Scientific Prerequisites for the Human Exploration of Space

Committee on Human Exploration, Commission on Physical Sciences, Mathematics, and Applications, National Research Council

ISBN: 0-309-12265-1, 64 pages, 8 1/2 x 11, (1993)

SCIENTIFIC PREREQUISITES FOR THE HUMAN EXPLORATION OF SPACE

Committee on Human Exploration

Space Studies Board

Commission on Physical Sciences, Mathematics, and Applications

National Research Council

NATIONAL ACADEMY PRESS

Washington, D.C. 1993

Copyright © National Academy of Sciences. All rights reserved.

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 competences 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. Frank Press 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. Robert M. White 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. Frank Press and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

Support for this project was provided by Contract NASW 4627 between the National Academy of Sciences and the National Aeronautics and Space Administration.

Cover: Mars mosaic image courtesy of Alfred McEwen of the U.S. Geological Survey, Flagstaff, Arizona. Lunar crescent image courtesy of Dennis di Cicco. Cover design by Penny Margolskee.

Copies of this report are available from
Space Studies Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418
Printed in the United States of America

Copyright © National Academy of Sciences. All rights reserved.

COMMITTEE ON HUMAN EXPLORATION

NOEL W. HINNERS, Martin Marietta Civil Space and Communications Company, *Chair*
RICHARD L. GARWIN, IBM T.J. Watson Research Center
LOUIS J. LANZEROTTI, AT&T Bell Laboratories
ELLIOTT C. LEVINTHAL, Stanford University
WILLIAM J. MERRELL, JR., Texas A&M University
ROBERT H. MOSER, University of New Mexico
GEORGE DRIVER NELSON, University of Washington
SALLY K. RIDE,* California Space Institute

Staff

DAVID H. SMITH, Executive Secretary
BOYCE N. AGNEW, Administrative Assistant

* Former committee member who participated in writing this report.

Copyright © National Academy of Sciences. All rights reserved.

SPACE STUDIES BOARD

LOUIS J. LANZEROTTI, AT&T Bell Laboratories, *Chair*
JOSEPH A. BURNS, Cornell University
ANDREA K. DUPREE,[*] Harvard-Smithsonian Center for Astrophysics
JOHN A. DUTTON, Pennsylvania State University
LARRY ESPOSITO,[*] University of Colorado
JAMES P. FERRIS, Rensselaer Polytechnic Institute
HERBERT FRIEDMAN, Naval Research Laboratory
RICHARD L. GARWIN,[*] IBM T.J. Watson Research Center
RICCARDO GIACCONI, European Southern Observatory
NOEL W. HINNERS, Martin Marietta Civil Space and Communications Company
JAMES R. HOUCK,[*] Cornell University
DAVID A. LANDGREBE, Purdue University
ROBERT A. LAUDISE, AT&T Bell Laboratories
RICHARD S. LINDZEN, Massachusetts Institute of Technology
JOHN H. McELROY, University of Texas, Arlington
WILLIAM J. MERRELL, JR., Texas A&M University
RICHARD K. MOORE,[*] University of Kansas
ROBERT H. MOSER, University of New Mexico
NORMAN F. NESS, University of Delaware
MARCIA NEUGEBAUER, Jet Propulsion Laboratory
MARK SETTLE, ARCO Oil Company
WILLIAM A. SIRIGNANO, University of California, Irvine
FRED W. TUREK, Northwestern University
ARTHUR B.C. WALKER, Stanford University
MARC S. ALLEN, *Director*

[*] Term ended during 1992.

Copyright © National Academy of Sciences. All rights reserved.

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND APPLICATIONS

RICHARD N. ZARE, Stanford University, *Chair*
JOHN A. ARMSTRONG, IBM Corporation
PETER J. BICKEL, University of California, Berkeley
GEORGE F. CARRIER, Harvard University
GEORGE W. CLARK, Massachusetts Institute of Technology
MARYE ANNE FOX, University of Texas, Austin
AVNER FRIEDMAN, University of Minnesota
SUSAN L. GRAHAM, University of California, Berkeley
NEAL F. LANE, Rice University
ROBERT W. LUCKY, Bell Communications Research
CLAIRE E. MAX, Lawrence Livermore National Laboratory
CHRISTOPHER F. McKEE, University of California, Berkeley
JAMES W. MITCHELL, AT&T Bell Laboratories
RICHARD S. NICHOLSON, American Association for the Advancement of Science
ALAN SCHRIESHEIM, Argonne National Laboratory
A. RICHARD SEEBASS III, University of Colorado
KENNETH G. WILSON, Ohio State University
NORMAN METZGER, *Executive Director*

Copyright © National Academy of Sciences. All rights reserved.

Preface

For the past 20 years, the future directions of the U.S. program of human spaceflight have been a matter of discussion, debate, and controversy within and among the government, industry, the scientific community, and the public. Many advocates of human space exploration now agree that the next steps in piloted flight after Space Station Freedom involve returning to the Moon and, eventually, voyaging to Mars. The space science community, however, is agreed that there is no a priori scientific requirement for human exploration of the Moon and Mars. This view is reflected in *Toward a New Era in Space: Realigning Policies to New Realities* (National Academy Press, Washington, D.C., 1988), a report prepared by the National Academy of Sciences and the National Academy of Engineering, which stated that "the ultimate decision to undertake further voyages of human exploration and to begin the process of expanding human activities into the solar system must be based on nontechnical factors." In that light it is proper to ask, then, what *is* a proper role for the scientific community in any program of human exploration?

Well before a human exploration program is implemented, the U.S. scientific community must involve itself by providing the scientific advice and participation necessary for enabling human exploration. Then, because virtually all mission concepts for human exploration incorporate scientific research as a major goal, it is incumbent on the research community to study how it should respond to the opportunities enabled by the existence of human exploration. The time to do that is now, for it is during the

Copyright © National Academy of Sciences. All rights reserved.

conceptualization, and initial development of exploration programs that the research community has its greatest opportunity to shape the relevant political, technical, and scientific decisions. Such participation is responsive to the finding enunciated in the *Report of the Advisory Committee on the Future of the U.S. Space Program* (U.S. Government Printing Office, Washington, D.C., 1990), that science is "the fulcrum of the entire space effort."

Since its establishment in 1958, the Space Studies Board (SSB; formerly the Space Science Board) has been the principal nongovernmental advisory body on civil space research in the United States. In this capacity, the board established the Committee on Human Exploration (CHEX) to examine many of the science and science-policy matters concerned with the return of astronauts to the Moon and eventual voyages to Mars. The Board asked CHEX to consider three major questions:

1. What scientific knowledge must be obtained as a prerequisite for prolonged human space missions?
2. What scientific opportunities might derive from prolonged human space missions?
3. What basic principles should guide the management of both the prerequisite science activities necessary to enable human exploration and the scientific activities that may be carried out in conjunction with human exploration?

This report focuses on the first of these topics. Reports concerning the second and third topics are in their final stages of preparation and will be available in the near future.

The Space Studies Board and CHEX concluded that the existing research strategies of several of its discipline committees form a solid basis for determining the scientific research necessary to enable future voyages by humans to the Moon and Mars. To establish a context for its study, however, CHEX first examined the scientific aspects of various Moon/Mars mission concepts and determined the appropriate role of science in a program of human exploration. Having laid this foundation, CHEX then evaluated and integrated the *enabling requirements* for human exploration contained in the strategy documents of relevant SSB committees. (The details of the individual scientific strategies and the goals of these SSB committees are, however, not repeated in this report—they may be found in the original strategy documents listed in the bibliography.) These requirements were then classified according to their relevance to basic human survival and optimum mission performance.

Information on the conditions necessary to maintain the well-being of humans in space was provided by the Committee on Space Biology and Medicine. Requirements for data on the properties of planetary atmospheres and surfaces and exobiology, needed for basic mission operations and sci

Copyright © National Academy of Sciences. All rights reserved.

ence research, were supplied by the Committee on Planetary and Lunar Exploration. *A Strategy for the Scientific Exploration of Mars* (NASA, Jet Propulsion Laboratory, Pasadena, Calif., 1991), a report written by NASA's Mars Science Working Group, was consulted for additional information on the planetological and exobiological aspects of Mars precursor science. The space radiation environment, including its characterization and predictability, is the responsibility of the Committee on Solar and Space Physics and the Committee on Solar-Terrestrial Research. Advice on some technological issues was provided by the Committee on Microgravity Research. Full membership lists for these Space Studies Board discipline committees appear in the appendix.

Copyright © National Academy of Sciences. All rights reserved.

Contents

Copyright © National Academy of Sciences. All rights reserved.

Copyright © National Academy of Sciences. All rights reserved.

Executive Summary

"To expand human presence and activity beyond Earth-orbit into the solar system"[1] was the goal established by President Ronald Reagan in 1988 for the nation's program of piloted spaceflight. This goal formed the basis for the subsequent proclamation by President George Bush on July 20, 1989—the 20th anniversary of the Apollo 11 lunar landing—in which he proposed that the nation go "back to the Moon, ... And this time, back to stay. And then—a journey into tomorrow—a manned mission to Mars."[2] The resulting long-term program to expand the human presence in the inner solar system has been called many things, including the Human Exploration Initiative, the Space Exploration Initiative (SEI), and the Moon/Mars program. The Advisory Committee on the Future of the U.S. Space Program identified these objectives as Mission from Planet Earth.[3]

It is a long way from the broad goals of human exploration to a program of implementation, with many political, technological, and scientific hurdles to be overcome. Do successive administrations and congresses, as well as the American people, have the desire to dedicate necessary national resources to support such an ambitious program? Do they have the will and patience to support a program lasting for several decades? Can humans function effectively on the Moon for long periods of time? Can they survive a lengthy mission to Mars? What will they do when they get there? These are but a few of the myriad questions to be addressed before our species can realize the ancient dream of human voyages to, and eventual settlement of, our neighboring planets.

Copyright © National Academy of Sciences. All rights reserved.

THE ROLE OF SCIENCE

The role of science in human exploration is paramount and its challenges no less daunting than those facing the engineering community. New scientific data concerning the health and safety of astronauts are essential prerequisites for the human exploration of space. Research must be done to understand and alleviate the deleterious effects of microgravity on human physiology, the risks posed by radiation in space, and the environmental stresses humans will experience travelling to and operating on and around other planetary bodies. The U.S. scientific and engineering community is obliged to provide the best and most constructive advice to help the nation accomplish its space goals, as was stressed in a 1988 space policy report to the newly elected president by the National Academy of Sciences and the National Academy of Engineering.[4] To that end the National Research Council's Space Studies Board established the Committee on Human Exploration (CHEX) and charged it, as its first responsibility, to determine what scientific questions need to be answered before humans can undertake extended missions to the Moon and travel to Mars.

Defining these scientific prerequisites entails a degree of judgment about both our current state of knowledge of the relevant science and the potential modes of mission implementation. CHEX determined that some issues are critical to the basic survival and elementary functioning of humans in space. Other issues concern the effectiveness and efficiency of operations and their impact on overall mission success. The line between the two is sometimes fuzzy, and the committee anticipates that with time crossover will occur.

Beyond the information needed to provide for the basic health and well-being of astronauts operating in extraterrestrial environments, the expansion of human presence and activity into the solar system does not demand any a priori scientific research component. Nor is a Moon/Mars program driven by any demands for scientific discovery. The latter view is expressed in the National Academies' 1988 space policy report, which states that "the ultimate decision to undertake further voyages of human exploration and to begin the process of expanding human activities into the solar system must be based on nontechnical factors."[5] Given a nontechnical decision, what then is the proper role of science?

That *there is a role* is not open to much debate. The Paine report,[6] the Ride report,[7] the Augustine report,[8] and the report of the Synthesis Group[9] all recommend, to varying degrees, that significant scientific research be conducted in association with human exploration. In fact, "exploration" does not exist in isolation from scientific research. There are, however, two distinctly different categories of science that must be considered. There is the "enabling" science required if we are to conduct human exploration at all. Then, there is the "enabled" science made possible, or significantly

Copyright © National Academy of Sciences. All rights reserved.

enhanced, because it is carried out in conjunction with a program of human exploration. This report deals with the former topic. The latter is treated in a preliminary fashion insofar as it impacts the scientific effectiveness of Moon/ Mars missions. For example, conducting certain preliminary robotic missions to the Moon and Mars can result in a more effective scientific return from eventual human exploration. This report also contains some preliminary discussion of technology requirements, aspects of international scientific cooperation, and the approach used to manage the scientific component of a program of human exploration.

ENABLING SCIENCE

In establishing the scientific prerequisites for the human exploration of space, CHEX has identified two broad categories of enabling scientific research. This classification is based on the degree of urgency with which answers are needed to particular questions before humans can safely return to the Moon or travel to Mars.

Critical Research Issues

The lack of scientific data in some areas leads to unacceptably high risks to any program of extended space exploration by humans. These critical research issues concern those areas that have the highest probability of being life threatening or seriously debilitating to astronauts and that are thus potential "showstoppers" for human exploration. The areas in which additional scientific information *must* be obtained prior to extended exploration of space by humans include the:

1. Flux of cosmic-ray particles, their energy spectra, and the extent to which their flux is modulated by the solar cycle;
2. Frequency and severity of solar flares;
3. Long- and short-term effects of ionizing radiation on human tissue;
4. Radiation environment inside proposed space vehicles;
5. Effectiveness of different types of radiation shielding and their associated penalties (e.g., spacecraft mass);
6. Detrimental effects of reduced gravity and transitions in gravitational force on all body systems (especially the cardiovascular and pulmonary systems) and on bones, muscles, and mineral metabolism, together with possible countermeasures;
7. Psychosocial aspects of long-duration confinement in microgravity with no escape possible and their effects on crew function; and
8. Biological aspects of the possible existence of martian organisms and means to prevent the forward contamination of Mars and the back contamination of Earth.

Copyright © National Academy of Sciences. All rights reserved.

Optimal Performance Issues

The second category of research includes issues that, based on current knowledge, do not appear to pose serious detriments to the health and well-being of humans in space. They could, however, result in reduced human performance in flight or on planetary surfaces and, thus, in a less than optimal return from the mission. Some of these issues may become critical research issues relative to long-term human spaceflight and return to terrestrial gravity following extended flights, or when extraterrestrial habitation is considered. Research issues related to optimal mission performance include the:

1. Vestibular function and human sensorimotor performance;
2. Effects of the microgravity environment on human immunological functions;
3. Long-term effects of microgravity on plant growth;
4. Feasibility of closed-loop life support systems;
5. Interplanetary micrometeoroid flux and its time dependence;
6. Surface and subsurface properties of the Moon and Mars at landing sites and at the locations of possible habitats;
7. Hazards posed by martian weather and other martian geophysical phenomena;
8. Atmospheric structure of Mars relevant to implementing aerobraking techniques; and
9. Microgravity science and technology relating to long-duration spaceflight. Two additional issues, while not directly related to human performance, are included for their potential to significantly enhance and optimize the scientific return of the mission:
10. Methods of detecting possible fossil martian organisms and the chemical precursors of life; and
11. Availability and utilization of in situ resources (e.g., ice/water and minerals) on the Moon and Mars.

References

1. President Ronald Reagan, Presidential Directive on National Space Policy, 11 February, 1988, (Fact Sheet, page 1), The White House, Washington D.C.
2. President George Bush, Remarks by the President at 20th Anniversary of Apollo Moon Landing, 20 July, 1989, The White House, Washington D.C.
3. Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (the "Augustine report"), U.S. Government Printing Office, Washington, D.C., 1990.

Copyright © National Academy of Sciences. All rights reserved.

4. Committee on Space Policy, *Toward a New Era in Space: Realigning Policies to New Realities* (the "Stever report"), National Academy Press, Washington, D.C., 1988.
5. See Ref. 4, p. 14.
6. National Commission on Space, *Pioneering the Space Frontier,* The Report of the National Commission on Space, Bantam Books, New York, 1986.
7. Office of Exploration, *Leadership and America's Future in Space,* A Report to the Administrator by Dr. Sally K. Ride, August 1987, NASA, Washington, D.C., 1987.
8. See Ref. 3.
9. Synthesis Group, *America at the Threshold,* Report of the Synthesis Group on America's Space Exploration Initiative, U.S. Government Printing Office, Washington, D.C., 1991.

Copyright © National Academy of Sciences. All rights reserved.

1

Introduction

THE HUMAN EXPLORATION OF SPACE

On July 20, 1989, President George Bush set an ambitious vision before the American people: to go "back to the Moon, ... And this time, back to stay. And then—a journey into tomorrow—a manned mission to Mars."[1] This proposal to expand human presence in the solar system has been given a number of different names, including the Human Exploration Initiative, the Moon/Mars program, Mission from Planet Earth, and, most recently, the Space Exploration Initiative (SEI). In this report, the term "Moon/Mars program" is used to refer generically to any future program directed toward the human exploration of the Moon and Mars.

In the last decade, many committees, commissions, and studies have assessed the future of the U.S. space program and have come to broadly similar conclusions regarding the future of human spaceflight. The most recent major assessment, performed by the Stafford Commission (or Synthesis Group) in a report[2] submitted to Vice President J. Danforth Quayle on May 3, 1991, set forth six defining themes to guide human exploration:

1. Increase our knowledge of the solar system and the universe;
2. Rejuvenate interest in science and engineering;
3. Refocus the U.S. position in world leadership away from the military to the economic and scientific spheres;
4. Develop technology that has terrestrial application;

Copyright © National Academy of Sciences. All rights reserved.

5. Facilitate further space exploration and commercialization; and
6. Boost the U.S. economy.

The fundamental premise of a Moon/Mars program, given the overarching goal of human presence and activity beyond Earth, is directly articulated by the first theme, an increase in knowledge of the universe. Thus "the Space Exploration Initiative is an integrated program of missions by humans and robots to explore, to understand and to gain knowledge of the universe and our place in it."[3]

As its name suggests, the Synthesis Group's report was the distillation of a nationwide outreach campaign to ascertain the nation's space exploration aspirations. The group devised four broad concepts, or architectures, each embodying an alternative goal. The first emphasizes an accelerated human mission to Mars, with an intermediate return to the Moon. The second concentrates on scientific research on the Moon and Mars. The third provides for long-term habitation on the Moon, accompanied by a Mars exploration phase. The final architecture envisages the utilization of in situ lunar and martian resources to expand human capabilities in the inner solar system.

The report of the Synthesis Group proposed a strategic approach with its use of "waypoints." Each waypoint describes a level of capability that is, in itself, a significant achievement. At each waypoint the accumulation of infrastructure, technology, and knowledge would allow selection of both the emphasis and detailed implementation needed to achieve the next waypoint. The architecture is thus an assemblage of successive waypoints.

While not intended as detailed blueprints for the execution of a program of human exploration, the architectures characterize broad alternative goals for a Moon/Mars program. Science plays a major, albeit different, role in each concept. However, certain recurring scientific elements are found in all four architectures and, incidentally, in previous studies of the human exploration of space. These common themes include the following:

- The principal barriers to human exploration, particularly of Mars, are uncertainties in medical science. These uncertainties include, in particular, the physiological and psychological burdens placed on the crews and the acceptable level of risk that can be assumed;
- A mix of robotic and human exploration missions. The former (precursors) may provide information necessary for the planning and successful execution of the latter or may undertake purely scientific tasks (although the report of the Synthesis Group did not emphasize their scientific potential);
- Initial human activities on the Moon. Some are specifically preparatory for Mars missions. Others deal with study or use of the Moon for science;

Copyright © National Academy of Sciences. All rights reserved.

- The prime objectives of the Mars missions are exploration and science; and
- Significant technical advances are required if humans are to return to the Moon and travel on to Mars. These are primarily engineering developments of existing or understood technologies rather than the development of totally new scientific or technological approaches.

The Space Studies Board's Committee on Human Exploration (CHEX) presumes that, eventually, one of these architectures, or perhaps even a new theme, could be selected to provide a focus for Moon/Mars exploration. Once this is done, the subordinate objectives can be deduced and mission planning begun.

Regardless of which specific architecture is ultimately selected, human exploration of the Moon and Mars will be a long-term program of progressively more complex and demanding missions. These will challenge the nation's technical capabilities, management skills, and, perhaps, financial resources.

SCIENCE AND THE HUMAN EXPLORATION OF SPACE

Ever since the successes of the Apollo program 20 years ago, the future directions of the U.S. program of human spaceflight have been a matter of discussion, debate, and controversy within the government and the scientific community and among the public. A report on space policy by the National Academy of Sciences and the National Academy of Engineering stated that "the ultimate decision to undertake further voyages of human exploration and to begin the process of expanding human activities into the solar system must be based on nontechnical factors."[4] Nevertheless, the U.S. research community is obliged to provide the best and most constructive scientific advice it can to shape the political and technical decisions regarding piloted flight. This role is consistent with the recommendation of the Augustine Committee that science is "the fulcrum of the entire space effort."[5]

Part of the task facing the scientific community is determining what knowledge is prerequisite for prolonged human space missions. However, these prerequisites depend on the goals of such missions. If the goal of future space missions were solely to satisfy the "human imperative" to explore or to enhance national prestige or other nontechnical and nonscientific objectives, there would be a limited set of requirements. There would, for example, be relatively little need for precursor robotic missions to characterize the martian surface, because sufficient data are at hand from the Viking mission to allow selection of a safe landing site. But because the goals of most Moon/Mars concepts to date do include the expansion of

Copyright © National Academy of Sciences. All rights reserved.

knowledge and other objectives such as long-term habitation and utilization of in situ resources, the set of prerequisites is larger. For example, a martian landing site must not only be safe but must also be desirable from a scientific perspective. This creates a need for precursor robotic missions and provides linkages between the scientific knowledge that is prerequisite for human exploration and the scientific opportunities deriving from such a program.

The relative role of humans and robotic probes in space exploration has long been a contentious issue. If the acquisition of knowledge were the only goal, then the criteria for selecting between humans and robots would be clear: select the most cost-effective method of obtaining the desired results. The Augustine report recognized the important role humans can play in exploration. However, it went on to say that "in hindsight . . . it was . . . inappropriate in the case of the *Challenger* to risk the lives of seven astronauts and nearly one fourth of NASA's launch assets to place in orbit a communications satellite."[6] A rational approach is to use robots until we can define objectives for which humans are essential. We could also conduct experiments to determine the contribution to field exploration that is gained by having humans in situ. No compelling case has yet been made that human exploration is necessary to accomplish the goals of lunar and martian science or, for that matter, any other goal except the "human imperative" to explore. The report of the Synthesis Group gives five visions other than science. However laudable these other visions are, there has been no cost-benefit analysis to show that human exploration is the best way of achieving them.

The tension between the science and nonscience goals suggests the following criteria for selection between human and robotic options. Robotic probes should be used to provide enough information to:

1. Optimize the sites chosen for human exploration. Mars especially, but also the Moon, presents varied environments, and the number of sites astronauts can visit will be limited, as will be the range of their traverses at each site; and
2. Define a set of scientifically important tasks that can be *well* performed by humans in situ.

The first criterion should not be interpreted to mean that there is currently a scientific justification for human exploration. Nor does the second demand (at least initially) that scientific tasks would be best and most cost-effectively performed by humans. It is possible that future experiments and flight experiences will show that some tasks are better, and perhaps more cost-effectively, performed by humans, given the state of the art of robotic technology. If this should turn out to be the case, a scientific justification for human exploration might evolve.

Copyright © National Academy of Sciences. All rights reserved.

The inclusion of science goals in a Moon/Mars program raises two serious concerns for the scientific community. The first is that human exploration may displace other programs and initiatives that have a higher scientific significance or priority. The second concern is that the scientific objectives be of high quality and be competitive with other scientific opportunities. Toward this end, the scientific component of human exploration should be managed so that:

1. The stated scientific objectives of the human exploration program are achievable with a high probability of success;
2. The architecture is flexible and able to respond to new scientific discoveries and, thus, to ensure that the scientific benefits of the program are maximized;
3. Scientific advice is included in day-to-day decisions on the strategy and implementation necessary to execute the programs; and
4. All goals (e.g., scientific research, human presence, utilization of resources) of a Moon/Mars program are clearly stated and represented in project management in such a manner that open and effective decision making can be accomplished.

Management issues will be dealt with in depth in the third CHEX report; they are mentioned here to emphasize the necessity to deal with the approach to science management ab initio.

ENABLING SCIENCE

A Moon/Mars program requires the acquisition of scientific data either prior to, or in conjunction with, actual piloted flight and planetary surface activity. Establishing the requirements for such data is, to a major extent, a task for the scientific community. This entails both a responsibility and an opportunity. The responsibility is to state clearly what scientific data are essential to enable a Moon/Mars program and to propose programs and mechanisms to acquire, analyze, and interpret data, and to assure the overall quality of the scientific research. An opportunity arises because some enabling data will have a value over and above that immediately required by a program of human exploration. Such information might, however, be accorded a different priority in the absence of a program of human exploration.

Developing the full set of requirements for enabling data is an iterative process that will depend eventually on the specific architecture selected. If, for example, establishing astronomical observatories on the Moon becomes a goal, particular information on the lunar environment that might otherwise not be needed will become essential. Similarly, if long-term habitation becomes a goal of lunar or martian exploration, then the search for in situ

Copyright © National Academy of Sciences. All rights reserved.

resources such as water becomes a high priority simply because of the major impact that easily recoverable resources would have on the entire program.

Conversely, consideration of a set of enabling requirements derived from a particular architecture, and the ability to satisfy those requirements, could produce changes in the architecture. For example, if it turns out to be impossible to devise countermeasures to the deleterious effects of long-term exposure to microgravity, then the development of a vehicle that incorporates artificial gravity or the development of advanced propulsion systems with decreased transit times may be the only practical options.

Scientific information is clearly needed to assure the safety of humans and the effectiveness of human and machine operations. Although the Apollo missions have proven that humans can undertake brief expeditions to the Moon, the prospect of long-term or permanent habitation raises serious safety issues, particularly where current knowledge is only rudimentary. Apollo data provide some clues as to areas in which our ignorance harbors the greatest potential dangers. These areas include the long-term and short-term prediction of solar flares,[7] the character of the interplanetary meteoroid flux, the detailed nature of the lunar subsurface, and the possible detrimental effects of long-term interaction with the ubiquitous lunar dust.

Some of the basic knowledge about the atmosphere and surface of Mars required for human exploration is already in hand. The United States successfully operated two robot landers for more than one martian year. Yet, despite the wealth of data gathered by the Viking probes, extensive human activities on Mars will require the acquisition of significant amounts of new information. The variability of the martian atmosphere, the planet's surface and subsurface characteristics, and the risk of volcanic activity must be studied. The existence or abundance of significant, life-critical resources needs to be determined. Attention must be given to avoiding the transport of microorganisms from Earth and vice versa. The identification of likely abodes of any past life will follow from a better understanding of the martian environment and its history.

Precursor robotic missions (including sample return missions) can permit analyses that would greatly improve the selection of landing and exploration sites that could, in turn, enhance the science to be accomplished by human exploration. A Mars sample return mission may be desirable to settle questions of forward contamination and back contamination. Indeed, the Space Studies Board has recommended that "the next major phase of Mars exploration for the United States involve detailed in situ investigations of the surface of Mars and the return to Earth for laboratory analysis of selected martian surface samples."[8]

In examining the enabling science for the human exploration of space, CHEX identified two categories of research topics, each with differing de

Copyright © National Academy of Sciences. All rights reserved.

grees of urgency. *Critical research issues* are those related to conditions known to be life-threatening or seriously debilitating: they are the potential "showstoppers" of human exploration. The other category, *research for mission optimization*, includes issues that, based on current knowledge, do not appear to represent immediate threats to the health and well-being of humans in space. They could, however, result in reduced astronaut performance in flight or on the surface of the Moon or Mars, leading to a suboptimal mission. They could also impact the health of astronauts long after a mission is completed. In addition, it must be recognized that our current state of ignorance about prolonged human spaceflight leaves open the possibility of phenomena that cannot be anticipated.

CHEX emphasizes that, as new information is acquired, some optimal performance issues could become critical to ensuring the well-being of astronauts. If, for example, it is necessary to minimize payload mass, development of a partially closed, if not fully closed, life support system could become mandatory for missions to Mars.

The exploration of Mars by humans will be one of the most complex, challenging, and expensive technical endeavors ever attempted. These missions will, however, be carried out by even more complex entities—humans. It is therefore vital that as much effort be put into understanding the effects of the space environment on humans as has been put into understanding the mechanisms of getting a spacecraft to Mars and back.

It is widely assumed that since a small number of astronauts have survived and operated for as long as a year in space, there are no major physiological problems that would prohibit long-term human exploration. This assumption is unwarranted. An assessment of current research in space biology and medicine shows that the major problems posed by prolonged exposure to microgravity remain no nearer solution in 1993 than they were in 1961, the year of the first human spaceflight. For reasons outlined in earlier reports,[9] space biology and medicine are in the very earliest stage of development as rigorous scientific disciplines. These fields must mature if any attempt is made to send humans on extended missions to Mars.

The danger posed by biomedical uncertainties is related to another important matter, not often publicly stated—the role of courageous individuals. Humans who venture into space must accept a degree of personal risk. But, as the *Challenger* accident made clear, the public will not accept losses that can be anticipated and avoided. A sustained program of human exploration must adopt the prudent strategy of reducing to an acceptable minimum both the immediate and long-term risks astronauts will face. Thus, the potential hazards of exposure to radiation and microgravity must be addressed within the context of a comprehensive program of health and safety. To do otherwise imposes unacceptable risks on the entire human exploration enterprise.

Copyright © National Academy of Sciences. All rights reserved.

SPACE STATION FREEDOM

What role does Space Station Freedom play in the future human exploration of space? The Augustine report recommended that the primary objective of a space station should be life sciences research.[10] The Space Studies Board strongly affirms the position that a suitably equipped space-based laboratory is required to study the physiological consequences of long-term spaceflight.[11] The 1987 report of the Space Studies Board's Committee on Space Biology and Medicine laid out the critical requirements for such a space station.[12] They include:

1. A dedicated life sciences laboratory with adequate crew to conduct research;
2. A variable-speed centrifuge of the largest possible dimensions;
3. Sufficient numbers of experimental subjects (humans, plants, and animals) to address the stated scientific goals; and
4. Sufficient laboratory resources, including power, equipment, space, computational facilities, and atmosphere, to support the above research requirements.

NASA's current plans for Space Station Freedom are the subject of much controversy because of the project's escalating cost, lengthening construction schedule, and declining capabilities. On several occasions, the Space Studies Board has expressed concern that the current, descoped design of Space Station Freedom does not meet all the basic research requirements outlined above[13] and therefore will *not* fulfill its role as the first and necessary step in the human exploration of space. This is especially true if we are to use Space Station Freedom to perform the necessarily long program of enabling biomedical research and still meet the oft-stated goal of landing humans on Mars by 2019. The prudent strategy is, as the Augustine report recommended, to be flexible and not set a rigid schedule for the exploration of Mars by humans. However, the difficulties currently being experienced by the space station project do not negate the essential need for such a facility to perform the enabling research on human adaptation to the microgravity environment necessary for a Moon/Mars program.

INTERNATIONAL CONSULTATION AND COLLABORATION

The magnitude and comprehensive nature of a Moon/Mars project will present unprecedented opportunities for cooperation with other nations. Just as other countries will play important roles in building the spacecraft and systems to support human exploration, so too will they be intimately involved in both the scientific research necessary to enable human explora

Copyright © National Academy of Sciences. All rights reserved.

tion of the Moon and Mars, and in the enabled science opportunities arising from such explorations.

To a great degree, space science is already broadly international. A multitude of mechanisms exist for involving the most creative minds around the world in space science, from canvasing the international community to determine scientific objectives to inviting participation in specific missions. Just as the space hardware programs of other countries have matured, so also have their space science capabilities; thus they will expect to be treated as equal, not junior, partners in the human exploration enterprise. CHEX believes, therefore, that a consensus of the international space research community on the scientific goals and objectives of a Moon/Mars program, and on a strategy for their implementation, is essential to the development of any framework for cooperation in the overall human exploration program.

NOTES AND REFERENCES

1. President George Bush, Remarks by the President at 20th Anniversary of Apollo Moon Landing, 20 July, 1989, The White House, Washington D.C.
2. Synthesis Group, *America at the Threshold,* Report of the Synthesis Group on America's Space Exploration Initiative, U.S. Government Printing Office, Washington, D.C., 1991.
3. See Ref. 2, p. 2.
4. Committee on Space Policy, *Toward a New Era in Space: Realigning Policies to New Realities* (the "Stever report"), National Academy Press, Washington, D.C., 1988, p. 14.
5. Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (the "Augustine report"), U.S. Government Printing Office, Washington, D.C., 1990, p. 5.
6. See Ref. 5, p. 3.
7. It is worth noting that the crews of Apollos 16 and 17 were very lucky in that their flights bracketed the large flare of August 4, 1972. If the mission timings had not been so fortuitous, the astronauts could have suffered potentially fatal exposure to radiation.
8. Space Studies Board, *International Cooperation for Mars Exploration and Sample Return,* National Academy Press, Washington, D.C., 1990, p. 1, p. 3, and p. 25. See also, Space Studies Board, *1990 Update to Strategy for the Exploration of the Inner Planets,* National Academy Press, Washington, D.C., 1990, p. 40, and Space Science Board, *Strategy for Exploration of the Inner Planets: 1977–1987,* National Academy of Sciences, Washington, D.C., 1978.
9. See, for example, Space Science Board, *A Strategy for Space Biology and Medical Sciences for the 1980s and 1990s, National Academy Press,* Washington, D.C., 1987.
10. See Ref. 5, p. 29 and p. 47.
11. Space Studies Board, *Assessment of Programs in Space Biology and Medicine 1991,* National Academy Press, Washington, D.C., 1991.
12. See Ref. 9, pp. 13-16.
13. See Space Studies Board, *Space Studies Board Position Paper on Proposed Redesign of Space Station Freedom,* March 1991, and *Space Studies Board Assessment of the Space Station Freedom Program,* March 1992.

Copyright © National Academy of Sciences. All rights reserved.

2

Critical Research Requirements

The cardinal consideration in any discussion of prolonged human exploration is the safety and well-being of the crew. This led CHEX to define a set of critical research requirements related to conditions known to be life threatening or seriously debilitating: they are the potential "showstoppers" of human exploration. All previous experience from Mercury to the Space Shuttle and from Vostok to Mir is helpful in indicating possible problems. This experience is, however, insufficient to provide all the answers about the long-term effects of spaceflight on humans, since that experience is limited to less than three months for U.S. astronauts (almost 20 years ago) and just over one year for a small number of cosmonauts. In addition to the limited time, many of the effects were inadequately studied from a research protocol point of view.

In contemplating round-trip voyages to Mars of two years or more, we enter a new arena of human experience. Factors such as radiation, the effects of prolonged exposure to microgravity on physiologic functions, the psychosocial phenomenon of sequestration of a small crew in a confined area, with a closed environmental system and without any prospect of escape in the event of catastrophe, are all without precedent.[1] Ground-based research characterizing the effects of psychosocial and radiation phenomena should be continued and enhanced.

Space biology and medicine are in such a primitive state of development that knowledgeable researchers cannot state with any degree of assurance that human crews will be able to operate their spacecraft or function

Copyright © National Academy of Sciences. All rights reserved.

usefully on Mars after their voyage. Even if nuclear- or solar-thermal (or nuclear- or solar-electric) propulsion systems can be realized, trip time will still be nearly six months each way. Even this is well beyond U.S. experience, and the former-Soviet Union's program offers very limited solid biomedical data for missions of this duration.

Once astronauts reach their destinations, they may face additional problems. We have no information at all about the physiological effects of long-duration (more than one year in some scenarios) exposure to the fractional-*g* lunar or martian environments. One recent report asserts that "it is expected that while crews are on the martian surface, the three-eighths Earth's gravity will help maintain their physiological health."[2] There is absolutely no scientific evidence to support this expectation.

Some space planners are optimistic that essential information can be obtained and necessary measures taken to ensure reasonable safety for crew members. In the view of CHEX this is far from a certainty. Thus life-sciences research must be the dominant factor in any consideration of prolonged human spacefaring. All other aspects of a Moon/Mars program fade into secondary importance until the relevant life-sciences research has been conducted and preventive or ameliorative measures investigated. It is critical that planners recognize that current knowledge about human performance in space is predicated on relatively short-term experiences. CHEX predicts that human problems that we cannot anticipate today will be discovered during long-term missions.

It has been suggested that some of the enabling biomedical data can be gained in operations conducted on the Moon.[3] Such operations will not, however, be sufficient to yield the biological and physiological information required for a comprehensive understanding of the effects of microgravity. There can be no assurance that countermeasures derived in an ad hoc manner will be effective for all crew members in all situations.

CHEX recommends that those implementing a Moon/Mars program commit to and lead a comprehensive program of basic and applied life-sciences research on the effects on human physiology of the microgravity, reduced-gravity, and space-radiation environment prior to finalizing spacecraft designs or undertaking long-duration flights. For this purpose, a long-term research program in adaptation to microgravity and reduced gravity, properly conducted in a suitably equipped space station in low Earth orbit, will be required. Such a research program may require 5 to 10 years because of the necessarily long-duration of individual experimental protocols.

Copyright © National Academy of Sciences. All rights reserved.

RADIATION

Bombardment by energetic particles is a major hazard facing space travellers.[4] Indeed, NASA has recognized that the cumulative radiation dose "will probably be the ultimate limiting factor for human exploration."[5]

Humans conducting extended space voyages face two different radiation hazards: a protracted exposure to galactic cosmic rays at a low dose rate and some probability of exposure to considerably higher doses of solar energetic particles. Depending on the total exposure suffered, these twin effects will increase the probability of stochastic effects (such as cancer and genetic damage) and may also increase the incidence of deterministic effects (physical damage to tissues). The effects of acute irradiation during solar particle events are of particular concern. The high-dose-rate exposures they could inflict on astronauts could cause acute damage to the skin, gut, bone marrow, and germinative tissues and, at a later date, cause cataracts. Estimating the probability of very large solar flares and predicting the resultant exposure of astronauts to radiation are among the principal concerns that need to be addressed before we can safely design new space vehicles and plan voyages of human exploration.

Radiation Levels

The health hazard posed by energetic particles depends, in part, on the energy deposited as the particles pass through tissue or come to rest in vital organs. This is traditionally characterized by the "dose equivalent," which reflects the biological effect of exposure to radiation. The dose equivalent is equal to the absorbed dose multiplied by the "quality factor" (Q), which varies from ~1 for minimally ionizing particles such as gamma rays to ~20 for neutrons and heavy ions such as iron nuclei.

The International Commission on Radiological Protection has recently recommended that the term "quality factor" be replaced by "radiation weighting factor" (W_R). The values of W_R for specific types and energies of radiation have been selected to be representative of the relative biological effectiveness (RBE) of radiation in inducing stochastic effects at low dose.[6] There are, however, no recommendations for values of W_R for causing either early or late deterministic effects such as acute tissue damage and cataracts, respectively. However, the RBE for cell killing by radiation with high linear-energy-transfer rates (e.g., heavy ions and neutrons) is considerably lower (by factors of about two to five) than that for the induction of cancer.

NASA currently has no limits for exposure to radiation during deep-space missions conducted beyond the protective shield of the geomagnetic field because little is known about the physiological effects of the heavy ions found in cosmic rays. In terms of the traditional dose-equivalent for

Copyright © National Academy of Sciences. All rights reserved.

mulation. NASA's current limits for exposure of astronauts in low Earth orbit are 0.25 sievert (Sv) per month, 0.5 Sv per year, and 1 to 4 Sv for a lifetime exposure (depending on age and sex). (For comparison, the typical dose used to sterilize food and drugs is 20,000 Sv.) NASA's current limits correspond to a 3% excess risk of eventual death due to cancer and are about 10 times that allowed for terrestrial radiation workers and about 100 times that allowed for the general population.

Sources of Hazardous Radiation

As mentioned above, two types of radiation are hazardous to astronauts—galactic cosmic rays and solar energetic particles. The risk posed by galactic cosmic rays is principally due to protons (with a broad range of energies) and heavy ions (in particular, energetic iron nuclei). The principal danger from solar energetic particles is posed by sporadic, large fluxes of energetic protons.

Galactic Cosmic Radiation

Galactic cosmic rays consist of ions of all atomic numbers from 1 to 92, with energies ranging up to 10^{20} electron volts (eV). Those combining high (H) atomic number (Z) and high energy (E) are collectively called HZE particles. Of these, the iron-group ions are the most hazardous because they combine relatively high abundance, a high rate of energy deposition (proportional to the square of their electric charge), and a high Q-factor. To a lesser extent, ions with atomic numbers between those of oxygen and silicon are also important.

Many questions concerning HZE particles are unanswered. How effective are they, for example, in inducing cancers? Can the late deterministic effects of HZE particles be predicted from our present understanding of the long-term effects of radiations with low linear-energy-transfer rates such as x rays and gamma rays?

Two other areas where more data are needed are of particular relevance to human exploration. The first is the 10 to 30% range of uncertainty in the measured fluxes of heavy ions in the critical energy range from 50 to 5000 MeV per nucleon (which includes more than 90% of the cosmic-ray flux). Second, the Sun's 11-year activity cycle modulates the cosmic-ray flux such that the flux at energies below 5000 MeV per nucleon is greater during years of solar-activity minimum than during solar maximum. As alluded to previously, a better understanding of the biological effects, both acute and long-term, of energetic radiation must also be achieved.

The materials that form the spacecraft or the layers of a spacesuit shield astronauts from radiation to some extent. In addition, the human body

Copyright © National Academy of Sciences. All rights reserved.

provides ~5 cm of additional shielding for *some* critical organs, which is equivalent to about 4 cm (or 10 gm/cm^2) of aluminum. Figure 1 illustrates the estimated dose equivalent at 5-cm tissue depth for aluminum shielding of different thicknesses for galactic cosmic rays during the cosmic-ray maximum (solar-activity minimum) in 1977.[8] As can be seen, only the first 5 cm of shielding is very effective; disproportionately thicker shields are required for greater protection. For comparison, one third of the solid angle inside the space shuttle has a shielding of less than 8 cm of aluminum, while 11% of the solid angle has a shielding equivalent to less than 0.8 cm of aluminum.[9] In addition to attenuating the flux, the thickness and type of shielding determine how cosmic rays fragment into secondary particles. The nature and abundance of these secondaries, which account for the flattening of the dose-versus-shielding curve, are a major determinant of the radiation dose astronauts will receive.

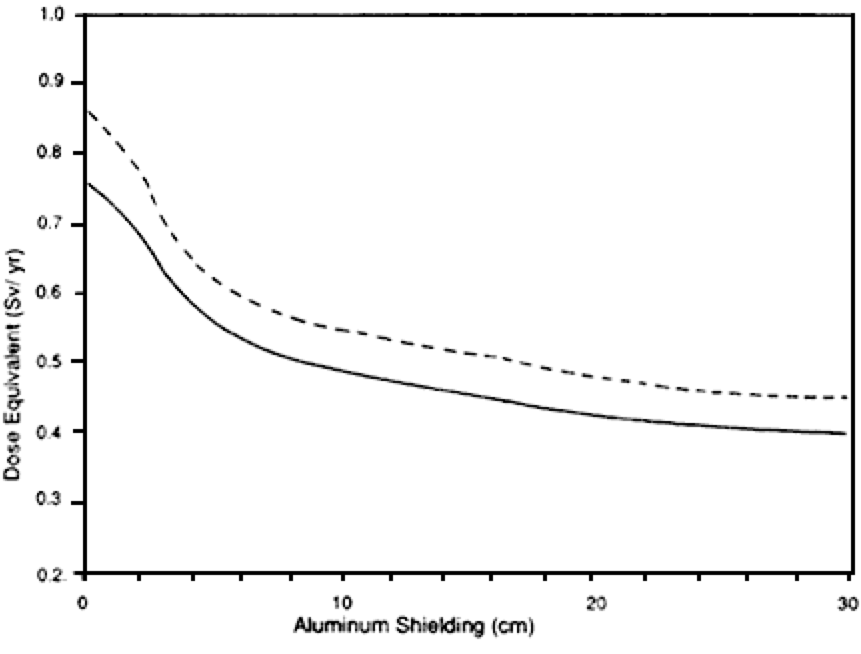

Figure 1
Estimates (solid curve) of the radiation dose equivalent received from galactic cosmic rays at a depth of 5 cm in body tissue (representative of, for example, bone marrow) versus aluminum shielding thickness during the 1977 solar-activity minimum. The dashed curve is an upper bound on the dose equivalent at the 90% confidence level. From Adams et al., 1991 (see reference 8).

The great penetrating power of cosmic rays combined with their high RBE suggests it may be impractical to shield against them in deep space.

Copyright © National Academy of Sciences. All rights reserved.

Therefore, if background cosmic rays were the only radiation hazard, the safest time for a mission to Mars might be when the Sun's activity is near maximum and the flux of galactic cosmic rays might be 10 to 30% lower due to the modulation effect. Unfortunately this time corresponds to the period of the highest probability of solar-flare occurrence. Thus, a voyage to Mars during solar maximum should be conducted only if timely forecasts of solar energetic particle events will exist to allow adequate defensive measures to be taken. Before any final conclusions on mission timing are drawn, the probability of solar-flare occurrence must be considered along with the uncertainties in cosmic-ray fluxes, their modulation, attenuation, and fragmentation in shielding, and biological effects.

Solar Energetic Particles

The intensity, spectra, and composition of energetic particles from solar flares are much more variable than those of galactic cosmic rays. The flare-produced energetic-particle population can also be dramatically enhanced by strong shocks in the solar wind associated with coronal mass ejection. An unprotected astronaut caught in a very large flare event could be exposed to a very high or even a lethal dose in a few hours to a day. The most dangerous events are those that include solar protons with energies above a few tens of MeV. The alpha particles, electrons, and heavier nuclei accompanying the protons pose comparatively slight additional hazards.

Shielding can provide some degree of protection against solar energetic particles. Figure 2 shows the effectiveness of aluminum shielding for the large flare of August 1972 and a hypothetical "worst case" combining the very-high-energy particles observed in the February 1956 event with the very high flux levels attained in the August 1972 event.[10] As can be seen, a worst-case event would place astronauts at considerable risk because of their prolonged exposure to energetic protons at relatively high dose rates even if they were shielded by 16 cm of aluminum. It must be noted that detailed measurements of solar flares have been available for only a few decades, and so events with characteristics even more extreme than this "worst case" cannot be excluded with any confidence.

A lunar or martian base could be partially buried so that its inhabitants would be protected from radiation when inside. They would, however, still be at risk in transit between Earth, the Moon, and Mars and when on the lunar and martian surfaces. Thus space travellers will likely need some type of early warning system to alert them to dangerous solar events. In addition, mission rules would need to take into account the time needed to seek shelter.

Copyright © National Academy of Sciences. All rights reserved.

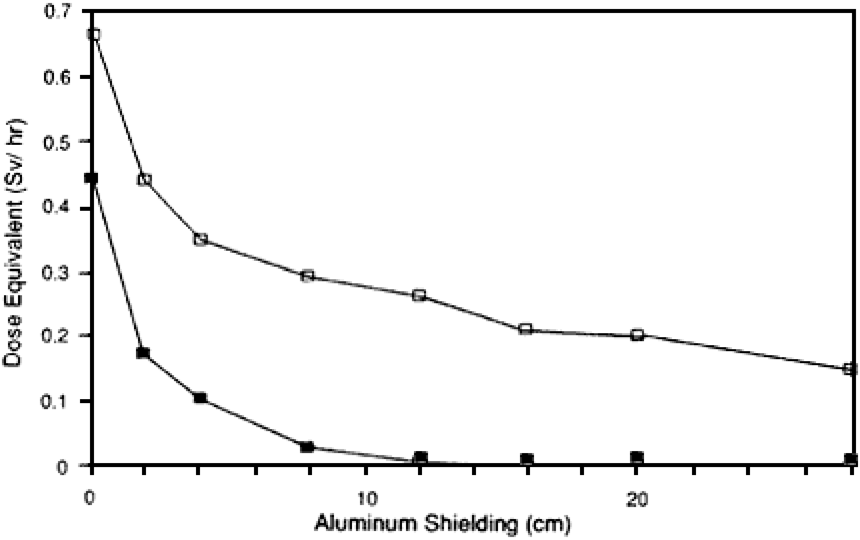

Figure 2
The radiation dose equivalent received at a depth of 5 cm in body tissue (representative of, for example, bone marrow) versus aluminum shielding thickness for the August 1972 solar flare (solid squares) and a composite, worst-case solar energetic particle event (open squares). Reprinted with permission from J.R. Letaw, R. Silberberg, and C.H. Tsao, "Galactic Cosmic Radiation Doses to Astronauts Outside the Magnetosphere," in *Terrestrial Space Radiation and Its Biological Effects,* P.D. McCormack, C.E. Swenberg, and H. Bucker (eds.), Plenum Press, New York, 1988. Copyright 1988 by Plenum Publishing Corp.

In addition to hazardous energetic particles, solar flares produce energetic neutrons and enhanced electromagnetic emissions at all wavelengths. Although the increased radio, optical, ultraviolet, and x rays do not constitute a hazard, they do signal the onset of proton acceleration in the Sun. This electromagnetic radiation travels at the speed of light and takes only eight minutes to reach the Earth-Moon system in contrast to energetic solar-flare protons, which may take from 15 minutes to 60 hours to travel the same distance.[11] Thus, a flare-radiation detection system could give adequate warning for crews working near a lunar base. For astronauts engaged in surface traverses on the Moon or Mars, emergency procedures must be developed to provide temporary shielding rapidly. Orbital transfer vehicles will need storm shelters where crew members can take refuge during an event. The need for emergency procedures will tend to be minimized if dangerous flare conditions can eventually be predicted a day or more in advance.

Copyright © National Academy of Sciences. All rights reserved.

Relevant Measurements and Research

There are several possible approaches for making significant progress in reducing some of the current uncertainties in the flux of heavy ions in galactic cosmic rays. These include the following:

- The fluxes of cosmic-ray nuclei (especially oxygen through iron) should be measured throughout the 22-year magnetic solar cycle using a new generation of instruments with large geometric factors, such as NASA's planned Advanced Composition Explorer;
- Measurements of the intensities of the electron and positron components of galactic cosmic rays over most of a 22-year cycle would separate charge-sign-dependent effects from other cosmic-ray propagation effects, thereby leading to better understanding of the modulation process;
- Measurement of the galactic cosmic-ray intensities beyond the boundary of the heliosphere would establish an upper limit to the radiation intensity independent of its modulation by the solar wind and magnetic field. Continued tracking of the Voyager spacecraft is clearly cost-effective in this respect; and
- Theoretical studies of the solar- and plasma-physical processes that modulate the intensity of galactic cosmic rays are required to better understand and predict their variability.

Improved measurements of cross-sections and better modeling of heavy-ion interactions, particularly for the yield and spectra of neutrons and other secondary particles generated in the shielding material, are also required. NASA currently helps support the Bevalac heavy-ion accelerator and some cross-section studies. However, the Bevalac has been threatened with closure, thus endangering some of the enabling research on both cross-section measurements and the long-term biological effects of ionizing radiation.[12]

Research conducted during the International Geophysical Year in the late 1950s helped lay the groundwork for the basic theoretical understanding of the triggering of solar flares: fast magnetic reconnection in a magnetically dominated plasma. Since then, progress in understanding the details of the solar-flare mechanism has been slow. Moreover, in the absence of human spaceflights beyond low Earth orbit, flare prediction has not been the focus of solar-flare researchers for the last 15 years. There is, however, reason to believe that significant progress can be made if the objectives are compelling.

Two types of research programs should be considered: first, those that help us understand the process of particle acceleration and release and that might eventually lead to improved forecasting of energetic-particle events, and second, those that provide warning that a potentially dangerous event has occurred.

Copyright © National Academy of Sciences. All rights reserved.

In the first category, the following programs would lead to significant progress in understanding flares:

- A meter-class space telescope to observe the Sun continuously with 100-km resolution. This facility should advance our fundamental understanding of flare-production mechanisms by spotting such precursor events as the emergence of magnetic flux through the photosphere and the buildup of magnetic shear;
- A global network of some 6 to 10 small Earth-based solar telescopes to measure magnetic fields and optical radiation over the full solar disk with approximately 700-km resolution. By monitoring active regions and logging flare precursors, these instruments should lead to better flare forecasting on time scales of hours to days;
- An x-ray and gamma-ray imaging telescope in space to provide information on the acceleration and propagation of energetic electrons and ions in the flare plasmas, and hence on the nature of the flare process. When coupled with direct and proxy measurements of the evolution of the magnetic-field structure in the flaring regions, this could substantially increase our ability to predict the acceleration and release of energetic flare particles; and
- Theoretical studies and computer simulations of flare-related magnetohydrodynamic processes to interpret the required measurements and direct future observations.

Whether or not we are ever able to forecast flares with high confidence, the following space-based measurements could be used as part of an advance-warning system for energetic particles once a flare has occurred.

1. A solar-observing spacecraft stationed 1 astronomical unit from the Sun in solar orbit 60 to 90 degrees ahead of Earth. Its payload would consist of an extreme-ultraviolet/x-ray telescope, a white-light coronagraph, and a small telescope designed to detect the onset of flares.
2. A network of satellites spaced at 90-degree intervals in a solar orbit with a radius of 0.3 to 0.5 astronomical unit. These satellites would carry energetic-particle detectors to provide reliable early warnings of energetic flare particles.

A solar-observing spacecraft is an important component of a short-term (a few minutes to a few hours) warning system because it would allow modeling and predictions of the paths taken by energetic particles as they are channeled from flare sites into interplanetary space.

The coronagraph would allow coronal mass ejections (CMEs) to be observed and their initial speeds to be determined. Such observations provide 1- to 3-day advance warning of the arrival of the CME-driven shocks

Copyright © National Academy of Sciences. All rights reserved.

that can dramatically enhance the population of flare-produced energetic particles. A single spacecraft is sufficient to cover the Earth-Moon system, but a network of three or four spacecraft (with 90- to 120-degree spacing) is required to cover Mars exploration, because Earth and Mars have different orbital periods and solar longitudes.

BONE DEGENERATION AND MUSCLE ATROPHY

Microgravity has major, potentially dangerous effects on human physiology. Extensive research is required to understand the responses of humans to microgravity and to assess their implications for long-duration spaceflight. Because a small number of astronauts and cosmonauts have survived long-duration missions in low Earth orbit, there is a false perception that there is no need to be concerned about health-related issues when contemplating interplanetary voyages. According to the Committee on Space Biology and Medicine, "Based on what we know today, this assumption of continued success cannot be rigorously defended."[13] The committee continued, "If this country is committed to a future of humans in space, particularly for long periods of time, it is essential that the vast number of uncertainties about the effects of microgravity on humans and other living organisms be recognized and vigorously addressed. Not to do so would be imprudent at best—quite possibly, irresponsible."[14]

The bone degradation (osteopenia) and muscle atrophy that occur in a microgravity environment are severe hurdles to an extended human presence in space.[15] The primary risk is to the functioning of the musculoskeletal system upon reexposure to planetary gravity. At present, our understanding of the causes of space-induced osteopenia and muscle atrophy is inadequate to devise effective countermeasures to be taken on long-duration space missions. Also lacking are data on the temporal sequence of bone remodeling and muscle atrophy in prolonged exposure to microgravity and the ways in which these processes may depend on other risk factors such as age, gender, race, or nutrition. Without such data, we cannot be confident that a prolonged microgravity mission such as a Mars flight would not lead to irreparable musculoskeletal damage. Such damage could both impair the effectiveness of crew members during their stay on Mars and pose serious problems upon their return to Earth. There is also the possibility that some bone demineralization will occur during prolonged flight in spite of countermeasures. If so, astronauts en route to Mars might be at risk for bone fracture with mild trauma and for the formation of kidney stones.

There is great depth and breadth to current research on osteopenia, muscle atrophy, and their underlying causes, thanks to sponsorship by the National Institutes of Health. These studies have concentrated on the problems of bone metabolism in relation to aging, menopause, endocrine disor

Copyright © National Academy of Sciences. All rights reserved.

ders, poor nutrition, immobilization, and extended bed rest. A major effort is now needed to develop parallel studies to acquire basic knowledge about these problems as they occur in microgravity and to begin devising appropriate countermeasures. A critical factor in such studies must be the use of appropriate animal models and the development of computational and experimental methodologies to test and validate mechanisms of bone remodeling and muscle conditioning. In addition, the development of suitable in vitro systems using bone and muscle tissue cultures should be undertaken.

One approach to counteracting the physiological effects of microgravity is to subject organisms in space to artificial gravity. Although such an environment could correct bone degeneration, muscle atrophy, and other changes due to microgravity, it could also exacerbate other effects not now perceived to be major problems. Head movements made in a spinning environment or Coriolis effects can lead to disturbing vestibular sensations and motion sickness. Changes in gravity experienced when moving to different parts of a spinning spacecraft or when changing the spin rate might induce symptoms of disequilibrium.

A comprehensive program is required to (1) determine the gravity threshold required to reverse or prevent the deleterious effects of microgravity and (2) evaluate the effects of centrifugation on behavior and/or sensorimotor function. Part of the required research could be accomplished by using human surrogates, including nonhuman primates, on a dedicated centrifuge in low Earth orbit. Studies of human responses to spinning will require a centrifuge of sufficient dimension to accommodate humans. An alternative strategy would be to investigate the use of rotating tethered spacecraft[16] to provide artificial gravity. It is possible that the detrimental vestibular effects of spinning can be eliminated if the tethers are sufficiently long.

Even assuming an optimistic schedule for lunar operations or space station activation, the relevant life-sciences knowledge developed from them will probably not be available before the beginning of the second decade of the 21st century. This implies a substantial technical risk in any program of Mars exploration that relies on a comprehensive solution to problems of human adaptation to microgravity. The prudent alternative is to carry forward, during conceptual design phases, alternatives providing for artificial gravity (as recommended in a National Research Council report[17]) during the cruise flight phase, and possibly in Mars orbit as well. If satisfactory countermeasures are confidently identified during a vigorous and rigorous program of orbital life-sciences research, this alternative design path can be abandoned. Conversely, if an effective artificial-gravity system is developed, research on countermeasures will become less urgent.

The design, construction, and operation of rotating spacecraft may pose formidable technical challenges. Nonetheless, all investments in the program will otherwise be hostage to a favorable outcome in the human adap

Copyright © National Academy of Sciences. All rights reserved.

tation issue. In the view of CHEX, the Synthesis Group's report erred ab initio in discarding consideration of artificial-gravity scenarios in its four architectures. Indeed, the provision of artificial gravity may well prove to be an architectural variable of more fundamental importance than the thematic differences between alternative mission emphases presented in the report of the Synthesis Group.

CARDIOVASCULAR AND PULMONARY FUNCTION

The redistribution of intravascular fluid toward the head is one consequence of exposure to a microgravity environment.[18] This shift has not impaired astronauts' cardiovascular and cardiopulmonary function during the relatively short periods of exposure to microgravity experienced thus far. It has, however, caused clinically significant dysfunction following return to Earth. This dysfunction manifests itself as an orthostatic intolerance and decreased capacity for exercise. Full recovery appears to occur rapidly (within 2 to 5 days) following short flights but can take as long as 30 days following long flights. The potential exists for permanent impairment following prolonged adaptation to microgravity. Both acute and longer-term problems could occur upon landing on Mars, since its gravity is only about three-eighths that of Earth's. With limited health support available, reduced cardiovascular function could threaten the success of crew activities on Mars.

Microgravity leads to a reduction in plasma volume that also contributes to orthostatic and exercise intolerance upon return to Earth. When the blood volume in the chest and head increases, the kidneys excrete more fluid. Another factor contributing somewhat to orthostatic hypotension and reduction in exercise performance is a decrease in total red blood cell mass. When exposures to microgravity are brief, both of these effects are reversible.

Atrial and ventricular rhythm disturbances have occurred with significant frequency in both astronauts and cosmonauts and thus require attention. Particular examples include the following:

1. One cosmonaut was prematurely returned from Mir because of a refractory atrial rhythm disturbance.
2. Apollo 15's lunar module pilot sustained premature ventricular contractions (PVCs) with some episodes of bigeminy; 60 hours later he also had premature atrial contractions (PACs). Apollo 15's commander also sustained a run of PVCs.
3. The crew of Skylab 3 showed occasional PVCs and ectopic supraventricular contractions.
4. Atrioventricular block of brief duration has been observed in several crew members upon release of lower-body negative pressure before reentry.

Copyright © National Academy of Sciences. All rights reserved.

5. PACs have been observed in several astronauts during extra-vehicular activity.

The mechanisms for these effects remain unknown but could be related to shifts in intravascular volume and ensuing perturbations of regulatory hormones. The significance of these effects is also unknown but *could* be a prelude to more severe problems.

Further studies of the response of humans and animals to changes in gravitational force are essential to complete our understanding of the mechanisms responsible for cardiovascular and pulmonary deconditioning in space. Questions about the reversibility of deconditioning can be answered only by careful studies of animals and eventually humans, during and after prolonged exposure to microgravity. Adequate experimental controls require a centrifuge designed to accommodate primates.

Specific high-priority areas of cardiovascular investigation include:

1. The role of exercise and physical fitness before, during, and after flight;
2. Countermeasures against cardiovascular dysfunction during flights and rehabilitation after long flights;
3. Validation of ground-based models of microgravity for short-term and long-term studies; and
4. Characterization of drug pharmacodynamics in microgravity.

It is necessary to study the effects of long-term spaceflight on:

1. Cardiodynamics (e.g., cardiac output, chamber pressures and dimensions, and performance);
2. Cardiac rhythm (as shown by electrocardiograms taken at rest and during maximum exercise);
3. Hormone release and metabolism (e.g., of antidiuretic hormone, atrial antidiuretic peptide, and aldosterone);
4. Baroreceptor function (neural regulation of blood pressure);
5. Peripheral resistance (resistance offered to blood flow through the circulatory system); and
6. Pressures, degree of tone, and capacitance of the venous system.

Ventilation and blood flow to the different regions of the lung are affected by gravity and so will obviously be affected by microgravity. To quantify these effects, studies of the rate and depth of respiration, the component lung volumes, air flow, gas exchange, and pulmonary pressures at 1 *g* and at different levels of microgravity are necessary.

Another topic needing attention is potential effects of the space environment on cardiovascular and pulmonary physiology when modified by disease processes or pharmacological agents.

Copyright © National Academy of Sciences. All rights reserved.

Empirical evidence suggests that the performance of crews composed of competent, highly trained individuals is critically determined by psychological and social factors.[19] Moreover, psychosocial considerations necessarily assume greater importance when people are confined in isolated and inescapable environments. Reports from both cosmonauts and astronauts confirm the importance of psychological factors during long-duration missions. Despite awareness of the importance of these issues, systematic research into the determinants of human performance and adaptation under these conditions has received only minimal support. Only limited progress has been made since publication in 1987 of the Committee on Space Biology and Medicine research strategy, which included a chapter on human behavior.

Because of the limited number and duration of American spaceflights, systematic research in this field could be conducted in analog environments such as polar stations, undersea habitats, and aviation settings. However, generalizing the results of research in such analogs has its limitations. Nevertheless, available data strongly indicate that focused research on small groups in confined quarters may result in practical knowledge that could reduce the incidence of interpersonal conflict and psychological problems. The utility of such data should be even greater when groups work for prolonged periods in isolation and when experimental interventions can be conducted under controlled conditions.

The psychological factors relevant to the success of a mission can be organized into three domains: individual, group, and environmental. More basic research is urgently needed in each area. In addition to investigations in analog environments on Earth, the psychological determinants of current space operations, even short-duration shuttle missions, need more intensive study. Any single investigation, however, will lack features of a Mars mission such as the microgravity environment, exposure to radiation, mission duration, and lack of escape capability. Nevertheless, the aggregate findings from many such studies should provide important guidelines for the planning and conduct of very long missions.

Individual Factors

Just as technical competence is a prerequisite for task fulfillment, so also will the personality and motivation of each crew member critically influence the success of long-duration space missions. Efforts must be directed toward determining psychological profiles associated with performance and adjustment under conditions of prolonged isolation. Psychological selection strategies must be refined to focus not on screening out those

Copyright © National Academy of Sciences. All rights reserved.

candidates showing evidence of psychopathology but rather on selecting those candidates with optimal attributes.

Disruption of normal circadian (i.e., 24-hour) rhythms is another important factor to consider when planning long spaceflights. If unchecked, such disruption can lead to serious perturbations in human performance and productivity, with both psychological and physical consequences. Problems arising during exploration missions may be particularly severe since these rhythms appear to be disrupted by microgravity and/or high stress. Studies are needed to determine the optimal environmental conditions necessary to create the sense of normal circadian rhythms within the body during long-duration space missions.

Group Factors

Even the most technically competent and highly motivated individuals do not necessarily perform effectively and harmoniously when sequestered for prolonged periods in a confined environment. Moreover, the effects of seclusion can be exacerbated if escape is impossible. Improved methods are necessary for selecting and training teams so that they can sustain high levels of motivation, work quality, and interpersonal relationships. Training techniques developed to improve leadership, crew coordination, decision making, and conflict resolution in civil- and military-aviation settings need to be refined and validated in the space environment.

Environmental Factors

On long spaceflights, the crew's psychological environment is no less important than its physical environment. Additional research in operational, analog settings is required to determine the best social organization for human exploration missions. Issues central to crew effectiveness include:

1. How to organize daily activities to maximize performance and satisfaction (e.g., by providing meaningful, intellectually challenging work and enjoyable leisure activities) and to avoid boredom;
2. How to establish levels of automation that will balance efficient operations against operator control and satisfaction; and
3. How to establish an optimal division of responsibility between ground and space components to provide appropriate mission control while maintaining an efficient, cooperative relationship. Since crew safety is of paramount importance, the spacecraft commander must be vested with the final authority in all questions relating to the crew's health and welfare.

The design of the physical environment for long-duration missions should be based on research into requirements for privacy, habitability, and social

Copyright © National Academy of Sciences. All rights reserved.

interaction. A balance is necessary between engineering constraints and the requirements for harmonious group living over extended periods. In addition, the characteristics of the physical environment and the scheduling of work, leisure, and sleep cycles should minimize disruption of normal circadian functions. Many of these environmental and organizational issues could be profitably investigated in polar research stations and undersea habitats.

BIOLOGICAL ISSUES

The biological aspects of missions to Mars fall into two categories: those related to human well-being and those related only to exobiology. These overlap if a crew member is infected by a putative martian microorganism or if such organisms are returned to Earth. Although the chance is small that organisms, pathogenic or otherwise, exist on Mars today, public and legal concerns dictate close attention to this issue.

The protocols for the preparation of Mars-bound craft or the handling of martian samples returned to Earth will depend both on the relevant planetary protection regulations promulgated by the Committee on Space Research (COSPAR) and on public perception of the risks. The latter arises now much more stridently than it did in the past when the issues of forward and back contamination were first raised. Existing COSPAR regulations (currently under review) may require that landers be sterilized to prevent the introduction of terrestrial organisms to the martian environment.[20] The Viking spacecraft, for example, were decontaminated by a combination of presterilizing components and dry-heating the assembled landers prior to launch. Although these procedures were time consuming and extremely expensive, it may be required that they be applied to future robotic missions. Similarly, there is no question that rigorous procedures will be required for handling samples returned to Earth by robotic missions. A recent study[21] has concluded that the question of forward contamination by robotic missions is an issue only for those that include life-detection experiments, where the concern is contamination of the experiment. It would, however, be virtually impossible to avoid forward contamination of Mars or back contamination of Earth from human exploration.

Using the return flight as an incubation period and the crew as guinea pigs (as has been suggested[22]) is not a solution to back contamination on human missions. Would the whole mission be risked if an unanticipated contamination occurred? How would the cause of an infection be known with enough certainty to justify destroying the returning spacecraft before it entered Earth's atmosphere? The whole spacecraft, not only the astronauts, would be contaminated. In addition, infection might not be the only risk. A returning organism could possibly cause some long-term changes in our

Copyright © National Academy of Sciences. All rights reserved.

environment, perhaps remaining undetected for a while. Although such an event may be judged to have a very low probability, a convincing case that prudence has been exercised will have to be made to the public.

The scientific requirements relating to planetary protection and the assessment of the possibility of health-threatening microorganisms include:

1. How to detect the presence of indigenous microorganisms (potential pathogens) and their activities in samples returned to Earth prior to a human visit to Mars. A corollary is how to certify the biological safety of samples returned to Earth and of potential sites for human habitation. Simple culture experiments are insufficient because some organisms (e.g., the cholera-causing pathogen *Vibrio cholerae*) are not culturable using standard microbiological techniques. In fact, there is no unbiased assay to enable detection of even terrestrial microorganisms present at low concentrations.
2. How to detect potential pathogens during residence on Mars. The need for such detection may arise as novel habitats are encountered or as humans make use of martian resources such as water.
3. How to treat and handle an explorer in the highly unlikely event of infection by a martian life form.
4. How to monitor the fate and impact of terrestrial microorganisms unavoidably transported to Mars by vehicles or humans.

Addressing these issues will involve investigations of Mars-like environments on Earth as well as laboratory studies to develop the necessary tests, procedures, and protocols.

NOTES AND REFERENCES

1. Space Science Board, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015: Overview,* National Academy Press, Washington, D.C., 1988, pp. 67–68. Also see Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (the "Augustine report"), U.S. Government Printing Office, Washington, D.C., 1990, p. 6.
2. Synthesis Group, *America at the Threshold*, Report of the Synthesis Group on America's Space Exploration Initiative, U.S. Government Printing Office, Washington, D.C., 1991, p. 24.
3. See Ref. 2, p. 27.
4. NASA, *Report of the 90-Day Study on Human Exploration of the Moon and Mars,* NASA, Washington, D.C., November 1989, p. 6–2.
5. See Ref. 4, p. 6–3.
6. International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, *Annals of the ICRP* 21(1–3):1–201, 1991.

The equivalent dose in tissue, H_T, is given by the summation:

$$H_T = \Sigma_R W_R \cdot D_{T,R}$$

Copyright © National Academy of Sciences. All rights reserved.

where $D_{T, R}$ is the absorbed dose averaged over the tissue or organ T due to radiation R. The weighting factor, W_R, is selected for the type and energy of the radiation incident on the body. Its value is based on the relative biological effectiveness (RBE) for the radiation in *inducing stochastic effects (that is, cancer and genetic damage) at low doses*. It is vitally important to remember that these effects of long-term exposure to relatively low doses of radiation are in addition to any deterministic effects (the physical damage to tissues) likely to result from large doses of ionizing radiation.

7. The sievert is the unit of dose equivalent and is equal to the absorbed dose (in grays) multiplied by the quality factor. One gray is an absorbed dose of 1 joule per kilogram. One sievert = 100 rem. One gray = 100 rad.

8. J.H. Adams, Jr., G.D. Badhwar, R.A. Mewaldt, B. Mitra, P.M. O'Neill, J.F. Ormes, P.W. Stemwedel, and R.E. Streitmatter, "The Absolute Spectra of Galactic Cosmic Rays at Solar Minimum and Their Implications for Manned Space Flight," *Galactic Cosmic Radiation Constraints on Space Exploration*, NRL Publication 209–4154, Naval Research Laboratory, Washington, D.C., November 1991.
9. J.R. Letaw, R. Silberberg, C.H. Tsao, and E.V. Benton, *Advances in Space Research,* Vol. 9, No. 10, p. 257, 1989.
10. J.H. Adams, Jr., and A. Gelman, "The Effects of Solar Flares on Single Event Upset Rates," *IEEE Transactions on Nuclear Science,* NS-31, pp. 1212–1216, 1984.
11. National Council on Radiation Protection and Measurements, *Guidance on Radiation Received in Space Activities*, NCRP Report No. 98, National Council on Radiation Protection and Measurements, Bethesda, Maryland, 1989, p. 25.
12. Space Studies Board, Letter to James D. Watkins and Daniel J. Goldin, August 20, 1992, Washington, D.C., 1992.
13. Space Science Board, *A Strategy for Space Biology and Medical Sciences for the 1980s and 1990s*, National Academy Press, Washington, D.C., 1987, p. xiii.
14. See Ref. 13, p. ix.
15. See Ref. 13, Chapter 5.
16. L.G. Lemke, "An Artificial Gravity Research Facility for Life Sciences," *Proceedings of the 18th Intersociety Conference on Environmental Systems*, American Institute of Aeronautics and Astronautics, 1988. For more information on tethers, see P.A. Penzo and P.W. Ammann (eds.), *Tethers in Space Handbook,* Second Edition, NASA, Washington, D.C., 1989.
17. Committee on Human Exploration of Space, *Human Exploration of Space: A Review of NASA's 90-Day Study and Alternatives,* National Academy Press, Washington, D.C., 1990, p. xi.
18. See Ref. 13, Chapter 6.
19. See Ref. 13, Chapter 11.
20. Space Science Board, *Recommendations on Quarantine Policy for Mars, Jupiter, Saturn, Uranus, Neptune, and Titan,* National Academy of Sciences, Washington, D.C., 1978. See also Space Studies Board, *Biological Contamination of Mars: Issues and Recommendations,* Task Group on Planetary Protection, National Academy Press, Washington, D.C., 1992.
21. Space Studies Board, *Biological Contamination of Mars: Issues and Recommendations,* National Academy Press, Washington, D.C., 1992.
22. See Ref. 2, p. 77.

Copyright © National Academy of Sciences. All rights reserved.

3

Research for Mission Optimization

This chapter describes several issues that are relevant to the health and well-being of humans but that appear, at present, to represent less critical threats to the lives of astronauts than those discussed in the previous chapter. They are, however, no less important as related to optimum human performance during exploration missions. In addition, increased knowledge of the physical aspects of the Moon and Mars is required to ensure that human explorers perform efficiently. As new information accumulates, and as implementation decisions are made, the significance of any or all of the areas where research is needed to ensure mission optimization could increase to the point that they become critical issues.

SENSORIMOTOR INTEGRATION

Changes in the gravito-inertial environment during a space mission may lead to disturbances of sensorimotor function.[1] The consequences may include impaired spatial orientation, instability of position and gaze, and motion sickness. Fortunately these problems are of short duration because the central nervous system adapts to those changes within a few days *provided a constant environment is maintained* . There are, however, two caveats to this assessment of relative risk. First, gravito-inertial changes occur at the most critical times during a mission: takeoff and landing. Second, the crew of a spinning spacecraft (possibly used to counter the problems associated with prolonged exposure to microgravity) might suffer repeated changes in

Copyright © National Academy of Sciences. All rights reserved.

their gravito-inertial environment when moving to different parts of the craft or if the spin rate is changed. Fortunately, no known long-term health risks are associated with sensorimotor adaptation to microgravity.

Although both the National Institutes of Health and NASA are studying vestibular function and its interaction with other sensorimotor modalities, the etiology of motion sickness in general, and space adaptation sickness in particular, is still not known. The extent to which adaptive responses can be shaped or overridden by appropriate training in sensorimotor strategies is also unknown. Studies of vestibular function and its neuronal substrates in appropriate animal models are needed both on the ground and in a microgravity environment. Parallel studies of human sensorimotor performance in both environments must also be pursued.

IMMUNOLOGY

Can the immune system be damaged by spaceflight? This possibility stems from observations of abnormalities in the two major types of human lymphocytes, T-cells and B-cells, and in other white blood cells on the Spacelab D-1 mission. A reduction of function and disordered morphology of T-cells have been detected on some other flights. Moreover, changes in rat immunity have been observed on spaceflights conducted by the former Soviet Union.

Serious infections in humans during spaceflights are rare. Thus, there have been no opportunities to systematically assess the capacity of humans or other mammals to contain and eradicate infections by various types of terrestrial microbes while in space. The potentially devastating consequences of any immune dysfunction, particularly on long-duration flights, indicate the urgent need for further studies. The possible defects already identified in lymphocytes and also other elements of immunity vital to specific and adaptive defense mechanisms in humans need to be examined.

The potential effects of spaceflight on normal human immunity must be judged in terms of the antibody responses and reactions of lymphocytes, macrophages, and other white blood cells to different types of antigens. The most common antigens on Earth are proteins, carbohydrates, and complex lipids. These are presented to the immune system in soluble form and as a part of cells or other complex structures. The studies of responses to antigens in space should use both intact microbes, to mimic infections, and soluble purified proteins and carbohydrates, to simulate simple vaccines.

A vital aspect of immunity is a memory of exposure to antigens. Thus, comprehensive studies should encompass both new and previously encountered antigens of each major chemical class and physical form. This diver

Copyright © National Academy of Sciences. All rights reserved.

sity of experimental challenges is critical for assessment of immunity in space, because the variety and intensity of antigen challenges to the immune system will be substantially different from that experienced on Earth: the unique closed environment imposed by the spacecraft offers significantly decreased opportunities for the constant bombardment by new antigens encountered on Earth. The potential problem is that the immune system could become atrophic and render an individual more vulnerable to infection (especially if sufficiently rigorous measures are not taken to control microfloral contamination of the spacecraft).

If the T-cell defects are confirmed, then their effects should be delineated in relation to four factors:

1. The differences in responses to antigens and broader cell stimuli called mitogens;
2. Abnormalities in subsets of regulatory T-cells, which help or suppress activities of other immune cells;
3. The roles of diverse immune-cell-derived regulatory proteins called cytokines, which direct T-cell proliferation and functions; and
4. The functions of macrophages and other accessory white blood cells responsible for presenting antigens specifically to T-cells.

Effector systems, which eliminate toxins and kill microbes targeted by antibodies, such as white blood cells of the granulocyte series and serum proteins called complement factors, also should be assessed functionally. Some in vivo studies are required to detect and understand any deficiencies or excesses in integrated human immune responses.

The critical need for controlled variable-gravity studies cannot be overemphasized. Only such studies will produce data useful in identifying specific mechanisms, perceiving the impact of any immune system abnormalities on other systems, and providing clinical guidelines for preventing and countering any defects in human immune defenses.

The closed environment of the spacecraft may encompass a variety of living organisms (e.g., humans, animals, and plants), many types of energy-using equipment, and a wide variety of materials. The effluent from these multiple sources will contain microflora, gases (e.g., oxygen, carbon dioxide, and methane), and other chemical contaminants that must be collected and either disposed of or channeled through the life support system. The accumulation of colonies of microflora, pockets of gases, or dispersed trace chemicals could jeopardize the health of a crew and interfere with the success of a mission.[2] At this time we do not have adequate information to assess how microbial and immunological problems would affect humans during extended spaceflight.

Copyright © National Academy of Sciences. All rights reserved.

DEVELOPMENTAL BIOLOGY

A major scientific goal of studying developmental biology[3] in space is to "evaluate the capacity of diverse organisms, both plant and animal, to undergo normal development from fertilization through the subsequent formation of gametes under conditions of the space environment."[4]

Plants are key to the entire biological system that has developed on Earth. Thus, it is essential to understand the effects of gravity and its absence in order to grow plants in space for food or for use in life support systems (see next section). A considerable amount of scientific literature already exists on the biology of plants in space. However, most studies have not dealt with general questions about plant growth but, rather, have addressed the orientation and motion of roots and shoots or have focused on plant hormones and events associated with normal and gravity-stimulated cell and organ growth. Our understanding of plant signal transduction is scant and may well be enhanced by using models based on animal work. Such constituents as G-proteins, phosphoinositides, actin, and calmodulin also occur in plant cells and may have active roles. The increasing applicability of techniques of molecular biology to problems in plant growth and development will be useful in attempts to understand the responses of plants to the space environment and in developing breeding programs designed to increase plant performance in microgravity environments.

A major question is whether plants are capable of producing multiple generations in microgravity. The definitive space experiment is to observe a plant's life cycle from seed to seed to seed. The first generation of "on-orbit" seeds could have ground-born flowers upon germination, and thus produce seeds with ground-born tissues, since seed has maternal material in it. These seeds, however, would produce flowers exposed only to microgravity. Thus, their offspring, the third generation of seeds, would be entirely free of any prior terrestrial gravitational influence.

Another important question is whether microgravity affects the single cell or if some plant cells acclimate to gravity deprivation. Some space-based studies suggest that chromosome behavior is fundamentally changed in microgravity. Should this be the case, the consequences and their implications for cell development must be determined.

The lack of thermal convection in the microgravity environment may affect short- and long-distance transport phenomena in plants. For example, the function of cell membranes, the pathways for ion uptake and nutrient absorption, plant-water relations, and the transport of organic and inorganic molecules must be investigated to determine whether any of these is affected by microgravity. For example, is the plant-supporting structure of lignin and cellulose modified in space in ways analogous to the loss of bone density?

Copyright © National Academy of Sciences. All rights reserved.

LIFE SUPPORT SYSTEMS

Closely related to the question of plant growth in space is the feasibility of a closed-loop life support system (CLLSS). CLLSSs are integrated self-sustaining systems capable of providing potable water, a breathable atmosphere, and ultimately, food for astronauts on long-duration missions. Some such systems may be able to operate in a small enough volume to be practical in a space vehicle, while larger systems could be deployed at lunar and martian outposts. Although it is not yet clear if the initial phases of the human exploration of Mars demand a CLLSS, it is certain that without one, long-term missions will require either vast amounts of on-board stores or access to prepositioned supplies. Thus, an effective and reliable CLLSS, even if limited to generating air and water from crew waste, would greatly simplify the logistics of long-duration missions.

While a first-generation CLLSS would recycle only air and water, more advanced versions would be highly integrated subsystems for plant growth, food processing, and waste management. We have very little data on the operation of individual system components under realistic conditions. A small amount of information has been gathered on the performance of a few arbitrarily chosen plant species in open growth chambers. In addition, some encouraging, but still tentative, experiments have been initiated on plant growth in closed environments. Virtually nothing seems to have been done with respect to microbial and other systems of waste recycling, soil microbes and other microflora, or pathogen control. Nor have any of the food-processing technologies for converting biomass into palatable human nutrients been developed.

Green plants are critical components of even the simplest CLLSS. They can fix carbon dioxide, produce food and oxygen, and purify water. However, as noted in the previous section, we do not yet know if plants will grow in space well enough to support a CLLSS for significant periods of time. A major scientific goal is simply to grow plants in space for extended periods of time—over several life cycles—while carefully monitoring their performance. This goal is related to the more general need, outlined in the previous section, to investigate how diverse organisms undergo development in the space environment. For development of a CLLSS, this overall scientific goal assumes immediate practical importance. As we have already seen, processes such as reproductive development, fluid transport, and photosynthetic gas exchange may be adversely affected in low-gravity and microgravity environments. Even small effects may have serious consequences when performance is integrated over long time periods.

Many other components of a CLLSS must also receive attention. Diverse plant, animal, and microbial species must be evaluated, environmental parameters optimized, and procedures developed for food processing and

Copyright © National Academy of Sciences. All rights reserved.

for recycling liquid and solid waste materials. In many cases, we do not know enough to produce a suitably sized CLLSS on the ground, much less in space. Obtaining the required scientific knowledge and engineering experience will require extensive experimentation under actual conditions in space.

MICROMETEOROID FLUX ON THE MOON

Long-duration activities on the surface of the Moon increase the potential risk of experiencing lethal impacts by micrometeoroids. The use of average collisional fluxes may give a false sense of security as excursion times outside protective habitats increase. The occurrence of periodic terrestrial meteor showers related to comets is well known. Recent reanalysis of lunar seismic data reveals that lunar impacts are neither temporally nor spatially random. Moreover, not all observed meteoroid showers on the Moon correlate with known terrestrial meteor showers.

The potential dangers meteoroids pose to a long-duration presence on the Moon are twofold. First, there is an increased risk of direct hits during peak activity. Second, there is a risk of high-velocity impacts from secondary and ricocheting debris. The potential for lethal damage depends on the actual flux, the size distribution of the impactors, and the effect of spatially clustered impacts. These unknowns need to be studied over a sufficiently long period not only to assess the short-term risks (day to month), but also to recognize annual events and possible catastrophic swarms during orbital passage of newly discovered comets.

Lunar seismometers have proven their usefulness as meteoroid impact detectors. Establishing a seismic network on the Moon to characterize the flux, size distribution, spatial clustering, and possible directional anisotropies of impacts over a multiyear period is essential to evaluating the hazards posed to astronauts by meteoroids. The potential dangers of unexpected meteoroid storms can be assessed through continued monitoring and evaluation of newly discovered comets. Experience gained from seismic monitoring of small impactors will be important for assessing risks over even greater durations en route to, and in orbit around, Mars.

SURFACE AND SUBSURFACE PROPERTIES

Humans exploring the Moon and Mars will require knowledge about their proposed landing sites not only to ensure a safe touchdown and subsequent departure, but also to identify regions of potentially high scientific interest. Prime questions to be answered for candidate sites involve the mechanical properties of the landing zone and the surrounding terrain to be explored and sampled. Size distributions of rocks at potential landing sites

Copyright © National Academy of Sciences. All rights reserved.

are required for three reasons: first, to ensure sufficient clearance for the landing vehicle; second, to allow reasonable leveling of the lander; and third, to certify that the terrain is sufficiently benign to be traversed by astronauts on foot and with rovers to carry out mission objectives. Of equal importance is a priori knowledge of the mechanical or bearing strength of the surface, particularly at the precise landing site but also over the region to be explored by the astronauts.

The distribution of rock size can be obtained by precursor flights using remote sensing and in situ robotic exploration. Imaging with a resolution of less than 1 meter is necessary for selecting the landing sites themselves. Information on bearing strength is more difficult to obtain remotely. Significant estimates can be made of the near-surface soil densities using radar reflection and microwave emission techniques. Robotic landers may be required to achieve sufficient confidence to certify sites for human landings unless the areas selected are familiar (e.g., Apollo or Viking sites or demonstrably similar ones).

In addition to rocks, the lunar surface is blanketed with unconsolidated debris generated by meteoroid impacts. This material, called regolith or soil, contains broken mineral and rock fragments, impact-produced glasses, and rocky glass-bonded aggregates. On average, about 20% of the regolith is composed of particles smaller than 20 microns in size. These properties, coupled with the hard lunar vacuum (10^{-12} to 10^{-14} torr), make the regolith extremely abrasive. This will affect the longevity of all moving parts it comes in contact with. To make matters worse, regolith tends to cling to surfaces, leading to additional wear and tear on mechanisms such as gears, habitat airlocks, and spacesuit joints. Further in situ and remote sensing of the lunar surface and subsurface, together with studies of the abrasive and adhesive properties of lunar soil under hard vacuum conditions in terrestrial laboratories, will help in designing equipment to operate on the Moon's surface. Large-scale simulation facilities might also be needed to conduct long-duration, full-scale tests on engineering equipment and transport vehicles.

The nature of the lunar subsurface at depths of 1 to 10 meters is poorly known. Although the size distributions of surface blocks in the regolith are known for typical mare and highland regions, there is little knowledge of how these distributions may change with depth. In most regions, bedrock occurs at depths of just a few meters, but the nature of its interface with overlying fragmental debris is unknown. Moreover, subsurface discontinuities, including interbedded lava flows, bedrock ledges, and voids, may pose additional hazards to landing craft, rovers, and excavation equipment. The elimination of such hazards may require active seismic imaging.

Like the lunar regolith, the martian surface material may also be hazardous, but for different reasons. Existing data show that it contains highly

Copyright © National Academy of Sciences. All rights reserved.

reactive components in sufficient concentration to have oxidized the organic compounds used in one of the Viking life-sciences experiments. Such compounds may perhaps be responsible for the complete absence of any organic compounds in samples examined by Viking's gas chromatograph/mass spectrometer. Toxicity analysis could probably be carried out by a precursor robotic mission and might not require the analysis of martian material in terrestrial laboratories.

Based on current knowledge, the oxidizing material is likely to be associated with fine, windblown, particulate material. Thus, specific precautions against this dust will have to be built into the airlock system on a lander. Moreover, spacesuits will have to be decontaminated as astronauts reenter the lander after completing extra-vehicular activities. Perhaps the spacecraft itself will have to be "cleaned" prior to its return to Earth.

The data required to certify landing sites for safety may be highly desirable for other purposes such as planning surface construction, instrument installation, and the layout of extended surface traverses. Construction, prospecting, and mining operations will require subsurface sampling around the landing point. This can be carried out by the astronauts if the site has been selected on the basis of good information from precursor flights. That is, good measurements of surface rock distributions can be used to infer the subsurface geology. For Mars, such information is particularly critical because broad regions of the planet were not emplaced as primary geologic units, but, rather, have undergone episodic resurfacing tied to atmosphere-surface interactions. Astronauts can locate regions free of subsurface hazards for construction and mining using seismic and electromagnetic sounding devices on their rover.

The need for some of these data could be partly alleviated through the use of a robust and forgiving design for excavation and construction equipment. For example, if the capability to efficiently crush and remove rock is a requirement for a lunar bulldozer, the need for knowledge of the sizes and locations of subsurface boulders is diminished.

POTENTIAL MARTIAN HAZARDS

Potential hazards posed by martian weather and climate, volcanic and seismic activity, and a number of other factors need to be considered in the context of concern for astronaut safety and the major investment of resources in any program of human exploration. A mission failure due to lack of adequate assessment of all plausible and sensible potential hazards, however unlikely, would be inexcusable. Following appropriate studies, some of the potential hazards may be realized; others may turn out to be either non-existent or of such low probability that they can be dismissed.

Severe martian weather (such as dust storms, dust devils, and other

Copyright © National Academy of Sciences. All rights reserved.

vortices) may pose hazards to man-made structures or to field operations. Data on near-surface winds, including local wind shear and vorticity, are available only for the two Viking lander sites. Winds may affect descent vehicles by posing a hazard to, for example, parachute deployment or the spacecraft's ability to land precisely at a desired site. Ascent vehicles may also be affected by strong wind shears or turbulence. Variations of atmospheric density with local time, with solar activity, and with variations in the lower atmosphere (e.g., dust storms) may affect the operations and lifetimes of near-Mars support spacecraft, such as site-reconnaissance orbiters and communications satellites. Long-term meteorological measurements of temperature, pressure, wind velocity, and dustiness from orbit and at a variety of surface sites are required to assess these hazards. The current Mars Observer mission is directly relevant to this need.

Large dust devils and clouds associated with local storms have been observed. Although dust storms may occur in any season, one or more may grow to regional and, on occasion, even global scale during southern spring and summer. Dust storms reduce surface visibility and insolation, thus affecting, for instance, the efficiency of solar cells. Moreover, the movement of sand-sized particles near the surface may pit, scratch, and erode surfaces, and may foul joints. Continued remote sensing of the martian atmosphere will help define this hazard.

As is the case on the Moon and in free space, components of solar radiation reaching the surface of Mars may pose hazards to field workers and equipment (e.g., ultraviolet degradation of plastic material). Unlike the lunar surface and space, however, the total flux and the spectral distribution will change with variations in atmospheric aerosols and the seasons.

Information on the diurnal and seasonal variation of atmospheric temperature, density, and wind speeds is needed to design a martian outpost. Other factors such as local and regional topography can present additional hazards (e.g., strong winds on steep slopes or in canyons, or regions of local fogs). Certification of landing and base sites in regions of large interannual variability (mainly at mid and high latitudes) may require observations spanning several martian years or longer to characterize the complete range of conditions likely to be experienced.

Practically nothing is known about electric fields on Mars. The presence of moving dust particles in an atmosphere nearly as dry as Earth's stratosphere, however, could produce significant electrostatic charging. Besides being a nuisance (e.g., fine dust clinging to optical surfaces), such charging and discharging could severely affect crucial electrical equipment, such as computers. Large discharges—such as lightning—may also occur.

Although the hazard posed by meteorites falling on Mars is small, the impact flux could range from a nominal lunar value to one larger by as much as an order of magnitude. The circum-martian meteoroid flux could

Copyright © National Academy of Sciences. All rights reserved.

be determined by a spacecraft akin to NASA's Long Duration Exposure Facility in orbit around Mars, by detectors of meteors passing through the martian atmosphere, and by seismic networks on the martian moons.

The long-term safety of a martian outpost also requires assessment of the hazards due to seismic or volcanic activity. Insufficient data currently exist to make confident statements about martian seismicity. Volcanic activity has been widespread on Mars in the past. We do not know, however, if there has been any recent volcanism or if near-surface thermal activity or magma chambers exist. A network of seismometers and heat-flow measuring devices could provide the information to measure current activity. Other geologic hazards, including slides and slope failures, need to be assessed.

Areas of scientific interest in potentially dangerous locations, such as deep martian canyons or close to known volcanic vents, may require precursor visits by robot landers or rovers. Such sites may be especially important in deciphering the history of Mars, particular the role played by liquid water in both geological and biological contexts.

AEROBRAKING AT MARS

Aerobraking, or aerocapture, is a technique using atmospheric drag to reduce a space vehicle's orbital energy. It can thus cut down on the amount of propellant needed to achieve orbital insertion. Indeed, aerocapture may significantly reduce (perhaps by a factor of three or more) the mass that must be delivered into Earth orbit for a Mars exploration mission. Aerocapture could be critical to the feasibility of such a mission, and a proper understanding of the atmospheric structure of Mars and its variability should be considered part of the enabling science for such a mission.

Successful aerobraking requires a detailed knowledge of not only the mean density structure of the martian atmosphere but also its temporal and spatial variations. The Viking 1 and 2 landers, for example, measured vertical density profiles differing by more than 20% as they descended from an altitude of 100 kilometers to the surface. Most of the atmospheric variations at aerobraking altitudes on Mars (20 to 70 kilometers) are due to gravity waves. These are thought to be generated by thermal tides and by high-speed winds flowing over surface topography.

Further understanding of the statistics of density variations in the martian atmosphere is required before human landings using aerobraking are attempted. NASA's Mars Observer mission should answer many of the outstanding questions on this issue. However, a longer mission (with greater seasonal coverage) and some in situ measurements of the atmosphere will be required to calibrate remote observations. A better understanding of the temporal and spatial variations of atmospheric dust is also needed and should

Copyright © National Academy of Sciences. All rights reserved.

be obtained either from direct atmospheric measurements or by ground-based opacity observations. These concerns are addressed in considerable detail in a recent report.[5] This NASA document likewise concludes that mission safety requirements lead to a significant need for understanding the statistical behavior of the martian atmosphere. Remote spacecraft monitoring of atmospheric properties should be carried out both before and during the arrival of humans at Mars.

MICROGRAVITY SCIENCE AND TECHNOLOGY

Human exploration will require more understanding of fluid flow and transport under reduced (and sometimes increased) gravity conditions. In order to support extended space travel, we must know more about the processing of materials, thermal management, and the handling of fluids. Microgravity studies must be viewed as more than the advancement of science and technology for its own sake or as a means to obtaining potential benefits for society on Earth; these studies are essential to the advancement of spaceflight.

Many examples of challenges associated with a modified gravity field can be found: producing needed materials from available raw materials; washing and drying of clothing, equipment, humans, and animals; handling of hazardous and obnoxious wastes; improving and ensuring spacecraft fire safety; and achieving temperature control for humans, animals, plants, and electronics. The challenges occur predominantly in the life support areas but extend well beyond them. For example, modern electronics are becoming so compact that, in the near future, volumetric heat-generation rates are expected to rival those values for controlled nuclear fission. Also, there is overlap with the life sciences since fluid transport is essential to life itself, as, for example, the transport of liquid from the roots to the leaves of plants.

There is a strong need to address the underlying science as well as the technology. The relevant technology for related Earth-gravity-level processes is often based on empirical methodology. Therefore, engineering extrapolations cannot be readily made.

EXOBIOLOGY ISSUES

While there may be little chance that life exists on Mars today, this may not always have been the case. Thus, many of the science requirements relating to exobiological exploration of Mars revolve around technologies for detecting and analyzing fossil organisms or the chemical precursors to life. Closely related is the question of the history and present occurrence of liquid water and ice on Mars. Some specific questions include:

Copyright © National Academy of Sciences. All rights reserved.

1. How to detect indigenous martian microorganisms and assess their biological activities;
2. How to recognize and analyze fossil remains of such indigenous microorganisms;
3. How to search for the presence of chemicals that might relate to past activities of life forms or that might relate to prebiotic chemistry;
4. Where to seek evidence for past life or prebiotic chemistry; and
5. How to detect the current, and understand the past, distribution of liquid water and ice.

Beyond laboratory studies, answering these questions will involve acquiring a more detailed knowledge of Mars and its history. The location of ancient lake beds and of possible wind- and water-emplaced sediments will surely play a major role in selecting martian sites of interest to exobiologists.

The development of new organic analysis instrumentation with perhaps a 1000-fold improvement in sensitivity over the Viking mass spectrometer is likely to be needed. This needs to be coupled with a flexible "wet" chemistry input. If we are to adequately investigate the possible prehistory of biology on Mars, we need to answer whether or not there are any organic compounds of either abiogenic or biogenic origin on the surface or below the surface. Determining the ratios of different stereoisomers of amino acids will help distinguish between those of biogenic or abiogenic origin.

RESOURCE UTILIZATION

Long-term human exploration of Mars may require or greatly benefit from landing sites in close proximity to exploitable resources. If, for example, water needs to be acquired on Mars, it might be extracted from the air, from surface materials containing chemically bound water, or from sub-surface ice or permafrost. Which reservoir should be tapped depends on trade-offs between various extraction technologies available and detailed knowledge of the martian environment. The atmospheric abundance of water is known adequately for this purpose, but the location (particularly the depth) of subsurface ice is not.

If there is a requirement to mine water at the landing site, then precursor flights should be designed to locate regions where subsurface ice may exist. Similarly, detailed knowledge of the local mineralogy should be obtained on precursor flights for in situ extraction of water from mined minerals. If habitation is chosen as a long-term goal of Mars exploration, then the technology necessary to locate subsurface water or permafrost will probably need to be developed.

Copyright © National Academy of Sciences. All rights reserved.

NOTES AND REFERENCES

1. Space Science Board, *A Strategy for Space Biology and Medical Sciences for the 1980s and 1990s*, National Academy Press, Washington, D.C., 1987, Chapter 4.
2. For an assessment of this problem in the context of Space Station Freedom, see Board on Environmental Studies and Toxicology, *Guidelines for Developing Spacecraft Maximum Allowable Concentrations for Space Station Contaminants,* National Academy Press, Washington, D.C., 1992.
3. See Ref. 1, Chapter 2.
4. See Ref. 1, p. 32.
5. Mars Atmosphere Knowledge Requirements Working Group, *SEI Engineering Requirements on Robotic Missions,* Roger D. Bourke (ed.), JPLD-8465, NASA, Jet Propulsion Laboratory, Pasadena, Calif., May 1991.

Copyright © National Academy of Sciences. All rights reserved.

4

Conclusions

The Committee on Human Exploration finds that a program for the exploration of the Moon and Mars by humans offers both challenges and opportunities for the participation of the scientific community. Foremost is the fact that particular, enabling scientific information is required if a Moon/Mars program is ever to succeed in one of its prime goals, the expansion of human presence and human activity beyond Earth orbit into the solar system. This will remain the case even if a major Moon/Mars program is not initiated for 5 years or 25 years. The information that the committee deems critical is concerned largely with aspects of space biology and medicine and associated characteristics of the radiation environment. This in itself is not a new finding; recognition of the need for such information has been building over the past 30 years with little progress on solutions. What is required is that NASA (and other agencies involved in implementing a human exploration project) make a long-term commitment to sponsoring a rigorous, efficient, high-quality research program on the ground and in space. The resources required will be significant and challenge NASA to structure, market, implement, and ultimately manage an adequate plan.

To enable long-duration human flight to, and operations on, the Moon and Mars, we must obtain critical relevant data. However, we must also consider ab initio that the enabling research has a purpose above and beyond the simplistic, but prime, goal of achieving human presence and implied elementary survival. If a Moon/Mars program is to accomplish more than merely establishing a human presence in space, then achieving the

Copyright © National Academy of Sciences. All rights reserved.

program's yet-to-be-established specific goals and objectives demands that human performance and "pre-presence" preparation be optimized. This imperative places additional weight on the acquisition of scientific data on, for example, the distribution of potential lunar resources, details of the atmosphere of Mars, and information on the physical, chemical, and biological properties of the martian surface.

Science permeates all aspects of human exploration, no matter which architecture is finally selected and regardless of which set of candidate goals and objectives evolves. The involvement of the scientific community is needed to help set the goals for purely robotic missions, to analyze both scientific and engineering data, to structure appropriate tasks for humans, and to assist in the optimal integration of human and robotic activities. This pervasive requirement for scientific input mandates that the piloted spaceflight community develop a new understanding of and attention to the conduct of space science. It simultaneously requires that the scientific community interact constructively with those charged with implementation of a Moon/Mars program. In fact, success will require a technical and programmatic approach that eliminates the historical dichotomy between the "manned" and "unmanned" spaceflight programs.

Copyright © National Academy of Sciences. All rights reserved.

Bibliography

Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* , U.S. Government Printing Office, Washington, D.C., 1990.

Committee on Human Exploration of Space, *Human Exploration of Space: A Review of NASA's 90-Day Study and Alternatives*, National Academy Press, Washington, D.C., 1990.

Committee on Space Policy, *Toward a New Era in Space: Realigning Policies to New Realities*, National Academy Press, Washington, D.C., 1988.

Mars Atmosphere Knowledge Requirements Working Group, *SEI Engineering Requirements on Robotic Missions,* Roger D. Bourke, (ed.), JPLD-8465, NASA, Jet Propulsion Laboratory, Pasadena, Calif., May 1991.

Mars Science Working Group, *A Strategy for the Scientific Exploration of Mars*, JPLD-8211, NASA, Jet Propulsion Laboratory, Pasadena, Calif., 1991.

NASA Advisory Council, *Exploring the Living Universe: A Strategy for Space Life Sciences*, Report of the NASA Life Sciences Strategic Planning Study Committee, NASA, Washington, D.C., 1988.

NASA Advisory Council, *Strategic Considerations for Support of Humans in Space and in Moon/ Mars Exploration Missions*, Vol. I & II, Life Sciences Research and Technology Programs, Aerospace Medicine Advisory Committee, NASA , Washington, D.C., 1992.

NASA, *Report of the 90-Day Study on Human Exploration of the Moon and Mars*, NASA, Washington, D.C., 1989.

National Commission on Space, *Pioneering the Space Frontier,* The Report of the National Commission on Space, Bantam Books, New York, 1986.

National Council on Radiation Protection and Measurements, *Guidance on Radiation Received in Space Activities*, NCRP Report No. 98, National Council on Radiation Protection and Measurements, Bethesda, Maryland, 1989.

Office of Exploration, *Leadership and America's Future in Space*, A Report to the Administrator by Dr. Sally K. Ride, August 1987, NASA, Washington, D.C., 1987.

Office of Exploration, *Beyond the Earth's Boundaries: Human Exploration of the Solar System in the 21st Century*, NASA, Washington, D.C., 1988.

Copyright © National Academy of Sciences. All rights reserved.

Office of Space Science and Applications, *Cardiopulmonary Discipline Science Plan,* Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Controlled Ecological Life Support Systems* (CELSS), Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Developmental Biology Discipline Plan,* Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Human Factors Discipline Science Plan*, Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Musculoskeletal Discipline Science Plan*, Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Neuroscience Discipline Science Plan*, Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Regulatory Physiology Discipline Plan*, Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Space Biology Plant Program Plan*, Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Space Radiation Health Program Plan,* Life Sciences Division, NASA, Washington, D.C., 1991.

Office of Space Science and Applications, *Space Life Sciences Strategic Plan*, Life Sciences Division, NASA, Washington, D.C., 1992.

Office of Technology Assessment, *Exploring the Moon and Mars: Choices for the Nation,* OTA-ISC-502, U.S. Government Printing Office, Washington, D.C., 1991.

Space Environment Laboratory, *Solar Radiation Forecasting and Research to Support the Space Exploration Initiative*, NOAA Space Environment Laboratory, Boulder, Colo., 1991.

Space Science Board, *HZE-Particle Effects in Manned Spaceflight*, National Academy of Sciences, Washington, D.C., 1973.

Space Science Board, *Post-Viking Biological Investigations of Mars* , National Academy of Sciences, Washington, D.C., 1977.

Space Science Board, *Recommendations on Quarantine Policy for Mars, Jupiter, Saturn, Uranus, Neptune, and Titan*, National Academy of Sciences, Washington, D.C., 1978.

Space Science Board, *Strategy for Exploration of the Inner Planets: 1977–1987*, National Academy of Sciences, Washington, D.C., 1978.

Space Science Board, *Life Beyond the Earth's Environment: The Biology of Living Organisms in Space*, National Academy of Sciences, Washington, D.C., 1979.

Space Science Board, *Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980's*, National Academy of Sciences, Washington, D.C., 1981.

Space Science Board, *A Strategy for Space Biology and Medical Sciences for the 1980s and 1990s*, National Academy Press, Washington, D.C., 1987.

Space Science Board, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015—Life Sciences* , National Academy Press, Washington, D.C., 1988.

Space Studies Board, *International Cooperation for Mars Exploration and Sample Return*, National Academy Press, Washington, D.C., 1990.

Space Studies Board, *1990 Update to Strategy for the Exploration of the Inner Planets*, National Academy Press, Washington, D.C., 1990.

Space Studies Board, *The Search for Life's Origins: Progress and Future Directions in Planetary Biology and Chemical Evolution*, National Academy Press, Washington, D.C., 1990.

Space Studies Board, *Assessment of Programs in Space Biology and Medicine 1991,* National Academy Press, Washington, D.C., 1991.

Space Studies Board, *Biological Contamination of Mars: Issues and Recommendations,* National Academy Press, Washington, D.C., 1992.

Synthesis Group, *America at the Threshold,* Report of the Synthesis Group on America's Space Exploration Initiative, U.S. Government Printing Office, Washington, D.C., 1991.

Copyright © National Academy of Sciences. All rights reserved.

Copyright © National Academy of Sciences. All rights reserved.

Appendix

COMMITTEE ON SPACE BIOLOGY AND MEDICINE

FRED W. TUREK, Northwestern University, *Chair*
ROBERT M. BERNE, University of Virginia, Charlottesville
PETER DEWS, Harvard Medical School
R.J. MICHAEL FRY, Oak Ridge National Laboratory
FRANCIS (DREW) GAFFNEY, Southwestern Medical Center, Dallas
EDWARD GOETZL, University of California Medical Center, San Francisco
ROBERT HELMREICH, University of Texas, Austin
JAMES LACKNER, Brandeis University
BARRY W. PETERSON, Northwestern University
CLINTON T. RUBIN, State University of New York, Stony Brook
ALAN L. SCHILLER, Mt. Sinai Medical Center
TOM SCOTT, University of North Carolina, Chapel Hill
WARREN SINCLAIR, National Council on Radiation Protection and Measurements
WILLIAM THOMPSON, North Carolina State University, Raleigh
FRED WILT, University of California, Berkeley

Copyright © National Academy of Sciences. All rights reserved.

COMMITTEE ON SOLAR AND SPACE PHYSICS

MARCIA NEUGEBAUER, Jet Propulsion Laboratory, *Co-Chair*
THOMAS CRAVENS, University of Kansas
JONATHAN F. ORMES, Goddard Space Flight Center
GEORGE K. PARKS, University of Washington
DOUGLAS M. RABIN, National Optical Astronomy Observatories
DAVID M. RUST, Johns Hopkins University
RAYMOND J. WALKER, University of California, Los Angeles
YUK L. YUNG, California Institute of Technology
RONALD D. ZWICKL, National Oceanic and Atmospheric Administration

COMMITTEE ON SOLAR-TERRESTRIAL RESEARCH

DONALD J. WILLIAMS, Applied Physics Laboratory, *Co-Chair*
ALAN C. CUMMINGS, California Institute of Technology
GORDON EMSLIE, University of Alabama
DAVID C. FRITTS, University of Colorado
ROLANDO R. GARCIA, National Center for Atmospheric Research
MARGARET G. KIVELSON, University of California, Los Angeles
DAVID J. McCOMAS, Los Alamos National Laboratory
EUGENE N. PARKER, University of Chicago
JAMES F. VICKREY, SRI International

NOTE: The National Research Council's Committee on Solar-Terrestrial Research (CSTR) and Committee on Solar and Space Physics (CSSP) meet jointly as a federated committee and report directly to their parent National Research Council boards, the Board on Atmospheric Science and Climate for CSTR and the Space Studies Board for CSSP.

Copyright © National Academy of Sciences. All rights reserved.

COMMITTEE ON PLANETARY AND LUNAR EXPLORATION

LARRY W. ESPOSITO, University of Colorado, *Chair*
RETA BEEBE, New Mexico State University, Las Cruces
ALAN P. BOSS, Carnegie Institution of Washington
ANITA L. COCHRAN, University of Texas, Austin
PETER J. GIERASCH, Cornell University
WILLIAM S. KURTH, University of Iowa, Iowa City
LUCY-ANN McFADDEN, University of Maryland
CHRISTOPHER P. McKAY, NASA Ames Research Center
DUANE O. MUHLEMAN, California Institute of Technology
NORMAN R. PACE, Indiana University
GRAHAM RYDER, Lunar and Planetary Institute
PAUL D. SPUDIS, Lunar and Planetary Institute
PETER H. STONE, Massachusetts Institute of Technology
GEORGE WETHERILL, Carnegie Institution of Washington
RICHARD W. ZUREK, Jet Propulsion Laboratory

COMMITTEE ON MICROGRAVITY RESEARCH

ROBERT F. SEKERKA, Carnegie Mellon University, *Chairman*
ROBERT A. BROWN, Massachusetts Institute of Technology
FRANKLIN D. LEMKEY, United Technologies Research Center
WILLIAM A. SIRIGNANO, University of California, Irvine
THOMAS A. STEITZ, Howard Hughes Medical Institute

Copyright © National Academy of Sciences. All rights reserved.

Copyright © National Academy of Sciences. All rights reserved.