovery of water provides the greatest opportunity for savings, making up the majority of the total. Also, as a rule of thumb, recycling technologies become more “expensive” as the processing requirements become more complicated: the recovery of water requires the removal of impurities; the recovery of oxygen from carbon dioxide requires a basic oxidative process; and closure of the food loop requires photosynthesis. To determine the overall benefit of recovering a particular resource, the trade-off between the mass savings from a reduction in resupply and the additional mass, power, volume, and thermal load requirements imposed by the recovery system should be evaluated.

From Project Mercury through the Space Shuttle, life support systems have been open-loop, using expendables and on-board storage for providing resources and handling waste. Exceptions to the use of expendables for atmosphere revitalization were the molecular sieve for CO₂ concentration used on Skylab and the recent incorporation of solid amines to control CO₂ on some long-duration Space Shuttle missions. These two technologies are regenerable, with the concentrated carbon dioxide either vented into space or stored for further processing to recover oxygen. On spacecraft with fuel cells (Gemini, Apollo Command Module, and the Space Shuttle), potable water was supplied from the water produced by the reaction of H₂ and O₂ to produce energy. The open-loop life support systems on Mercury, Gemini, Apollo, and Skylab were intended to be used just once. The Space Shuttle life support systems, however, have been used for more than one mission, with ground maintenance and repair between flights.

Life support system control has been either manual or by conventional controls peculiar to the subsystems, with little or no interactive control between subsystems. Mass, power, and reliability have been significant design drivers, but because mission durations have been relatively short, the optimum design was a

TABLE 2-1 Metabolic Values for Normal Spacecraft Operation of One Astronaut

Parameter	Resource Requirements
Metabolic Oxygen Consumption	0.636–1 kg/day
Food (dry ash based)	0.5–0.863 kg/day
Potable Water	2.27–3.63 kg/day
Hygiene Water	1.36–9 kg/day

Source: Eckart, 1996.

simple system based on expendables. In-flight maintenance was not a significant design requirement.

With the advent of an orbiting space station with a permanent crew, the design drivers have changed significantly. The ISS requires at least 10 years of continuous operation, on-orbit maintenance and repair, and no extended system down time. For the ISS, because of the logistics burden, the operational costs of conventional open-loop systems would have been prohibitive. Therefore, closed-loop designs were seriously considered for some subsystems. The baseline system for the current ISS design incorporates the processing of shower water, condensate, personal hygiene water, and urine into potable water. The CO₂ is concentrated by a four-bed molecular sieve and vented overboard. Once assembly of the ISS is complete, oxygen will be supplied via water electrolysis, and nitrogen will be provided from on-board storage, replenished by resupply flights. It will also be necessary to resupply the ISS periodically with water to provide oxygen and make up for losses due to the less than 100 percent efficiency of water recycling technology. Food will be stored on board and resupplied. Therefore, the current ISS design, although more of a closed-loop system than on previous spacecraft, is still mostly an open-loop system (with the exception of water processing) and requires considerable resupply of expendables.

For missions beyond the ISS, including the establishment of lunar and Mars bases and Mars transit vehicles, increased system closure, automatic control, and improved reliability will be critical and will drive the design. System trade-off factors to be considered include launch mass, power, heat rejection, resupply mass, safety, reliability, maintainability, and life-cycle costs. It should be noted that a reduction of resupply mass does not necessarily mean a reduction of transportation costs. There is a trade-off between these savings and the mass required for additional resource recovery and power supply systems. The technical challenge for ALS R&D is to provide the designer of future missions with appropriate mature technologies and hardware designs, and extensive supporting performance data. Mature technologies will be necessary to provide the confidence that highly reliable ALS systems can meet future mission constraints.

TECHNICAL AND SCIENTIFIC TOPICS RELATED TO ADVANCED LIFE SUPPORT

According to NASA briefing documents, the mission of the ALS program is to “open the space frontier for exploration, utilization, and development by developing safe, efficient, and effective closed-loop life support systems.” The goal is to “provide self-sufficiency in life support for productive research and exploration in space, for benefits on Earth, and to provide a basis for planetary exploration.” The objectives of the ALS program are:

- to provide ALS technologies for long-duration missions that significantly reduce life-cycle costs, improve operational performance, promote

self-sufficiency, minimize the expenditure of resources for long-duration missions, and provide spin-offs

- to ensure the timely transfer of new life support technologies to NASA missions
- to resolve issues of hypogravity performance through space flight research and evaluation
- to develop and apply methodologies for systems analysis and engineering to guide technology investments, resolve and integrate competing needs, and steer the development of systems
- to transfer technologies for the benefit of the nation

These objectives are highly interdependent. System analysis and engineering help identify ALS technologies that will significantly reduce life-cycle costs and resolve issues of hypogravity performance and will be key to providing timely transfer of new technologies to NASA missions. Because of their operational history and relative maturity, initial missions back to the Moon or to Mars are likely to rely on existing P/C technologies until other options have been extensively tested and are shown to be flight ready and to meet reliability and safety requirements.

The following sections discuss life support functions provided by P/C technology, potential applications of bioregenerative systems, and systems analysis, engineering, and integration. Development challenges and areas for potential improvement are highlighted in each section.

Description of the Life Support Subsystem and Challenges for Physical/Chemical Technologies

The functions to be provided by ALS systems are shown in Table 2-2.¹

Temperature and Humidity Control

Maintaining the temperature and humidity on board a spacecraft requires removing sensible heat produced by the operation of equipment and sensible and latent heat generated by the presence and activities of the crew (e.g., showering). Condensing heat exchangers are a well developed technology for controlling temperature and for condensing moisture from the atmosphere and have been used on all crewed spacecraft to date. Separating condensed water from the air stream in a microgravity environment is usually done with a centrifugal separator, a complicated mechanical device that is subject to failure. In order to simplify the system design, researchers are investigating using membranes instead of mechanical separators.

¹The functions of life support systems for applications in space are discussed in detail in Peter Eckart's *Spaceflight Life Support and Biospherics* (Eckart, 1996) and in Paul Wieland's *Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems* (NASA, 1994).

TABLE 2-2 Summary of Advanced Life Support System Functions

Function	Details
Temperature and Humidity Control	Removal of sensible and latent heat loads
Atmosphere Control and Supply	Partial and total pressure control
Atmosphere Revitalization	CO ₂ removal, CO ₂ reduction, O ₂ replacement, N ₂ replacement, trace contaminant and particulate removal
Water Recovery and Management	Humidity condensate, urine, hygiene and wash wastewater processing; water storage and distribution
Waste Management	Fecal collection, urine collection and pretreatment, waste processing (including food/plant wastes)
Food Management	Food production, processing, storage

Atmosphere Control and Supply

The cabin atmosphere is maintained at the desired total pressure, with a partial pressure of oxygen sufficient to sustain human life (the Space Shuttle, Mir, and the ISS nominally operate at sea level equivalents for total pressure and partial pressure of oxygen). The subsystem to accomplish this requires pressure sensors and regulators, shutoff valves, check valves, relief valves, distribution lines and tanks, and valves and controls to provide the proper concentrations of oxygen and nitrogen. These components are already well developed and, except for improving reliability, are not the subject of ALS research.

Atmosphere Revitalization

The quality of the cabin atmosphere must be maintained: CO₂ must be kept below a critical level; O₂ must be kept within a specified range; N₂ must be present in sufficient quantity to maintain total pressure; and trace gases and particulates (including microorganisms) must be removed.

CO₂ Removal. The closed cabin of a spacecraft requires a system that can remove carbon dioxide produced by the crew, other living organisms, and chemical processes, such as the oxidation of waste materials. In early and current U.S. spacecraft (Mercury, Gemini, Apollo, and the Space Shuttle), nonregenerable lithium hydroxide has been used to absorb CO₂. This process is well understood and is useful for short missions. The first use of a regenerable CO₂ system was in Skylab, which employed a four-bed molecular sieve to remove CO₂ and vent it into space. This is the baseline technology for the ISS, with the possibility of processing CO₂ to recover oxygen in the future. The Space Shuttle has used a

solid amine CO₂ removal system as an alternative to lithium hydroxide for certain long-duration missions to reduce the need for expendable lithium hydroxide canisters. This reduces mass and saves crew time. The four-bed molecular sieve planned for the ISS will essentially eliminate the need for resupply but still has significant mass and power penalties. Improving the selectivity of sorption materials for CO₂ would eliminate problems associated with high humidity in the cabin air and with contaminants in the concentrated CO₂. Other technologies for CO₂ removal being funded by NASA include metal hydrides and membranes.

The current NASA requirement for CO₂ levels on board a spacecraft is 0.5 to 1.0 percent, which is an order of magnitude higher than atmospheric CO₂ levels on Earth (less than 0.1 percent ambient CO₂). The elevated CO₂ levels complicate the analysis of biomedical and life sciences data as compared to data collected on Earth. Achieving CO₂ levels of less than 0.5 percent using P/C technologies becomes increasingly difficult because the removal efficiency typically decreases as CO₂ levels decrease. The potential role of plants in the removal of CO₂ is important, especially for permanent bases on the Moon or Mars. This is discussed in the section on Potential Applications for Bioregenerative Systems.

CO₂ Reduction. Currently, the ISS does not include CO₂ reduction to recover O₂. The exothermic Sabatier process for CO₂ reduction, which reacts CO₂ with H₂ to produce CH₄ and H₂O, is currently a mature technology but has not yet been qualified for use in space. The H₂O produced can be electrolyzed to produce O₂ for the atmosphere and H₂ for recycling to the Sabatier. The CH₄ can theoretically be used in resistor jets for attitude control or can be vented overboard. Because this process results in a net loss of H₂ (unless the CH₄ is decomposed), the system requires resupply.

Another process, the exothermic Bosch process, reacts CO₂ with H₂ in the presence of a catalyst to produce carbon and H₂O. This process does not require venting gas overboard but does require replacing the catalyst bed because of carbon accumulation. Another process that has been investigated is CO₂ electrolysis, which converts CO₂ to carbon and O₂ directly. Plants can also reduce CO₂, converting it to edible biomass through photosynthesis. There are currently no fully mature technologies for CO₂ reduction.

O₂ Supply. The oxygen consumed by the crew, experimental animals, or aerobic bioreactors, as well as oxygen lost through leakage, must be replaced. Oxygen can be provided by resupply, by producing it on board, or from in situ resources. Stored gaseous or cryogenic oxygen has been used on every U.S. crewed spacecraft to date. These open-loop technologies have the typical mass penalty as mission duration increases. Although more efficient means of storing oxygen are being investigated, water electrolysis (which dissociates H₂O into H₂ and O₂) to supply O₂ is the technology of choice for proposed future systems and the one most developed to date. The H₂ can be used in CO₂ reduction processes or vented overboard.

At least three competing technologies are being investigated for water electrolysis: static feed water electrolysis, which uses KOH as the electrolyte; solid polymer water electrolysis, which uses a perfluorinated sulfonic acid polymer; and circulating KOH electrolysis. A circulating KOH electrolysis system is currently being used on Mir. The other two processes have been developed in the U.S. and are candidates for use on the ISS. General concerns that must still be addressed in oxygen generation techniques include: O₂ delivery pressure; power consumption; the presence of corrosive materials on board the spacecraft; and operational flexibility.

The role of plants in providing oxygen is also an important consideration, especially for a permanent lunar or Mars base. This is discussed in detail in the section on Potential Applications for Bioregenerative Systems.

N₂ Replacement. Nitrogen is required to produce the desired total atmospheric pressure and to compensate for nitrogen losses from the spacecraft. Nitrogen losses from leakage, airlock operations, and experiment venting are “non-recoverable,” and N₂ is generally resupplied from stored gaseous or cryogenic tanks. It is technically feasible to provide N₂ by the catalytic dissociation of hydrazine (N₂H₄) or ammonia (NH₃), which may have a lower mass penalty than storing N₂. In-flight use of one of these processes depends on the trade-offs of mass, power, heat rejection, and mission length. The investigation of in situ resource availability or the recovery of nitrogen from metabolic waste products may also be worthwhile.

Trace Contaminant Removal. Controlling trace contaminants begins with the careful screening and control of materials allowed on board the spacecraft to limit offgassing, which can cause the crew discomfort or sickness. Some contaminants are common to all missions (e.g., the products of human metabolism); others will vary from one mission to another or over time during a given mission. Some experiments require the use of substances that are potentially hazardous to the crew but are necessary for experimental protocol; special efforts are made to ensure that these compounds are highly contained. This can involve double or even triple containment of the substance.

Despite these precautions, there will always be contaminants produced by humans, by experimental activity, or by material offgassing that must be controlled and removed. Activated carbon has typically been used to remove organic contaminants; chemisorbant beds are used to remove nitrogen compounds, sulfur compounds, and halogens; and catalytic burners are used to oxidize the remaining contaminants. Dust particles, aerosols, and airborne microbes and allergens are removed by screens and high-efficiency particulate air (HEPA) filters in the return air ducts. Current technologies use significant amounts of expendable materials, especially activated carbon beds. One of the key challenges in the removal of trace contaminants is reducing the use of expendable materials. If plants are integrated into a life support system (primarily for their other uses), they could

contribute to the removal of many trace contaminants; however, they might also produce other trace compounds.

Water Recovery and Management

For long-term missions, the recovery and reuse of wastewater produced by humans offers the greatest potential for reducing resupply of any resource in the life support system. A number of P/C and bioregenerative processes are available to process humidity condensate, urine, and hygiene and wash water for reuse as potable water or for other uses. Distillation is an effective means of purifying water, and several distillation methods for use in space are being developed, including vapor compression distillation (VCD), thermoelectric integrated membrane evaporation, vapor phase catalytic ammonia removal, and simple air evaporation. Among the filtration techniques being investigated are reverse osmosis, multifiltration, and electro dialysis.

Significant steps have been taken to recover wastewater in space, but for the foreseeable future, some resupply or special storage reserves to make up for losses will continue to be necessary for long-duration space missions. The baseline system for the ISS uses a single system to produce water for hygiene and consumption by the crew. Urine is pretreated and processed in an ambient-temperature VCD system. The distillate from the VCD is delivered to the wastewater network, which also receives humidity condensate and hygiene return water. The wastewater network delivers water to the water processor, which uses multifiltration technology and a volatiles removal assembly. The product water from the system is monitored by the Process Control and Water Quality Monitor. If the water is acceptable, it is delivered to product water storage. If it is not, it is recycled through the system again. Multifiltration technology requires little power and provides 100 percent recovery efficiency but relies on expendable beds. Therefore, it is subject to storage and resupply constraints. Current vapor compression technology has moving parts and provides about 90 percent recovery efficiency. Power consumption is fairly low, and resupply requirements are negligible. Other issues to be addressed in water recovery and management include in-flight maintenance, reliability, the disposal or recycling of brine, as well as the potential for microbial contamination and the accumulation of toxins in long-term water processing, storage, and distribution systems.

Waste Management

The waste management system includes a toilet subsystem for collecting urine and feces and an overall housekeeping system for managing other wastes, e.g., food waste, refuse, and biomass from bioregenerative components. The toilet subsystem for operation in microgravity has presented particularly difficult mechanical system/human interface design problems. In all U.S. space projects to

date, feces and refuse have been collected and stored on board for eventual return to Earth. Little or no processing, other than vacuum desiccation, has been done to stabilize or neutralize waste materials. Some processing to render waste material biologically inactive may be required for long-term storage. For planetary missions of extended duration, recovering the water from feces and food waste, and recycling solids will be beneficial, particularly if bioregenerative systems are used to provide food and/or to process waste materials.

Food Management

Food for space flight has improved dramatically since the early days of Mercury, Gemini, and Apollo, but it is still not as varied or fresh as everyday food on Earth. Food currently provided on space vehicles is preserved using a mixture of old and new technologies, including freeze-drying, canning, radiation-stabilization, thermostabilization, and other methods. Food scientists, often in concert with military programs, have made significant advances in food preservation and storage techniques in recent years, and NASA has been a participant in, as well as a beneficiary of, this work. Applicability of these techniques for space is being investigated by NASA, and foods preserved by these new techniques are now being flown on the Space Shuttle and are expected to be used on the ISS.

Food production in space through biological processes is discussed in the following section. The use of significant quantities of food produced in space will raise new issues in food processing, storage, and preparation. (All missions to date have used food produced and packaged on the ground.) In addition to the nutritive value of fresh produce, anecdotal information from the Mir space station, Antarctic stations, and other closed environments indicates that the mere presence of living plants enhances the crew's psychological well-being. Little information is currently available for evaluating the trade-offs between the psychological benefits to the crew and the additional power, mass, and volume that the inclusion of plants would require.

Potential Applications for Bioregenerative Systems

On Earth, biological agents, acting in concert with abiotic aspects of the biosphere, have provided a closed-loop life support system for millions of years. Bioregenerative life support systems are based on the idea of utilizing the natural biological abilities of living organisms to provide life support in a microcosm. The challenge is to make the microcosm small and reliable. The primary components of a microcosm and their relationships are shown in Figure 2-1. Bioregenerative processes are capable of fulfilling many of the functions listed in Table 2-2, with the exception of temperature and humidity control and atmosphere control and supply. Bioregenerative processes may play a major role in removing CO₂ and producing O₂, potable water, and food. They may play a

smaller role in contamination control and waste processing. Incorporating bioregenerative techniques, although increasing system closure, generally comes at the expense of increasing volume, power, and thermal load requirements.

Incorporating biological components into an ALS system would increase the self-sufficiency of the system by producing food and reducing the need for expendable air, water processing systems, and other materials. A common perception among some engineers, however, is that biological systems are inherently less reliable than P/C systems because the death of a living organism is more likely than an equipment failure, which is repairable and is not usually propagated to other P/C components. However, ground-based research in the past

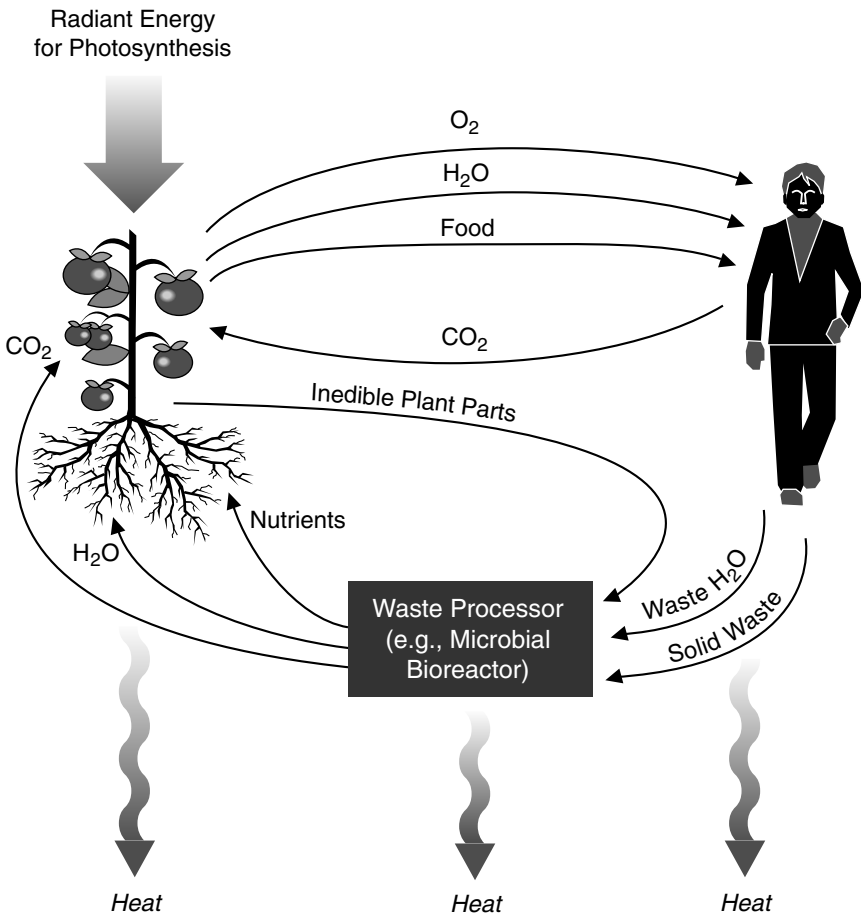


FIGURE 2-1 Principal relationships in a bioregenerative life support system.

decade indicates that microorganisms and higher plants are more reliable than the equipment required to provide environmental control. In other words, equipment failures (of pumps, fans, or sensors) have been shown to be more common than failures caused by biological problems, such as disease. Because biological productivity is highly dependent on the P/C support components, a fundamental understanding of the effects of short- or long-term mechanical failures on biological productivity is essential before biological components can become critical components of a life support system. Real-time monitoring of plant and microbial metabolism will provide detailed data on plant responses to short- and long-term stress. Improved monitoring methods will enable monitoring of parameters such as: carbon and water fluxes associated with plant and microbial metabolism; leaf and canopy temperatures; plant morphology, including stem elongation, leaf number, branching, and reproductive development; as well as machine vision analysis of leaf enlargement.

Both biological and P/C systems can purify water and regenerate O₂ from CO₂, but growing higher plants is currently the only viable approach to producing food in space. Proteins and carbohydrates can be chemically synthesized, but this process is energy-intensive, and the product is a half-and-half mixture of D- and L-rotation isomers.² Humans can only metabolize L-rotation isomers (which are produced by other living organisms on Earth) because of the way the enzymes in human cells have evolved. Plants require high radiation (light) levels to produce food, but if there is enough light for maximum photosynthesis, the caloric requirements of one person can be met with a growing area as small as 10 m², when wheat is the only crop (Bugbee and Salisbury, 1988). This level of productivity requires a light level equivalent to full summer sunlight at noon, 24 hours a day. When other crops that cannot tolerate these high light levels are incorporated into the diet, the production area for one person increases to 20 to 50 m². Through transpiration, this same area can, theoretically, provide at least four times the purified water needed for a single crew member.

Algal systems are photosynthetically efficient, but an excess of indigestible cell wall material, nucleic acids, and chlorophyll make algae unpalatable for more than a few percent of daily calories. Fungal organisms, such as mushrooms, can be grown directly on waste products without a light energy source, but, like algae, mushrooms cannot provide a significant fraction of caloric requirements.

The ability of plant/microbial systems to decompose organic wastes and absorb inorganic wastes on a continuous basis has not yet been rigorously quantified. Plants have evolved effective mechanisms for preventing the uptake of unnecessary organic and inorganic compounds, and these compounds might, therefore, accumulate in the water made available to the plant roots. However,

²D- and L-isomers are two forms of the same compound that are not superimposable. For example, the letter "p" is identical to the mirror image of the letter "q" and, in that sense they are identical, but "p" and "q" are not superimposable.

roots exude a wide variety of low molecular mass carbon compounds that increase microbial activity on the root surfaces. These microbes decompose most organic compounds to CO_2 . Perhaps undesirable inorganic compounds could be concentrated on root surfaces and could be harvested with the crop. Cost-effective options for recycling, storing, or eliminating the inedible portions of plants after harvest need to be modeled and investigated.

Figures 2-2 and 2-3 show plants using CO_2 during photosynthesis to produce carbohydrates (food) and oxygen. The harvest index, which is the ratio of edible biomass to total biomass produced, is assumed to be 0.5 for both figures. Figure 2-2 represents a fully closed food loop that provides 100 percent of the crew's diet and oxygen, as well as oxygen for recycling solid inedible waste material. Figure 2-3 represents a partially closed food loop, which provides approximately 50 percent of the crew's diet, all of their oxygen, but no oxygen for recycling solid waste materials. Full closure of the food loop is not necessary for atmosphere revitalization (removing CO_2 and providing O_2) or for water processing. Closure of the food loop above about 50 percent to reduce the need for food resupply places additional burdens on the temperature and humidity control system to remove excess transpired water and on the waste processing system to recycle CO_2 from inedible waste material. For these reasons, the degree of food loop closure and the recycling of inedible biomass are key issues that must be addressed by careful systems analysis.

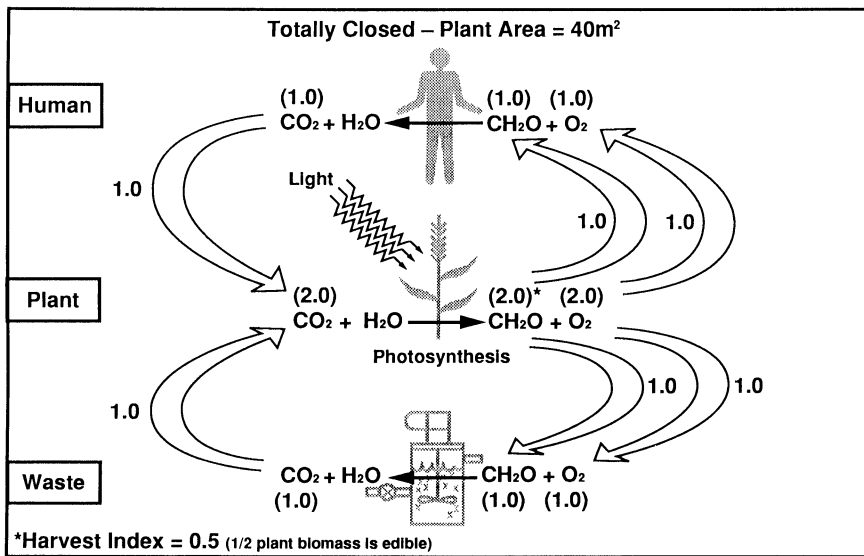


FIGURE 2-2 Fully closed food loop. Source: Wheeler, 1996.

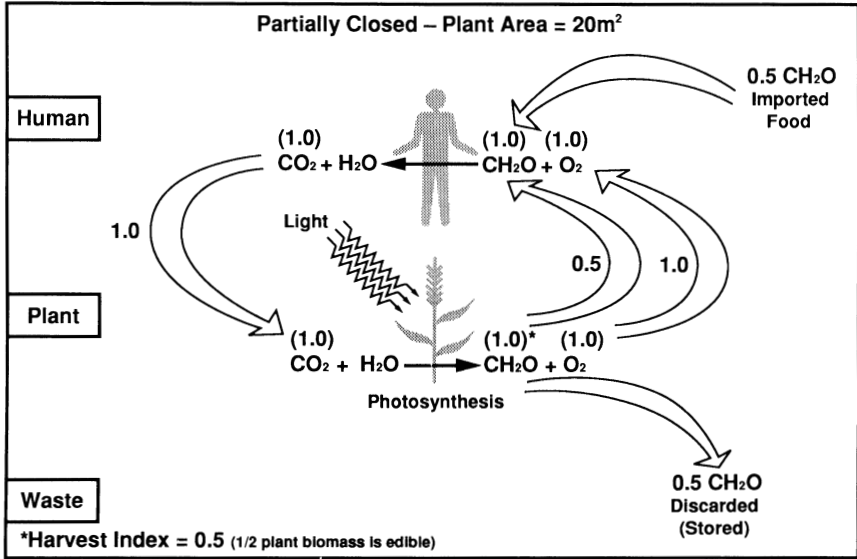


FIGURE 2-3 Partially closed food loop. Source: Wheeler, 1996.

Growing Plants in Space

The specific mission environment can play a significant role in the selection of plants to be grown in space. Mission constraints may mean that a small area of plants can be used only for water recycling and diet supplementation. Crops with a high ratio of edible to total biomass (high harvest index) and crops that require little post-harvest processing may be particularly attractive in this scenario. Examples of such crops are leafy greens, like lettuce and spinach. Radishes and strawberries require little processing, but have lower harvest indexes. All of these crops are short and can be grown in a small growth chamber. Food production on a planetary surface must be done under different conditions from those encountered in microgravity. Volume and energy (if ample power is available) may be less constraining, and a larger variety of crops could be grown.

The optimal conditions for some plants may not always be suitable for humans, so the plant growth area might have to be separated from the crew quarters. For example, the optimum temperature for several plants is higher than the optimum temperature for people, and some plants (e.g., wheat) grow best in continuous light. Neither plants nor humans require sea-level atmospheric pressure for growth and development. A significant portion of the food on Earth is grown at an atmospheric pressure of 0.85 atmospheres (1.5 km elevation [5000 ft.]), and some food is produced at pressures as low as 0.6 atmospheres. Normal growth and development of plant seedlings has been observed at pressures as low as

0.2 atmospheres (Musgrave et al., 1988). Low-pressure, enclosed volumes for plant growth environments may enhance the engineering economy of food production on planetary surfaces because the strength and mass of the structure can be decreased as the internal/external pressure difference is reduced. However, the structure must still provide protection from radiation and micrometeoroids. Other factors associated with low pressure plant growth environments may offset any mass savings benefit, such as special provisions required for crew access, the development of support equipment designed to operate under low pressure conditions, and the expense of conducting life support system R&D at low pressure on Earth.

Low-pressure experiments are expensive to conduct on Earth because of the need for hypobaric chambers with gas composition and humidity control. But additional studies of plant productivity at low pressure are necessary if pressures less than about 0.6 atmospheres are to be utilized in space. Because different plant species have different optimal temperatures, some separation of environments for different species will probably be cost effective. It will probably not be cost effective to provide the exact optimum conditions for each crop. The cost/benefit trade-offs between the increased structural and system costs of separation and maximum food production have not been well documented. Optimal photoperiods and temperatures are likely to be driving parameters for separate environments. Separation for disease control may also be a useful precaution. The decreased production in less than optimal, shared environments needs to be modeled and studied to determine cost-effective alternatives for designing the plant growth facility.

The optimal CO₂ levels for plants may also be different from the CO₂ level in the crew compartment. Despite the fact that plants require CO₂ to survive and humans do not, some plants appear to be adversely affected by CO₂ levels at which humans suffer few or no ill effects. Although plant productivity increases with elevated CO₂ (to about 0.1 percent), preliminary evidence indicates that the productivity of some plants begins to decrease when CO₂ levels exceed about 0.2 percent. NASA currently tolerates CO₂ levels of up to 1.3 percent for up to 24 hours on its spacecraft, and 0.7 percent for 180 days (NRC, 1996b). A separate, low CO₂ area for plant production may be useful. The following section discusses some of the requirements and issues for growing plants in space and identifies where advances in technology could contribute significantly.

The roots of healthy plants absorb water and consume oxygen rapidly. If water is not continuously resupplied to all root surfaces, cell expansion decreases in a few seconds. If oxygen is not resupplied, anaerobic conditions occur, and respiration becomes highly inefficient. The simultaneous requirement for water and oxygen is satisfied in controlled plant growth environments on Earth, either by rapidly flowing hydroponic solutions or by multiple air/water interfaces in a porous matrix. Gases and liquids do not separate in microgravity, so delivering water and oxygen to root surfaces is a significant challenge. The challenge is compounded by the small root volumes that are necessary to minimize volume in

space. Several technologies are promising, especially microporous tubes that allow controlled leakage of nutrient solution to the root zone.

Plants require high levels of light for optimal growth. For a 10-year lunar base with a crew of four, it has been projected that 90 percent of the total mass of the systems will be required to support the plant component of a bioregenerative life support system, with one-third of that mass devoted to lighting (Drysdale, 1995). When electric lamps are used, most of the energy input for plant growth is used to provide radiation for photosynthesis. Electric lamps range in efficiency from 9 percent (incandescent) to 19 percent (fluorescent) to a high of 37 percent (high pressure sodium lamps). In addition to electrical efficiency, the cost of lighting in space includes the lamp mass and volume, heat rejection requirements, and mass and labor for replacing light bulbs. NASA is investigating many lighting technologies, but when all factors are taken into account, light-emitting diodes (Bula et al., 1991) and microwave lamps (MacLennan et al., 1995) seem to have good potential for near-term and long-term use in space (Drysdale, 1995). The development of lighting that is efficient in terms of mass, energy, and volume is extremely important. However, in the next decade and beyond, NASA is likely to benefit from lighting technologies being developed or advanced elsewhere.

The direct use of sunlight could dramatically reduce the energy requirement but would require an extremely strong, durable, highly transparent window that could efficiently filter out cosmic and ultraviolet radiation. Fiber optics are a promising new technology, particularly when coupled with a fresnel lens to selectively focus photosynthetic radiation on the end of the fiber-optic bundle. Unfortunately, sunlight is not available during the 14-day lunar night, so other options must be considered for use on the Moon. The direct use of sunlight in space (when it is available) is one area where technology advancement could yield significant cost benefits.

Bioregenerative Components for Recycling Waste

The questions of when resource recovery is actually needed and whether the partial recovery of resources might be adequate remain to be answered by systems analysis. In general, however, as mission duration and crew size increase, the recovery and recycling of nutrients from solid wastes to support food production becomes an economical consideration. Microbial bioreactors can be used to break down plant and human waste so that the primary inorganic nutrients (N, P, K, Ca, Mg, and S) are retained in a water-soluble form that can be directly returned to plants. Although plants and their associated rhizosphere microbes can facilitate the recycling of gray water, the effects of chronic exposure to the chemicals present in gray water have not been well characterized. Work has begun at KSC and ARC to study the impact of combustion or bioreactor wastes on plant growth. NASA's use of biological waste conversion and control is in the early stages, despite the maturity of, and conceptual similarity to, terrestrial

transformation systems, which have been produced after many years of R&D and have been used in large-scale operations.

Analyses of various closure scenarios, including partial conversion of waste residues, the roles of various oxidation reactions, and the challenges of final disposal, can be used to evaluate the applicability of specific resource recovery technology options. The conversion/transformation of biodegradable materials to substances that might be useless in space, but useful on a planetary surface (for example, lignin as a contribution to the eventual creation of a root-zone media for plant growth), is an additional consideration in determining the circumstances under which the recovery of resources from solid waste is warranted.

Systems Analysis, Systems Engineering, and Systems Integration

Systems analysis, engineering, and integration include methods to guide investments in technology, resolve and integrate competing needs, and guide the evolution of complex systems. Systems analysis is particularly important for ALS where multiple technologies can perform the same function. In the absence of a defined target mission, it is essential that systems analysis and trade-off studies be conducted to support strategic planning and to provide direction for decisions about technology development. Systems analysis tools then evolve into tools that can help determine the best technology for a given application. The best technology becomes apparent only after a rigorous quantitative analysis of system inputs and outputs within the context of mission parameters and constraints.

The realization of a closed, reliable, autonomous life support system will require complex integration. The complexity of this task will require the conscious application of systems engineering principles to ensure a low life cycle cost and a safe final product. Systems engineering of a complex system typically starts with an understanding of the mission or product requirements. The life support systems being developed in the ALS program must be engineered for many different mission scenarios. The system analysis must be flexible enough to identify high-leverage technology needs so cost-effective designs can be generated when detailed mission requirements become available.

Design factors for future missions need to be determined, even in the absence of specific missions. Table 2-3 outlines some differences in design drivers between past and future missions. Even from a top-level view, it is clear that the evolution of current capabilities is unlikely to meet all of the design challenges for future life support systems. Revolutionary steps in regenerable processes, autonomous controls, and reparability and reliability will probably be required. As advances are made in EMC, a concerted effort will be required to integrate them during the transition from the current conventional controls to a more highly automated control system that utilizes sensor feedback. Systems engineering and program management capabilities must be developed to encourage and incorporate revolutionary developments throughout the development process and to

TABLE 2-3 Comparison of Design Factors for the Development of Life Support Systems

Past Systems	Future Systems
Smaller, less complex	Larger, increasingly complex
Intermittent use	Continuous use
Return for maintenance and repair	Maintenance and repair during mission
Open loop	Increasingly closed-loop
Manual or nonintegrated controls	Autonomous, continuous control and monitoring of nonlinear systems
Physical/chemical processes	Integrated physical/chemical and biological processes
Microbiological issues a minor factor	Microbiological issues critical to survival

provide a means for evaluating competing new technologies against the current technology baseline.

As life support systems become increasingly complex, and particularly as the integrated components of life support systems operate across a wide range of time constants, the capability to use analytic/computational simulations will become critical to verifying requirements and designs. The reliability requirements for an integrated, long-term life support system will also require the use of high-fidelity simulations and will lead to other challenges, such as the need for new materials, simplified designs for mechanical components, and multiply-redundant systems (e.g., sensors or computers). On-mission maintenance will require careful “design-for-assembly/design-for-disassembly” analyses that account for work being done in reduced gravity.

The development of closed-loop, regenerable systems presents new challenges in mass and elemental partitioning within the system, adding reserves to accommodate system perturbations, understanding the varying time constants for P/C and biological processors, monitoring and controlling the generation and accumulation of microbial contaminants, and integrating biological processes into existing P/C-based life support systems. As the need to address these issues becomes more pressing, especially in the absence of specified mission scenarios, assessing the capabilities of ALS systems will become even more dependent on the development of adequate computer design tools and system models that can simulate processor performance, compare alternative design scenarios, understand system dynamics, develop reliability, availability and maintainability requirements and models, conduct both broad and focused trade-off studies, and perform analyses that support all elements of determining the cost of the program, from the technology development stage to the testbed stage to space-qualified designs.

System studies necessarily require test data. The combination of computer/system models and testbed-acquired data makes adequate and increasingly detailed system assessments possible. System modelers must be in close contact

with those making the measurements to maximize the efficiency of the modeling process. Because testbed testing is costly, it is essential that specific test goals be established and that an analysis of test parameter sensitivity be conducted before each test is run to ensure that goals are reasonable and attainable. Initial system assessments typically produce “quick-look” results that identify areas where data are either poor or lacking altogether. The identification of data gaps enables the development of requirements for testbeds and, thus, for the structure and format of a testbed program. This iterative process should be carefully considered during the development of multiyear funding plans to avoid the potential difficulties caused by accelerating the development of one component past the others before the next series of requirements has been established.

In the past, system studies programs have been initiated in the ALS program. But, apparently, they were not sustained or integrated and yielded little follow-up and no integrated effort to guide the overall ALS program. For example, in the 1970s and 1980s, CELSS and P/C trade-off studies were conducted with gross calculations of the relative benefits of growing higher plants in a closed life support system. These studies were mostly proof-of-concept models for a CELSS, single processor trade-off studies, and life support analyses of the early stages of the ISS.

In the late 1980s and early 1990s, the development of ongoing system analysis was begun at ARC (where decision analysis was applied to life support system trade-off studies and where system analysis models of lunar and Mars outpost missions were developed) and at JPL (where the life support systems analysis [LiSSA] code was developed and lunar and Mars outpost missions were analyzed). The analysis work at both centers came to a halt when funding was re-directed. These efforts were never integrated, and data gaps and methods for dealing with them were never addressed. Many of the viewgraphs shown to the committee on “break-even points” for bioregenerative systems were derived from this relatively old work.

A wide variety of modeling tools are used to conduct systems analyses, from very basic spreadsheets to expert system interfaced models with sophisticated chemistry codes. Systems engineers have sometimes been limited in conducting analytical studies because many codes do not have the chemistry, biology, or dynamic capabilities to truly represent regenerative systems, especially systems with biological components. The most glaring problem for analysis of life support system studies is the clear lack of integration across the various programs. Several comprehensive assessments of modeling and system analysis tools are available,³ but there is little evidence that any of these have been analyzed or used in the ALS program.

³The Mission Operations and Data Systems Directorate at Goddard Space Flight Center maintains an extensive data base of systems engineering tools and lessons learned, as well as applications. These can be accessed through the Goddard home pages on the Internet. The International Council of Systems Engineers (INCOSE) maintains an excellent Internet reference page with papers on system engineering methodologies, evaluations of software tools, and examples of system engineering applications throughout the federal government.

The committee found few examples of systematic methodology development. Both JPL and ARC had brief programs in the early 1990s (Ganapathi et al., 1992, and Zookin, 1993), and some ongoing work by contractors includes methodological development as well as modeling. But the committee found little or no evidence that this work has ever been integrated in the planning for the ALS program or for feeding the results of system modeling into testbed development, following the iterative process described above. There appears to be one effort at ARC (Finn and Srinivasan, 1995), but this was discovered by the committee by reading a paper, and was neither presented to the committee nor recognized by any of the other centers in their presentations.

PROGRAMMATIC TOPICS RELATED TO ADVANCED LIFE SUPPORT SYSTEMS

NASA Programs and Funding for Advanced Life Support

The objectives of the NASA OLMSA ALS program are managed or carried out at NASA headquarters, JSC, ARC, KSC, and MSFC. The program also funds work at universities and in industry. Other parts of NASA fund additional work relevant to ALS. These include: the Small Business Innovative Research (SBIR) Program (managed until recently by OSAT and now managed by the Office of Aeronautics), which funds a considerable number of projects; OLMSA, which sponsors one of the relevant NASA Specialized Centers of Research and Technology (NSCORT) at Rutgers University; OLMSA and the Office of Equal Opportunity, which jointly sponsor a University Research Center (URC) at Tuskegee University; OSF and JSC, which fund considerable work at JSC through the JSC Crew and Thermal Systems Division (CTSD) directly related to ALS; and OSF alone, which also funds other relevant work at JSC and MSFC under the auspices of the Space Shuttle and ISS programs.

A breakdown of NASA work related to ALS during FY96 is shown in Figure 2-4. The total of \$16.8 million is an estimate based on data from NASA. OLMSA funding constitutes \$10.46 million (62 percent of the total), and non-OLMSA funding constitutes \$6.34 million (38 percent). ISS and Space Shuttle work on operational life support systems are not included in this estimate. Perhaps most noteworthy are the facts that SBIR funding comprises nearly a quarter of the NASA funding dedicated to ALS and that the human-rated test programs at JSC are the largest elements of the OLMSA program. At the time of the final meeting of the committee on August 31, 1996, there were no official estimates available from NASA regarding ALS or related funding beyond FY96. Like all NASA programs, the OLMSA ALS program budget depends on the overall NASA and OLMSA budgets determined by the administration and Congress. The ALS program budget also depends on NASA for its priorities because there is no line item in the NASA budget for the ALS program (or for any of the other three human

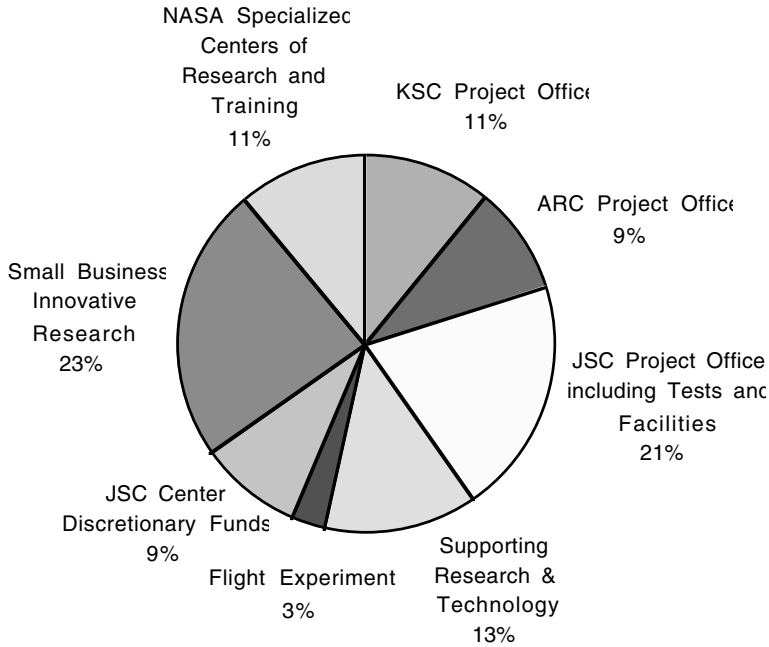


FIGURE 2-4 FY96 NASA funding for advanced life support. Source: NASA.

support programs). The ALS program is funded primarily from the portion of the NASA OLMSA budget allocated to supporting research and technology (SR&T). With this accounting method, there are no official projections of funding levels for the next several years, as there are for programs that have dedicated line items (such as facilities for the ISS).

At the committee's request, NASA provided detailed information on all the ALS-related projects under way in FY96 at ARC, KSC, and JSC. A summary of this information is provided in Appendix E. Funding for these projects falls under the SBIR, SR&T, and center office and discretionary funds identified in Figure 2-4. The figure also shows that the present ALS funding profile is heavily oriented toward in-house projects, with more than 50 percent going to NASA centers and NSCORTs. University involvement primarily falls under the SR&T portion of the OLMSA program. Allocation of this funding is primarily based on projects selected by peer review from proposals submitted in response to NASA Research Announcements (NRAs). The 13 percent (\$2.2 million) for SR&T is based on funding data from JSC, ARC, and KSC. SBIR awards accounted for a significant percentage of NASA ALS technology funding in FY96, i.e., \$4.5 million of the \$16.6 million total. The current ALS program described to the committee includes a relatively minor role for industry other than small businesses.

Traditional prime and first-level subcontractors are not significant participants in NASA-funded technology development projects, but industry is funding some of their own projects, and interaction with NASA appears to be initiated primarily by industry.

Historically, challenges in spacecraft life support technology, from the beginning of human space flight through the ISS, have been met by strong ties between NASA and industry. This has encouraged industry to invest financial resources, as well as company talent and facilities to support NASA goals. Independent research and development (IR&D) by industry is typically directed to near-term business opportunities. In the absence of explicit exploration projects for a return to the Moon or a mission to Mars, IR&D funding will most likely be concentrated on evolutionary improvements to P/C systems that can benefit the Space Shuttle or the ISS. If there is no reasonable expectation of NASA advanced development funding as a follow-on to industry contributions, industry funding will probably be shifted to more promising business opportunities. This will diminish the industrial base and industry's ability to make contributions in the future. The lack of industry participation is likely to result in a less cost-effective and less innovative program.

The NASA headquarters "road map" for ALS R&D is shown in Figure 2-5. There are four key elements of the road map: science and technology R&D; low-gravity research on the ISS; ground integrated testbed; and zero-gravity integrated testbed on the ISS. Note that a technological capability for a lunar/Mars base appears on the schedule in approximately 2010, preceded by a technological capability for a lunar/Mars planetary outpost. Neither the NASA nor the HEDS Strategic Plans yet supports actual missions. Note also that the schedule for closing the food loop is apparently driven by the requirement to have such a technological capability for a planetary base by 2010. The road map assumes that there will be a significant ability to do research and technology demonstrations and tests on the ISS. However, at the time of this study, no ISS facilities or resources had been designated for ALS research.⁴

The JSC CTSD plans for future work in ALS are primarily directed toward the "Ground Integrated Testbed" portion of the NASA headquarters road map. These plans are shown as detailed road maps in Figures 2-6a and 2-6b. Figure 2-6a shows JSC projects, beginning in 1995 and continuing through 2010 and beyond. The key aspects of this road map are the "Early Human Testing Initiative," which began in 1995, and the "Human Rated Test Facility," which is projected to be used beginning in about 2000. Figure 2-6b shows the post-2010 scenarios assumed by JSC, that the life support system for a new space vehicle for transportation beyond Earth orbit would be based on P/C technologies and that the life support system for a habitation on a planetary surface would be biologically based.

⁴Since the final meeting of the committee on August 31, 1996, NASA has taken initial steps to allocate some ISS resources to tests and demonstrations of new ALS technology.

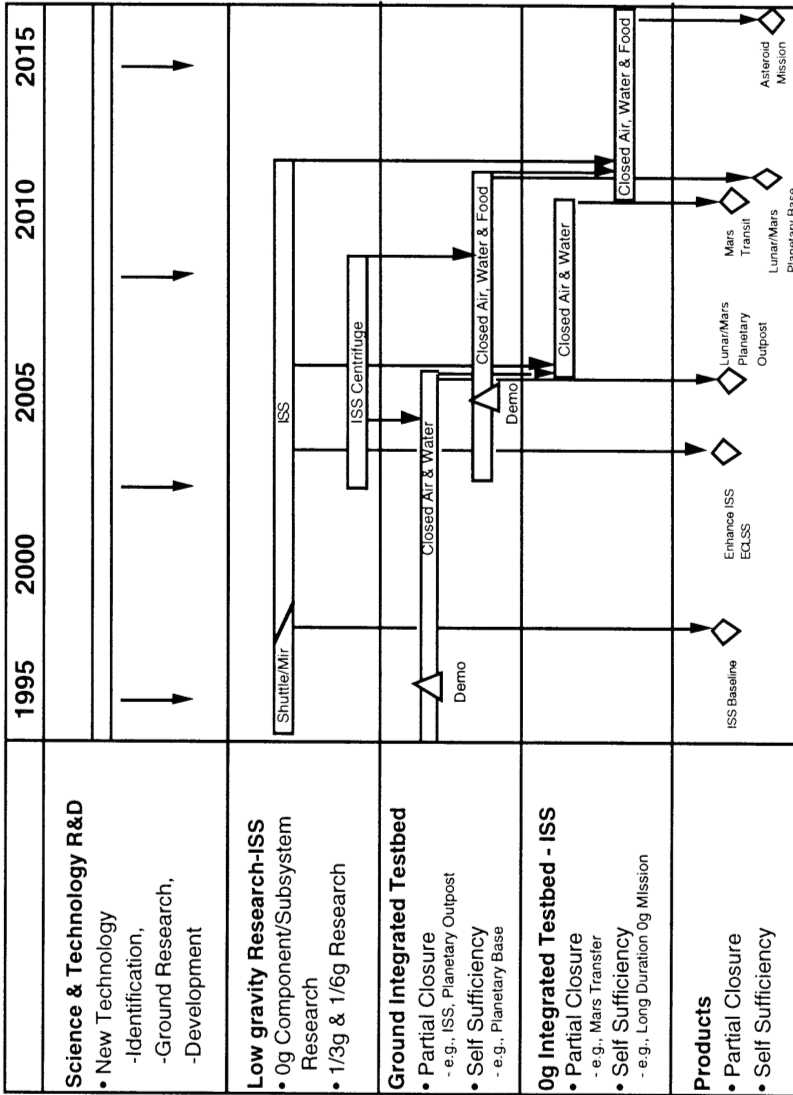


FIGURE 2-5 NASA headquarters technology development road map, 1995 to 2015. Source: NASA.

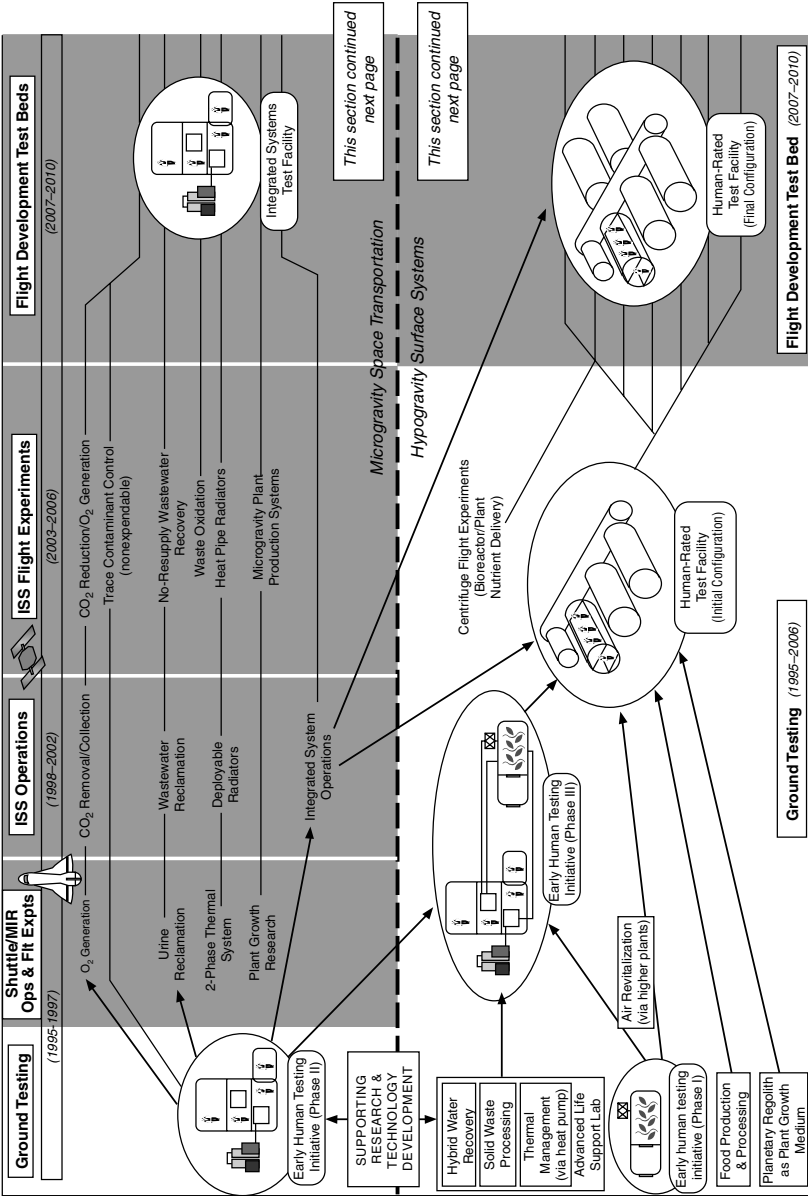


FIGURE 2-6a ISSC technology development and validation road map, 1995 to 2010. Source: NASA.

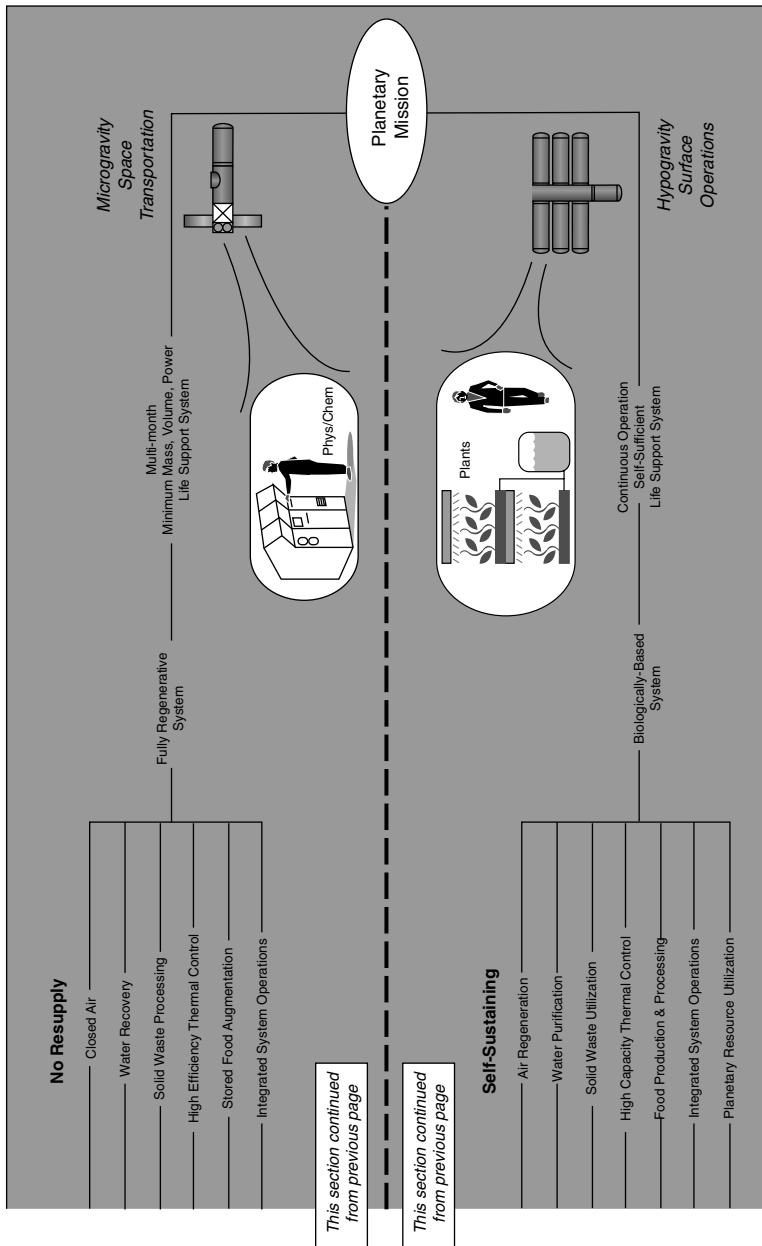


FIGURE 2-6b JSC ALS road map, post-2010. Source: NASA.

Program Management and Planning

At the outset of this study in March 1996 and at the final meeting in August 1996, the committee was informed that NASA was in the process of transferring program management of the ALS program from NASA headquarters to JSC. However, no definitive steps were made during this period to establish JSC as the NASA organization responsible for the program. Throughout the study, JSC CTSD was identified as the group most likely to be responsible for the management of the ALS program. The CTSD organization has worked with the staff at NASA headquarters to take increasing responsibility for the program during the period of the study. This seems to have been done by individuals on their own personal initiative to fill a definite need, without specific guidance from NASA upper management.

JSC has directed life support technology R&D for human space flight since 1962. In addition, JSC has provided oversight for industry to provide life support systems for all of the crewed space programs, from Project Mercury through the Space Shuttle. For the ISS, NASA assigned life support design, development, and oversight responsibility to MSFC. Much of the technology used in the ISS was developed under the direction of JSC through advanced development programs in the 1970s and 1980s. From the standpoint of technical and programmatic continuity, many found this shift to MSFC confusing. It is not clear to the committee why the overall NASA policy statement released in February 1996 (NASA, 1996a) calling for the transfer of most program management functions from NASA headquarters to the NASA centers had not been implemented for the ALS program. This was particularly difficult to understand because the NASA 1996 Strategic Plan lists JSC as the lead NASA center for human exploration.

At the first meeting of the committee, NASA presented a study approach for developing requirements and R&D priorities to support the exploration scenario with the following tasks:

- to establish ALS technology requirements
- to assess current technology capabilities
- to prioritize technology development needs
- to develop a technology maturation process

NASA's proposed approach for developing requirements and prioritizing projects is logical. Although the planning process has not yet been implemented, if it is followed by scheduling, funding, and implementation plans, it appears likely to produce an integrated technology development plan that would meet mission needs.

Large human space flight programs have historically taken about 10 years from authorization to first flight. Despite reorganizations and redesigns, experience with the ISS and Space Station Freedom has shown that developing technology and building hardware and facilities for human space missions is not a straightforward proposition. As the ALS program develops its plans, the proper

mix of evolutionary and revolutionary technology development to be funded by the ALS program should be considered. It is a truism that although revolutionary breakthroughs can lead to the greatest gains, trying to achieve these gains is risky in terms of the allocation of resources (i.e., projects with the potential to produce revolutionary gains are also the projects most likely to fail). It is reasonable for the ALS program to pursue evolutionary improvements in mass, power, volume, reliability, life-cycle cost, maintainability, and durability of existing systems, while simultaneously investigating revolutionary improvements. A significant point to remember in seeking a balance between revolutionary and evolutionary projects is that there is no consistently successful way to solicit, find, or fund proposals for revolutionary technologies with a reasonable probability of success. Standard evaluation criteria for assessing the advantages of a new technology over the baseline technology must also be developed (e.g., cost/risk to benefit/need analysis).

HIGH PRIORITY AREAS FOR ADVANCED LIFE SUPPORT TECHNOLOGY RESEARCH AND DEVELOPMENT

Summary Finding. High priority areas for ALS R&D include systems analysis and P/C technologies for system loop closure to minimize resupply.

Finding. Current systems analysis is inadequate to support strategic planning or to provide direction for making decisions about technology development.

NASA has not targeted a specific mission, such as a return to the Moon or a mission to Mars, as the next definitive step to follow the ISS. Therefore, it is essential that the ALS program conduct systems analysis and trade-off studies with the objective of creating a comprehensive set of generic requirements for meeting future mission needs. More work needs to be done to update trade-off studies and “crossover” charts and to standardize analysis approaches for determining conditions that warrant different degrees of closure. A good example of the lack of analysis is the widespread acceptance of the value of 2.6 years (Winkler and Henninger, 1996) as the break-even point at which bioregenerative life support systems become advantageous, despite the fact that this figure is not based on a definitive analysis. Models of processes, systems, and subsystems are essential for adequate analysis. Test data for P/C and bioregenerative technologies, under both nominal and off-nominal conditions, are essential for validating models.

Recommendation 2-1. NASA should perform systems analyses using representative reference mission scenarios to develop generic technology development requirements that can be used as a basis for defining advanced life support subsystem and component research and development programs. Systems analysis should also be used to help determine the proper sequence and timing for subsystem and system-level testing, both with and without humans. It is important

that systems analysis work be completed early to ensure proper planning to develop the best technologies to meet the goals of the NASA Strategic Plan and to provide the flexibility to react to a specific mission when it is defined.

Recommendation 2-2. The advanced life support program should evaluate the analytical tools and skills available both inside and outside NASA. The evaluation must include an assessment of the resources, or combination of resources, that can be assembled to meet the needs of the advanced life support program. The best analytical tools, processes, procedures, and skills must be integrated to ensure that the program can conduct the highest quality systems work in the most cost-effective and timely manner. Evaluation criteria should be standardized so that processes, subsystems, and systems can be compared on a consistent basis.

Finding. There is little OLMSA-funded research and development on advanced P/C technologies for use beyond the ISS, particularly in the area of atmosphere revitalization.

Although the P/C and bioregenerative advanced life support programs have been successfully merged into a single program, the current program does not put enough emphasis on developing P/C subsystem technologies. Except for the teams directly involved with the development of P/C life support systems, there is a sense that the technologies necessary for closed systems have already been developed and are available for future use on long-term missions. But P/C life support technology is not fully mature.

Technologies have been developed for the ISS that will come close to closing the water loop, but the current technologies require a significant amount of expendables, such as prefilters and multifiltration beds. There are a few water recovery projects, which appears to be the proper emphasis, but increased efforts to push the envelope of the current technologies could bring benefits. In the area of air revitalization, a few projects investigating improvements in CO₂ removal and trace contaminant control are under way, but virtually none of them explores options for closing the oxygen loop, which will be the next major material closure challenge. There are similar levels of effort in the program for P/C and bioregenerative technologies for waste management.

Recommendation 2-3. Greater emphasis should be placed on developing advanced physical/chemical technologies to reduce dependence on resupply and on closing the oxygen loop. Water recycling initiatives should address technologies or processes that can reduce expendables, and power and volume requirements, either by incremental improvements to the International Space Station baseline system or by the adoption of new technologies. Air revitalization initiatives should concentrate on the recovery of oxygen from carbon dioxide in order to further close the oxygen loop.

Recommendation 2-4. NASA should perform systems analysis to determine when processing waste material is beneficial and what degree of recovery is

needed (e.g., water, carbon, and nutrients). Special attention should be placed on the management of process residues and effluents.

RELATIONSHIP BETWEEN THE ADVANCED LIFE SUPPORT PROGRAM AND THE SUCCESS OF FUTURE NASA MISSIONS

Summary Finding. Advanced life support is a critical technology for the success of long-duration future missions. Current technology cannot provide life support functions for long-duration human exploration in a cost-effective manner.

Finding. At current funding levels, the program plans are overly ambitious and do not represent a balanced approach for meeting future needs in technology for advanced life support. The program schedules appear to be unrealistic and unlikely to be accomplished with the most promising technologies without increased emphasis on early basic and applied research and development.

The current ALS program is operating in the absence of a NASA plan to take humans beyond LEO before 2010. Without a significant increase in resources, the program cannot support an earlier Moon or Mars mission. The ability of the program to support missions in the 2010 to 2020 time period depends on whether the programs will be funded and managed at the levels necessary to support the development of new technologies and systems with capabilities beyond present systems.

Recommendation 2-5. In the absence of specific mission objectives, research and development should be focused on long-term, mission-independent technology needs. When an exploration mission is initiated, research and development should be reexamined and refocused, and corresponding budget adjustments should be made.

Recommendation 2-6. For now, technology development should focus on microgravity and lunar and Mars surface missions. Near-term priorities for physical/chemical, bioregenerative, and hybrid systems should be determined based on these scenarios.

PROGRAM OBJECTIVES AND MILESTONES

Summary Finding. There is no current program plan for the development of advanced life support technology. In order to establish meaningful milestones, program objectives should be coordinated with an overall plan to develop the advanced life support technologies necessary for long-duration space missions.

Finding. There is no agency-endorsed plan for future missions to meet the HEDS objective of “establish[ing] a human presence on the Moon, in the Martian System, and elsewhere in the inner solar system.” (NASA, 1996b)

Meeting the technology development needs of a specific mission requires a highly focused program. But, if mission objectives change, the relevance of the

program may be jeopardized. Fundamental requirements for life support are well known and, with system analysis in areas where fundamental R&D are required, can be identified for a broad range of missions. NASA's goals for human exploration will require that more than one type of mission be supported by advanced R&D. Life support will be required for transportation vehicles with various crew sizes and missions, pressurized work spaces, planetary habitats (either short-term or permanent), and pressurized rovers.

Recommendation 2-7. NASA should continue to develop a program plan and road map for technology research and development that (1) is consistent with the NASA Strategic Plan, (2) takes into account the relative benefits of physical/chemical and bioregenerative technologies, and (3) is based on realistic development schedules. If the road map continues to focus on new technologies to enable planetary missions, but no specific mission is identified, then metrics should be put in place to evaluate the relative benefits for a range of possible missions.

Finding. A major emphasis of the current NASA ALS program is on integrated ground testbeds, which is only one of the four key elements of the NASA headquarters road map. Developing new technologies at the component and subsystem level is a relatively small portion of the ALS program.

The primary focus of the ALS program from 1996 to 1998 is integrated testing, and programs using integrated human testbeds consume a large portion of the NASA resources allocated to advanced life support systems. According to the FY96 budget, almost half of the approximately \$10 million OLMSA will spend is designated for human testbeds.

The tests are designed to bring existing subsystem concepts to a level of maturity that will reduce the risk of incorporating them into plans for future flight programs; these are the first tests of this kind in the U.S. in more than 20 years. The committee considers the ground testbeds important and valuable but is concerned with the relative balance between testing and advanced technology development. Although it is possible to conduct future interplanetary missions using current technology, new technology will be necessary to reduce the logistics burden, increase reliability, ensure acceptable risk to crew health and mission success, and provide a level of self-sufficiency that could accommodate potential deviations in missions plans. Therefore, it is crucial that the testbeds not consume an inappropriately large portion of the funding and other resources available for work in ALS. Closed system tests of existing technologies with humans is not an appropriate end in itself. There must be an ongoing programmatic and fiscal commitment to the development of new technologies in the near term, or the tests are likely to become less and less valuable.

Recommendation 2-8. The emphasis on developing new technologies for advanced life support should be increased and a process established for incorporating them into ongoing programs.

Recommendation 2-9. The research done using the testbeds could be significantly more valuable if:

- initial system assessments are performed to identify areas where modeling and system data are either missing or are of poor quality and this information was used to develop requirements for testbed programs
- rigorous analytical models were developed and validated using an iterative process that utilizes testbed-based data acquisition and increased model fidelity to describe and predict the overall operation of the various functions of life support systems and subsystems (successful models could be adapted to predict the performance of space-based systems)
- actual flight subsystems were used in tests designed to predict the function of flight subsystems (e.g., when tests use prototypes that represent flight systems but are not identical to flight systems, the test team should carefully document the differences between test hardware and flight hardware so test results can be properly interpreted)
- ground tests were tied to a commitment that NASA will continue testing promising new technologies in space on the International Space Station or, to a lesser extent, on the Space Shuttle
- technology demonstration tests were more rigorously integrated with relevant human factors research on people living together in small, closed environments and with related topics, such as hygiene, nutrition, and performance evaluation
- there were some sort of routine peer review of the test plans by individuals not directly involved in the test program (NASA staff should not be excluded)
- there were ample time between tests to analyze the results and apply lessons learned to subsequent tests

OVERALL SCIENTIFIC AND TECHNICAL QUALITY

Summary Finding. Some of the research performed under the ALS program is of world class status, as evidenced by the publication record in prestigious journals. However, the overall scientific and technical quality is uneven.

Finding. Many projects are published only as NASA technical memoranda or as nonreviewed papers. Although proposals written in response to NASA Research Announcements undergo external peer review, some NASA center projects do not undergo adequate internal and external peer review.

Recommendation 2-10. NASA scientists should be continuously encouraged to expand their associations with professional societies through participation on committees, publication, and attendance at national meetings. NASA management should ensure the rigorous application of scientific method (which is essential in basic research projects) through internal and external reviews.

PROGRAM REQUIREMENTS

Summary Finding. NASA has a good understanding of the general requirements for advanced life support, but the requirements for continuous, long-term, autonomous control are not well understood, and the baseline requirements for the current program have not been established. Materials presented to the committee did not indicate that all of the important areas were being systematically addressed. The following areas, in addition to those identified earlier as high priority areas for research and development, should be emphasized.

Finding. Little testing has been done for off-nominal operating conditions. Data from off-nominal tests would provide valuable information for systems analysis and modeling. Although many traditional physical, chemical, and microbial treatment techniques are technically feasible, linking them to food production through the reuse of gas, liquid, and solid-phase mixtures creates a complex and difficult recycling challenge. NASA has begun to probe this issue, but most work has been conducted under almost “ideal” conditions for systems optimization that do not incorporate subtle influences that can often lead to instability or even system failure.

Recommendation 2-11. System perturbations, including toxicity, inhibition, and adulterations caused by the invasion and/or buildup of alien microbial species and/or refractory chemicals, need to be addressed in a transitory as well as steady-state fashion. Such a protocol would permit an analysis of reliability and outcomes requisite for making recommendations in response to disasters incorporating such loops. Test objectives and procedures should be coordinated with model developers.

Finding. Initially, plant-based bioregenerative systems will provide only a fraction of the total food requirement. The requirements for intermediate closure levels of the food loop are currently underfunded.

Recommendation 2-12. Intermediate food loop closure levels warrant additional study. Issues to be considered include: the mixture of crop species that should be used; crop sensitivity to high CO₂ levels (about 1 percent); crop capacity to recycle gray water; the engineering impact on support systems and waste processing for different levels of food loop closure.

Finding. The incorporation of plants into bioregenerative systems and the use of plants for food production impose unique constraints and demands. Although there is a tremendous data base on the efficiency of crop production on Earth, there is considerably less data on growing plants in controlled environments.

Recommendation 2-13. Plant growth research should focus on resolving issues unique to growing plants in controlled environments for space applications. Some of these issues include: standardization of procedures for reporting production

efficiency; optimization of environmental conditions during different periods of plant growth to increase production efficiency; the ability of plants to tolerate high levels of ammonium nitrogen typical of recycled wastes in regenerative systems; techniques for providing aerobic, well watered root zones to reduce plant stress; adaptation of commercial processes for food processing and storage; provision of oil in a primarily vegetarian diet; selection of a plant growth medium; and fluid handling under micro- and hypo-gravity conditions.

PROGRAM DIRECTION AND ORGANIZATION

Summary Finding. The current ALS program is a result of the unification of two NASA programs, in two different NASA headquarters offices (both of which were dedicated to the development of ALS systems). In 1993, the consolidation of the P/C and bioregenerative programs was a significant step toward the formation of a coherent ALS program. However, NASA has still not specified an organizational structure to manage the program. This has resulted in a lack of focus and a delay in program planning and implementation.

Finding. Since the reorganization of NASA's ALS programs began in 1993 (which placed P/C and bioregenerative life support programs in a single NASA headquarters office), NASA groups working in the two areas have been more coordinated. The present R&D program has improved because it recognizes the potential systems engineering advantages of both technical approaches. This increases the likelihood that combined ALS systems will be rationally developed to meet long-term needs in space.

Finding. NASA headquarters has tentatively assigned responsibility for the ALS program to JSC, the lead center for the HEDS Enterprise. JSC management has not yet identified an ALS program manager or support structure. This has had an adverse effect on the planning and implementation of the program.

Recommendation 2-14. Johnson Space Center management should define an advanced life support program management structure. The organization should be headed by a program manager who has the authority and responsibility to plan and execute the program. The program manager, in concert with the supporting centers, should develop a summary document that clearly defines the tasks to be accomplished by each NASA center that receives advanced life support program funds, as well as tasks to be accomplished by industry and universities.

Recommendation 2-15. Assuming that management of the program is transferred to the Johnson Space Center, the funding for advanced research and development should continue to be allocated separately from operational programs and responsibilities, such as the Space Shuttle or the International Space Station, to ensure that advanced life support research is not subordinated by immediate operational concerns.

Finding. Expertise and activities at NASA centers are spread across the ALS spectrum (with some overlap) and generally support the division of responsibility.

JSC's primary focus in the ALS program is on integrated testing of humans in engineered systems. JSC's CTSD has a long history of developing technology for spacecraft life support systems and significant expertise in most aspects of ALS systems.

Current life support work at MSFC is primarily funded by the ISS program and is directed toward the development and evolution of the baseline ISS Environmental Control and Life Support System (ECLSS). MSFC has ground-based facilities for developing and testing water recycling and air revitalization technologies, using volunteer subjects to supply products for the water recycling tests and metabolic simulators for the air revitalization tests. MSFC has proposed a number of projects for the evolution of the ISS ECLSS. If these are funded and successful, they could reduce resupply and power demands. MSFC also plays a small role in testing advanced subsystems in space on the Space Shuttle, as part of the OLMSA ALS program.

Research at KSC is carried out by a small civil service and contractor staff, supplemented by postdoctoral fellowships, university grants, and SBIR contracts. KSC's work in ALS focuses on plant growth and is well grounded scientifically, as demonstrated by papers in refereed journals and presentations at professional meetings. KSC also has expertise in processing Space Shuttle payloads, including life sciences payloads; this provides a skill base and synergy for some aspects of the research focusing on growing plants in space.

Work on life support systems at ARC includes research on both bioregenerative and P/C systems. The work at ARC appears to have great potential, although the work on bioregenerative systems lacks a strong focus, and, in general, ARC's work is currently not well integrated with other elements of the NASA program. If the P/C projects and expertise were carefully integrated with work at other centers, ARC could provide a much needed basic research capability to the ALS program. ARC has also done significant work in systems analysis in the past and might be a site for research into the integration of bioregenerative and P/C technologies.

Recommendation 2-16. Program management should conduct a comprehensive evaluation of the resources required to conduct the advanced life support program, and determine the technical and organizational roles of NASA headquarters and the relevant NASA centers.

Recommendation 2-17. Management of an excellent plant research program should involve a working group with a broad knowledge of basic plant biology, advanced training, and awareness of the special requirements imposed by microgravity and a closed environment. Managers should also encourage active participation in professional societies, a consistent record of publication in peer-reviewed journals, and collegial relationships with other NASA centers, academia, and

industry. The current program at the Kennedy Space Center exemplifies these attributes, and this center should continue work in plant research and should play a larger role in the management of plant research related to advanced life support.

Finding. Current mechanisms for soliciting and supporting ALS contributions from industry are inadequate.

NASA has adopted the NRA as the primary method of soliciting proposals from academia and industry. This is appropriate if the objective is to solicit proposals for basic research and revolutionary concepts for new processes, bread board, or prototype developments. Universities should play a role in the development of revolutionary approaches to improving P/C systems, and, most importantly, to improving bioregenerative technologies that are not a high priority for IR&D. In the past, the NRA process has been only marginally successful in attracting such proposals. At the higher technology levels, it is generally better to solicit specific proposals through the competitive request for proposal process or, when appropriate and justified, through a noncompetitive procurement process.

Recommendation 2-18. NASA should use the NASA Research Announcements primarily to request proposals at the early levels of technology development. The highest priority technology areas for advanced life support should be carefully and fully communicated in each announcement. Through outreach programs, NASA should attempt to reach a wider population of universities and industrial organizations that have generally not been involved in space research.

Recommendation 2-19. For more mature technologies that are closer to being used in operational space systems, NASA should primarily use the competitive request-for-proposals process to attract proposals from companies likely to provide flight systems in the future.

Recommendation 2-20. NASA should invite companies to propose cooperative agreements for using the ground system testbeds at the Johnson Space Center and Marshall Space Flight Center to test advanced hardware developed with company funds.

Recommendation 2-21. NASA technical and management staff should make a concerted effort to keep abreast of developments in independent research and development projects.

Recommendation 2-22. For the present, bioregenerative research should primarily be conducted at universities and NASA centers. However, it is imperative that NASA exert stronger leadership to keep this research focused on NASA goals.

Finding. Developing a coherent ALS program has been complicated by individuals other than the ALS program manager selecting SBIR and NSCORT projects, as well as by the inherent unpredictability of new project proposals and funding allocations in response to NRAs.

Recommendation 2-23. Advanced life support management should provide clear direction and priorities for selecting Small Business Innovative Research (SBIR), NASA Specialized Center of Research and Technology (NSCORT), and NASA Research Announcement (NRA) technology development projects. Advanced life support program management should receive regular status reports for all ongoing projects.

Recommendation 2-24. A mechanism/process should be developed and implemented to integrate SBIR, NSCORT, and NRA projects into mainstream NASA technology development programs, including integrated system testing, testbed data acquisition, and the eventual incorporation of promising technologies into flight programs.

SYNERGISM WITH OTHER PROGRAMS

Summary Finding. The potential for synergy between the OLMSA ALS program and other NASA programs is significant. Areas for cooperation include SBIR, SHF, EMC, the ISS, and the Space Shuttle programs. The ALS program should continue to recognize and make use of the scientific results generated by other OLMSA programs in areas such as plant biology and microgravity sciences related to transport phenomena.

Finding. The SBIR projects are significant contributors to the development of ALS technologies and provide an opportunity for small businesses to bring forward innovative concepts.

The SBIR program has proved to be a valuable source of innovative technology initiatives for the ALS program. The funded projects presented to the committee were generally of high quality and addressed appropriate technology areas. However, there appears to be a lack of effective coordination among the NASA centers that manage the individual contracts, and the solicitation and selection process has not ensured that the areas of highest priority are addressed.

Recommendation 2-25. NASA should target the Small Business Innovative Research (SBIR) solicitation and selection process to specifically request proposals that address areas of highest priority. Through technical exchange meetings, NASA should fully inform advanced life support researchers throughout the agency about SBIR activities.

Finding. There is little quantitative information on the psychological value of plants in closed environments, which may become a significant SHF issue for long-duration missions.

Much of the incentive for using higher plants for food, oxygen, and water on short missions (less than two years) is based on the assumption that plants will provide a critical psychological boost. This assumption is based on reports from people in partial isolation (e.g., Mir). There seems to be unanimous agreement

that plants will be psychologically important, but detailed information on their importance is lacking. For example, how many plants are necessary and where should they be placed to provide a psychological boost? Higher plants make people feel they are living, rather than simply surviving, in space. This has prompted NASA to study the use of plants for purposes beyond their immediate value in reducing resupply and increasing self-sufficiency.

Recommendation 2-26. NASA should work to quantify the psychological value of plants in closed environments and take advantage of the advanced life support human rated testing opportunities for space human factors investigations.

Finding. ALS systems maintain the parameters that the newly formed EMC program is responsible for monitoring. Currently, monitoring and control functions for the provision of life support have been decoupled and have essentially no direct feedback or automated control of life support system functions (with the exception of oxygen partial pressure). As control systems become more sophisticated and life support systems are required to provide and respond to more variable environmental conditions, control strategies (predicated on the availability of required monitoring equipment) will be critical.

Recommendation 2-27. Communication between the advanced life support and environmental monitoring and control programs should be strengthened to allow them to evolve in a coordinated and synergistic manner.

Finding. There is little coordination with the Space Shuttle and ISS programs to ensure the utility of ALS projects directed at near-term needs or to make provisions for use of on-orbit facilities to support the development of ALS technology.

There is presently no commitment for volume or other resources on the ISS for ALS testing, although since the final meeting of the committee on August 31, 1996, NASA has taken initial steps to allocate some ISS resources for testing and demonstrating new ALS technology. At present, OLMSA has no budget to produce ALS test hardware for the ISS or to sponsor an ISS test facility for ALS. The ALS program is expected to provide upgrades for the ISS, but there is no specific interface between the ALS programs and the ISS. It is imperative that a mechanism be established for transferring information between the ISS and ALS programs.

Over its lifetime, the ISS could benefit from ALS developments leading to a system to recover O₂ from CO₂, systems to reduce the logistics burden of the current water processing design, the addition of laundry facilities to reduce the clothing resupply burden, and other subsystem improvements to reduce logistics and power requirements.

Recommendation 2-28. The advanced life support program should recognize the International Space Station (ISS) environmental control and life support system (ECLSS) as a point of departure for technology initiatives. OLMSA along with the Human Exploration and Development of Space Enterprise (with the ISS

Program Office) should develop a funded plan to use the ISS as an engineering testbed for advanced life support research.⁵ This plan should address the evolution of the ISS, as well as the development of processes, subsystems, and systems for lunar bases, Mars transit vehicles, and Mars bases.

The NASA team at Marshall Space Flight Center, which currently has the most expertise in the ISS ECLSS, should continue to be involved in any long-term projects to provide enhancements to the system.

Research and development of bioregenerative or plant-based technology should be included in the plans for any advanced life support testbed on the ISS. If such a testbed were expanded to a module, the module could help form the basis for an ALS module on a Mars transit vehicle or a long-term planetary base.

Finding. There are no definitive requirements for the selection of crop types to be included in bioregenerative life support systems.

Recommendation 2-29. NASA personnel working in space human factors and the development of foods and meals for space crews need to help establish requirements for the selection of food crops for representative mission scenarios (based on nutritional, cultural, processing, and crew time considerations). Researchers responsible for growing plants in space should consider processing requirements when making crop selections, as well as coordinate with those whose task is to turn the processed crops into acceptable meals.

DUAL-USE TECHNOLOGIES

Summary Finding. The NASA-sponsored research in ALS emphasizes resource recovery from solid waste (primarily to support controlled environment plant growth) and contaminant removal from the water and atmosphere. Spacecraft life support systems are designed to perform these functions to support humans in confined environments at remote locations where resupply is difficult and costly. Other applications that share one or more of these attributes may be dual-use candidates if the economic and/or political environment is favorable.

Finding. The processing of solid and liquid waste materials can be motivated either by a need for the recovered resources or by a need to convert waste materials into something more environmentally benign. Spacecraft conditions tend to require the former, while terrestrial spin-offs tend toward the latter. Regardless of the motivation, the same technology can be used. Several projects currently under way demonstrate the potential dual use of ALS waste processing. Both applications described below are in remote locations where living conditions make growing plants in a controlled environment an attractive option.

⁵Issues regarding engineering research on the ISS are reviewed in *Engineering Research and Technology Development on the Space Station* (NRC, 1996).

NASA is a technical contributor to the collaborative effort, Advanced Life [Support] Systems for Extreme Environments Project, with the University of Alaska, the North Slope Borough, the Ukpeavik Inupiat Corporation, and Lisagvic College. The primary goal of this effort is to establish a research and operational facility in the Alaskan North Slope Borough to introduce and distribute socially, environmentally, and economically compatible technologies to improve life in remote communities. The project emphasizes: waste and wastewater treatment and sanitation; food production; environmental protection and remediation; and the introduction of technologies to the Arctic environment that will not adversely affect the traditional subsistence activities and ways of life of the indigenous peoples. It is expected that some of the waste treatment processes developed in the ALS program will be applicable to this project.

A similar project, funded by the National Science Foundation, is under way to apply the waste treatment and plant growth technologies developed in the NASA program to reduce the accumulation of waste at the South Pole Station and to provide a source of fresh vegetables during the winter confinement.

The removal of contaminants generated by human occupants and material offgassing from the atmosphere in a confined environment becomes more difficult as the exchange with the external environment decreases. On board a spacecraft, exchange with the external environment is negligible, which means that contaminants will build up over time unless they are actively removed. Other applications, such as energy-tight buildings and aircraft, have varying degrees of exchange with the external environment. In most cases, exchange with the external environment is kept low to maintain the desirable attributes of the internal environment (e.g., air pressure, temperature, etc.). A low exchange can also be used to keep undesirable external elements out (e.g., cold, air pollutants, etc.).

Early commercial jet aircraft circulated outside air through the cabin to reduce contaminants and vented it through a thrust recovery nozzle at the rear of the aircraft. The cabin atmosphere was maintained at a higher pressure than the external atmosphere by using bleed air from the engine compressors. Recently, aircraft designers have begun recirculating some air through the cabin to reduce performance penalties from the 100 percent flow-through. Passenger density and the resulting contaminant load (particularly CO₂) limits the amount of recirculated air that can be used without additional processing. Other air quality concerns are cabin humidity and microbiological and trace gas contamination. When higher levels of recirculation are necessary or when the outside air quality is not good (e.g., when the plane is sitting on the runway waiting to take off) atmosphere revitalization technologies being developed by the ALS program are potentially applicable.

Recommendation 2-30. NASA's work in advanced life support should continue to contribute improvements to technologies and systems for use on Earth, but the program should remain focused primarily on the development of technologies

and systems for advanced life support in space (the unique goal of the program and the basic reason for its existence).

REFERENCES

- Bugbee, B., and F.B. Salisbury. 1988. Exploring the limits of Crop Productivity: Photosynthetic Efficiency in High Irradiance Environments. *Plant Physiology* 88: 869–878.
- Bula, R.J., R.C. Morrow, T.W. Tibbitts, D.J. Barta, R.W. Ignatius, and T.S. Martin. 1991. Light-emitting diodes as a radiation source for plants. *HortScience* 26 (2):203–205.
- Drysdale, Alan. 1995. McDonnell Douglas 1995 Annual Report. St. Louis, Missouri: McDonnell Douglas Corporation.
- Eckart, Peter. 1996. *Spaceflight Life Support and Biospherics*. Torrance, California: Space Technology Library, Microcosm, Inc.
- Finn, C., and V. Srinivasan. 1995. Dynamic simulation of the laboratory-scale CELSS. *Life Support and Biosphere Science, International Journal of Earth/Space* 2(2): 49–57.
- Ganapathi, G.B., P.K. Seshan, J. Ferral, and N. Rohagti. 1992. Human life support during interplanetary travel and domicile. Part VI. Generic modular flow schematic for hybrid physical/chemical - biological life support systems. Society of Automotive Engineers Paper 921120. Warrendale, Pennsylvania: Society of Automotive Engineers.
- MacLennan, Donald, Brian Turner, James Dolan, Michael Ury, Paul Gustafson. 1995. Efficient, full spectrum, long-lived, non-toxic microwave lamp for plant growth. *International Lighting in Controlled Environments Workshop*, held in Madison, Wisconsin. NASA Conference Publication Number 95-3309. Washington, D.C.: NASA.
- Musgrave, M.E., W.A. Gerth, H.W. Scheld, and B.R. Strain. 1988. Growth and mitochondrial respiration of mungbeans (*Phaseolus aureus* Roxb.) germinated at low pressure. *Plant Physiology* 88: 19–22.
- NASA (National Aeronautics and Space Administration). 1994. *Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems*. NASA RP-1324. Marshall Space Flight Center, Alabama: NASA.
- NASA. 1996a. FY 1996 Administrator's Guidance. Letter from NASA Administrator to NASA Center Directors. February 2, 1996. Washington, D.C.: NASA.
- NASA. 1996b. *Human Exploration and Development of Space: Strategic Plan*. Washington, D.C.: NASA.
- NRC (National Research Council). 1996a. *Engineering Research and Technology Development on the Space Station*. Aeronautics and Space Engineering Board. Washington, D.C.: National Academy Press.
- NRC. 1996b. *Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants*. Vol. 2. Committee on Toxicology. Washington, D.C.: National Academy Press.
- Wheeler, Raymond M. 1996. Gas Balance in a Plant-Based CELSS. Pp. 207–216 in *Plants in Space Biology*. Sendai, Japan: Institute of Genetic Ecology, Tohoku University.
- Winkler, Gene, and Don Henninger. Early Human Testing Program Overview. 1996. Briefing presented to the Committee on Advanced Technology for Human Support in Space, at the Johnson Space Center, Houston, Texas, April 24, 1996.
- Zookin, Gary. 1993. *Advanced Life Support System Analysis: Methodological Framework and Application Studies*. Society of Automotive Engineers Paper 932129. Warrendale, Pennsylvania: Society of Automotive Engineers.

3

Environmental Monitoring and Control

INTRODUCTION

The closed environment of a spacecraft with a closed-loop or nearly closed-loop life support system will present unique challenges to both scientists and engineers who must manage the quality of the crew's air and water. It will be necessary to maintain the composition, temperature, feed rates, and operating pressures of the solid, gaseous, and liquid constituents to ensure the mechanical "health" of the system (i.e., reliability, maintainability) and the health of the human crew.

Environmental monitoring and control (EMC) encompasses the internal environment of a human occupied spacecraft, including the atmosphere, water supplies, and all surfaces. The term "monitoring" implies continuous vigilant oversight of the status of these areas over time to ensure that conditions are maintained within acceptable limits. (This also implies that acceptable limits have been established and that detection methodologies are available.) The term "control" implies some form of feedback to the systems responsible for maintaining each parameter. In most cases to date, the feedback has been in the form of a message to the crew, via the Caution and Warning System, that a parameter is moving out of the acceptable range. The message may include an indication of the possible causes. In a few cases, such as monitoring of in-line water quality, feedback can be directed to the processor logic, which would result in operational adjustments.

TECHNICAL AND SCIENTIFIC TOPICS RELATED TO ENVIRONMENTAL MONITORING AND CONTROL

Environment inside a Crewed Spacecraft

The initial atmosphere of a NASA spacecraft is a mixture of nitrogen and oxygen. Anything else in the atmosphere, including water, heat, chemicals (i.e., gases, vapors, and particulates), and microorganisms can be considered a contaminant if they are present at unacceptable levels. Sources of contamination include living organisms (people, plants, animals, and microbes), equipment, experiments, the chemical or physical degradation processes of spacecraft materials, and the external environment (in a planetary setting). Environmental monitoring for such contaminants inside a spacecraft must go beyond traditional methods. Tables 3-1 and 3-2 summarize the categories of potential contaminants in spacecraft environments. The nearly airtight nature of space vehicles, the limited availability of evacuation options, the possibility that crews will spend 600 to 1000 days¹ in a closed environment (for a mission to Mars), and other aspects of space flight have resulted in and will continue to necessitate stringent, sometimes unique, requirements regarding atmospheric contaminants.

The focus on EMC at NASA has been on chemical contaminants. A wide variety of these chemicals have been identified, and their individual concentrations have been measured in the cabin air during previous Space Shuttle or Mir missions. One can expect that similar contamination will be present during future space missions, especially if the missions become more complex (such as revisiting the Moon, transit to Mars, or the development of lunar or Mars bases). Some

TABLE 3-1 Major Categories of Contaminants

Category	Examples
Water	Vapor, liquid from condensation and leaks
Gases	CO ₂ , CO, NO _x , SO _x
Inorganic chemicals	Cations, anions
Volatile organic compounds	Formaldehyde, benzene, etc.
Nonbiological particles	Combustion particles, fibers from fabrics, paper, etc.
Living microorganisms	Viruses, bacteria, fungi
Plant parts	Pollen, leaf hairs, etc.
Nonliving particles from biological sources	Allergens, toxins, danders, urinary, salivary, fecal proteins, endotoxins, etc.

¹Sample scenarios for short-duration and long-duration human missions to Mars are provided in *America at the Threshold: America's Space Exploration Initiative* (Stafford et al., 1991).

TABLE 3-2 Potential Sources for Some Major Contaminants

Source	Examples of sources	Contaminant examples
Humans	Respiratory effluents, skin, excretory products, exhaled air	CO ₂ , volatile organic compounds, and other metabolic wastes, viruses, bacteria, dander
Water	Showers, hand washing, clothes washing, dish washing, drinking	Bacteria, viruses, organic and inorganic chemicals
Surfaces	Microbial growth in condensation, dust accumulation	Bacteria, bacterial toxins, fungal effluents (spores, allergens, toxins, volatiles), other allergens, other volatile chemicals
Food	Cooking, spoilage organisms	Volatile chemicals, fungal effluents (spores, allergens, toxins, volatiles), bacteria and their products
Cabin materials and processes	Natural off-gassing, fire, cleaning materials, etc.	Volatile chemicals, nonbiological particles, CO, CO ₂
Scientific research	Chemicals, animals	Trace volatiles, organic compounds, animal allergens, other metabolites and associated microorganisms
Plants	Leaf surfaces, growth medium, etc.	Volatile chemicals, pollen, plant hairs, bacteria, fungal spores and other effluents
Wastes	Transformation products of biological, chemical, and physical interactions	CO ₂ , NO _x , H ₂ S, NH ₃ , O ₂ , methane, microorganisms

types of contaminants are well characterized; others have been recognized but not yet measured. Because conditions are likely to vary over time throughout a long-duration mission, the capabilities of monitoring and control systems for chemical contaminants need to be able to adapt to new conditions. For example, contaminants that may not have been identified at the beginning of a mission or that may form as a result of reactions with other contaminants or environmental media may require attention after the mission has begun.

Qualitative methodologies provide information on the types of chemical contaminants present in an environment. This information can be used for making decisions related to the development of spacecraft maximum allowable concentrations (SMACs) and can also provide direction for the development of technology for contaminant removal as well as limits for equipment that outgasses into the spacecraft environment. SMAC levels drive the requirements for detection methodologies and sensitivities, as well as for contaminant removal and the efficiency and performance requirements of transformation technologies. At the

present time, NASA has established SMACs for approximately 40 trace contaminants, based on chemical speciation and the duration of exposure.²

SMACs provide guidelines for chemical exposure during normal and emergency operations. However, these established safe levels for airborne contaminants are only applicable for relatively short durations (1 and 24 hours; 7, 30, and 180 days). These limits may not be appropriate for longer missions, and need to be reevaluated and extended. As longer-term SMACs are developed, the concomitant development of accurate and reliable quantitative measurements will be critical for ensuring that standards are met.

Microorganisms as pollutants have received far less attention than chemical pollutants because of the complexity of populations, the widely disparate agent-specific requirements for sensitivity, and the general lack of methods of analysis that can be used in the spacecraft environment. To date, spot-check sampling has been done for a limited range of microorganisms, and guidelines for interpreting the data have been based on extremely limited information. SMACs have not been developed for any microbial contaminants.

Rationale for Monitoring

A basic purpose of monitoring is to diagnose and feed back information to a warning or control procedure, so that the risk of unacceptable exposures is minimized. The value of monitoring is reduced if control will be too slow to prevent or significantly diminish negative health effects, or if no control is possible. For example, 90-day intervals between monitoring events for agents of infectious disease, as planned for the ISS, may be too long to be of significant use for crew protection. The incubation period for most infectious diseases is significantly less than 90 days, and many diseases are likely to run their course before they are indicated by the currently planned monitoring system. In some cases, no interval sampling technique is likely to be effective. For example, contagious and waterborne virulent diseases can develop following single, low-level exposure events. Therefore, if any exposure occurs, environmental monitoring is likely to be too late, and measures to prevent additional cases must focus on the isolation and treatment of infected individuals or sources of contaminants. Useful environmental monitoring to control such diseases would have to focus on very low detection limits (single agents in large volumes of air/water) in real time.

Even when control of exposure is not possible, however, monitoring may produce valuable data for the design of future missions, or may indicate the presence of agents that could pose a future risk of disease. Monitoring for infectious agents involves identifying specific reservoirs and developing monitoring protocols based on background data and risk assessments that include the nature of the

²The most recent report on SMAC levels is by the NRC's Committee on Toxicology, *Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants* (vol. 2) (NRC, 1996).

TABLE 3-3 Microbiological Monitoring and Control Prioritization

Procedural Steps	Description
Prioritization of monitoring needs	This decision needs to be based on: (1) failure, health risk, and mission impact; and (2) the ability to adequately monitor so that unacceptable risk can be prevented.
Follow-up sampling	Monitoring and control must account for upset conditions as well as preventive measures. Once a problem has occurred, sampling may be important for tracing the source and for focusing controls. This is an acute response process, and is very different from routine process monitoring. In the case of a human health problem, sampling can be focused on specific causal agents. Guidelines are: (1) Is the agent present in one or more reservoirs? and (2) Is there a logical pathway for exposure? In case of equipment failure or off-nominal conditions, sampling can be focused on the specific failure scenarios that could have caused the fault.
Guidelines/standards	Neither monitoring nor sampling are useful unless guidelines are available for interpreting data, and the guidelines are tied to control strategies. Ideally, guidelines should be based on the risks of failure or disease or the risk of a mission being compromised. However, guidelines that specify monitoring below the detection limit of available technologies may not be useful unless they acknowledge this problem and are clear enough to guide the research and development of new technologies.
Monitoring/control	There need to be clear links between monitoring and control. As the EMC program matures, monitoring protocols should be closely tied to control procedures. As with detection limits, control procedures should be within the limits of available technology unless this issue is clearly acknowledged and addressed with a view towards specifying requirements for the development of new technologies.

agent, the probability of presence and exposure, as well as likely levels of infectious agents and variability over time. These kinds of detailed assessments regarding when and how monitoring should be used would enhance the viability and cost-effectiveness of operational EMC programs planned for future missions. The baseline plan for the ISS is still based on culture methods to detect bacteria. Standard microbiological techniques encourage fungi and bacteria to grow in the space environment. Given the close quarters and closed environment of the ISS, this technique should be reevaluated (especially for fungi, which produce spores that readily become airborne). Table 3-3 shows a general outline for the prioritization and use of monitoring and control schemes.

For long-term missions beyond LEO, when rapid returns to Earth will be impossible, real-time monitoring of potentially toxic contaminants will become increasingly essential. First, the crew must be aware of chemical hazards when they occur; then, they must be able to determine the source, nature, and risk associated with exposure; last, they must take appropriate measures. Airborne chemicals may be hazardous even at very low concentrations. The capability of detecting, identifying, and quantifying airborne contaminants in a timely manner must have high priority. Therefore, the continual development of sensitive, reliable, and validated technologies for monitoring spacecraft atmospheres for chemical contamination is essential.

Crew Health and Safety

Chemical Pollutants

The monitoring of airborne chemical contaminants must be detailed enough to ensure the health, performance, and comfort of the crew. Continuous (or almost continuous) monitoring of major air components would be desirable. The frequency of sampling for trace contaminants must take into account the ordinary fluctuations of the atmosphere. The specificity and sensitivity of the analytical methods need to meet the established SMAC levels. The design of such analytical systems depends directly on requirements imposed by the established SMACs.

Monitoring chemicals in the air presents some temporal and spatial challenges. Typically, sampling is performed on a periodic basis from discrete locations. This protocol is adequate for analyzing long-term trends but does not address localized, transient conditions and peak exposure levels. For example, the inadvertent release of contaminants may be a significant threat to the health and safety of the crew. One possible way to detect an unexpected release would be to develop “concentration-activated” sensors designed for specific hazardous chemicals that would be triggered when a specified concentration is reached. Spacecraft lack natural convection and air circulation due to the absence of gravity. Inadequate ventilation resulting from obstructed vents or faulty equipment could potentially result in air stagnation or pocketing of contaminants. This is particularly critical in crew areas. Sample ports for monitoring are typically hardwired to one or several locations within a module, which means that these conditions may go undetected. One possible solution could be to develop a roving sampler that could traverse the pressurized volume and could also be used to sample behind racks and panels for pockets of stagnant air. Another possible solution could be portable monitoring devices worn by crewmembers. Another issue related to monitoring in space is that some sensors rely on gravity-dependent properties for operation (e.g., hydrogen detectors). In these instances, gravity-independent alternatives will need to be developed for use in space applications.

Microbial Pollutants

Diseases related to microbial and other biological pollutants, including infections from environmental and other sources, hypersensitivity diseases, and biological toxicoses, may be of special concern for long-term space missions. Contagious and waterborne virulent diseases will be of concern on board space stations and on permanent lunar or Mars colonies where isolated groups could be periodically exposed to new agents. Another possible concern is the activation of latent viruses or the mutation of strains with limited virulence that may be resident in water systems or members of the crew.

Microbial amplification will occur on crewed spacecraft and planetary outposts. Biofilms, macroscopic layers of microorganisms and their secretions that adhere to moist or immersed surfaces, are inevitable in recirculating water systems on surfaces, filters and in charcoal beds. Fungi and bacteria will also grow wherever water is inadvertently present in reservoirs, on materials, or on surfaces. Microbial amplification levels will depend primarily on the duration of continuous occupancy and the level of environmental control (including failures).

Such microbial amplification raises concerns about specific infectious diseases in the closed spacecraft environment, where space-induced changes in hosts, and possible changes in the virulence of organisms, may increase risks to the crew. In addition to infections, however, microbial amplification in closed environments can increase the risks of hypersensitivity and toxic diseases. Exposures to mixtures containing bacteria and fungal spores can lead to adult-onset asthma and hypersensitivity pneumonitis, diseases for which human risk factors are unknown (i.e., one cannot screen crews for susceptibility). In addition, evidence is accumulating that exposure to microbial toxins in closed environments may result in an array of symptoms, ranging from eye irritation to severe central nervous system reactions that could seriously compromise the health of the crew and their performance capabilities.

Systems Engineering and System "Health," Reliability, and Maintainability

The technologies supported by the EMC program will ensure life support system "health" as well as human health. This means that the components of environmental systems will have to be monitored, assessed across a variety of performance characteristics, and controlled. The complexity of closed-loop systems will mean that "system health" technologies must have many of the same characteristics as required for maintaining human health: very high reliability; rapid response times a high degree of autonomy; and ease of maintenance.

Meeting these requirements will most likely require the development of new, possibly revolutionary, sensors. Major new developments will almost certainly be required to meet the reliability and goals of control autonomy. In all cases, the use of system studies, in close conjunction with studies of advanced life support

technologies (including testbed programs) will be necessary. Sensor placement studies, changes in expected performance due to low gravity or microgravity operation, and complex system dynamics are some areas where system modeling and assessments will play a critical role.

Microorganisms may also play a role in system health. If allowed to develop unchecked, bacterial biofilms will foul water systems and may lead to system deterioration as well as unpotable water. Fungi will degrade any organic material if sufficient moisture and oxygen are available. Damp conditions and condensation will lead to fungal deterioration of colonized materials, possibly even vital components of life support systems. Fungi are well-known to colonize and destroy most carbon-containing materials, including cellulosic materials (paper, fabrics), lignin (paper, wood products), natural rubber, some plastics, and other materials.

CURRENT STATUS OF THE ENVIRONMENTAL MONITORING AND CONTROL PROGRAM

The EMC program is relatively new. Previously, sensor development for space environmental systems had been the responsibility of either life support or biomedical research programs. In 1994–1995, OLSA found it appropriate to create a separate EMC program. OLSA recognized that the complexity of the environmental system will increase greatly as system closure becomes more complete and as mission durations increase. Advances in sensor technologies may enable new approaches to monitoring and controlling spacecraft environments.

The 1996 Advanced EMC Strategic Plan provides strategic goals, objectives, deliverables and metrics for the program. The plan seems to meet the needs of the program and is a well conceived document that defines a clear, reasonably achievable mission. The goals and objectives of the EMC program, as stated in the Strategic Plan, are shown in Table 3-4. The deliverables of the EMC program are shown in Table 3-5.

NASA has also drafted a requirements document for the development of advanced EMC technologies, the objective of which is to define a set of requirements for EMC systems for advanced human missions, based on prioritization and risk assessment. The committee reviewed this document in draft form.³ The document, which was developed as a part of the Environmental Monitoring and Controls Workshop (held in April 1996 in Pasadena, California, sponsored by JPL), focused primarily on two essential needs: (1) the requirements for the health of the crew; and (2) the requirements for monitoring life support systems. It was

³The final version of this document, *Advanced Environmental Monitoring and Control Program: Technology Development Requirements* (NASA, 1996b), was published by NASA in October 1996, after the committee had completed its data-gathering process, on August 31, 1996.

TABLE 3-4 Goals and Objectives of the EMC Program

Goals	Objectives Associated with Each Goal
Determine the requirements for EMC systems aboard future human spacecraft	<ul style="list-style-type: none">• Establish and continuously update integrated environmental monitoring requirements• Determine the state of the art in environmental technologies in other government agencies, industry and academia in order to maximize efficacy of limited program funds
Obtain state-of-the-art, revolutionary technologies for spacecraft EMC	<ul style="list-style-type: none">• Sponsor development of high-risk, high potential return environmental sensor and control systems technology development• Obtain state-of-the-art technologies to enhance EMC from industry, academia, and other government agencies or off the shelf as appropriate for NASA's use
Provide mature, tested environmental monitoring technologies for use in flight systems	<ul style="list-style-type: none">• Select EMC technologies whose proof of concept has been demonstrated for further development in increasingly realistic environments• Provide EMC systems for use in integrated testbeds• Provide advanced integrated EMC technologies for use in flight systems for the human exploration and development of space
Provide the benefits of NASA-developed EMC technologies to U.S. industry and for improving human welfare	<ul style="list-style-type: none">• Establish criteria in announcement of research opportunities and subsequent progress reviews encouraging early technology transfer• Establish partnerships and Memoranda of Understanding with industry, academia and government organizations to use NASA-developed EMC technologies for the economic benefit of the U.S. and for improving human welfare

Source: NASA, 1996a.

recognized that, in order to maintain the health, comfort and well-being of the crew, these two needs are closely related and will be essential to the success of future missions.

Research Currently Funded by the Environmental Monitoring and Control Program

The 17 technical development projects funded in 1995–1996 by the EMC program are summarized in Table 3-6.

The majority of current NASA-funded EMC research is focused on the detection of chemical compounds and infectious agents in air and water. The focus of chemical analysis has been primarily on organic compounds. Other

TABLE 3-5 EMC Schedule and Program Deliverables

Time Period	Top Level Deliverables of the EMC Program
1995–2000	<ul style="list-style-type: none"> • Breadboard demonstrated sensor systems capable of monitoring a wide variety of atmospheric contaminants • Initial demonstration of microbial sensor systems • Breadboard demonstrated water contamination sensor systems • Initial demonstration of advanced integrated control systems for ALS systems • Flight demonstration of selected air monitoring technologies
2000–2005	<ul style="list-style-type: none"> • Integrated monitoring and control systems demonstrated in ground testbeds • Initial integration of microbial sensors achieved • Initial testing of sensor and control systems on board ISS (rack level) • Continuing development of advanced EMC technologies
2005–2010	<ul style="list-style-type: none"> • Fully integrated monitoring and control systems demonstrated in high-fidelity ground testbeds with humans in the loop • Full autonomous control of ALS systems achieved • Integrated monitoring and control systems demonstrated aboard ISS • Continuing development of advanced EMC technologies
2010–2015	<ul style="list-style-type: none"> • Integrated EMC of ISS achieved • Delivery of technologies suitable for EMC on lunar and planetary missions

Source: NASA, 1996a.

TABLE 3-6 Funded Technical Development Projects (1995–1996)

Application Area	Number of Projects	Comments
Air/trace contaminant control	8	All multiple gas sensing technologies: 2 entirely new technologies 2 miniaturizations of existing projects 3 high reliability, smaller, low power technologies 1 adaptation of other technology
Water	2	1 miniaturization of an existing project 1 increased sensitivity and miniaturization of an existing project
Microbiological control	4	1 biofilm study 3 microorganism identification/quantification
Process control	3	1 modeling/sensor placement study 1 trend prediction study 1 gas sensing study

contaminants that may become important, particularly for long-duration missions, include water and airborne contaminants that can accumulate from processing equipment and endotoxins produced by microorganisms. Relatively little work is being done in the area of airborne particulate contaminants, such as inorganic materials, fibers, metals, bacteria and fungi that do not cause infectious disease but may still contain allergens or toxins (e.g., from pollen), material debris, or liquid droplets.

The Advanced EMC Strategic Plan stresses an efficient program operating on a lean budget. This seems appropriate, given budget realities and the fact that a specific, long-term or planetary mission has not yet been selected by NASA. By these standards, the schedule of deliverables in the Strategic Plan is probably overly-ambitious, partly because the program budget was only approximately \$4 million in FY96. The FY95 budget was \$1.84 million, \$1.01 million of which was spent on R&D grants and contracts, \$600,000 on technology development at JPL, and \$230,000 on the development of SMACs.

HIGH PRIORITY AREAS FOR ENVIRONMENTAL MONITORING AND CONTROL TECHNOLOGY RESEARCH AND DEVELOPMENT

Summary Finding. The development of risk-based prioritization processes, understanding the ramifications of system perturbations, and the development of a detailed plan to use the ISS as a testbed for advanced EMC technologies and issues related to environmental chemical contaminants and microbiology on long-duration missions are the highest priority technologies.

Finding. Evaluating and prioritizing health and system risks with respect to environmental exposures is an important element of the EMC program. Research focused primarily on ground-based areas of concern may have limited relevance for the (long-duration) space environment.

Recommendation 3-1. NASA should develop a process whereby research and development programs for environmental monitoring and control are based on relative risk and use risk prioritization to determine requirements. Risk analysis should include the impact of exposure on health, the likelihood of exposure, impact of exposure on the mission, and the ability to control exposures. An immediate program focus should be the analysis of risks presented by failure and upset modes. Work should be prioritized to address these risks based on overall program needs.

Finding. Understanding what happens when a system is perturbed will be critical to controlling ALS systems. Not enough effort has been expended on developing requirements related to potential perturbations or upset conditions. For instance,

the need to understand biological process upsets and their ramifications is a significant change from current investigations using steady-state conditions for process optimization.

Many traditional P/C and microbial techniques for facilitating ALS require sensitive monitoring and rapid, effective control mechanisms during both ideal (steady-state) and transient (off-nominal) conditions. Therefore, system optimization incorporating such monitoring and control strategies sufficient to address those factors that could lead to system instability and failure is crucial, as is the capability to institute swift and effective corrective action. This approach would permit an analysis of the reliability and outcomes necessary for sustained human survival by incorporating integrated P/C and biological processes necessary for resource recycling and potential loop closure. This approach is also consistent with the desire for system reliability in the EMC Strategic Plan.

Recommendation 3-2. Experiments with testbeds should be intentionally perturbed to simulate worst-case conditions (e.g., upset scenarios) and should be monitored for results. These test results should then be used to establish critical requirements for sensors and control systems, recognizing that effective control is not possible without adequate understanding of cause and effect.

Finding. The ISS provides a unique opportunity for NASA to improve the fundamental understanding of how living and working in a microgravity environment can influence the needs of various ALS systems and how such an environment may accumulate and distribute toxic environmental contaminants. Human and animal studies for assessing the physiological changes during long-term space flights require that sensors be developed and strategically placed to assess the adequacy of strategies for controlling possible life support system perturbations and/or failures.

Recommendation 3-3. NASA should develop a plan for testing and demonstrating environmental monitoring and control sensors, controls, and other technologies using the International Space Station as a testbed to help determine human health risks for future long-term missions beyond low Earth orbit.

Finding. Evaluating and prioritizing the risk of long-duration chemical and microbial exposures is an important element of the EMC program. Research focused on ground-based concerns may not be relevant for the (long-duration) space environment.

Recommendation 3-4. Microbiological concerns should be included with other (related) monitoring and control efforts, including the possible development of multi-use sensors, to focus on important (or controllable) problems in the spacecraft environment. High-priority technical issues in microbiology include:

(1) developing methods and processes for screening crews to prevent infectious and hypersensitivity diseases; (2) understanding surface contamination by fungi and bacteria in water and ventilation systems; and (3) developing risk-based guidelines for infectious agents and appropriate monitoring and control strategies.

RELATIONSHIP BETWEEN THE ENVIRONMENTAL MONITORING AND CONTROL PROGRAM AND THE SUCCESS OF FUTURE NASA MISSIONS

Summary Finding. Long-duration, crewed missions cannot succeed without a healthy EMC program that has the means to follow the NASA Strategic Plan.

Finding. Adequate monitoring and control of advanced human life support cannot occur without the development of a successful advanced EMC system. If a system is developed that does not meet all of the risk-based needs for monitoring and supporting humans results in a human death or in catastrophic mission failure, the endorsement and realization of any future crewed missions would be severely limited.

It should be self-evident that a complex, integrated life support system (even with components that perform adequately) will be of little functional value if it cannot be controlled to perform within specifications. The design and use of advanced sensors and controls will enable the development of a functioning, lower cost, integrated system that can respond rapidly to environmental changes and perform to requirements continuously over a period of years with minimal maintenance. The development of a sensory and control system that will achieve these objectives must start with a specific set of long-range goals, as presented in the Strategic Plan.

Recommendation 3-5. The committee recommends the appropriate allocation of resources, budget, and personnel needed to fully accomplish the programmatic goals as stated in the Advanced Environmental Monitoring and Control Program Strategic Plan.

PROGRAM OBJECTIVES AND MILESTONES

Summary Finding. The Advanced EMC Program Strategic Plan is a good one. However, meeting the current schedule will require more realistic resource planning, and accelerated research on control systems.

Finding. The Advanced EMC Program Strategic Plan is well focused and comprehensive. The goals and objectives are responsive to the mission of providing “future spacecraft with advanced microminiaturized networks of integrated sensors to monitor environmental health and accurately determine and control the

physical, chemical and biological environment of the crew living areas and the environmental control system.”

The Advanced EMC Program Strategic Plan provides a relevant and useful template for the development of an advanced EMC program. The document outlines the mission, goals, objectives, and deliverables for a program, and ably demonstrates a clear, concise vision of the contributions the program must make. The plan is not overly prescriptive, and provides guidance for the future, regardless of which programmatic structure or future mission is selected. Addressing NASA’s unique needs are important to deriving new technologies from limited intramural and extramural resources. The attempt to link monitoring and control technology development deliverables within a projected implementation schedule is a good feature of the Strategic Plan, as is the recognition of a need to measure progress toward meeting goals, objectives and associated deliverables. The metrics of cost and performance, in terms of reliability and risk reduction, will need definition as EMC technologies for use in space mature.

Recommendation 3-6. NASA should develop a test plan for integrated system control that includes validation. The test plan should be driven by an analysis of nominal operations as well as expected failure modes, and any other anticipated vulnerabilities of the system. The skills and facilities needed to fully implement the proposed schedule should be identified and appropriate funds should be allocated. The necessary resources should be balanced against the expected budget, and an implementing schedule should be developed accordingly.

Finding. The Advanced EMC Program Strategic Plan is a well conceived document, and its emphasis on risk prioritization and the development of metrics to measure the success of technology and systems under development is crucial. However, the EMC program has not yet explicitly defined NASA’s unique needs, such as the need for miniaturization and the challenges of operating in microgravity.

Regardless of the mission selected, new and novel monitoring and control technologies must correspond with the ALS goals of smaller, cheaper, closed systems that can run autonomously for years. One shortcoming of the Strategic Plan is that it does not define how NASA’s truly unique needs will be planned for and accommodated in the EMC program. Examples of these needs are the challenges associated with measuring and interpreting data in microgravity, and the identification of technical challenges associated with allocating volume and electric power.

The Advanced EMC Program Strategic Plan provides a long-term strategy for designing programs and projects that need to be accomplished if the long-term goals and objectives of the Advanced Human Support Technology Program are to be met. This Strategic Plan addresses the needs for new technologies in EMC necessary for the future human exploration of space. The plan can be an

effective aid to NASA for prioritizing limited resources by ensuring that relevant technologies are identified as critical. The plan highlights the goals and objectives associated with: (1) technical requirements needed for monitoring and controlling the environment of future spacecraft; (2) criteria for assessing, prioritizing, and selecting technologies for further development; and (3) identifying areas where EMC technologies can be transferred to benefit and improve human welfare and enhance the quality of life on Earth. The plan properly focuses on research necessary to improve NASA's ability to sustain a long-term human presence in space.

Recommendation 3-7. NASA should implement the environmental monitoring and control program largely as described in the 1996 Advanced Environmental Monitoring and Control Program Strategic Plan. The program should be continuously monitored to ensure that these goals are fully met and are on schedule. NASA should consider revising the document with an overlay of NASA's truly unique needs in the area of environmental monitoring and control.

OVERALL SCIENTIFIC AND TECHNICAL QUALITY

Summary Finding. The scientific and technical quality of the EMC program needs to continue to be enhanced by ongoing peer reviews and the interaction of NASA personnel with outside scientists and engineers. NASA should ensure that oversight of the program is provided by highly qualified scientists and engineers.

Finding. Existing tendencies toward insularity, not only within NASA as a whole, but within specific NASA centers and even within specific programs, is limiting access to state-of-the-art science and developments as well as to the benefits derived from continuous peer review.

Recommendation 3-8. Resources should be provided for NASA scientists and engineers involved in environmental monitoring and control projects to have more interaction with the broader scientific and engineering communities. This could take the form of expanding and maintaining active participation in professional societies, sponsoring internships for NASA scientists in appropriate academic settings, and publishing in peer-reviewed publications. Interaction with other organizations with shared interests should be pursued to determine if progress made elsewhere can contribute to the environmental monitoring and control program. Organizations to consider include the Occupational Safety and Health Administration, the National Institute for Occupational Safety and Health, the Department of Defense, the Department of Energy, and the Environmental Protection Agency.

Finding. The oversight of monitoring programs requires broad knowledge and advanced training as well as a full awareness of the special requirements imposed

by the spacecraft environment. This type of oversight has been minimal for microbial monitoring and control (as described in the draft requirements document) and would significantly benefit the current EMC program.

Recommendation 3-9. NASA should take steps to minimize the isolation of sub-disciplines and media (e.g., air, water, surfaces) within the environmental monitoring and control specialty. This could promote the development of multi-use sensors and the implementation of integrated physical/chemical and biological life support systems. The oversight of NASA microbiological activities should be assigned to a scientist who has broad experience in environmental microbiology (air and water) as well as the qualifications and authority to interact with NASA administrators, engineers, physicians, and others to help establish priorities and to obtain adequate resources.

PROGRAM REQUIREMENTS

Summary Finding. NASA should make an effort to define NASA's truly unique EMC requirements. One means that must be used to do this is through the development of risk assessment methodologies to prioritize contaminants. If risk assessments indicate that monitoring is necessary, long-term limits for contaminants must be developed.

Finding. NASA needs to provide methodologies for determining contaminant limits, and for prioritizing environmental contaminants that require limits. Setting these limits is a critical first step in the development of monitoring and control requirements for ALS systems. Although the Advanced EMC Program Strategic Plan states that SMACs for longer durations in space need to be established, it is not evident that a plan is being developed to establish them.

NASA recognizes that the spacecraft environment may become periodically contaminated by trace chemicals, which could adversely affect the health and well-being of the crew or impair their performance. A wide variety of chemical contaminants have been identified and their concentrations measured during Space Shuttle and Mir flights. One can expect that planetary missions or a crewed lunar base will require humans to spend extended periods of time in space with the possibility that they will be subjected to long-term exposures in contaminated environments. At present, NASA has set SMAC limits for certain airborne toxicants but only for durations ranging from 1 hour to 180 days. For extended missions, it will be critical to have operational guidelines and procedures in place for assessing possible human health risks from long-term exposure to such contaminants. Similar standards will be needed for waterborne contaminants. Limits will have to be set low enough to prevent either acute or long-term health risks. As these longer-term limits are developed, the concomitant development of accurate, quantitative measurements and the operating

ranges of monitoring and control instruments can be defined, which will be critical to ensuring that these standards are met.

Recommendation 3-10. Spacecraft maximum allowable concentrations have been established for many, but not all, airborne chemical contaminants for durations of up to 180 days. NASA should now develop or adapt methodologies for assessing the relative environmental health risks from airborne and waterborne contaminants on long-term space missions. Theoretical risk assessment models could be developed for expected contaminant exposures and for some pollutants. Biomarkers could be useful for monitoring responses to long-term exposure.

Finding. There is a continuing need for the integration of ground-based research and spaceflight research. In planning and designing future long-duration missions, success will depend on many factors, such as the requirements of the mission, technology readiness, timeliness, and cost constraints. These technological challenges may be successfully met through an extensive array of both ground-based and space-based research. Such interaction requires a well coordinated, integrated program with the capability to stimulate and accelerate innovative ground-based research and testing. Such programs are necessary in order to have confidence in the safety of long-duration spaceflight missions. Extensive research with well controlled environments on Earth can be performed before applying the technology to space. Ground-based research and testing can significantly reduce the high costs, health risks, and logistical penalties of space-based experimentation. The ISS will provide a more realistic environment than ground-based research for further tests of EMC technologies and solutions for long-duration space missions.

Recommendation 3-11. Existing and developmental ground-based technologies and models should be assessed for their application to the space environment.

PROGRAM DIRECTION AND ORGANIZATION

Summary Finding. A successful EMC program will depend on an appropriate organizational structure, proven technology development capabilities, and the development of a mechanism that integrates the capabilities of NASA centers.

Finding. The budget for the EMC program is likely to be constrained. The program managers plan to make the best use of limited resources by focusing on new technologies to meet NASA's needs. Because of the goals and budget of the program, the day-to-day administration of the program should be separate from programs with other responsibilities (i.e., flight operations, life support technology testing, etc.) so that EMC program managers are not compromised by other responsibilities.

Communication between NASA centers working in EMC appears to be poor. This is probably partly related to fears of downsizing, the isolation of projects, and poorly defined roles. This lack of communication has had a negative influence on the program. The current work in EMC at JSC is focused on supporting the operational aspects of the Space Shuttle and ISS programs. Planning for long-term needs does not appear to be part of the current EMC program at JSC. The current work in EMC at JPL is clearly relevant to the development of advanced sensor technology. JPL has experience in miniaturization and the development of complex control systems. It has less experience with crewed missions than the other centers working in human support.

For a technology development program such as the EMC program, management of the program should reside in an organization with a background in leading relevant technology development projects, such as the miniaturization of sensors, microgravity applications and controls. The group should strongly emphasize allocating enough staff to perform the research, and maintain strong ties with academia. Less critical, but also important, should be the ability to work interactively with the developers of advanced life support system hardware, system simulations, and testbeds. This will become increasingly important to program management in later years, particularly as control needs become better defined by maturing system-level tests and simulations. A proven capability for technology development in areas needed by this program is thus critical, as are experience managing relatively small intercenter programs and well-established relationships with academia. JPL is an example of a center that has demonstrated these qualities (i.e., experience developing novel technologies, strong academic ties with the California Institute of Technology, and management of the New Millennium Program), despite their somewhat limited experience with human missions.

Recommendation 3-12. NASA should develop a programmatic structure with clear, simple lines of responsibility and funding. A panel of experts to advise and critique the program should be an integral element of this structure. This panel should include professionals from outside NASA as well as from each NASA center involved in the program.

Finding. Insufficient interaction among the various NASA centers working in EMC has limited the efficiency and cost-effective use of available talent and resources. The self-sufficient, insular style of operation observed by the committee will have to change in order for NASA to maintain a core capability in the centers. The centers involved in EMC have not been working together to improve communications and the exchange of information.

Recommendation 3-13. A mechanism should be developed for integrating the research activities in environmental monitoring and control at various NASA

centers without eliminating valuable capabilities. NASA should eliminate duplications of effort and increase efficiency and productivity, thereby promoting the likelihood of program success.

SYNERGISM WITH OTHER PROGRAMS

Summary Finding. Cohesive interactions with the ALS program, and regular, planned exchanges of information throughout OLMSA, including the EVA and SHF communities, are critical to the success of the EMC program. The program is also likely to benefit from interactions with other government agencies.

Finding. Scientifically sound and technically achievable EMC deliverables are intrinsic to the development of closed-loop, autonomous ALS systems. For example, with future long-term missions, real-time monitoring and control of both system fidelity and the accumulation of potentially toxic contaminants will be essential.

The Advanced EMC Program Strategic Plan recognizes that the human health requirements for environmental monitoring will be developed by the aerospace medicine and medical sciences communities, and that these requirements will determine the threshold limits, sensitivities, and accuracies of monitoring instrumentation. It is also true, however, that maintaining contaminants below these threshold limits will depend on the ability of the system to control the atmospheric and water conditioning components. Thus, adequate interaction between the developers and those who generate requirements for ALS will be critical to the success of the advanced EMC tasks. Responding to the needs identified by the medical community will not suffice. Adequate attention must be paid to the development of equipment to ensure that medically determined limits are met.

Recommendation 3-14. The development of highly automated monitoring and control technologies that are fully capable of interacting directly with systems that control environmental contaminants and life support systems should be a high priority. The environmental monitoring and control program and the advanced life support program need to directly address the necessary synergy between monitoring/control issues and advanced life support technologies. Therefore, the plans for environmental monitoring and control and the advanced life support programs should be developed in a cohesive and complementary fashion. The environmental monitoring and control program should also work closely with programs that are developing requirements or standards in related areas, such as noise or radiation on long-duration missions, so that cross-over, or dual-use, technologies can be more readily identified. At a minimum, those elements of the environmental monitoring and control program that may have some bearing on radiation protection and noise mitigation should be identified.

Finding. The continuous interaction and communication between toxicologists and microbiologists, physicians, advanced life support engineers (developing processor requirements), and engineers and scientists responsible for monitoring and control technologies are critical. Interaction with engineers in the other human support programs is also critical.

A key to the success of the EMC program is maintaining a continuous interface with scientists focusing on various health and human factors issues that may be associated with spaceflight, as well as with those engineers responsible for designing, developing, and applying new monitoring and control technologies. Such interaction should begin in the initial planning phase of the process so that an understanding of the relevant scientific data and technologies can be used for future technology development and criteria for prioritizing certain scientific goals and missions can be established. This will help planners ensure that necessary research and testing will be identified and that resources will be available to accomplish the tasks. This interaction will help ensure an adequate, systematic knowledge base, which will be useful for designing critical systems that will operate efficiently and reliably in space. EMC needs to aggressively encourage such interactions among other components of the HEDS Enterprise. The effectiveness of this interaction needs to be periodically reviewed by experts from other field centers, industry, and academia.

Recommendation 3-15. NASA should develop a program for personnel exchanges or regularly scheduled exchanges of information between the environmental monitoring and control program and the three other programs in the OLMSA Advanced Human Support Technology Program.

Finding. NASA needs to coordinate research goals and accomplishments with other government agencies, such as the U.S. Department of Energy, the National Institutes of Health, the National Science Foundation, the Environmental Protection Agency and the U.S. Department of Defense, as well as with relevant academic and industrial participants.

Recommendation 3-16. NASA should consider including representatives from outside agencies and other key organizations on the advisory panel recommended above to help support the environmental monitoring and control program.

DUAL-USE TECHNOLOGIES

Summary Finding. There will be many technology transfer opportunities both into and out of the EMC program. NASA should seek to develop these opportunities as the program matures.

Finding. In order to fully capitalize on the array of technology transfer opportunities, NASA should seek to expand its partnerships with industry, academia, and

other government organizations engaged in the development and application of similar and complementary monitoring and control technologies. Many terrestrial-based closed or isolated environmental settings have requirements similar to those for spacecraft or planetary habitats. Dramatic advances in the monitoring and control of technologies operating in restricted environments, e.g., medical facilities, mining operations, submarines, and “sick buildings,” may be relevant to the space program and vice versa. For example, the miniaturization of monitoring technologies could lead to terrestrial applications, such as inexpensive, home-based contaminant monitors. The development of new, sensitive biomarkers of exposure and effects could be used to monitor humans in a variety of potential exposure situations on Earth.

Recommendation 3-17. NASA and the environmental monitoring and control program should continue to interact with academia and industry, as well as with other government agencies, for the transfer of useful technologies and to seek opportunities for collaborative efforts in the planning and financing of the environmental monitoring and control program. However, technology that addresses issues directly related to crew safety, and not “spin-offs,” should be the primary driver of the program. NASA should also strive to work with other government agencies that fund research in related areas, such as the Occupational Safety and Health Administration, the National Institute for Occupational Safety and Health, the Department of Defense, the Department of Energy, and the Environmental Protection Agency.

REFERENCES

- NASA (National Aeronautics and Space Administration). 1996a. Advanced Environmental Monitoring and Control Program: Strategic Plan. Washington, D.C.: NASA.
- NASA. 1996b. Advanced Environmental Monitoring and Control Program: Technology Development Requirements. Washington, D.C.: NASA.
- National Research Council (NRC). 1996. Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants. Vol. 2. Committee on Toxicology, Board on Environmental Studies and Toxicology. Washington, D.C.: National Academy Press.
- Stafford, Thomas P., et al., 1991. America at the Threshold: America’s Space Exploration Initiative. Washington, D.C.: White House Office of Science and Technology Policy.

4

Extravehicular Activity Systems

INTRODUCTION

Extravehicular activity (EVA) is essential to conducting complex work outside the pressurized volume of a crewed space vehicle or planetary base. EVA equipment consists of: the spacesuit itself; the primary life support system (PLSS), which provides the suit with pressurized oxygen and ventilation while removing carbon dioxide, water vapor, and trace contaminants; thermal conditioning; and the tools (including robotic tools) that enable the EVA crewmember to accomplish the necessary tasks. Taken together, the suit and life support system are called the extravehicular mobility unit (EMU).

An EMU is a unique design challenge because it is a miniature spacecraft that must sustain human life. Many space engineering disciplines are required to provide the needed independent life support, mobility, and communications. For the ISS, the EVA system may even incorporate a miniature propulsion system, the Simplified Aid for EVA Rescue (SAFER), which can be attached to the EMU.

The earliest U.S. spacesuits, for the Mercury and Gemini programs, were adaptations of the full pressure suits used for military aviation. They were air cooled, provided minimal mobility, and were only designed to permit the astronaut to operate spacecraft controls in the event of cabin depressurization. The first U.S. EVAs were performed from the Gemini spacecraft using this type of suit, with life support provided through an umbilical. However, limited mobility and the use of air-cooling greatly limited the effectiveness of these suits. A better suit was clearly needed for EVAs on the lunar surface.

The Apollo EMU was a great step forward. Mobility of the joints was improved, and the helmet was replaced with a dome-type helmet inside which the head could move freely, which increased the field of view. These new suits were

composed mostly of fabric and other soft materials and were custom fitted to each astronaut. The PLSS was back-mounted and completely independent of the spacecraft. An important new feature was the improved cooling system; the astronaut wore a liquid cooling garment (much like long underwear with tubing throughout the fabric) through which water was circulated, absorbing body heat and rejecting it through the primary heat sink, a sublimator in the PLSS. The Apollo EMUs met the requirements for a crewmember operating outside the confines of the Lunar Module spacecraft.

The current Space Shuttle EMU consists of a spacesuit assembly (SSA) and an integrated PLSS. The SSA is made of multiple layers of fabric and other flexible materials attached to a fiberglass unit called the "hard upper torso." The hard upper torso is the primary structural member of the SSA; the helmet, arms, lower torso assembly, and PLSS are all mounted to it. The PLSS maintains a pressurized 29.6 kPa (4.3 psi), 100 percent oxygen environment for breathing and ventilation. The helmet protects the crew member against ultraviolet light and provides light attenuation. The EMU also provides some protection from ionizing radiation and micrometeoroids. The PLSS controls the suit pressure, makes up losses from leakage and metabolism, circulates ventilation gas and cooling water to the crewmember, and provides power, communications, and caution and warning systems. The PLSS also removes carbon dioxide, water vapor, and trace contaminants released into the ventilation stream by the crewmember. The spacesuit gloves are the crewmember's interface with virtually all of the equipment and tools he or she uses. The EMU gloves include a pressure bladder, a restraint layer, and a thermal micrometeoroid garment outer layer. The spacesuit and life support system has a mass of approximately 118 kg (260 lb.) when fully charged with consumables for EVA. Tools contribute additional mass. EMU support equipment stays in the Space Shuttle airlock during an EVA; the primary functions of this support equipment are to replenish consumables and to assist the crew member with donning and doffing the EMU.

For the precursor to the ISS, Space Station Freedom (SSF), a new zero prebreathe suit was initially envisioned.¹ This suit was to be maintainable in orbit by the crew and last for one year of uses, i.e., up to 52 EVAs, without ground maintenance. This new EMU was to reduce the use of consumables, and would have necessitated rechargeable systems for cooling and CO₂ removal on the space station. In 1989, The EVA Commonality Study (Hoffman et al., 1988) concluded

¹When the human body is exposed to a sudden decrease in ambient pressure (for instance, from a 70.3 kPa [10.2 psi] cabin pressure to the 29.6 kPa [4.3 psi] of the EMU) nitrogen dissolved in the bloodstream and body tissues comes out of solution during decompression. This can create tiny bubbles and the potential for decompression sickness, often colloquially referred to as "the bends." The symptoms associated with decompression sickness run the gamut from mild joint pain to paralysis, coma, and death. In order to prevent this, the astronaut must purge nitrogen from his or her tissues before entering the low-pressure environment of an EMU. This is often done by having the astronaut "prebreathe" pure oxygen.

that the current Space Shuttle EMU, with enhancements, could meet the requirements on SSF. This initiated a program of gradually updating the Space Shuttle EMU to extend the number of uses between ground maintenance cycles. Plans call for the current EMU to be used on the ISS 13 times before being returned to Earth for maintenance, and the EMU has been certified for up to 25 uses. Rotation of EMUs from Earth to the ISS will occur during scheduled resupply missions, and will be coordinated to meet the requirement for as many as 52 EVAs per year.

TECHNICAL AND SCIENTIFIC TOPICS RELATED TO EXTRAVEHICULAR ACTIVITY SYSTEMS

Outstanding technical issues and design trade-offs that continue to need attention for the development of advanced EMUs include: interior pressure levels; gloves that provide improved manual dexterity; enhanced mobility and locomotion capability; easy on-orbit maintenance; mass reduction; increased service life; improved environmental protection (including protection from dust on planetary surfaces and space debris in orbit); visual displays and other human factors concerns; and regenerable, low-mass life support systems. EMUs for planetary use must also be designed for improved locomotion, with particular attention to lower body mobility in partial gravity. Teleoperated end effectors that complement or take the place of gloves are also worthy of consideration.

The current Space Shuttle EMU, which will also be used on the ISS, operates at 29.6 kPa (4.3 psi). Certain measures are necessary to allow an EVA crew member to go from the normal Space Shuttle pressure of 101.3 kPa (14.7 psi, which is equal to sea-level atmospheric pressure on Earth) to the EMU pressure in order to avoid decompression sickness. In general, measures to avoid decompression sickness either (1) reduce the amount of dissolved nitrogen in the body by having the astronaut breathe pure oxygen or another gas mixture lacking nitrogen for an extended period of time (denitrogenation via "prebreathe"), or (2) reduce the magnitude of the percentage change in pressure associated with the transition from a higher spacecraft pressure to a lower EMU pressure.

Current NASA procedures call for operating the Space Shuttle at sea-level pressure and for temporarily lowering the pressure to no less than 70.3 kPa (10.2 psi). This means that the only measures presently available to avoid decompression sickness are those using denitrogenation strategies. Present SSA and glove technologies do not permit a high enough internal pressure for the SSA to keep the percent reduction in ambient pressure to a level that reduces the probability of decompression sickness to an acceptable level. Studies have been conducted to evaluate increasing pressure for the current EMU.

Early spacesuits were constructed primarily of fabric and other "soft" materials, whereas current spacesuits include hard components (metal, composites, etc.). The Space Shuttle EMU is a hybrid of fabric and hard components, and

future EMUs are likely to be similar in this respect. Fabric components historically have offered advantages, such as lower mass and more sensory feedback to the crewmember. The use of rigid materials in components, like metals and fiberglass, are advantageous in that their engineering properties are well understood, and thus can contribute to ensuring greater control over quality and reliability.

The joint mechanics that govern suit mobility depend in part on the characteristics of the components that bound the interior volume. With fabric components, the interior volume changes slightly during crew motion; with rigid components, the volume remains constant. Flexing the fabric components reduces the interior volume, causing the interior pressure to increase. This causes the crewmember to use more force to flex suit components than is required for suits with constant-volume (rigid) components, which may contribute to fatigue. Current rigid, constant-volume components have no springback characteristics (i.e., no “memory”) in the joints, so no force is required to maintain position once a joint is flexed.

Under pressurization, fabric components can support part of their own weight when used on a planetary surface. This weight-bearing capability is considered by some to be advantageous for planetary EVA spacesuits because it offers greater latitude in the design of the life support system and can make it easier for the crewmember to stand. Future bearing technology for use in EMUs with rigid components may also incorporate mechanical friction or springback mechanisms to help support their own weight. EMUs for future planetary use must provide for locomotion in partial gravity environments, suggesting the need for hip and ankle joints, which were features of the Apollo EMU.

The prolonged service life of SSA and PLSS equipment is of paramount importance for future ISS and planetary EVAs. Among the key factors for future EMU designs will be ease of on-orbit maintenance and cleaning. For example, Space Shuttle EMU maintenance can entail hundreds of hours of seam inspection, pressure leak checks, and PLSS processing after each Space Shuttle mission (0 to 3 EVAs). The frequency of ground maintenance will change because the EMU has been certified for up to 25 EVAs for ISS without ground maintenance. Storage space for spare parts aboard the ISS or in a planetary base will probably be limited, and neither is likely to be able to afford frequent resupply of EMU parts.

Crew members must be protected from harsh space or planetary environments during EVAs. For use on planetary surfaces, EMUs must have robust components and designs that are tolerant to continuous exposure to planetary dust. Planetary dust is composed of small, gritty mineral particles that might damage suits or the interiors of space habitats over the long term if special measures are not taken.

Advanced PLSS designs must be regenerable, low in mass, and easily maintainable. The heat rejection systems currently used for thermal control of an EVA astronaut consume between 0.5 and 1.0 kg of water per hour. Future mission scenarios requiring extensive EVAs will be penalized by the need for resupply;

therefore, minimal or no consumption of mass is desirable. Currently available regenerable thermal control systems are generally too large for the types of future missions being proposed. Self-contained thermal control systems without rejection to the environment (e.g., a fusible heat sink) are attractive for future mission scenarios.

Atmospheric control within the EMU involves providing a breathable atmosphere, removing waste gases such as CO₂, controlling humidity, and removing trace gases and particulates. The atmospheric control subsystems must: minimize the use of expendables; minimize mass and volume by efficient packaging; reduce the need for maintenance through the use of robust designs; provide for on-site regeneration and repair; and maintain the atmosphere within desired ranges. Oxygen systems might be enhanced by considering cryogenic or chemical techniques for supply and storage. New technologies for removing CO₂, as well as for controlling heat, humidity, and trace contaminants, look promising for planetary EVA. Real-time environmental monitoring systems and innovative display and vision systems may be incorporated, as well as improvements in battery technology. An evolvable design is presently advantageous, and commonality between the EVA life support systems and the vehicle/station life support systems should be sought whenever appropriate.

The factors of reliability and maintainability will assume immense importance as U.S. human spaceflight advances to extended operations in deep space, on the lunar surface, and on Mars. There will be no rapid return capability; resupply will be slow, difficult, and expensive; refurbishment now accomplished on the ground will have to be accomplished on site.

The development of hardware to meet the needs of missions like these must begin with a search for technologies that meet the basic requirements. A prime example in EVA systems is a suit cooling system with minimal or no use of consumables. Innovative chemical or physical methods for heat removal must be sought and tested, with the goal of proving the feasibility of one or more techniques for full development. This work can—and should—be done in advance of a commitment to the planetary program. Account also must be taken at this early stage of the harsh environments in which the operational system must function—loads, temperatures, pressures, radiation, dust, and so forth.

When hardware development begins, systems engineering is used to develop the actual configuration—defining the requirements in detail, specifying the final operating environments, and allocating functions to various parts of the system. Then hardware development can begin, and the desired characteristics of reliability, redundancy, and maintainability can be designed into the hardware and rigorously tested.

This report only addresses NASA's technology development programs, and not the hardware development phase. Nevertheless, in selecting and evaluating new technologies, priority must be given to those technologies with the potential to function reliably in operational systems.

PROGRAMMATIC TOPICS RELATED TO EXTRAVEHICULAR ACTIVITY

NASA Programs

In 1989, President Bush announced the Space Exploration Initiative (SEI), a long-range national goal for a return to the Moon and a human landing on Mars. One of the results of the SEI was an increased focus on advanced EVA systems. The SEI has since disappeared, but NASA's long-term plans, as stated in the 1996 NASA Strategic Plan, still call for missions beyond LEO.

In early 1996, a new EVA Project Office was established at JSC to coordinate all EVA work within NASA. This office has been given responsibility for the Space Shuttle and ISS EVA operations, for the development of all EVA hardware, and for advanced EVA R&D. All OLMSA and OSF funding for these purposes is to be directed by this office. The organization chart for the EVA Project Office is shown in Figure 4-1. One of the stated goals for the Advanced EVA R&D branch of this office is to manage the development of technologies for future EMUs. At the end of the committee's study, the Advanced EVA R&D branch had begun to consult with experts and other interested parties from government, industry, and academia to establish EVA requirements based on an approved set of reference missions, establish a technology road map, and set funding priorities. The office has stated that it will seek international cooperation and will work closely with the space medicine community in setting physiological parameters.

The research and technology goals of the Advanced EVA R&D branch currently concentrate on three potential uses for new technologies:

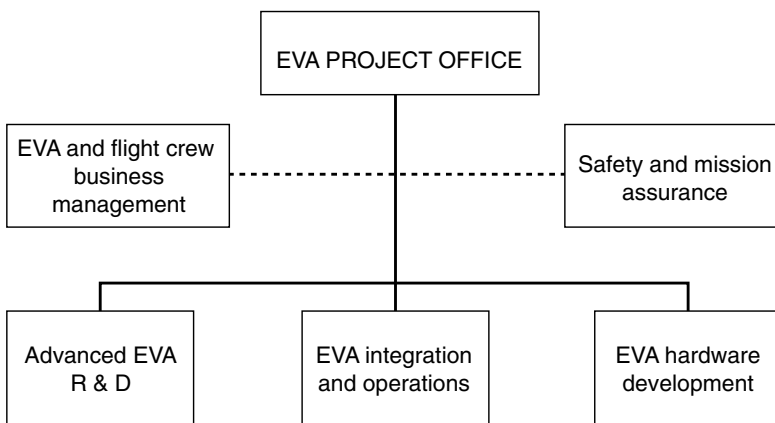


FIGURE 4-1 NASA EVA Project Office organizational chart. Source: NASA.

- a lunar surface EMU adapted for locomotion on the Moon, with an extremely simple, lightweight PLSS that relies on the availability of abundant oxygen from in situ lunar resources
- a Mars surface EMU adapted to that planet's colder environment, higher power requirements, and the presumed availability of hydrogen
- improvements to the current Space Shuttle and ISS EMU

Advanced R&D for EVA has suffered because there are no human lunar or Mars missions currently planned and because NASA has decided to use the Shuttle EMU for the ISS. NASA recognizes that its long-term goals will require improvements in EVA technology, but in recent years NASA's priority for EVA technology development has been low. Those who have been responsible for EVA R&D, at JSC and ARC, have attempted a number of times to stimulate the development of technologies needed for future programs. In 1993, the "Fast Track" zero-g EMU was proposed to OACT, but development was not funded. Later in 1993, after the Russians were made partners in the ISS, a common EMU between the U.S. and Russia was proposed at the Gore-Chernomyrdin level, but funding was short lived. In 1994, after responsibility for advanced EVA technologies was transferred to OLMSA, the "X-Suit" project met a similar fate. In 1995, the Office of the Chief Engineer at NASA headquarters recommended a next generation EMU development program, but it too was canceled. Like Alice's Red Queen,² EVA has been running faster and faster, while staying in the same place.

Since 1995, NASA has been conducting internal studies of a human lunar return mission. The recent findings of possible traces of life in an Antarctic meteorite, thought to be of Martian origin, may increase support for sending an expedition to Mars in the foreseeable future. But today, NASA's goal of planetary exploration has little substance.

Currently Funded Research

The absence of a specific mission beyond the ISS is reflected in the history of funding for EVA advanced technology in recent years. In the mid-1980s, the Space Station Freedom program funded EVA research to make the station EMU feasible. Funding was about \$8 million dollars in 1987. This figure dropped to \$2.5 million in 1991 and has zigzagged since then with the false starts described above (see Figure 4-2). The amount for 1996 was approximately \$2 million for advanced technology R&D, out of a total EVA budget of approximately

²This principle was proposed by the evolutionary biologist L. van Valen, and is based on the observation to Alice by the Red Queen in Lewis Carroll's *Through the Looking Glass* that "in this place, it takes all the running you can do to keep in the same place." The principle says that for an evolutionary system, continuing development is needed in order to maintain its (relative) fitness.

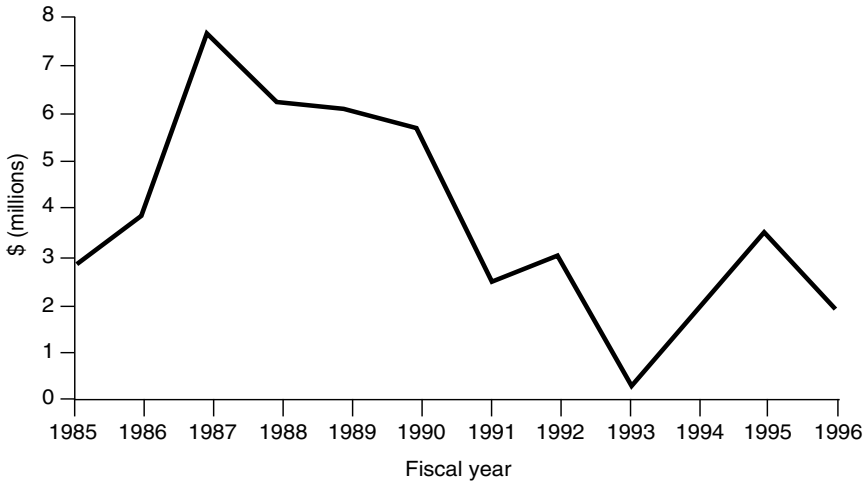


FIGURE 4-2 NASA funding for advanced EVA systems, 1985 to 1996. Source: NASA.

\$100 million dollars. (The large majority of the \$100 million was spent on operations for Shuttle and ISS EVA.)

Since 1994, most of the funding for advanced EVA R&D has come from OLMSA through the NRA process. OLMSA is now responsible for “human support” technologies in addition to its traditional responsibility for life sciences research and operations. This gave rise to the current situation where OSF is responsible for evolutionary capability improvements to the EMU, while OLMSA is responsible for long-term technology development. Other sources of funds for advanced EVA R&D are the SBIR program, center director discretionary funds at JSC, and IR&D funds from industrial companies. Tables 4-1 and 4-2 list the FY96 projects that have been proposed or are under way at JSC.

The objective of the projects described in Table 4-1 is to provide engineering solutions to real EVA problems. But many of these projects have not been funded, and the requests for future year funding greatly exceeds the current budget level. Despite the fact that for projects like these “faster is cheaper,” many of these projects are stretched out from year to year due to inadequate and inconsistent funding. Some of the SBIR projects appear promising, but because EVA managers have not been involved in the final selection process (the SBIR program is run by another NASA office), there has been a tendency for these projects to be less than optimally focused on future NASA requirements.³ There are very few projects from universities (only one funded project) on the list.

³Recent management changes indicate that EVA management staff are now involved in SBIR and NRA funding decisions.

TABLE 4-1 Current Evolutionary (or Zero-g EMU) Technology Projects

Project Description	Funding level (in \$k) in FY96	FY the project would be completed if fully funded	Total funding (\$k) necessary to complete project
Dexterous gloves	50	98	700
Mark III suit weight reduction	0	98	350
Twin-bed regenerable CO ₂ removal	150	97	300
Membrane CO ₂ removal	0	99	300
Carbonic anhydrase CO ₂ removal	0	99	300
Automatic cooling algorithm	0	98	80
Composite water radiator	50	97	100
Membrane water boiler cooling system	140	97	160
Freezeable radiator	0	98	400
Freezeable radiator (SBIR)	0	96	70
Modular maintainable PLSS	0	97	20
Oxygen ejector circulation	0	98	20
Miniaturized air bearing fan electronics	0	98	120
Membrane humidity control	44	96	561
Small optical display	SBIR	97	700
Direct projection display	SBIR	96	70
Built-in helmet display	SBIR	96	70
Robust water pump	SBIR	96	500
Piezoelectric water pump	SBIR	96	500
Fluorescent gas sensors	SBIR	97	700
Totals	434		6,021

HIGH PRIORITY AREAS FOR EXTRAVEHICULAR ACTIVITY TECHNOLOGY RESEARCH AND DEVELOPMENT

Summary Finding. The NASA OLMSA program for developing advanced technology for EVA systems has recently been reorganized and does not yet have official priorities. The handful of advanced technology development projects in the present program are primarily directed at making evolutionary improvements to existing systems. Quantum advances through revolutionary technology development are not being vigorously pursued.

Finding. The first priority for developing advanced technology for EVA systems should be to help enable planetary surface missions—lunar or Martian. A good advanced technology development program for EVA should also improve the EMU and related systems that will be used on the ISS and increase the productivity of ISS maintenance and related activities.

TABLE 4-2 Current Revolutionary (or Lunar/Mars) Technology Projects

Project Description	Funding level (in \$k) in FY96	FY the project would be completed if funded	Total funding (\$k) necessary to complete project
Planetary dust protection	0	97	50
Mars thermal protection	0	97	75
Planetary mobility of ISS and Mark III suits	0	98	200
Ionization removal of CO ₂ and H ₂ O	0	99	200
Microencapsulated materials for cooling	0	99	200
Metal hydride thermal control system	80	96	516
Variable conductance heat rejection	0	99	300
Increased thermoelectric module efficiency	0	97	10
Convection/radiation radiator for Mars	0	00	400
Lightweight fuel cell	0	98	300
Minimum mass and volume airlock	0	97	40
Liquid oxygen PLSS	0	98	500
Variable pressure O ₂ regulator	0	00	500
Carbon fullerene O ₂ storage	0	99	250
Mars atmospheric pressure analysis	0	97	40
Totals	80		3,581

Recommendation 4-1. Improvements in areas where current technologies can meet mission requirements should be given lower priority. The emphasis should be placed on developing techniques that have the potential to make large improvements. In general, in the absence of a requirement for a new extravehicular mobility unit, the first priority of research and development should include the development of components and subsystems. The second priority should be systems integration, testing, and the packaging of technologies in prototypes. Specific high priorities for extravehicular activity research and development include (not in rank order):

- achieving zero prebreathe capability
- reducing the total mass of extravehicular mobility units
- minimizing consumables through advanced subsystem designs (thermal control, CO₂ removal, humidity control)
- enabling adequate mobility on planetary surfaces
- protecting against dust contamination
- designing to fit multiple crewmembers
- increasing reliability and maintainability of extravehicular mobility units (e.g., possibly by using modular components and subsystems)
- improving gloves and end-effectors

Finding. Lower spacecraft/planetary base operating pressure would make the transition to EVA faster by eliminating the need for prebreathing (denitrogenation) and the risk of decompression sickness. Lower operating pressure would also have other beneficial effects for the space vehicle, such as requiring less strength in the structure, reducing atmospheric leakage to space, etc. Lower pressure would impose some requirements for heat rejection, etc., that will need to be kept in mind for the design of hardware, such as computers and compressors. On the ISS and Space Shuttle, sea-level pressure has been required to allow for the comparison of biomedical and biological data collected on orbit with data taken on the surface of the Earth.

Recommendation 4-2. For a mission to Mars or a long-duration lunar base, comparison of biomedical and biological data collected in space with data collected on the surface of the Earth will not be as important. Therefore, the requirements for sea-level operating pressure should be reconsidered.

RELATIONSHIP BETWEEN THE EXTRAVEHICULAR ACTIVITY PROGRAM AND THE SUCCESS OF FUTURE NASA MISSIONS

Summary Finding. Human planetary exploration is a stated future mission goal for NASA and, despite the current lack of a specific human mission beyond the ISS, NASA recognizes that improved EVA systems will be required to carry out its long-term goals.

Finding. EVA is an essential capability for planetary exploration. For a long-term planetary stay, EVAs will be required for the external maintenance of laboratories, habitats, power systems, thermal control systems, manufacturing facilities, and rovers, as well as for sample collection. The committee considers that achieving EVA capability for planetary missions is feasible, but not all of the engineering solutions needed are known, and new technologies will be required. The EVA technology development initiatives currently being pursued by NASA do not represent a complete program for producing new technology for a lunar or Mars EMU, even according to the cautious schedule projected in the 1996 NASA Strategic Plan.

Recommendation 4-3. Despite the consensus that there is no need for a new extravehicular mobility unit in the near future, NASA should identify and plan to develop the new technologies that will be crucial to the development of a lunar or Mars extravehicular mobility unit for use in the 2010 to 2020 time frame, at which time a new extravehicular mobility unit is likely to be necessary.

PROGRAM OBJECTIVES AND MILESTONES

Summary Finding. Despite many studies, reviews, and proposals over the last several years, the advanced EVA technology program has lacked high-level

support, and NASA does not currently have specific technical objectives or milestones for the development of advanced EVA technology.

Finding. Previous planning documents (Callaway et al., 1994; Webbon, et al., 1994; NASA, 1994; NASA, 1995) show that NASA has a good understanding of the technology required for future missions. However, it is not clear that the program is currently addressing the most important needs. Neither schedules nor clear prioritization of technology needs and requirements, both of which are necessary to make prudent budgetary decisions, were available.

Recommendation 4-4. The new EVA Project Office should set specific, integrated technical objectives (with tasks assigned and scheduled) for the projects it sponsors and should work to transfer technological improvements as enhancements to the present extravehicular mobility unit where appropriate.

OVERALL SCIENTIFIC AND TECHNICAL QUALITY

Summary Finding. The NASA/industry/university EVA community is competent and capable of developing the technology for productive, cost-effective EMUs for microgravity, lunar surface, and Mars surface exploration. But until recently, interaction has been limited.

Finding. Most of the current work sponsored by NASA in advanced EVA technology is being done in house, with limited industry, and very limited academic, involvement. This has restricted the awareness of complementary resources that might be available outside NASA. Many new technologies and findings by NASA related to EVA technology have not been disseminated to the external engineering and scientific communities. Few papers have been published describing NASA's ongoing work in this area.

Recommendation 4-5. NASA engineers and scientists working on extravehicular activities need to be encouraged to expand their associations with industry and universities, as well as with professional societies, through publication and attendance at national and international meetings. The advanced extravehicular activity program should also increase the participation of industry to ensure the best use of community resources and ensure that the knowledge base is present in industry to support NASA's long-term goals.

PROGRAM REQUIREMENTS

Summary Finding. Studies in the last few years, as well as years of evolutionary technology improvements, indicate that the NASA/industry/university community understands the basic requirements for improvements in EVA technologies.

Finding. The current advanced EVA program has not identified a clear set of specific requirements to be used as a basis for the program. Some technologies are unique to EVA systems; the vacuum, thermal, and radiation operating environments impose unique design requirements on the PLSS, gloves, and spacesuits. However, some features of EVA suits and systems are not unique, but are based on technologies that are more likely to be advanced by non-NASA researchers, or even by NASA researchers not focusing on EVA applications, e.g., battery technology. Distinguishing between technologies unique to EVA needs and technologies that are not can be aided by the use of reference missions.

Recommendation 4-6. Extravehicular activity technology development requirements should be predicated on carefully developed reference missions to drive out the functional requirements. (Good design reference mission studies already exist and can be adapted and used by all related groups. The program should not spend significant resources on developing new reference missions but should focus its technology development efforts on unique extravehicular activity technologies.)

Recommendation 4-7. While NASA managers have already established strong lines of communication with the Wright Patterson Air Force Base Armstrong Laboratory, the program should also aggressively reach out to academic, government, and industrial sources for ideas and solutions. NASA should conduct a comprehensive search for suitable technologies that are not NASA-unique and should include active collaborations and consideration of organizations and agencies that are not generally associated with extravehicular activity research but that have relevant areas of expertise, such as the Bureau of Mines, the National Institute of Occupational Safety and Health, or the U.S. Navy.

Recommendation 4-8. NASA should direct its limited resources for extravehicular activity research on unique areas where advances are unlikely to be made by others. Outside of NASA, few organizations will be working on the design of portable life support systems, gloves, and suits for use in a space environment, while many will be working on advancing battery technologies.

PROGRAM DIRECTION AND ORGANIZATION

Summary Finding. The new EVA Program Office at JSC, which now controls all NASA work related to EVA (including for the Space Shuttle and ISS), appears to have an organizational structure suited to the task. Consolidating all EVA work was a prudent step.

Finding. The current OLMSA program for developing advanced technology for EVA systems, approximately \$2 million in FY96 (of approximately \$100 million

spent annually on all NASA work related to EVA), is clearly too small to foster many significant technology breakthroughs for EVA systems. Furthermore, the committee was informed by program management that the first priority of the EVA Project Office is to enable present and near-term mission operations rather than to develop new technology for advanced EVA systems. This is understandable, especially considering the demands that will be associated with assembling the ISS. However, concentrating on immediate operational demands may have a deleterious effect on research responsibilities, which are also the charge of the EVA Project Office. Funding for EVA technology development appears to have four sources: OLMSA (primarily from NASA Research Announcements); the SBIR Program; the JSC director's discretionary funds; and IR&D funds from industry. Inappropriate duplication of effort does not seem to be prevalent.

Recommendation 4-9. NASA should make special efforts as it combines operations and advanced technology research under a single organization to ensure that advanced research and development receives consistent support in an organization whose top priority is to meet NASA's near-term mission needs.

Recommendation 4-10. The Advanced EVA Technology Project Office at the Johnson Space Center should increase efforts to include universities and industry in its programs (small companies have access to the program through the Small Business Innovative Research Program). The roles and tasks of all groups (NASA and non-NASA) performing extravehicular activity research and development sponsored by NASA should be defined. NASA should also make special efforts to take advantage of industry's willingness to spend its own funds on relevant research and development projects.

SYNERGISM WITH OTHER PROGRAMS

Summary Finding. Some new and proposed cooperative projects appear promising, but there is still no apparent regular exchange of information between the EVA program and relevant work in areas such as robotics and human factors.

Recommendation 4-11. NASA's extravehicular activity systems and robotics technology development groups should increase their cooperation to maximize the efficiency of resources for accomplishing extravehicular tasks. One area where cooperation could be increased in the near-term to good effect is in maintenance and related activities of the International Space Station. New technologies and subsystems could also be tested on the International Space Station.

Recommendation 4-12. NASA should increase cooperation between the designers of extravehicular mobility unit hardware and the space human factors, advanced life support, and environmental monitoring and control communities

throughout the system design process (“concurrent engineering”). A combined effort between the EVA Project Office and the space human factors program should investigate the interaction between the human operator and the extravehicular activity system; the study should include anthropometry, suited and unsuited human performance, and human/machine interaction.

DUAL-USE TECHNOLOGIES

Summary Finding. In the past, some EVA technologies have found use in other areas. For example, materials for liquid cooling garments and space suits have been used by firefighters and by people with an impaired ability to tolerate heat (such as some cases of dysautonomia and multiple sclerosis). It is possible, but not yet clear, that new portable life support technologies may find similar applications.

Recommendation 4-13. Technologies should be transferred to applications outside of NASA as appropriate, but this should be a dividend from a good project and not become a major emphasis of such a small technology development program.

REFERENCES

- Callaway, R., et al. 1994. EVA Assessment Report: Spring 1993–Fall 1994. The Purple Team, National Aeronautics and Space Administration. Washington, D.C.: NASA.
- Hoffman, A., I. Isback, and W. Ayotte. 1988. NSTS/SS EMU Commonality Study. Hamilton Standard. Unpublished report.
- NASA (National Aeronautics and Space Administration). 1994. Advanced EVA Systems Program Plan. Life and Biomedical Sciences and Application Division, Office of Life and Microgravity Sciences and Applications. Washington, D.C.: NASA.
- NASA. 1995. X-Suit Study Team Report, December 1994–May 1995. Washington, D.C.: NASA.
- Webbon, B., M. Rouen, and R. Callaway. 1994. Advanced EVA Systems Project Plan, Extravehicular Activity Systems Project. Washington, D.C.: NASA.

5

Space Human Factors

INTRODUCTION

Human factors focuses on the role of humans in complex systems, the design of equipment and facilities for human use, and the development of environments for comfort and safety. Human factors research is conducted in several technical or academic subject areas, including ergonomics, biomechanics, anthropometrics, workload, and performance. Research on human activities in space is called space human factors (SHF) research. The mission of OLMSA SHF personnel is to understand the impact of SHF on crewed missions, to collect and interpret relevant human factors data in support of space and aerospace missions, to provide operational support for ongoing missions and mission planning, and to make available human factors data, research, and experimental studies to the aviation and aerospace communities at large.

Although human factors work is carried out at many NASA sites, the committee limited its analysis to the two sites where SHF research is funded by OLMSA: JSC and ARC. Standard “terrestrial” human factors concerns were not addressed, although it appears that NASA is generally aware of and responsive to human factors needs.

As with all things related to SHF, when humans participate in long-duration spaceflight, unknowns could affect planning. For example, a truly revolutionary propulsion system that would significantly shorten the time crews were exposed to microgravity, isolation, and radiation would vastly simplify the SHF problems. Likewise, the emergence of dramatically autonomous systems might affect crew size, training, and workload. It appears that the only safe assumptions at this time are (1) that available spaceflight technology will improve incrementally over the next two decades, and (2) that long-duration crewed missions will not be

influenced as much by new technology as by the inherent limitations of the human organism and its ability to survive the concomitant physical rigors, intellectual challenges, and psychosocial interactions in space. Accordingly, the committee's assessment of the present state of SHF research focuses on its application and applicability to future space missions, especially lunar surface habitation and an eventual Mars mission in the years 2010 to 2020.

TECHNICAL AND SCIENTIFIC TOPICS RELATED TO SPACE HUMAN FACTORS

By definition, the participation of humans in space exploration makes safety and the ability to perform physically and psychologically for prolonged periods integral parts of all planning. Areas where human factors information and expertise are relevant include spacecraft design, life support systems, and extravehicular suits and systems. Previous NRC reports have repeatedly stressed that there is a major difference between "short-term" and "long-term" human spaceflight (NRC, 1993, 1994). Almost all U.S. experience to date has been limited to "short-term" missions and indicates that, for the most part, short-term exposure is reasonably well tolerated. However, on voyages of the duration associated with a mission to Mars using chemical propulsion (about 600 to 1,000 days)¹ physiological and psychological *terra incognita* will be encountered, and no amount of "fully informed consent" or "volunteerism" can vitiate the need for serious scientific study of related problems and the pursuit of realistic solutions in order to manage intelligently the attendant risks. The Russian space program has shown that stays in space of more than 400 days are possible, but missions with a single crew kept together for more than 600 days are well beyond anyone's experience to date.

Based on information in NASA's Long Term Plans in Human Exploration (NASA's "official plans" for the future), the committee assumed that a Mars mission in about 20 years is a realistic goal. This hypothetical future beyond the ISS is divisible into three separate, but intimately related, phases: (1) lunar surface habitation; (2) transfer to and from Mars; and (3) Mars habitation. Based on the requirements for long-duration human missions, numerous topics of research and concern should be addressed. Some of these topics are shown in Table 5-1.

Research areas identified by the SHF program include:

- perception—mathematical models of human perceptual systems: vision, pattern perception, audition, motion perception, spatial understanding, and haptics
- cognition—understanding situational awareness, modeling cognitive workload, and evaluating usability and effectiveness of human-automation interfaces

¹Sample scenarios for "short-duration" and "long-duration" human missions to Mars are provided in *America at the Threshold: America's Space Exploration Initiative* (Stafford et al., 1991).

TABLE 5-1 Topics of Interest to the SHF Program

Topic	Description
Communication	<ul style="list-style-type: none"> • Interfaces for mission communications among all participants, ground personnel, vehicles, etc., in a multiplicity of modes (audio, video, data, etc.) • Undistorted messages in the presence of delays and limited bandwidth
Human interaction with information and automation	<ul style="list-style-type: none"> • Interfaces with robotic systems • Interfaces for repair and maintenance procedures • Interfaces with a variety of automated and semiautonomous systems, such as science experiments, vehicle systems, landing controls, etc.
Data analysis and distribution	<ul style="list-style-type: none"> • Human interfaces for effective and efficient data presentation and analysis • On-line interpretation of data from multiple sensors in various formats, etc.
Design/development/testing/evaluation	<ul style="list-style-type: none"> • Human factors guidelines for tools, facilities, crew aids, fasteners, etc. • Vehicle and work place/operator stations designed for crew size and performance variability while mindful of safety and overall usability • Distribution of tasks between crew members and automation with respect to human performance and capabilities, both physically and cognitively
Safety	<ul style="list-style-type: none"> • Medical facilities and materials required for in-flight diagnosis, stabilization, and treatment • Safety analysis for appropriate cautions, warnings, and risk management • Designs to support safe maintenance, both routine and unusual • Exposure to and safe handling of hazardous materials
Module features	<ul style="list-style-type: none"> • Specific human factors requirements for mission-specific modules, such as effective controllers for robotic manipulators, perceptual capabilities for science experiments, crew member strength, reach, fit, or visibility, as required for mission execution, etc.
Tools and equipment	<ul style="list-style-type: none"> • Uniform, well-designed tool sets for manual and/or gloved (EVA) use • Sufficient tools to support planned and contingency tasks • Standardized procedures to minimize time of skill acquisition or task learning time • Logistics support to ensure that supplies and equipment are convenient and accessible • Special equipment needs for safe transport of ill or injured crewmembers
Work force characteristics	<ul style="list-style-type: none"> • Psychosocial considerations for crew composition, especially for long-duration missions • Group interactions and command structure
Workload and task characteristics	<ul style="list-style-type: none"> • Evaluate tasks and tools for optimal human performance • Determine and schedule appropriate fatigue countermeasures • Ensure expected crew performance is within known SHF bounds

continued

TABLE 5-1 *Continued*

Topic	Description
Habitability and work environment	<ul style="list-style-type: none">• Personnel requirements for sustenance, privacy, hygiene, etc.
Training	<ul style="list-style-type: none">• Training for effective group communications• Training for decision making• Training for infrequent tasks (such as the final Earth landing at the end of an extended mission)• Cross-training in multiple specialties
Mission support	<ul style="list-style-type: none">• Appropriate decomposition of tasks into automated and human-controlled components• “On-line” documentation of procedures• Monitoring of in-flight activity and performance
Maintenance and logistics training	<ul style="list-style-type: none">• Training for normal and unusual events
Crew performance	<ul style="list-style-type: none">• Designs incorporating human reliability data• Adjustments for circadian rhythm effects and sleep deficits

- human physical performance—data on, and models of, human strength, stamina, fatigue, and motor skills, especially in microgravity; performance monitoring techniques and countermeasures to impediments to successful task completion and to safety
- personal, interpersonal, and group dynamics—personality measures, performance monitors, performance predictors, effects of various command structures, minimization of conflicts, team decision making and cooperation strategies, inter-cultural issues, and evaluation metrics
- habitability—maximize physical and psychological health of crew considering food, clothing, privacy, noise levels, hygiene, sleep, recreation, and entertainment, with sensitivity to culture, language, and gender differences

Technology needs identified by the SHF program include:

- automation and information systems—interfaces to, and essential control of, robotic, teleoperated, and autonomous systems; data storage access and display techniques; automated assistance; fault management, diagnosis, and repair, including training for novel situations
- function allocation, scheduling, and workload—appropriate distribution of tasks between crew and automated systems, between ground personnel and crew, and among crew members; workload and performance monitoring and assessment; schedule planning and optimization

- communications systems—multimedia, multichannel communication technologies responsive to human perceptual characteristics; compression techniques, lag minimization, and speech perception
- anthropometrics and physical interfaces—evaluations of human-tool interfaces; virtual prototyping to accommodate human variability; and ergonomic analyses of tasks in microgravity
- training procedures and technologies—methods and evaluation metrics for training skills, decision making, coordinated team activities, and routine and unusual tasks; technologies for recognizing the need for and delivering training, as required by the mission

PROGRAMMATIC TOPICS RELATED TO SPACE HUMAN FACTORS

The goals of the approved OLMSA Space Human Factors Program Plan (NASA, 1995) are to:

- “Expand knowledge of human psychological and physical capabilities and limitations in space through basic and applied research, tests and evaluations . . .”
- “Develop cost-effective technologies that support integrating the human and system elements of space flight . . .”
- “Ensure that mission planners use SHF research results and technology developments to increase the probability of mission success and crew safety . . .”
- “Make NASA technology available to the private sector for Earth applications . . . [and] use new technologies developed by private industry where appropriate . . .”

The NASA mission in human factors is currently rather segregated into space and aeronautic components. In general, JSC has the charter to examine SHF issues related to the Space Shuttle, the ISS, and future long-duration space flight but concentrates almost exclusively on the Space Shuttle and ISS. ARC is engaged in work on aviation human factors (especially cockpit issues) and more basic research. There is little overlap or connection between the two centers. The overall impression is that they are targeting very different problem areas. JSC primarily functions as an operational problem-solver, where research questions are raised by experience or known difficulties or are driven by mission requirements. JSC SHF activities are primarily concerned with the “here and now” of space operations. ARC primarily operates as a research community, studying issues of perception, workload, and cognition that have been encountered during aeronautical flight. Occasionally, specific crew-related problems have been catalysts for investigations at ARC, and some interest was expressed in finding applications for research going beyond aeronautics into spaceflight and other fields.

The SHF program has been funded at slightly less than \$2 million in FY94, FY95, and FY96. This is enough to fund only a handful of projects (about 10 in 1996).

During calendar year 1996, NASA staff involved in the program from NASA headquarters, JSC, ARC, and KSC were drafting a requirements document for SHF based on projected human lunar and Mars long-duration space flights in the second decade of the twenty-first century. The committee observed some of these discussions and examined a preliminary draft, but the final document was not completed by the end of this study.

In general, SHF research and technology areas are very broad and open-ended, especially as compared to EMC and EVA. It is difficult to establish clear baselines, given the inherent variability of human performance, workload, and personality. Given such breadth, the committee was aware that some of these topics overlapped other NASA codes and divisions, especially with regard to workload, performance, training, and engineering. Nevertheless, the presence of the SHF program within OLMSA as a crucial component of crewed spaceflight is an acknowledgment that a human presence in space will require dedicated, significant, new research, technology development, and resource investments.

HIGH PRIORITY AREAS FOR SPACE HUMAN FACTORS TECHNOLOGY RESEARCH AND DEVELOPMENT

Summary Finding. Lunar/Mars crewed missions will require careful consideration of numerous SHF issues. But at the time of this writing, no SHF priorities had been established with regard to NASA's long-term goals. Thus, research should be refocused from generating pure knowledge toward concerted, coordinated efforts to achieve prioritized goals ("goal-oriented" research) for crew safety and the overall success of long-duration missions.

Finding. Currently, there are no established priorities for future human missions, which magnifies the problems associated with the lack of communication and coordination among projects. There is a general awareness that SHF issues and questions related to a mission to Mars or the establishment of a lunar or Mars base must be understood, but there is no apparent programmatic design to answer those questions.

Recommendation 5-1. Programmatic priorities should be based on mission requirements. All parts of NASA with expertise in space human factors should contribute to the development of these priorities and should allocate resources (staff, time, and funding) to facilitate coordination and communication of the program. In a program of this kind, which needs to address many open questions, the need for "goal-directed" research should take precedence over the traditional encouragement of "heart's-desire" research.

Finding. NASA has not dedicated significant resources to long-duration SHF issues. Topics such as life support appear to dominate NASA's thinking in

preparing technology for long-duration missions; but these missions will create unique physiological, psychosocial, performance, and cognitive requirements that must also be understood prior to launch. The emphasis on predictive models, physical and biomechanical models, and passive monitoring is uneven. Some programs are aggressively pursuing them, while others are concentrating on more descriptive models with minimal predictive power. Both predictive and system models will fit very well within the large-scale, integrated, concurrent engineering effort that NASA will have to make for long-duration missions.

Recommendation 5-2. Solving problems specific to NASA's goals for crewed, long-term spaceflight should be the prevailing factor in developing NASA Research Announcements in advance of seeking proposals, in screening proposals prior to peer review, and in the final selection of proposals. Top priorities for long-duration crewed missions should include:

- understanding crew interactions in sustained, isolated, microgravity (vehicle, lunar or Mars) environments
- human performance (both cognitive and physical) and decision making in sustained microgravity environments, including the development of decision support systems
- information management and communication needs, including the role and deployment of virtual environment aids for training, mission rehearsal, maintenance, and emergency or unusual situations
- automation and allocation of functions between humans and computers
- interaction with intelligent systems

Recommendation 5-3. NASA should increase emphasis on the development of predictive models. For example, predictive models can be important with regard to mental workload. Because much of the work in this area so far has been descriptive, the mental workload for a given task can be measured only as the task is actually being performed. This deprives engineers of information that would help in designing new systems in which interactions among humans, equipment, and the environment could optimize mental workload. Predictive models would provide engineers with an analytical tool for evaluating alternative designs in order to study and devise mechanisms to facilitate intellectual performance.

RELATIONSHIP BETWEEN THE SPACE HUMAN FACTORS PROGRAM AND THE SUCCESS OF FUTURE NASA MISSIONS

Summary Finding. No discernible work in the SHF program is directed at the long-term needs for the OLMSA program, i.e., no projects are specifically directed at issues unique to lunar or Mars missions. Some work in support of current missions may be indirectly applicable to future missions, but this is fortuitous rather than purposeful.

Finding. No current work at JSC is dedicated to the direct support of lunar/Mars SHF goals. The committee's investigation revealed that some of the tools (see below) being developed might support far-term, long-duration missions, but they were being developed strictly in support of near-term mission operational requirements. Their applicability to the future would be fortuitous, not planned. Motivated individuals and teams are exploring possible ways they might impact future missions, but their success would be in spite of the system, not because of it. Some examples of promising ongoing SHF efforts that may be applicable to long-duration Mars missions include:

- the development of virtual environment tools and virtual reality displays for training, mission design, and mission rehearsal, especially for long-duration flights on which boredom, skills retention, and emergency planning must be considered
- work on "fatigue and countermeasures," which is significantly applicable to current programs, both in flight and on the ground. Obviously, the role of countermeasures to fatigue will be even more important on flights of long duration

Technologies and systems outside of NASA that might be directly applicable to future plans are not well known or properly appreciated. A consequence of this insularity is that NASA may attempt to apply or modify existing, frequently less than "state-of-the-art" and/or cost-effective technology, when better, perhaps cheaper, tools exist elsewhere.

Recommendation 5-4. Research should be devoted specifically to future long-duration missions. Research on space human factors should always be goal directed, seeking possible applications for far-term missions. Sufficient dedicated funding lines, personnel, and priorities will be needed if objectives are to be achieved.

Recommendation 5-5. Formal programs to increase interaction among projects within NASA space human factors must be established. NASA should encourage a broad view and promote effective and efficient programs between disciplines within the organization, as well as formal, periodic communication with extramural organizations to seek out technologies that may be applicable to NASA space human factors programs.

PROGRAM OBJECTIVES AND MILESTONES

Summary Finding. The SHF Program Plan, which was approved in December 1995, outlines topical areas only in general terms. The Program Plan describes a very broad and ambitious undertaking but lacks a specific, long-term mission to which goals can be tailored. It fails to delineate milestones or dates for specific

achievements or new capabilities. Therefore, the utility and relevance of the plan to current and future NASA programs are not clear.

Finding. The Human Exploration and Development of Space Strategic Plan (NASA, 1996) provides an evolutionary plan that moves from the ISS to the Martian surface, with a possible intermediate phase on the lunar surface. For the most part, this is a thoughtful document, but it contains many assumptions about areas that have not been completely researched. For example, it states, “Human factors research and technology will also ensure . . . that interpersonal interactions are planned to maintain a healthy, constructive attitude, thus enhancing productivity and mission success among an international, culturally-diverse crew (NASA, 1996).” This statement expresses assumptions about the psychosocial dynamics of small groups sequestered for prolonged periods of time that are not justified by current knowledge.

Recommendation 5-6. Crew time and the assignment of individuals to perform various space human factors experiments (psychological and physiological) aboard the ISS will require detailed advanced planning. Crew rotation will present problems for the investigation of the physiological effects of prolonged exposure to microgravity and for the investigation of the psychological effects of prolonged isolation and sequestration in a very limited living area. It will also be essential to study aspects of habitability on the ISS that must be incorporated into the design of a Mars transfer vehicle and other habitats. Thus, space human factors experiment time and crew participation must be integrated with the crew’s other scientific and operational chores. This is a daunting task, which will require milestones and coordination between researchers in space human factors and related topics in human behavior and performance.

OVERALL SCIENTIFIC AND TECHNICAL QUALITY

Summary Finding. At the time of this study, the SHF program consisted of mission support, external contracts, and individual projects selected from proposals submitted in response to NRAs. It was the committee’s judgment, based on documentation and briefings, that the quality of these projects varies widely. Some are of outstanding scientific quality, while some others do not meet the minimum standards of scientific and professional research.

Finding. Mission-oriented research is performed at both JSC and ARC, and there are some excellent projects at both centers. The work at JSC is primarily driven by the need to resolve issues related to operating Space Shuttle missions and for planning other near-term programs, such as the ISS. Virtually all the work at JSC is sponsored by NASA. In general, the researchers at ARC seem to be motivated by fundamental scientific questions, as well as by issues related to

aviation safety, airframe design, or enhancing pilot performance. Many of the projects at ARC appear to be supported by, or in cooperation with, specific industrial partners (such as the augmented reality system for wiring-buck cabling supported by Boeing Aircraft) or with other government agencies (such as the FAA for the aviation safety reporting system, and the U.S. Army for the MIDAS pilot simulation). Underlying “cultural” differences between the two centers have given rise to different evaluation metrics. At ARC, the dominant criteria are related to peer recognition; at JSC, they are related to solving near-term operational problems. The lack of an overarching, agency-wide mission and supporting SHF management has led to a lack of focus in the efforts of individual researchers and research teams. The quality of R&D at both JSC and ARC varies significantly.

Recommendation 5-7. Management should establish specific research goals relative to short-term NASA operational support as well as for long-duration, far-term missions. Prioritizing research goals can help focus resources, identify programmatic weaknesses, establish incentives, and establish a competitive, but positive, working atmosphere. Synergy between projects directed toward immediate, short-term missions and projects focused on far-term missions should be sought and encouraged.

Recommendation 5-8. Management should establish evaluation metrics that encourage quality research. They should further ensure that the characteristics that constitute a successful, high-quality project are applied across all programs. Periodic external reviews will also help ensure that all research projects are in line with stated space human factors program priorities.

PROGRAM REQUIREMENTS

Summary Finding. Although some work has been done to determine the requirements for the human exploration of space and relevant issues related to SHF, currently there is no official NASA document that establishes the priority of the key research areas. The current NASA structure is not adequately aware of current technologies that may be applicable to long-duration SHF issues.

Finding. NASA is currently at work on a requirements document for SHF research, but no priorities exist at this time. Because there is no official program requirements document, there is no focused effort toward achieving goals consistent with NASA’s long range plans for lunar/Mars missions.

Recommendation 5-9. NASA should complete and release an official document spelling out the requirements for space human factors research and technology. The document should be open to review, and once accepted by the agency, it should be used to focus sharply on the critical research that NASA will need to support long-term missions.

Finding. A fundamental problem within NASA relates to a research philosophy that has persisted since the Mercury program in the early 1960s. The unique characteristics of space flight (e.g., microgravity, EVA, life support, and isolation) dictated that NASA was solely dependent on the virtuosity of its own scientists and engineers to create its own tools. Since then, this situation has changed. Academia, industry, and other organizations have evolved technological capabilities in areas that can be helpful to NASA, and in certain disciplines, may even have outstripped NASA.

An example of this “insular mentality” is in work on advanced displays at JSC. Existing, off-the-shelf prototyping systems could have been of considerable help. Although it may be easier to write specific in-house software to integrate existing systems (such as integrating the AD software with the flight simulator), cost-benefit analyses comparing in-house and external software products should be used. Another example of insularity involves the long-term development (about 20 years) of the multimedia-media browser for PC display of the NASA STD-3000 human factors data. NASA STD-3000 has been an extraordinary and useful compilation of data on human factors. JSC has provided a valuable data organization and collection service and has promoted the idea of human factors standards, both within and outside the NASA community. However, the computer access aspect of the document project has faltered because the specialized on-line document viewer is clearly inferior to current hypertext markup language (HTML) browsers based on Internet technology. These HTML browsers can deliver a document to any web browser at any computer work station. By identifying and using or modifying off-the-shelf systems, NASA can focus on the *content*, rather than the *medium* (software delivery), which may be available elsewhere.

A good example of an SHF project that is working well at JSC is the Graphics Research and Analysis Facility (GRAF) laboratory. While solving real problems in day-to-day or mission-to-mission operations, the project also maintains a view of software tools that would be needed to help plan and manage future missions, EVA suits, and even human factors in microgravity. GRAF has attempted to use outside software rather than build it all in house, and GRAF has used internal resources to augment algorithms (developed elsewhere in JSC) for EVA suit modeling and suit sizing, to collect strength data, and to improve engineering-accurate illumination models.

Recommendation 5-10. The NASA space human factors program should focus on issues unique to the crewed exploration of space, which is the prime driver of the program. NASA should not assume that all software and hardware systems must be built by NASA from scratch; many products on the market can assist NASA’s mission. Good examples of these are Internet software browsers for documentation and even training, design and visualization software for display mockups and training, and 3D graphics software. Thus, the continuing search for “space-unique” tools should be expanded beyond NASA. Work by an outside

entity, even though it may not be *directly* applicable to space travel, could be modified or adapted to meet specific NASA requirements. NASA should establish a formal mechanism to *identify* work being done outside NASA that may be applicable to its purposes.

PROGRAM DIRECTION AND ORGANIZATION

Summary Finding. The recent establishment of JSC as the lead center for SHF provides an opportunity to consolidate management and invigorate NASA SHF-related programs and projects.

Finding. Understanding human behavior and performance is a high priority for crewed missions. But this area has been arbitrarily separated from SHF in the OLMSA organization. This separation appears to be drawn along the lines of scientific disciplines rather than with respect to functional problems or issues. The area of human behavior and performance includes many of the issues critical to the success of a human mission to Mars. Examples include crew selection and interaction, workload, training, etc. Traditionally and functionally, these programs belong together.

Recommendation 5-11. The OLMSA behavior and performance projects and space human factors projects should be brought under a single management structure and should be working toward the same set of goals.

Finding. If and when long-duration mission requirements are determined, it is unlikely that SHF staffing will be adequate to address the broad range of problems a crewed mission (e.g., to Mars) would encounter. It is also unlikely that the current funding level for SHF would be sufficient to support the needed SHF research for the safe and effective human exploration of the solar system.

Recommendation 5-12. The space human factors program requires strong leadership and advocacy with a long-term view of the entire space human factors area. The individual in charge of this program must have sufficient budgetary and other resources to ensure that the long-term problems of operational space flight and a mission to Mars can be addressed by appropriate, forward-looking research. This individual must have the experience and authority to coordinate disparate disciplines and entities. This can only be accomplished with a space human factors advocate at a high administrative level. Space human factors funding should be a line item in each program/project. This would foster better communication and allow resources to be applied more appropriately. Line item funding would also provide some flexibility for the timely pursuit of emerging issues rather than having to wait for a NASA Research Announcement cycle. Increasing the focus of the program while broadening the research base will require a well orchestrated team effort.

Recommendation 5-13. NASA should direct its limited resources for space human factors research to areas where advances are not likely to be made by others, e.g., issues related to long-term isolation and habitability, etc. Few others besides NASA will be working on the space human factors issues unique to going to Mars or living on the Moon, but others will be working on displays and controls, etc. Many of these technologies are likely to be ready for operational evaluation by the time NASA will begin its development of these missions.

Finding. The NRA process is appropriate for projects addressing long-term needs. However, the process of selecting projects for long-term research should be sharpened in order to foster research that addresses important SHF issues. Unless the NRA process is carefully implemented, it may produce excellent scientific studies on the wrong subjects.

The NRA funding mechanism with peer review puts the more operational SHF projects at JSC at a disadvantage compared to projects at ARC. Because of the inconsistent level of available research funding, JSC has focused on operational requirements but with a view toward the reusability of both data and software for future missions.

In general, the SHF work at JSC focuses on near-term problems (e.g., the Space Shuttle, ISS, Shuttle-Mir, ISS Human Research Facility, and issues related to the ALS tests). It is mission-to-mission oriented, iterative, in response mode, and stimulates little fundamental research. Overarching issues have not been clearly defined, and hence are rarely addressed because the program focuses on near-term “fixes.” This may be an appropriate operational mode in an environment of need-to-solve, immediate problems with limited funding, but it will not suffice for addressing long-duration SHF issues.

An SHF research program made up of proposals predominantly selected from NASA NRAs and SBIRs limits the range and focus of research. But the delineation of scientific and technical areas to be funded is not clear. The present NRA process is not structured to foster research directed at answering the critical questions that NASA must address before beginning human missions beyond LEO.

Although there is little duplication of effort among the OLMSA-funded SHF projects under way at JSC and ARC, no incentive or organizational structure to coordinate SHF disciplines currently exists. Work related to SHF at other NASA centers and not funded by OLMSA was not reviewed by the committee.

Recommendation 5-14. A serious effort to design long-duration space flight missions will require a more specific, technology-directed focus than the present NASA Research Announcement system allows. This focus should result in announcements that request proposals in critical areas, thus enabling the space human factors program to focus on the most pressing needs identified by NASA and its advisory groups. A technology-directed focus would simplify the selection process by making it easier for NASA to select among proposals that may be

excellent from a purely scientific point of view but are less relevant to solving pressing space human factors problems. This would also mean that prospective principal investigators (both inside and outside NASA) would not spend significant amounts of time and energy on proposals that are bound to be rejected because they are not relevant to current agency needs, exclusive of their scientific merit.

SYNERGISM WITH OTHER PROGRAMS

Summary Finding. The potential for synergy among projects funded by the SHF program and other NASA programs is high. But synergy must be nurtured, and not everyone appreciates that NASA's long-term goals can be advanced by building upon the work of others, e.g., in computer technology and human-computer interaction. SHF is an integral component of activities such as EVA, ALS, and EMC. All are designed to ensure the safety, survivability, and productivity of human beings in space environments.

Finding. SHF is an intrinsic component of other NASA activities, such as training, behavior and performance, aeronautics, safety, robotics, and tests of new life support technologies. Collaborations at ARC are satisfactory and frequently include scientists from outside NASA. There are also some international collaborations. Some of the research fields covered include, but are not limited to, cognitive science, virtual reality, perceptual limitation, medical imaging, team training and problem solving. With some exceptions, collaborations are less well developed at JSC.

Because the ISS is the acknowledged vehicle wherein critical SHF research related to long-term missions will be conducted, it was disappointing to realize that there is no formal plan for integrating SHF research into all aspects of ISS operations.

The lack of communication between the research and operational SHF communities, combined with the lack of a unified programmatic mission, goal, or priorities, creates an organization that, in large part, is pursuing projects that do not capitalize on potential intramural or external synergism. The lack of communication among overlapping and/or complementary NASA activities precludes the efficient use of resources and undermines technical and programmatic synergy. None of the SHF work at JSC is specifically connected with work on human factors at ARC. The work on virtual reality training at JSC is not part of SHF because it is considered mission planning and training. Also, somewhat arbitrary "turf" demarcations (e.g., separating aviation from space flight) have resulted in poor communication, which makes coordination even more difficult.

Recommendation 5-15. Space human factors personnel should be formally included in the concurrent engineering loop associated with the design, development, and construction of all space systems, such as extravehicular activities, advanced life support systems, habitations, and control and communication systems.

Recommendation 5-16. NASA should establish a formal method for sharing information about current or anticipated operational space human factors problems. NASA should also establish a method for sharing information concerning planned space human factors projects, including all work at NASA centers, so that limited resources can be optimized and leveraged for maximum gain. Regular (semi-annual or annual) space human factors meetings should be scheduled to ensure that researchers and others are aware of each other's work and areas of expertise.

NASA should establish a system for keeping appropriate staff up to date on the technical activities of external organizations involved in potentially applicable work. NASA should encourage and provide resources for researchers to participate in technical and professional conferences to foster an exchange of information and ideas with external organizations and individuals.

Recommendation 5-17. To maximize the probability of success of SHF programs for prolonged crewed space flight, NASA should call not only on the talents and capabilities of in-house scientists, but should also capitalize on the knowledge of the best scientists and professionals available, regardless of their location or affiliation. Some examples of areas where synergy should be encouraged include:

- Space human factors researchers could participate in the development of integrated system simulations and virtual environment technologies with humans in the loop, whether for piloting, mission specialist activities, or other training and performance evaluation studies.
- Better connections between the advanced displays group at JSC and the man-machine integration design and analysis (MIDAS) group at ARC would be helpful.

DUAL-USE TECHNOLOGIES

Summary Finding. Spin-off technologies should not be considered primary drivers for space human factors, although they are splendid fringe benefits. The focus of space human factors work must be to identify the problems and discover solutions that will make prolonged, crewed spaceflight as safe and productive as possible. The primary, abiding philosophy must be to seek out and solve these problems. Spin-offs should be viewed as dividends, never goals.

Finding. Several potential dual-use technologies have been developed within the NASA space or aeronautics human factors community, including the NASA-STD-3000, MIDAS, spatial auditory displays, and fatigue countermeasures.

Recommendation 5-18. The space human factors program should primarily allocate its resources on research, analysis, and designs that contribute to mission objectives. Spin-offs should always remain a desirable fringe benefit but should never be considered a primary driver of NASA research.

REFERENCES

- NASA (National Aeronautics and Space Administration). 1995. Space Human Factors Program Plan. Life and Biological Sciences and Applications Division, Office of Life and Microgravity Sciences and Applications. Washington, D.C.: NASA.
- NASA. 1996. NASA's Enterprise for the Human Exploration and Development of Space: The Strategic Plan. Washington, D.C.: NASA.
- NRC (National Research Council). 1993. Scientific Prerequisites for the Human Exploration of Space. Committee on Human Exploration, Space Studies Board. Washington, D.C.: National Academy Press.
- NRC. 1994. Scientific Opportunities in the Human Exploration of Space. Committee on Human Exploration, Space Studies Board. Washington, D.C.: National Academy Press.
- Stafford, Thomas P., et al. 1991. America at the Threshold: America's Space Exploration Initiative. Washington, D.C.: White House Office of Science and Technology Policy.

6

General Findings and Recommendations

Finding. During the period of the committee's study, the NASA Advanced Human Support Technology Program has suffered from a lack of clear direction. This situation seems to come from two basic realities: (1) NASA has not directed R&D to address specific, long-term goals in human space exploration; and (2) NASA has not decided who will lead the programs. Therefore, NASA staff and others working on human support projects often do not have clear long-term objectives, or know to whom they are responsible. But even without a presidential mandate for major human exploration programs, NASA has a basic mission to advance technologies for space exploration and should be able to organize and prioritize a small fraction of its resources on R&D for the technologies necessary for the safe human exploration of space in the next century. The situation has become so strained that many members of NASA management seem reluctant to admit that they are contemplating human exploration missions—even missions that would be launched more than 20 years hence—apparently because there is no presidential or congressional directive for any human space exploration mission after the ISS. Responsibility for advanced EVA technology R&D projects has been delegated to JSC, but those working on the other three programs have spent over six months without knowing if they will continue to be managed from NASA headquarters or if they will be managed by a NASA center. It is also unclear what management by any group other than NASA headquarters will mean (e.g., one of the first acts of the JSC management of the EVA Project Office was to virtually eliminate EVA research at ARC).¹

¹Since this study was completed, much of the program control has been transferred from NASA headquarters to NASA centers for the four human support programs.

Recommendation 6-1. NASA should establish a well defined management structure for the human support programs and forthrightly inform NASA personnel. OLMSA should then proceed with these programs to meet the unique needs for human support technologies for future crewed missions beyond low Earth orbit.

Finding. Requirements for technology development should be predicated on carefully developed reference missions and systems analysis to determine functional requirements. There are many good existing design reference mission studies that could be adapted and used by all programs.

Recommendation 6-2. OLMSA should not expend significant resources to develop new reference missions but should increase the use of systems analysis and modeling tools.

Finding. Current funding levels (less than \$20 million annually for all four OLMSA programs) are clearly not high enough to support R&D on all of the technologies for human space exploration. As long as funding remains at or near current levels, the committee believes that little progress will be made unless programs are narrowly focused and prioritized to meet the key technology needs in each area.

Recommendation 6-3. The roles and tasks of all groups (NASA and non-NASA) involved in human support research and development sponsored by NASA should be clearly defined and prioritized. Program resources should only be allocated to those projects that address the highest priority technology needs for future missions. NASA should direct its limited resources for research in areas where advances are unlikely to be made by others.

Recommendation 6-4. Systems analysis approaches should be included in ongoing and future processes to determine the highest priority technologies for human support in space.

Recommendation 6-5. Periodic NASA Research Announcements calling for proposals from prospective researchers in topics related to human support in space should clearly identify the high priority areas in each program. The selection process should give added weight to proposals that are most relevant to the high priority areas defined in the announcements.

Recommendation 6-6. Spin-off technologies should be transferred outside of OLMSA as appropriate, but only as dividends from a project aimed at furthering NASA objectives. Technology transfer should not become a major emphasis of these small technology development programs.

Recommendation 6-7. The International Space Station should be used as a site for research relevant to human support in space and for tests and demonstrations of new human support technologies.

Finding. NASA has unique technology needs, but there is too much technical insularity in the NASA human support programs.

Recommendation 6-8. NASA should put more emphasis on finding technologies and knowledge relevant to human support outside of the NASA centers and other locations where technology has been developed in the past. The Human Support Program should strive to include universities and industry in its projects and should make special efforts to take advantage of the willingness of industry to spend private funds on research and development projects relevant to NASA's long-term goals.

Recommendation 6-9. Technical communication—inter-, intra-, and extra-NASA—including publication, should be expanded and actively supported.

Acronyms and Abbreviations

ALS	advanced life support
ARC	Ames Research Center
CELSS	controlled environment life support system
CTSD	Crew and Thermal Systems Division
ECLSS	environmental control and life support system
EMC	environmental monitoring and control
EMU	extravehicular mobility unit
EVA	extravehicular activity
FY	fiscal year
GSFC	Goddard Space Flight Center
HEDS	Human Exploration and Development of Space
HEPA	high efficiency particulate air
IR&D	independent research and development
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center

LEO	low Earth orbit
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NRA	NASA research announcement
NRC	National Research Council
NSCORT	NASA Specialized Center of Research and Training
OACT	Office of Advanced Concepts and Technology
OLMSA	Office of Life and Microgravity Sciences and Applications
OSAT	Office of Space Access and Technology
OSF	Office of Space Flight
OSSA	Office of Space Science and Applications
P/C	physical/chemical
PLSS	primary life support system
R&D	research and development
SAFER	Simplified Aid for EVA Rescue
SBIR	small business innovative research
SEI	Space Exploration Initiative
SHF	space human factors
SMAC	spacecraft maximum allowable concentration
SR&T	supporting research and technology
SSA	spacesuit assembly
VCD	vacuum compression distillation

APPENDICES

APPENDIX

A

Statement of Task

National Research Council
Commission on Engineering and Technical Systems
Aeronautics and Space Engineering Board
Advanced Technology for Human Support in Space

Statement of Task

To evaluate the NASA Office of Life and Microgravity Sciences and Applications (OLMSA) programs in Human Support, the NRC will convene a committee to:

- A. Review the current OLMSA programs in Advanced Life Support, Extravehicular Activity Systems, Space Human Factors Engineering, and Space Environmental Factors and Technologies.
- B. Assess whether these programs reflect effective strategic and programmatic approaches for accomplishing (1) OLMSA goals in human support and (2) the agency's stated long-term goals for orbital research and the human exploration of space. To achieve this objective, the committee will:
 1. assess the apparent likelihood that the programs will lead to technologies that will contribute to the success of NASA's future missions;
 2. assess the overall scientific and technical quality of each of the four programs;
 3. identify areas of highest priority within each of the four program areas;
 4. identify important gaps or omissions, if any, in the programs;

5. identify research areas where NASA's requirements are unique and unlikely to be addressed by other entities;
 6. determine whether the programs possess focused objectives and verifiable milestones and deliverables; and
 7. determine if any programs clearly involve inappropriate duplication of effort or facilities.
- C. Suggest, as appropriate, methods by which the programs might be improved within existing financial constraints. If additional funding is recommended, identify specific areas for such increases and the expected benefits.
- D. Attempt to identify:
1. possibilities for synergism among the four programs;
 2. methods for increasing the transfer of promising technologies from industry and other sources into the programs and for fostering cooperation with non-NASA entities to increase the return and effectiveness of the programs;
 3. improved procedures whereby requirements can be regularly identified and transmitted to the programs; and
 4. dual-use technologies (i.e., technologies that offer utility to both NASA and industry or another government agency) that are being developed by the programs.

The committee will provide its findings in a single published report at the end of its study. The committee will meet about four times and subgroups of the committee will visit NASA and other research centers to examine specific research projects as appropriate. Efforts will be made to coordinate the committee's work with periodic OLMSA reviews of the projects it funds at universities, and some members may attend internal NASA reviews to gather information on these smaller projects.

APPENDIX B

Memorandum of Understanding Consolidating Human Support Research in the Office of Life and Microgravity Sciences and Applications

TRANSFER OF ADVANCED LIFE SUPPORT, EVA SYSTEMS, AND SPACE HUMAN FACTORS R&T PROGRAMS

Memorandum of Understanding between the
Office of Advanced Concepts and Technology
and the
Office of Life and Microgravity Sciences and Applications

I. PURPOSE

The Office of Advanced Concepts and Technology (OACT) and the Office of Life and Microgravity Sciences and Applications (OLMSA) have significant interests in the development of programs of space human factors and advanced life support systems for intravehicular (IVA) and extravehicular activities (EVA). The purpose of this Memorandum of Understanding is to delineate the areas of responsibility for the management of programs in space human factors and advanced life support, so that the development of these programs can be accomplished in a timely, cost-effective, and collaborative manner.

II. SCOPE

Under terms of this MOU, the OACT Advanced Life Support Program, inclusive of IVA and EVA systems, and the Space Human Factors R&T Program will be transferred to OLMSA, along with funding (FY94–FY98), as are agreed.

OLMSA will have the prime responsibility for the planning and implementation of an integrated program of research and technology development of advanced life support systems and space human factors in support of NASA programs in human space flight. In cooperation with OLMSA, OACT will have the responsibility for supporting this program through breakthrough technology development. OLMSA will manage the EVA programs in cooperation with the Office of Space Flight to assure effective, relevant, and timely EVA systems development.

III. PROGRAM DESCRIPTION

III.A. IVA PROGRAM

OLMSA will merge the transferred OACT Advanced Life Support Program with the current OLMSA Controlled Ecological Life Support Systems (CELSS) Program and Environmental Sensing and Control Program into a single Advanced IVA Life Support Program. The OACT program elements to be transferred are those within the Human Support RTOP (UPN 506-71) including: Life Support Chemical Processing (506-71-21), Sensors and Controls (506-71-41), and Wind Tunnels and Technical Facilities (506-71-84).

This integrated program will have responsibility for research and technology development for all phases of life support systems for microgravity and planetary surface applications and will have responsibilities for all phases of life support systems development through systems engineering and integration and flight testing of prototype systems.

III.B. EVA PROGRAM

OLMSA will merge the OACT EVA Systems Program with the current OLMSA activities in EVA into a single Advanced EVA Systems Program. The OACT program elements to be transferred are those within the Human Support RTOP (UPN 506-71) including: Space Suit Technology (506-71-11) and Portable Life Support (506-71-31). This integrated program will have responsibility for research and development for all phases of advanced life support systems for microgravity and planetary surface applications and will have responsibilities for all phases of life support systems development through systems engineering and flight testing of prototype systems in cooperation with the Office of Space Flight.

III.C. IN-STEP PROGRAM

OACT will complete the IN-STEP Electrolysis Performance Improvement Concepts Study (EPICS) experiment (UPN 506-74-21), including post-flight data analysis, and make all results available to OLMSA.

OACT will complete the evaluation and selection of proposals submitted in response to the 1992 In-Space Technology Experiments Program (IN-STEP)

Announcement of Opportunity. Any proposals selected by OACT in the area of Advanced Life Support or Space Human Factors that OLMSA desires to implement, with the intent to complete through flight, will be transferred to OLMSA along with the funding required to implement the Phase A contract(s). OACT funding liability for those experiments is limited to the Phase A cost. In addition, OACT will send copies of all proposals submitted in the Advanced Life Support and Space Human Factors areas to OLMSA, at their request. OLMSA may review any proposals selected for Phase A award as a result of the 1992 IN-STEP Announcement of Opportunity to consider if they wish to assume cognizance over those activities. In the event that OLMSA intends to conduct the experiment(s) through flight, OACT will eliminate those proposals from further consideration in IN-STEP and will transfer to OLMSA all relevant documentation. OACT will determine the future disposition of any remaining proposals selected for IN-STEP award. No funding will be transferred to Code U for conducting experiments, since there is none presently allocated to this (or any) technology category except that allocated for the Phase A awards.

III.D. HUMAN FACTORS R&T

OLMSA will have responsibility for Space Human Factors research programs. OLMSA will form a single integrated Space Human Factors program to assure human health, safety, general well-being and high levels of performance in space and on planetary surfaces. OACT will coordinate future technology requirements in this area with OLMSA.

IV. PROGRAM IMPLEMENTATION

IV.A. OLMSA will be responsible for implementation of all phases of the Space Human Factors R&T, IVA Life Support, and EVA Systems Programs. Specifically, OLMSA will:

IV.A.1. Formulate Program Plans through a team approach drawing on scientific and engineering expertise at Headquarters, Field Centers, and Universities.

IV.A.2. Establish science and technology requirements and priorities as necessary to initiate and complete implementation of the Program Plans.

IV.A.3. Identify candidate state-of-the-art technologies, conduct ground and flight research, and develop and test subsystems as well as integrated systems.

IV.A.4. Prepare Headquarters budget submissions, congressional testimony, formal technical documentation, educational and technology spin-off material, and other documentation to support the Programs.

IV.A.5. Draw on international expertise and experience of existing flight life support systems. Conduct technical discussions with U.S. and foreign space

agencies, international science and engineering organizations, and individual foreign investigators and managers who plan to contribute to or use ground or flight-based facilities for research in life support and human factors.

IV.A.6. Identify, in concert with OACT, requirements for new and novel breakthrough technologies not available through commercial sources to assure the continued enhancement of life support system performance.

IV.A.7. Identify, in concert with OACT, technologies within the OLMSA IVA and EVA life support and human factors programs that have useful application to OACT technology programs and cooperate with OACT to infuse these advances into relevant OACT programs.

IV-B. OACT will have responsibility for:

IV.B.1. Research and development on breakthrough technologies that can significantly improve the performance or reduce the cost and risk of human factors and IVA and EVA life support systems.

IV.B.2. Inclusion of Space Human Factors R&T, IVA Life Support, and EVA Systems opportunities in the Small Business Innovation Research Program managed by OACT.

V. COORDINATION

OLMSA will work with OACT to identify dual-use technologies, collaborate in programs of technology transfer, and will hold periodic joint meetings to discuss the status of the Programs and to initiate activities of mutual benefit.

VI. FUNDING

Consistent with the transfer of the OACT Advanced Life Support Program, EVA Systems Program, and Human Factors Engineering Program to OLMSA, funding (FY94-FY98) will be transferred as agreed.

Program Area	Budgetary Authority \$M				
	Fiscal Year				
	1994	1995	1996	1997	1998
Human Support R&T	6.5	6.0	6.0	5.9	5.8

Dr. Harry Holloway
Associate Administrator for
Life and Microgravity Sciences
and Applications

Date: 10/24/93

Mr. Gregory Reck
Associate Administrator for
Advanced Concepts
and Technology

Date: 11/26/93

APPENDIX C

Subcommittee Members and Meetings

SUBCOMMITTEE MEMBERS

Advanced Life Support (ALS)

Susan Doll, *ALS Subcommittee Chair*
Bruce Bugbee
Elizabeth Cantwell
Andrew Hoffman
Mary Musgrave
Frederick G. Pohland
Robert E. (Ed) Smylie

Extravehicular Activities (EVA)

Joseph Kerwin, *EVA Subcommittee Chair*
James Bagian
Norman Badler
Andrew Hoffman
Robert Moser
Dava Newman
Robert E. (Ed) Smylie

Environmental Monitoring and Control (EMC)

Elizabeth Cantwell, *EMC Subcommittee Chair*
Harriet Burge
Susan Doll
Donald Gardner
Frederick G. Pohland

Space Human Factors (SHF)

Norman Badler, *SHF Subcommittee Chair*
James Bagian
Robert Moser
Dava Newman
Gavriel Salvendy

COMMITTEE MEETINGS

March 27–28, 1996 Washington, D.C.
April 24–26, 1996 Johnson Space Center
June 3–4, 1996 Ames Research Center
August 29–31, 1996 Woods Hole, Massachusetts

SUBCOMMITTEE MEETINGS

Advanced Life Support

June 12–13, 1996, Marshall Space Flight Center

June 14, 1996, Kennedy Space Center

Environmental Monitoring and Control

June 10–11, 1996, Johnson Space Center

Space Human Factors

July 9, 1996, Johnson Space Center

July 30, 1996, Ames Research Center

Members of the committee also participated in two NASA meetings, the Advanced Environmental Monitoring Workshop, in Glendale, California on April 23–25, 1996, and a review of the Space Human Factors Requirements Document, at Johnson Space Center on May 1–2, 1996.

APPENDIX D

Letter Requesting Comments from Industry

June 21, 1996
(202) 334-2855

Dear

At the request of the National Aeronautics and Space Administration (NASA), the National Research Council (NRC) is conducting a study of advanced technologies for human support in space. The specific purview of the committee is the NASA Office of Life and Microgravity Sciences and Applications (OLMSA) programs to develop advanced technology for life support systems, extravehicular activity suits and systems, environmental monitoring and control (within pressurized habitats), and space human factors engineering. This letter is to request a written input from your organization on topics important to our study. Based on your experience in human support in space, and in consultation with NASA, your organization is one of several from which we are seeking information. Please be assured that information in your response identified as proprietary will be treated as such. Proprietary information can also be limited to distribution to certain members of the committee (as directed by you, please see enclosed roster of committee members). Our questions are as follows:

1. What are your company's priorities and areas of expertise in technologies for human support in space? Do you have technologies that you believe could contribute to NASA's long-term needs in human support? Do you believe that NASA is aware of these technologies? Of the technologies that you possess or are working on, which do you consider "evolutionary" or "revolutionary"? Are you working on "revolutionary" technologies

that might lead to large reductions in weight, volume, power, or cost requirements? Would you be willing to discuss your technologies with the committee?

2. What do you believe should be the priorities of NASA's programs to develop advanced technology for human support in space? For example, should NASA effort focus on improving existing technologies or on developing new "revolutionary" technologies?
3. To what extent has your organization sought funding for relevant technology development projects from NASA and OLMSA, or sought to coordinate your own independent R&D projects with those of NASA and OLMSA? How should NASA and industry interact in the development of new technology for human support in space?

We will consider the responses to this letter and expect to draw up an invitation list for industrial representatives to meet with the committee in Washington, D.C., some time in mid-August. Our study report is scheduled for delivery in December 1996. You will be sent a copy and it will be widely disseminated to NASA and other federal officials, selected members of Congress and their staffs, and others who are involved in research or national space science and technology policy. Briefings on the report will be given to NASA and other officials as appropriate.

Several relevant documents are enclosed: the statement of task for the study, the roster for the committee, and brochures describing the roles of the NRC and the Aeronautics and Space Engineering Board. I hope your organization will find the time to respond to this request. We respectfully request your input by August 5, 1996. If you have any question, please contact the study director of the project, Mr. Noel Eldridge, at the address above, or via e-mail at neldridg@nas.edu.

Thank you for your help in assuring that the committee is informed of your company's work.

Sincerely,

James Bagian, P.E., M.D.
Chairman
Committee on Advanced Technology for
Human Support in Space

Enclosures

APPENDIX E

Analysis of Advanced Life Support Technology Development Projects

To better understand the variety of projects under way at the NASA centers in advanced life support, the committee asked NASA for information on all the projects under way in FY96. NASA responded to the committee's request, and an enumeration of all the projects listed on the technology data sheets is tabulated in Table E-1. The functional categories in the table were chosen to reflect the life support system functions identified in Table 2-2. Additional categories were added for system management and environmental monitoring/sensors to accommodate projects being conducted in those areas.

The committee sorted the projects into appropriate categories based on the brief descriptions provided by NASA. The numbers in the table represent a simple tally of individual projects being pursued in each category and do not reflect relative funding. Funding levels for individual projects ranged from \$10,000 to \$600,000.

TABLE E-1 Compilation of Advanced Life Support Technology Development Projects

Functional Technology Categories	JSC	ARC	KSC
Temperature and Humidity Control	0	0	0
Atmospheric Control and Supply	0	0	0
Atmospheric Revitalization			
CO ₂ Removal/Concentration	2	2	0
Trace Contaminant Removal	3	1	0
O ₂ Generation	0	1	1
CO ₂ Reduction	0	0	0
N ₂ Make up	0	0	0
Particulate/Microbial Control	0	0	0
Water Recovery Management			
Waste Water Processing	3	4	0
Water Storage and Distribution	0	1	0
Waste Management			
Collection and Storage	0	0	0
Resource Recovery Process (P/C)	0	5	0
Resource Recovery Process (biological)	0	0	3
Food Management			
Storage/Preservation	0	0	0
Production			
Plant Requirements	0	2	9
Nutrient Delivery	2	0	4
Environmental Conditions	1	1	7
Other Biological Agents	0	0	1
Processing	1	0	0
System Management			
Analysis	0	2	3
Integration	1	3	3
Control	0	2	3
Automation	0	0	2
Environmental Monitoring/Sensors			
Microbial	0	0	3
Trace Contaminants	0	0	2
Major Contaminants	0	0	3
Water	0	0	3

APPENDIX

F

Biographical Sketches of Committee Members

James Bagian (chair) is a former astronaut, a physician, and a professional engineer. He is the deputy director for the Regional and State Programs Division, Office of Mobile Sources, of the Environmental Protection Agency. In this position, he is leading the effort to ensure that EPA air emission policies regarding mobile sources are consistent, data driven, and supported by scientific data. While he was a NASA astronaut, Dr. Bagian flew on the 1991 Spacelab Life Sciences-1 mission, the first Space Shuttle mission dedicated to life sciences research. He also flew on STS-29 in 1989 and trained as the lead contingency EVA crewmember for both these missions. Dr. Bagian was the astronaut office coordinator for Space Shuttle payload software and crew equipment and served as an investigator and diver in the aftermath of the explosion of the Space Shuttle Challenger. Before the Space Shuttle returned to service, he helped formulate and manage the design, development, and testing of the current Space Shuttle high-altitude escape suit and was one of the team leaders for the overall project to design, develop, and test the Space Shuttle escape system. Dr. Bagian has authored papers in the fields of human factors and environmental and aerospace medicine and has served on several relevant panels and review committees. Dr. Bagian also is a pilot (with more than 1,500 hours of flying time in propeller and jet aircraft, helicopters, and gliders) and parachutist, as well as a colonel in the U.S. Air Force Reserves with the Air Rescue Service.

Norman Badler is the director of the Center for Human Modeling and Simulation and a professor in the Computer and Information Science Department at the University of Pennsylvania. The Center for Human Modeling and Simulation studies computational models of human behavior and structure, both external

(movement) and internal (physiological and cognitive), and builds the Jack software, which is used at dozens of sites worldwide for human figure animation and human factors analysis. Dr. Badler earned his Ph.D. in computer science from the University of Toronto in 1975. The major foci of his research include computational anthropometry; computational approaches to human movement animation; and graphical and natural language interfaces for task simulation.

Bruce Bugbee is a professor in the Plants, Soils, and Biometeorology Department at Utah State University. Dr. Bugbee conducts both basic and applied research on photosynthesis, respiration, and plant nutrition. His research to study the beneficial effects of vegetation in contaminated soils has been funded by the Environmental Protection Agency and his work on measuring and modeling plant metabolic rates for bioregenerative life support systems is sponsored by NASA. He has authored papers and book chapters on research and commercial hydroponics techniques for growing crops on Earth and on the type of root-zone environment necessary for growing crops and recycling wastes on a lunar base, using either hydroponics or the lunar regolith as a growth medium.

Harriet Burge is an associate professor of Environmental Microbiology at the Harvard School of Public Health. Dr. Burge was the vice chair of the Institute of Medicine Committee on the Health Effects of Indoor Allergens, which produced the 1993 report, *Indoor Allergens: Assessing and Controlling Adverse Health Effects*. She also served on an earlier National Research Council study on airliner cabin air quality. Her expertise is in aerobiology (the occurrence, transportation, and health effects of airborne materials, such as viruses, pollen, or pollutants). Her research includes methods for the sensitive and precise monitoring of biological aerosols, and the prevalence and health effects of fungal aeroallergens and toxins, bacterial aerosols, and volatile organic compounds released by microorganisms during metabolism. She has been involved in research on the microbiology of spacecraft.

Elizabeth Cantwell is an environmental scientist at the Lawrence Livermore National Laboratory. Dr. Cantwell holds B.E., M.S., and Ph.D. degrees in mechanical engineering, as well as a B.A. in human behavior. Her work at Livermore focuses on input/output and total cost modeling of the environmental impacts of industrial systems. She has authored papers in the fields of life support, systems engineering, microgravity fluid physics, and industrial ecology. She has previously held positions with the Environmental Protection Agency (developing air regulations) and NASA's Ames Research Center (designing life support processors for air, water, and solid waste).

Susan Doll is an engineer with experience in systems engineering and medical research. She is currently a technical specialist at the Boeing Life Support

Technology Center in Huntsville, Alabama. For the last two years, she has been the lead technical liaison for Boeing's activities with a major Russian provider of life support hardware (NIICHIMMASH) and with the Siberian branch of the Russian Institute for Biophysics, a world leader in bioregenerative technology research. Ms. Doll's previous work at Boeing included system integration for the ISS environmental control and life support system (ECLSS), and life support system concept development for lunar and Mars applications. Ms. Doll earned a B.S. degree in medical technology and an M.S. degree in alternative energy engineering. Her thesis focused on the energy dynamics and carbon cycle of crops inside the Biosphere 2 closed habitat. She has been active in the field, giving seminars and lectures at the International Space University, Massachusetts Institute of Technology, and Harvard, as well as serving as program chairman for the first two International Conferences in Life Support and Biospherics.

Donald Gardner is an expert in environmental and occupational toxicology. Dr. Gardner currently chairs the Subcommittee on Spacecraft Maximum Allowable Concentrations of the National Research Council's Committee on Toxicology, which has prepared three reports for NASA since 1992. He is currently an independent consultant. He retired as vice president and chief scientist of Man Tech Environmental Technology in 1994. From 1971 to 1980, Dr. Gardner was chief of the Biomedical Research Branch at the Environmental Protection Agency and, from 1980 to 1982, was director of the Inhalation Toxicology Division. In addition to serving on several National Research Council panels, he has served on advisory committees for the Food and Drug Administration, Environmental Protection Agency, and for the National Institute for Environmental Health Sciences of the National Institutes of Health.

Andrew Hoffman is an expert in human space systems, having spent 33 years in the U.S. space program in technical, operations, and management positions. His areas of technical expertise include extravehicular mobility units, space vehicle life support, thermal control, and system analysis. He is currently the president of East Windsor Associates, a consulting firm in aerospace technology, manufacturing, and management, and was previously the executive vice president of Hamilton Standard Aerospace. Earlier in his career, Mr. Hoffman was the program manager for Hamilton Standard's Lunar Module life support system, Skylab crew equipment, and the Space Shuttle life support system. He has recently been involved in ad hoc NASA studies to evaluate the plans for Office of Life and Microgravity Sciences and Applications facilities for the International Space Station, as well as to evaluate the use of the current Space Shuttle extravehicular activity suit to meet the requirements for the International Space Station.

Joseph Kerwin is the president of Krug Life Sciences, Inc. Dr. Kerwin was the first medical doctor to go into space. In 1973, Dr. Kerwin was science pilot on the

Skylab 2 mission; he performed a three-hour space walk to repair the damaged Skylab solar arrays. Prior to joining NASA as an astronaut, he was a naval aviator with more than 4,000 hours of flying time, as well as a flight surgeon. As a naval detailee to NASA, he held many positions, including the director of space and life sciences at the Johnson Space Center and chief of the mission specialist and scientist-astronaut branches of the Astronaut Office. At Lockheed Martin, he has led projects related to the development of an assured crew return vehicle and extra-vehicular activity systems for the International Space Station. He is also the inventor of the simplified aid for EVA rescue (SAFER), which was subsequently flown on the Space Shuttle and is the planned standard EVA rescue equipment for Space Station astronauts.

Robert Moser is a member of the Institute of Medicine and an internist-cardiologist with experience in aerospace medicine going back to the beginning of the U.S. manned space program. He is currently a senior medical consultant working for Canyon Consulting Corporation in Chama, New Mexico, and a visiting professor at the Uniform Services Health Science Center and a clinical professor in the Department of Medicine at the University of New Mexico. He is a former member of the National Research Council's Space Studies Board (1989–1993), and a former member of the Aeronautics and Space Engineering Board's Committee on the Space Station (1991–1993). Earlier in his career, Dr. Moser was a medical flight controller in the Mercury program and a member of the medical evaluation team for the Gemini program. Since 1960, he has served on many medical advisory and editorial boards and has contributed to many studies and reports for the National Research Council and other organizations.

Mary Musgrave is a professor in the Department of Plant Pathology and Crop Physiology at Louisiana State University. She earned her doctorate from Duke University in botany and cell and molecular biology, and her current research is in the area of plant stress physiology, including the effects of space flight on flowering and seed production and the responses of plants to hypoxia. Dr. Musgrave has participated in planning meetings for joint U.S./U.S.S.R., U.S./Russian, and U.S./Ukrainian space biology research. She has also abstracted Russian technical articles and books. Dr. Musgrave has been the principal investigator for three flight experiments to grow plants in the Space Shuttle orbiter middeck and is currently president of the American Society for Gravitational and Space Biology.

Dava Newman is an assistant professor of aeronautics and astronautics at the Massachusetts Institute of Technology. Dr. Newman received her B.S. in aerospace engineering from Notre Dame, and Master's degrees in aeronautics and astronautics as well as technology and policy. She received her doctorate in aerospace biomedical engineering from the Massachusetts Institute of Technology.

Her multidisciplinary research in extravehicular activity systems and the dynamics and control of astronaut motion combines aerospace bioengineering, control and dynamics, human interface technology, and systems analysis and design; the work is being carried out through flight experiments, ground-based simulations, and mathematical and computer modeling. Dr. Newman has flown two previous spaceflight experiments and is the principal investigator for the enhanced dynamic load sensors experiment currently on the Russian Mir Space Station (April 1996 to December 1997), which studies the crew-induced dynamic response inside the spacecraft.

Frederick G. Pohland is a member of the National Academy of Engineering and a former president of the American Academy of Environmental Engineers. He holds the Edward R. Weidlein Chair of Environmental Engineering and is a professor of civil and environmental engineering at the University of Pittsburgh. Dr. Pohland earned his Ph.D. from Purdue University in 1961, and his research and teaching emphases have been in environmental engineering operations and processes; environmental chemistry and microbiology; solid and hazardous waste management; industrial waste minimization, treatment, and disposal; and environmental impact monitoring and assessment. He is currently a member of the National Research Council's Committee on U.S. Geological Survey Water Resources Research and the Committee on Evaluation Protocols for Commercializing Innovative Remediation Technologies.

Gavriel Salvendy is the NEC Professor of Industrial Engineering at Purdue University and a member of the National Academy of Engineering, elected "for fundamental contributions to and professional leadership in human, physical, and cognitive aspects of engineering systems." He is the recipient of the Mikhail Vasilievich Lomonosov Medal of the U.S.S.R. Academy of Sciences, holds an honorary doctorate from the Chinese Academy of Sciences, and is the author or co-author of more than 300 research publications, including 15 books. Dr. Salvendy has advised corporations and government agencies in 23 countries on the human side of effective design, implementation, and management of advanced technologies in the workplace. He earned his Ph.D. in engineering production at the University of Birmingham, United Kingdom.

Robert Edwin (Ed) Smylie is a mechanical engineer and technical manager with extensive experience in extravehicular activity systems and related technologies. He has held responsible positions in several major aerospace organizations, including Grumman's Space Station Integration Division, RCA's Government Communications Programs, NASA headquarters, NASA's Goddard Space Flight Center, and NASA's Johnson Space Center (1962 to 1973), where he was chief of the Crew Systems Division from 1968 to 1973. Since leaving NASA in 1983, Mr. Smylie has been involved in several reviews of related aspects of the NASA

program (recently he was a member of the NASA Federal Laboratory Review ordered by the White House Office of Science and Technology Policy). In addition to holding a master's degree in mechanical engineering from Mississippi State University, Mr. Smylie is also a graduate of the Massachusetts Institute of Technology Sloane School of Management.