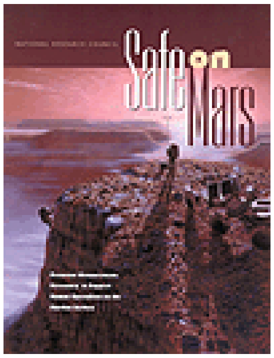

Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface

Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars, National Research Council

ISBN: 0-309-50200-4, 64 pages, 8.5 x 11, (2002)

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Advisers to the Nation on Science, Engineering, and Medicine

Safe on Mars

Precursor Measurements Necessary to Support Human Operations on the Martian Surface

Committee on Precursor Measurements Necessary
to Support Human Operations on the Surface of Mars

Aeronautics and Space Engineering Board
Space Studies Board

Division on Engineering and Physical Sciences

National Research Council

NATIONAL ACADEMY PRESS
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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 study was supported by Contracts No. NASW-96013 and No. NASW-99037 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number: 0-309-08426-1

Cover: “First Light,” by Pat Rawlings and commissioned by NASA, depicts the first human travelers to Mars exploring the enormous Noctis Labyrinthus canyon system. Just after sunrise, early morning fog masks the canyon floor 4 miles below. These scientists-explorers conduct geological and meteorological research in order to help us better understand the characteristics of our sister planet and possibly our own Earth. Reproduced courtesy of the artist and NASA.

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Preface

Humankind's fascination with Mars predates recorded history. The bright planet with the reddish tint is unique among the other celestial objects. Tycho Brahe's observations of its unpredictable motion were deciphered by Johannes Kepler in the early 17th century as he developed his laws of planetary motion. Galileo trained his telescope on Mars and saw it as a disk in 1610. Later in the 1600s, Christiaan Huygens and Gian Cassini drew the first maps of the Martian surface. In the late 18th century, Sir William Herschel, astronomer to King George III, measured the tilt of the planet's axis and noted the Martian atmosphere and its seasons. As recently as the beginning of the 20th century, the respected American astronomer Percival Lowell was writing popularly about Martians populating a planet hospitable to *a* life-form, if not to a *human* life-form.

During the space race of the late 20th century, U.S. and Soviet space programs sent the Mariner, Viking, and Mars probes to study the planet during fly-bys, from orbit, and on the Martian surface. In July 1997, the Mars Pathfinder spacecraft of the National Aeronautics and Space Administration (NASA) landed on Mars and released its tiny rover, Sojourner Truth. Anyone with access to the Internet could monitor its meanders, see the Martian landscape through its eyes, and get updates on the Martian weather.

Debate as to which agent, robot or human, is likely to reap the greatest rewards in the future exploration of Mars is outmoded and has evolved in the last decade into a discussion of how the two may complement each other.[1,2] In pursuing answers to this question, NASA has channeled the energies of the robotic and human exploration communities to "optimize the use of humans and robots to increase the pace of discovery at multiple destinations."[3] It sponsored the present study to assist it in validating the requirements identified by these communities, specifically as they relate to the preparation for human exploration of Mars. The statement of task for this study is included as Appendix A.

The Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars was confronted with the dilemma of being charged to "emphasize those technological issues which are directly relevant to managing environmental, chemical, and biological risks to humans operating on Mars" while recognizing that a major objective of such human missions will certainly be to search for (possibly hazardous) life on Mars. The committee took the approach of addressing only the earliest human missions to Mars, when the unknowns are the greatest and the steps taken must be the most cautious.

The members of the committee (see Appendix B) were appointed by the National Research Council

[1]NRC (National Research Council), 1993, *Scientific Prerequisites for the Human Exploration of Space,* National Academy Press, Washington, D.C.

[2]NRC, 1994, *Scientific Opportunities in the Human Exploration of Space*, National Academy Press, Washington, D.C.

[3]James Garvin, NASA, "Human Exploration Vision," briefing to the committee on May 30, 2001.

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(NRC). They were chosen for their expertise and ability to provide independent judgments, thereby fulfilling the study charter.

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

Vincent Castranova, National Institute for Occupational Safety and Health,
Christopher Chyba, SETI Institute,
Pamela Conrad, Jet Propulsion Laboratory,
Ann Druyan, Cosmos Studios,
Helen Evans, Case Western Reserve University,
Stephen Gorevan, Honeybee Robotics,
Noel Hinners, Lockheed Martin Astronautics,
Andrij Holian, University of Montana,
Glenn MacPherson, United States National Museum of Natural History,
Jeffrey Streator, Georgia Institute of Technology,
Lawrence Townsend, University of Tennessee, and
Ward Winer, Georgia Institute of Technology.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis Lanzerotti (NAE) of Bell Laboratories, Lucent Technologies. Appointed by the National Research Council, he was responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee also wishes to thank those in NASA who were so thorough in informing the committee and NRC staff, who facilitated the entire process. The committee would particularly like to recognize the efforts of the study director, Douglas Bennett, who diligently kept us on course and on time.

Frederick H. Hauck, *Chair*
Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars

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Executive Summary

This study, commissioned by the National Aeronautics and Space Administration (NASA), examines the role of robotic exploration missions in assessing the risks to the first human missions to Mars. Only those hazards arising from exposure to environmental, chemical, and biological agents on the planet are assessed.

To ensure that it was including all previously identified hazards in its study, the Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars referred to the most recent report from NASA's Mars Exploration Program/Payload Analysis Group (MEPAG) (Greeley, 2001). The committee concluded that the requirements identified in the present NRC report are indeed the only ones essential for NASA to pursue in order to mitigate potential hazards to the first human missions to Mars.

THE MARS PROGRAM IN CONTEXT

Even though NASA is actively pursuing a Mars exploration program, it is not yet actively pursuing a human mission to Mars, and there is no officially selected reference human exploration mission. Accordingly, the committee determined that it might best assist NASA by assuming that a long-stay mission to Mars will take place, as such a mission would levy the more stringent demand for the safety of astronauts while in the Martian environment. The reader should not conclude that this assumption implies an endorsement of the long-stay mission as a baseline mission, nor that the committee concluded that the long-stay mission is, in total, the least hazardous option.

In its review of the Mars robotic program, the committee found that NASA has done an excellent job of designing science rovers capable of operating on the surface of Mars. The committee believes, however, that the engineering knowledge being gained from the science rover experience will not scale up nor will it easily apply to human assistant rovers or larger human transport rovers. Furthermore, the committee notes that current science rover activities do not provide an adequate research base for the development of rovers needed for the human exploration of Mars.

NASA has allocated risk factors and reliability requirements for missions in low Earth orbit and for the International Space Station but has not done so for missions traveling beyond Earth orbit.

Recommendation: Because NASA has not allocated risk factors and reliability requirements for missions beyond Earth orbit, it should establish the risk standards necessary to provide preliminary guidance to Mars mission planners and hardware designers.

The concept of acceptable risk involves ethical, psychological, philosophical, and social considerations. The committee relied instead on standard risk sources. In reviewing the toxicology risk estimates for toxic metals, the committee chose to use an acceptable risk range (ARR) rather than a single risk level. In this report, the ARR for developing cancer as a result of exposure to toxic metals is between 1 in 10,000 and 1 in 100,000. The committee understands certain risks may overshadow others. Regardless of the large differ-

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ence between the risk of getting fatal cancer from radiation and the cancer risk from exposure to toxic metals, it is prudent to reduce risk in all areas that are amenable to such reductions. It is important to reduce risks in areas that are reasonably achievable, as there can be synergistic effects of combined hazards.

PHYSICAL ENVIRONMENTAL HAZARDS ON MARS

The committee categorized the hazards on Mars by their sources, or causes. It specifically defined the physical hazards on Mars separately from the chemical and biological hazards, because physical hazards can threaten crew safety by physically interacting with humans or critical equipment, resulting, for example, in impact, abrasion, tip-over (due to an unstable Martian surface), or irradiation.

Geologic Hazards

To ensure safe landing and operations on the surface of Mars, it is necessary for the landing site and the topography of the anticipated surface operation zone to be fully characterized with high-resolution stereoscopic imaging. The operation zone is the area around the landing site defined by the anticipated range of operations of extravehicular activities (EVAs), including the use of human transport and/or science rovers. The level of resolution required of this imaging will be determined by the capabilities of the equipment to be used on the surface.

Recommendation: NASA should map the three-dimensional terrain morphology of landing operation zones for human missions to characterize their features at sufficient resolution to assure safe landing and human and rover locomotion.

Recommendation: To ensure that humans and critical rover systems can land on and traverse the Martian surface in a safe, efficient, and timely manner, NASA should characterize the range of mechanical properties of the Martian regolith at the landing site or comparable terrain. Specifically, in situ experiments should be performed to determine the regolith's aggregate strength, stability, and sinkage properties, including bearing strength, bulk modulus, yield strength, and internal friction angle.

Recommendation: NASA should determine, in advance of human missions to Mars, rock size distribution and shapes in situ, at the landing site or on comparable terrain, in order to predict human and rover trafficability.

The abrasive properties of rocks on Mars, including hardness and surface roughness (as dictated by rock grain size and shape), are unknown. The committee believes that, even faced with this lack of knowledge, NASA can still design systems by making certain educated assumptions about the rocks on Mars. For this reason, no further in situ experiments to determine the abrasive properties of Martian rocks are required.

Airborne dust presents a potentially significant hazard to human operations on the surface of Mars. Dust intrusion and accumulation will need to be continuously monitored and will require well-designed filter systems and periodic housecleaning. After reviewing NASA's experience with dust on the Moon and Mars, the committee is confident that NASA engineers and scientists will be able to design and build systems to mitigate the hazards posed by airborne dust on Mars. Some systems that would be used on the first human mission can be designed either by employing what is currently known about Mars dust or by assuming a worst-case scenario in the design process.

The present Mars soil simulant that has been developed and characterized by NASA for engineering (JSC Mars-1: Martian Regolith Simulant) is not adequate for testing mechanical systems for human missions to Mars. However, the committee does not recommend that any precursor in situ measurements be taken on Mars to characterize the mechanical and abrasive properties of airborne dust. Rather, it expects that an appropriate simulant would adequately stress the design of any mechanical and seal systems that will be used during a human mission to Mars. It is critical, however, to fully characterize the adhesive properties of airborne dust in order to design systems that minimize the risk of failure resulting from dust accumulation.

Recommendation: NASA should determine the adhesive properties of Martian soil and airborne dust in order to evaluate the effects of dust adhesion on critical systems. This characterization must be conducted in situ by means of experiments to measure airborne dust adhesion.

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Hazards from Atmospheric Dynamics

The dry conditions and uncertainty about conductivity, charging, and discharging rates in the Mars environment create uncertainties about electrostatic effects on human operations in the Mars environment. However, even given the potential hazards, the committee believes that the risk to humans from electrostatic charging on the surface of Mars can be managed through standard design practice and operational procedures.

The committee believes that in light of the low dynamic atmospheric pressures experienced on Mars, no further characterization of wind speed on Mars is required prior to the first human mission. The surface winds are sufficiently characterized to allow system designers to ensure human safety on the planet by means of robust designs.

Radiation Hazards

Radiation exposure in space will be a significant and serious hazard during any human expedition to Mars. There are two major sources of natural radiation in deep space: sparse but penetrating galactic cosmic radiation (GCR) and infrequent but very intense solar particle events (SPEs) associated with solar storms.

There have been no direct measurements of the radiation environment on the surface of Mars. Rather, the radiation environment is estimated using computer codes that model the transport of the deep space radiation through the Martian atmosphere and after its interactions with the Martian surface. Because of the central role of radiation transport and absorbed dose models in the planning and design of human missions to Mars, it is important that the code predictions be validated by means of a precursor experiment on the surface of Mars. Radiation risk mitigation strategies will be an integral part of overall mission design and planning. Should the results of the in situ experiment prove that the radiation transport models are flawed, more time will be needed to adjust the models to account for the differences between the models and the measurement.

Recommendation: In order to validate the radiation transport codes, thereby ensuring the accuracy of radiation dose predictions, NASA should perform experiments to measure the absorbed dose in a tissue-equivalent material on Mars at a location representative of the expected landing site, including altitude and bulk elemental composition of the surface. The experiments should distinguish the radiation dose contribution induced by charged particles from that induced by neutrons. These experiments should be made a priority in the Mars exploration program.

CHEMICAL ENVIRONMENTAL HAZARDS ON MARS

In addition to the hazards from materials on Mars interacting dynamically with humans or critical systems, the committee has also assessed hazards associated with the chemical reactivity of materials on Mars.

Chemical Interaction of Martian Soil and Airborne Dust with Astronauts and Critical Equipment

Some dust and soil will in all probability be brought into the habitat through the airlock by returning astronauts, as was the case during the Apollo missions to the Moon. The committee has concluded that Martian airborne dust could present the same chemical hazards as Martian soil, so soil and dust should be characterized in the same way. In choosing the "worst" toxic chemical hazards to humans, the committee considered inorganic substances separately from organic substances. With respect to inorganic substances, it identified certain toxic metals as the worst threat to humans at the lowest concentrations.

Soil and airborne dust on Mars could contain trace amounts of hazardous chemicals, including compounds of toxic metals, which are known to cause cancer over the long term if inhaled in sufficient quantities. If NASA protects astronauts against the risk of developing cancer in the long term as a result of having been exposed to particulate matter on Mars, NASA will also be protecting astronauts from acute and short-term noncancer effects that could potentially interfere with mission success. While the committee is confident in its knowledge of the possible concentrations of most toxic metals on Mars, the committee believes the uncertainty surrounding the amount of toxic hexavalent chromium (Cr VI) on Mars warrants a precursor measurement. Hexavalent chromium on Earth is very rare in natural materials, but the great abundance of chromium (in unknown form) on the surface of Mars, combined with the high oxidation state of Martian soil,

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suggests that hexavalent chromium might be present in small but potentially hazardous amounts.

Recommendation: In order to evaluate if hexavalent chromium on Mars poses a threat to astronaut health, NASA should conduct a precursor in situ measurement to determine if hexavalent chromium is present in Martian soil or airborne dust at more than 150 parts per million (ppm). This measurement may take place anywhere on Mars where well-mixed, uniform airborne dust is present. If such a measurement is not possible, a sample of airborne dust and fine particles of Martian soil must be returned to Earth for evaluation.

The committee believes that NASA can provide filtration systems capable of minimizing the hazards of exposure to toxic elements, including hexavalent chromium, arsenic, and cadmium, that are present at concentrations of less than 150 ppm.

However, if a filtration system cannot be designed to limit the average astronaut respirable particulate inhalation exposure to 1 milligram of particulate matter per cubic meter of air (mg/m^3) in the habitat, then a sample of airborne dust, taken from the Martian atmosphere, and soil must be analyzed for toxic metal concentrations. The level of analytical precision required for this measurement will be dictated by the filtration capability of the astronauts' habitat.

It should be very clear to the reader that, in the view of the committee, the 1 mg/m^3 specification is the *maximum* acceptable respirable particle average concentration to which astronauts should be exposed. This concentration level will protect astronauts from exposure to toxic metals, which—of all inorganic chemicals—the committee considers to pose the greatest health risk to astronauts. Filtering at or below the recommended 1 mg/m^3 average with a 1.5 mg/m^3 peak concentration should be readily achievable for NASA. Indeed, to minimize risks from exposure, the committee strongly believes that filtering should be implemented below 1 mg/m^3, to as low a concentration as is reasonably achievable in the Martian habitat.

It is essential that NASA implement proper humidification in conjunction with the filtration system as part of habitat atmosphere conditioning to mitigate the threat of strong oxidants in Martian soil and airborne dust. The committee concluded that even if strong oxidants are present, there will be negligible risk associated with oxidation on the Martian surface if the proper humidification systems are in place and the particulate level is maintained at 1 mg/m^3 or less.

However, even with the filtering systems in the habitat as discussed above, the filtration level may not be stringent enough to protect astronaut health and critical mechanical equipment from dust and soil that are extremely acidic. There are high concentrations of sulfur and chlorine in Martian soil, which implies the possibility of acidity in both the soil and airborne dust (Clark et al., 1982; Wanke et al., 2001). When inhaled by astronauts, acidic soil and dust could degrade their lung tissue and, if humidified and allowed to penetrate control units inside the habitat, could corrode sensitive critical equipment, such as control circuits.

Recommendation: In order to evaluate the potential corrosive effects of Martian soil and airborne dust on humans and critical systems in a humidified environment, NASA should measure the pH and buffer capacity of soil and airborne dust either via an in situ experiment or on Earth with returned samples of soil and airborne dust collected from the Martian atmosphere.

If NASA decides not to implement the necessary engineering controls or for other science-related reasons chooses to measure the oxidation properties of Martian airborne dust and soil, then the measurement should be performed on the surface of Mars rather than via a sample return.

Certain organic compounds can be highly toxic to humans, even if those compounds are not associated with a life-form, and the threat should be evaluated in planning the first human mission to Mars. Any hazard from organic compounds would most likely come from handling subsurface samples that might contain organic compounds. The committee concludes that if organic carbon is present at a concentration of more than 150 ppm in soil to which astronauts might be exposed, a possible threat exists. Filtration systems that reduce astronaut exposure to organic carbon to concentrations less than 150 ppm would mitigate this threat. If experiments determine that organic carbon is present in concentrations greater than 150 ppm, the subsurface soil should be considered a toxic hazard until proven otherwise. The need to assess the potential threat posed by a hazardous life-form consisting of organic carbon requires a more stringent measurement of organic carbon concentration.

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Toxicity of the Martian Atmospheric Gases

The Martian atmosphere, when mixed in small amounts with the habitat atmosphere, does not pose a toxic risk for astronauts, and no further characterization is required before the first human mission takes place. The primary hazardous components are easily removed by standard cabin-atmosphere conditioning systems.

POTENTIAL HAZARDS OF THE BIOLOGICAL ENVIRONMENT ON MARS

The committee was charged with addressing issues of biological risks on Mars from two perspectives: (1) ensuring the safety of astronauts operating on the surface of Mars and (2) ensuring the safety of Earth's biosphere with respect to potential back-contamination from returning human missions.

The probability that life-forms exist on the surface of Mars (that is, the area exposed to ultraviolet radiation and its photochemical products) is very small. However, as a previous NRC study (NRC, 1997) notes, there is a *possibility* that such life-forms exist there "in the occasional oasis," most likely where liquid water is present, and, furthermore, that "uncertainties with regard to the possibility of extant Martian life can be reduced through a program of research and exploration."

This charge to the committee results in a dilemma. How can NASA use human ingenuity and creativity on Mars to search for life when that life (if it exists) may pose a threat to astronaut health and safety (and therefore the success of a human mission) as well as to Earth's biosphere?

Ensuring the Safety of Astronauts

The committee believes it is highly unlikely that infectious organisms are present on Mars. Nevertheless, once an astronaut has been directly exposed to such life, it would be very difficult, to the point of being impractical, to determine conclusively that the astronaut would *not* pose a contamination threat to Earth life. In such an event, NASA might be faced with requiring quarantine and surveillance of returning astronauts until it is determined that a threat no longer exists.

Ensuring the Safety of Earth's Biosphere

While the threat to Earth's ecosystem from the release of Martian biological agents is very low, "the risk of potentially harmful effects is not zero" and cannot be ignored (NRC, 1997). NASA should assume that if life exists on Mars, it could be hazardous to Earth's biosphere until proven otherwise. As such, NASA should ensure proper quarantine or decontamination of equipment that may have been exposed to a Martian life-form.

To protect Earth from contamination by Martian life-forms aboard a returning human mission and astronauts while they are on the surface of Mars, the committee recommends that NASA employ the concept of zones of minimal biologic risk (ZMBRs) for astronaut exploration. These zones, operational areas on the surface of Mars, would be determined, to the maximum extent practicable, to be devoid of life or to contain only life-forms that would not be hazardous to humans or Earth's biosphere.

The committee recognizes that the requirement to establish and operate in a ZMBR, while intrinsic to the study charter to manage risk to astronauts, may be in conflict with one of the primary goals of the exploration of Mars: to find extraterrestrial life.

To establish a ZMRB, NASA should first attempt to determine whether or not life exists (1) at the physical locations where astronauts will be operating and (2) in the Martian material to which astronauts will be exposed. The establishment of a ZMBR might initially be based on an in situ testing protocol conducted prior to the first human visit. Once a landing site is established as a ZMBR, the astronauts can land and freely operate within it.

While some have suggested that non-carbon-based life might be present on Mars, this committee agrees with assumptions made by previous NRC committees that should hazardous life exist on Mars it would be carbon-based and thus would contain organic compounds (NRC, 2002a, 2002b). A search for life should therefore include a search for organic carbon. The detection of organic carbon might indicate the presence of life-forms.

If a sample of Martian soil and airborne dust is returned to fulfill this requirement, the returned sample should be considered hazardous and NASA should follow quarantine procedures as outlined in previous

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NRC studies (NRC, 2002b). The committee also urges NASA to set an operational value for the life detection threshold limit through a separate advisory process drawing on a broad range of relevant expertise.

Recommendation: The committee recommends that NASA establish zones of minimal biologic risk (ZMBRs) with respect to the possible presence of Martian life during human missions to Mars. In order to do so, NASA should conduct a precursor in situ experiment at a location as reasonably close to the human mission landing sites as possible to determine if organic carbon is present. The measurement should be on materials from the surface and down to a depth to which astronauts may be exposed. If no organic carbon is detected at or above the life detection threshold, the landing site may be considered a ZMBR. If no measurement technique can be used to determine if organic carbon is present above the life detection threshold, or if organic carbon is detected above that threshold, a sample should be returned to Earth for characterization prior to sending humans to Mars.

There has been some concern that if a sample return is required, the planning for the first human mission to Mars may be delayed until a sample can be obtained. The committee believes that, even should a sample be required because organic carbon has been found, a baseline mission plan for a mission to Mars and even hardware development may still proceed under the assumption that a sample return will not find anything significant enough with regard to Martian biology to invalidate the baseline mission plan.

Return Vehicle Contamination

To prevent contamination of Earth by Martian material, great care must be exercised to ensure the containment of all material returned from Mars to Earth. There must be a sterile, intermediate transfer conducted in space that ensures Earth's environment will not be exposed to any Martian material, including dust or soil deposits on the outside surface of the return vehicle. The protocols for such a sterile transfer will be complex and, if the transfer is unsuccessful, may require that the return vehicle be discarded in space and never returned to Earth. Ultimately, however, only contained materials should be transported back to Earth, unless sterilized first (NRC, 1997).

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1

Introduction

NASA is actively pursuing a Mars exploration program. It is a "science-driven, technology-enabled effort to characterize and understand Mars, including its current environment, climate, and geological history and biological potential."[1] Every 2 years from 2001 to 2011, with the dates dictated by launch windows, another spacecraft, launched by NASA and/or NASA's international partners, is intended to visit Mars. Some spacecraft will orbit the planet, while others will land on the Martian surface. The NASA Mars Exploration Program Office (within the NASA headquarters Office of Space Science) has established the Mars Exploration Program/Payload Analysis Group (MEPAG), consisting of more than 110 individuals from the Mars community, with representatives from universities, research centers and organizations, industry, and international partners. The MEPAG participants propose the objectives, investigations, and measurements needed for the eventual exploration of Mars, focusing on four principal exploration goals (Greeley, 2001). These goals fall under four broad categories:

- Life—determine if life ever arose on Mars.
- Climate—determine the climate on Mars.
- Geology—determine the evolution of the surface and interior of Mars.
- Prepare for the eventual human exploration of Mars.

While there is currently no funded human mission to Mars, nor even a baseline reference human mission, one of the goals of the MEPAG is to ensure that sufficient information is developed in a timely manner to support such a mission, once it has been funded.

NASA commissioned this study from the NRC to examine what measurements must be made on Mars prior to the first human mission. These measurements would provide information about the risks to humans so that NASA scientists and engineers can design systems that will protect astronauts on the surface of Mars.

The principal objective of the study was to examine how robotic exploration missions sent to Mars could aid NASA in assessing the risks to astronauts posed by possible environmental, chemical, and biological agents on the planet. Of critical importance is whether it will be necessary to return Martian soil and/or airborne dust samples to Earth prior to the first human mission to Mars to assure astronaut health and safety. The entire statement of task is contained in Appendix A. The statement of task includes a list of relevant reports that were reviewed during the course of the study.

To respond to this task, NRC's Aeronautics and Space Engineering Board, together with the Space Studies Board, established the Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars. Brief biographies of the 10 committee members are included in Appendix B. Members were carefully chosen to reflect the expertise needed to address the environmental, chemical, and biological risks to the first humans to set foot on Mars.

[1]J. Cutts, Jet Propulsion Laboratory, Presentation to the robotic subcommittee (committee members Breazeal, Hauck, and Whittaker), Pasadena, Calif., on August 27, 2001.

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STUDY APPROACH

The committee held three full committee meetings, all of them open to the public. The first meeting was held in Washington, D.C., in May 2001. At the first 2-day meeting, NASA presented its overall strategy for future Mars exploration and the current status of the program. From that initial briefing the committee then determined that it would need to hear further details of specific NASA technical capabilities and hazards on Mars. The second meeting took place over 3 days at the Lunar and Planetary Institute in Houston, Texas, during early August 2001. Representatives from NASA's Lyndon B. Johnson Space Center in Houston and from the Jet Propulsion Laboratory (JPL) in Pasadena provided information on surface operations, space suits and equipment, detection of life on Mars, radiation health effects, lunar dust experience, Martian soil, and in situ instrumentation capability. The issue of whether or not there is need for a soil or airborne dust sample to be returned to Earth from Mars was also discussed.

Subsequently, the committee determined that further information was needed on the Mars robotic program. Three committee members, accompanied by NRC staff, visited JPL in late August 2001, when they were briefed on current research and development efforts in robotics.

The third and final meeting was held in Washington, D.C., in early September 2001; at that meeting the committee finalized the findings and recommendations contained in this report.

To ensure that it was including all previously identified hazards in its study, the Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars referred to the most recent MEPAG report (Greeley, 2001). The committee concluded that the requirements identified in the present report are indeed the only ones essential for NASA to pursue in order to mitigate potential hazards to the first human missions to Mars.

ORGANIZATION OF THIS REPORT

Chapter 2 presents the context in which this study was conceived and conducted. Chapters 3, 4, and 5 address the physical, chemical, and biological hazards likely to be encountered by the first human visitors to the Martian surface. Each of these chapters addresses the risks associated with potential hazards. In each chapter there is a section that details what precursor measurements, if any, should to be made prior to the first human landing on Mars. Appendix C lists the acronyms and abbreviations used in this report.

As a general rule, the committee made recommendations only when it determined that a precursor mission to Mars is required to provide information critical for the safety of the first human missions. The exception to this rule is the first recommendation, which deals with the establishment of risk standards, because the risk standard adopted has the potential to greatly affect the need for precursor missions. The committee presented findings if, in its judgment, there are ways of ensuring the safety of astronauts without carrying out a robotic precursor mission to Mars.

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2

The Mars Program in Context

Sending astronauts to the Red Planet, having them land, conduct a mission on the surface, and then return safely to Earth will be an enormous undertaking. The mission will be broken into a transit phase, that portion of the journey that takes place in deep space when astronauts are traveling from Earth to Mars, and the surface phase, when astronauts are resident on the surface of the planet. The time it takes to complete any mission to Mars depends on the relative positions of Earth and Mars in their orbits. This means that there are specific launch windows, preferred instances when Mars and Earth are ideally positioned in their respective orbits, for a human mission to take place. The duration of the mission also depends on the type of propulsion used. Depending on the alignment of Earth with Mars and the amount of propulsive energy available, two basic types of missions can take place, a long-stay mission and a short-stay mission. The names refer qualitatively to the amount of time astronauts spend on the Martian surface.

A long-stay mission would require that astronauts spend 16 to 20 months in orbit around Mars or on the surface, with total mission duration being 2½ to 3 years. On a short-stay mission, astronauts would be able to remain in orbit around Mars or on the surface for only 30 to 45 days before they would have to embark on the return journey to Earth. If they stayed longer, Earth and Mars would move out of optimum alignment and the return to Earth would require an excessive amount of propellant.

There are many safety and mission elements that must be considered in deciding whether to spend 30 to 45 days (short stay) or 16 to 20 months (long stay) in orbit around Mars or on the surface. Some of these include the following:

- *Transit time*. The short-stay mission would require a longer round-trip transit time in space. A short-stay mission scenario would have astronauts traveling in space for 11 to 21 months, versus 10 to 14 months for a long-stay mission. Unless provisions can be made to counter the microgravity environment (by means of exercise protocols or by inducing artificial gravity) and harsh radiation conditions in space, the potential negative effects on health of the longer transit time (short-stay mission) may be prohibitive. In fact, the cumulative effects of radiation on the astronauts during the shorter transits involved in the long-stay mission might be more benign than those for the short-stay mission because of the shielding provided by the planetary mass and atmosphere while on the Martian surface (Cucinotta et al., 2001). However, the effects on astronaut health of a long duration stay in the low-gravity Martian environment are unknown.
- *Closest approach to the Sun*. The short-stay mission would result in transits that bring the spacecraft closer to the Sun (inside the orbit of Venus, 0.72 AU) than would the long-stay mission (1.0 AU). The closer approach might increase the severity of the effects of solar particle events.
- *Crew exposure to the Martian surface environment*. This would obviously be minimized by a short stay.
- *Susceptibility of critical hardware to failure*. The

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crew would be dependent on hardware used in surface operations for a longer period of time on a long-stay mission.

Once the astronauts are on the Martian surface, there are a variety of operational scenarios that could be conducted by NASA. The simplest would be that astronauts land and never leave a stationary habitat. The most complex scenario could include astronauts using large, pressurized rovers to travel long distances from a base habitat to conduct extravehicular activities (EVAs). The committee anticipates that a long-stay mission would probably involve the following:

- The use of unpressurized rovers similar to the lunar rover from the Apollo program;
- Walking EVAs of several kilometers (round-trip) from the base camp; and
- Pressurized rovers for transporting the astronauts greater distances. These could allow walking EVAs from the rover to take place, extending human presence even farther from the base camp.

The committee determined that it might best assist NASA by assuming that a long-stay mission to Mars will take place, as such a mission would levy the more stringent demand for the safety of astronauts while in the Martian environment. The reader should not conclude that this assumption implies an endorsement of the long-stay mission as a baseline mission, nor that the committee concluded that the long-stay mission is, in total, the least hazardous option.

SCOPE OF THIS REPORT

As dictated by the statement of task (Appendix A), this report examines only those hazards to which astronauts will be exposed while on the surface of Mars. For instance, the committee did not address the need for so-called pinpoint landing on Mars, nor did it look at what technologies must be developed to accomplish pinpoint landing. However, the committee does address the terrain issues associated with setting down on the Martian surface.

Also, in accordance with the statement of task the committee considered only indigenous risks on Mars—that is, those hazards presented by the Martian environment itself, not risks based on engineering design. For instance, the committee did not examine the reliability of habitat control systems or the likelihood of their failure, but it did consider the effects acidic airborne dust or soil might have on such control circuits.

This report does not examine the hazard of forward contamination, that is, transporting Earth life to Mars from a contaminated spacecraft. There are risks associated with forward contamination of Mars by life from Earth, including the possibility of generating false positive tests in life-detection experiments (NRC, 1992a, 2002). This could certainly be a critical issue when astronauts on the surface of Mars are looking for life. A false positive result could inadvertently require a long-term astronaut quarantine. While this is a topic for continued study and debate, it is beyond the scope of this committee's charge.

Similarly, this report does not address technologies associated with in situ resource utilization (ISRU) or deep drilling. ISRU is the use of indigenous materials to produce consumables (e.g., breathable oxygen, propellant), thus reducing the tonnage of materials that must be transported to Mars. As such, ISRU does not deal directly with the "management of environmental, chemical, and biological risks," as set forth in the statement of task. Drilling systems might be used on human missions to Mars to explore the subsurface of Mars for scientific purposes. However, these systems are not critical to human survival. In fact, by using a drill, astronauts might become exposed to other indigenous Martian hazards. The hazards of subsurface probing by astronauts are discussed in detail in this report.

Other potential hazards the committee did not address involve the effects on astronaut health of a long-duration mission to Mars. A recent Institute of Medicine report states that the three most important health issues that have been identified for long-duration missions are radiation, loss of bone mineral density, and behavioral adaptation (IOM, 2001). The committee acknowledges that these issues are important, as is the need to ensure a benign social environment during a multiyear voyage, but again such considerations fall outside the scope of this report.

ROVER TECHNOLOGIES AND ROBOTICS

Even though there is no baseline mission defined for human missions to Mars, it is likely that rovers of some form will be used to perform functions critical to the safety of the astronauts. For example, human assistant rovers may carry life support equipment, while others robots, such as slow-moving scientific rovers, will likely perform mission-critical functions.

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For these reasons, the committee explicitly considered the technologies used in current and planned Martian scientific rovers and whether such rovers can be scaled up to support critical tasks for human exploration (see Box 2.1).

In its review of the Mars robotic program, the committee found that NASA has done an excellent job of designing science rovers capable of operating on the surface of Mars. The Mars Pathfinder rover is a success story that testifies to the skill of NASA scientists and engineers. And, the Mars exploration rovers now in development offer some significant advances in rover capabilities.

The committee believes, however, that the engineering knowledge being gained from the science rovers will not scale up nor will it easily apply to human assistant rovers or larger pressurized or unpressurized human transport rovers. Furthermore, the committee notes that current science rover activities do not provide an adequate research base for the development of rovers needed for the human exploration of Mars.

Typical science rovers generally move very slowly and for short distances. This is understandable, because once on the surface the rovers do not need to go very far to conduct scientific research in most cases. However, the science rovers are not necessarily good platforms for testing future rover technology. The Mars exploration rover, scheduled to launch in 2003, will be approximately 180 kg (~400 lb) in mass and is expected to have a speed of 1 cm/sec (~0.4 in./sec). The total distance the rover is expected to travel in one Martian day is 100 meters. The NASA Smart Lander with rover capabilities, scheduled to launch in 2009, is expected to be approximately 1,000 kg (2,200 lb) in mass, with a speed of anywhere from 2 cm/sec (~0.8 in./sec) to 10 cm/sec (4 in./sec).

On the human missions to Mars, rovers will need capabilities far beyond what is currently planned. Human assistant rovers would have to be able to keep pace with an astronaut walking on the surface of Mars, to operate for a long time, to have an extended range, and to navigate rough terrain quickly. These needs would be especially important for a long-stay mission, where there might be many hundreds of astronaut EVAs that would require a robotic assistant to traverse hundreds of kilometers over the course of the mission. Such human assistant rovers would require kilowatts of continuous electric power during the EVA. Compact sources of power at that capacity do not exist today.

BOX 2.1
The Anatomy of a Critical System

Critical systems are those upon which a crew's lives depend. NASA has specific requirements for such critical systems (NASA, 1998):

> All critical systems essential for crew safety shall be designed to be two-fault tolerant. When this is not practical, systems shall be designed such that no single failure shall cause loss of the crew. For the purposes of this requirement, maintenance can be considered as the third leg of redundancy so long as missions operations and logistics resupply permit it.
>
> For long duration missions . . . fault tolerance is not sufficient. For these missions, multiple failures are expected, and the response must include maintenance and system reconfiguration to restore the failed functions. In the case of Beyond Earth Orbit vehicles, it is unlikely that resupply vehicles can supplement the resources aboard the vehicle unless that capability was planned for in advance via prepositioned spares. Therefore, safe operation of the vehicle requires that sufficient reliability be achieved through a combination of reliable hardware design, installed redundancy, and logistics capability to support maintenance.

It is important to differentiate systems critical for human safety from those critical for mission success. The latter are for the most part subjected to less stringent, though still demanding, standards. For instance, any robot operating inside the habitat in a labor-saving capacity, such as EVA suit cleaning, is not considered critical. Not all robots that operate outside of a habitat (i.e., in contact with the hostile Martian environment) are critical. Specifically, a human assistant rover that carries oxygen and must keep up with a human walking on Mars is a critical system. A human transport rover (pressurized or not) is also a critical system, since its performance is required to ensure astronaut safety.

However, a science rover that astronauts use to search for life in a remote area before conducting an EVA to that location is not critical. Presumably if such a robot failed, an EVA to that location would simply not take place, so astronaut safety would not be a concern. Nor is a machine that drills to look for subsurface life a critical system, in that if it were to fail, humans would not be directly at risk. The reader should note that this report deals with issues critical to the safety of the crew, not mission success.

Human transport rovers have the same performance issues as human assistant rovers, but on a larger scale. For a long-stay mission, human transport rovers would

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need to be able to operate for up to 20 months and traverse thousands of kilometers over the life of the mission. Tens of kilowatts of power might be required to accomplish these goals, and it would most likely not be practical to use solar photovoltaic systems given the relatively large size of those systems.

Even looking ahead to the 2009 rover from the NASA Smart Lander at the optimistic forecast of 10 cm/sec, NASA would have to increase the speed of such a rover by a factor of 13 to reach a human walking speed of 4.8 km/hr (3 mph). The same rover would have to increase its speed by a factor of 44 to reach the 16 km/hr (10 mph) mark that a human transport rover would probably require.

The mass of the 2009 rover from the NASA Smart Lander is comparable to that of the human assistant rovers that may be required on the human missions to Mars, but the dynamic nature of the vehicles is entirely different.

In the committee's judgment, the design and testing of human transport rovers that can traverse long distances and that have long lifetimes and adequate power supplies may be a pacing item in the mounting of the first human mission to Mars.

Finding: NASA's current focus on small, slow robotic rovers with short lifetimes and modest power supplies does not provide an adequate research base for the development of the rovers needed for the human exploration of Mars.

ESTABLISHING RISK STANDARDS

NASA has established detailed requirements and standards for ensuring the safety and reliability of space shuttle and International Space Station operations. There is an ongoing effort to establish a set of requirements for "human rating" the next generation of human-occupied spacecraft that will permit humans to operate more efficiently in Earth orbit and to explore beyond Earth orbit. A human-rated system risk rating is one that "incorporates those designs, features, and operational procedures needed to accommodate human participants, allowing NASA to safely conduct human operations, including safe recovery of astronauts from any credible emergency situation" (NASA, 1998).

As stated in the above-mentioned NASA human missions requirements document, "many of the detailed requirements required to implement these . . . missions are very different. Even with the very high level of the requirements [contained herein] there are some that cannot be applied consistently across [all] missions." The document further states that "the program shall be designed so that the cumulative probability of safe crew return over the life of the [space flight] program exceeds 0.99" (NASA, 1998).

Using this guideline, a program that involves only 10 flights can absorb a greater risk per flight than one that involves 100 flights. NASA has yet to publish risk allocation guidelines for missions beyond Earth orbit. This report suggests the use of risk factors based on those established by federal agencies or suggested by other studies. For example, in the absence of NASA standards for the risk associated with exposure to toxic metals on Mars, the committee suggests the establishment of a risk factor based on a study by the NRC Committee on Toxicology (COT) and on Environmental Protection Agency (EPA) risk estimates. Given the level of inherent risk associated with space exploration missions, NASA may well choose to establish risk factors different from those proposed in this report, especially if risk estimates change in the future.

Recommendation: Because NASA has not allocated risk factors and reliability requirements for missions beyond Earth orbit, it should establish the risk standards necessary to provide preliminary guidance to Mars mission planners and hardware designers.

The concept of acceptable risk involves ethical, psychological, philosophical, and social considerations. The committee relied instead on standard risk sources. In reviewing the toxicology risk estimates for toxic metals, which are used extensively in Chapter 4, the committee chose to use an acceptable risk range (ARR) rather than a single risk level. In this report, the ARR for developing cancer as a result of exposure to toxic metals is between 1 in 10,000 and 1 in 100,000.

Historically, for the general population, EPA has considered a 1 in 100,000 risk of getting cancer acceptable. The committee based part of the ARR selection on the fact that the EPA usually (with no overriding regulations or site-specific requirements) takes cleanup action on a site that has a risk of greater than 1 in 10,000 of causing cancer in humans, while the EPA never takes action at a risk of 1 in 1,000,000 (Travis et al., 1987). Therefore the committee chose the lowest reasonable level of acceptable risk for the ARR at 1 in 100,000 of astronauts getting cancer during their lifetime as a re-

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sult of exposure to toxic metals in Martian soil or airborne dust.

The 1 in 10,000 maximum risk in the committee's ARR is based on studies by the NRC's Committee on Toxicology (see Box 2.2). It is notable that the Committee on Toxicology adopted a less stringent standard than EPA for carcinogens, namely, 1 in 10,000 (NRC 1992b, 1994, 1996, 1997, 2000). NASA, EPA, and this committee are in general agreement on the concentration limits for hazardous chemicals producing acceptable risks for astronauts. The reader is referred to Box 2.2 for further discussion of the committee's consideration of hazardous chemical exposure limits.

BOX 2.2
Exposure Limits for Chemical Hazards

The use of toxic chemical exposure limits serves to protect individuals from excessive health risk due to exposure to harmful chemicals. Exposure limits or recommendations have been established by a variety of groups; among the most prominent are EPA, the Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists. There is a fundamental difference in the limits established by EPA and those of other groups, in that EPA regulations are designed to protect the whole public, including sensitive groups such as the very young and the very old as well as people with respiratory diseases and other illnesses. In contrast, occupational limits are meant to protect healthy adults in the workplace, usually for an exposure duration of an 8-hour workshift, with a substantial recovery period at home. For these reasons, occupational standards allow for considerably higher exposure concentrations than EPA risk estimates, as shown in Table 2.1.

For the present study, the committee based its consideration of potential chemical exposure hazards on the conservative risk estimates established by EPA for long-term cancer risk at the 1 in 100,000 level and the NRC's Committee on Toxicology (COT) at the 1 in 10,000 level. The EPA risk estimates are published in EPA's Integrated Risk Information System database.

It is clear that NASA has for some time recognized the need to consider exposure of astronauts to potentially hazardous chemicals. It commissioned the COT to recommend maximum concentrations of spacecraft contaminants three decades ago (NRC, 1972). More recently, COT published four reports setting spacecraft maximum allowable concentrations (SMACs) for a total of 40 individual contaminants based on guidelines it developed for SMACs in 1992 (NRC, 1992b, 1994, 1996, 1997, 2000). COT has expended considerable effort in developing SMACs, basing its recommendations on an extensive review of toxicity data with application of safety factors. Specifically, SMACs for carcinogenic chemicals are established using toxic element concentrations that produce an estimated 1 in 10,000 increased lifetime risk of a neoplasm, following U.S. Department of Defense practice. The detailed rationale for each recommendation is presented in the related NRC report. In general, these SMACs for 1 in 10,000 risk are comparable to EPA limits estimated for the 1 in 100,000 risk level.

It is notable that the SMACs have focused on the International Space Station. As such, the 40 airborne chemicals considered to date pertain to operation in a closed-loop environment for a maximum of 180 days, which is a shorter period than many proposed missions to Mars. The 40 contaminants include primarily chemicals outgassing from man-made materials within the space station itself. The contaminant list does not include dust or soil infiltrating from outside the habitat, which are a concern for planetary exploration. When reviewing the committee's findings and performing its own assessment of the risks and acceptable exposure levels of potential chemical hazards, NASA must consider the unique scenarios for operation on Mars.

TABLE 2.1 Exposure Limits for Some Respirable Chemical Hazards (micrograms per cubic meter)

Chemical	EPA[a]	OSHA[b]	NIOSH[b]
As (inorganic as As)	0.002	10	2
Cd (inorganic as Cd)	0.006	5	Not listed
Acetaldehyde	5	360,000	Not listed
Benzene	2.9	3,200	320
Ethylene dibromide	0.05	150,000	350
Formaldehyde	0.8	900	20
Vinyl chloride	2.3	2,560	Not listed

[a]From EPA Integrated Risk Information System database; 1 in 100,000 risk level.
[b]From NIOSH (1997).

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The committee chose not to use Occupational Safety and Health Administration (OSHA) exposure limits since those limits are based on working periods only (8 hours per day, 5 days per week). Once the astronaut living area on Mars is contaminated with soil or airborne dust, the astronauts may be exposed to low levels of Martian airborne particulates on a continuing basis for up to 1.5 to 2 years. Therefore using the risk estimates discussed above for continuous (24-hour) exposure represents a conservative approach for health protection.

The committee understands certain risks may overshadow others. For instance, as discussed, the committee assumes the allowable risk for astronauts getting cancer (not necessarily fatal cancer) as a result of exposure to toxic trace elements is the range between 1 in 10,000 and 1 in 100,000. For low Earth orbit, NASA has established the limit of 3 percent excess risk of fatal cancer from radiation exposure, or 1 in 33.

Regardless of the large difference between the risk of fatal cancer from radiation and the risk of getting cancer from toxic metal exposure, it is prudent to reduce risk in all areas that are amenable to such reductions. It is important to reduce risks in areas that are reasonably achievable, as there can be synergistic effects of combined hazards. For instance, radiation exposure may weaken the human immune system and make a person more susceptible to other hazards. Balancing risks from various hazards will be necessary to allow NASA to make informed decisions regarding risk.

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3

Physical Environmental Hazards

The committee categorized the hazards on Mars by their sources or causes. It has specifically defined physical hazards on Mars separately from the chemical and biological hazards, because physical hazards can threaten crew safety by physically interacting with humans or critical equipment, resulting, for example, in impact, abrasion, tip-over (due to an unstable Martian surface), or irradiation.

It is known that the gravitational force that will be experienced by humans on the Martian surface is approximately 3/8 (0.375) that on Earth. The committee notes that very little, if anything, is known about the long-term effects on human health from residing in a 3/8 Earth gravity environment. These long-term effects could represent a hazard to astronauts on Mars. However, since no further precursor missions are necessary to quantify the gravity on Mars, the committee has not included the low-gravity environment in the hazards discussed in this report.

The physical environments that might pose risks to crew safety on Mars fall into three categories: geologic, atmospheric, and radiation. This chapter elaborates on each of those categories in light of what is currently known about the hazards and what needs to be known in order to establish confidence in the safety of human missions to Mars.

GEOLOGIC HAZARDS

The geologic features of interest in this study are airborne dust, regolith, and terrain. Airborne dust, with an average diameter of 3.4 microns, is the smallest geological feature (see Box 3.1). The Martian regolith is the complex outer layer of fractured rock and soil on the surface of Mars. This is the material that will support astronauts and roving vehicles as they traverse the Martian surface.

The aggregate form of the regolith creates the terrain of Mars. The term "terrain" includes large-scale features such as mountains, hills, valleys, and canyons as well as smaller-scale features such as craters, dunes, and gullies. The smallest-scale terrain on Mars includes boulder and rock fields.

Terrain Trafficability

When an aircraft operates near the surface of Earth, it is imperative that the pilot know the shape and composition of the terrain beneath, be it ocean, forest, desert, or a concrete runway. The same is true for a mission descending on Mars, except in this case the terrain will not include any prepared landing surfaces. A Mars landing craft will be designed to land on a wide range of terrains, but cost and weight considerations in the design of the lander will mandate that mission planners target the most benign landing areas.

Similarly, the terrain around a landing site, specifically including the area in which astronauts will be operating, must also be studied to ensure that the astronauts are provided with the most suitable equipment for their operating environment. For example, if they will be traversing a relatively flat plain scattered with rocks 5 to 8 centimeters in diameter, a human transport rover with fairly narrow wheels, similar to the Apollo lunar rover vehicle, may be adequate. If the same plain is covered in boulders one-third of a meter in diameter,

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BOX 3.1
Definitions of Martian Regolith, Soil, and Dust

For the purposes of this report, the committee developed operational definitions of the solid particulate materials on or near the Martian surface. The Martian regolith is the complex outer layer of loose rock and soil on the surface of Mars. Owing to repeated meteorite impacts and surface weathering processes, rock fragments of all sizes are mixed with weathered soils in various proportions to produce a regolith of unknown thickness. The composite physical properties of the regolith are likely to be different from the physical properties measured in Martian soils.

The term "soil" describes deposits of fine-grained, largely unconsolidated materials on the planet's surface. The planetary, or non-Earth, usage of the word "soil" differs from terrestrial usage, which specifies that soil must have an organic component. Martian soils may be mixtures of very small particles resulting from deposits of airborne dust and coarser, sand-size particles. The chemical composition of the soil has been measured at three spacecraft landing sites separated by thousands of kilometers, and the soil analysis results are similar.[1] The mineralogy of the Martian soil is not well understood at this time, but it is commonly inferred to resemble that of palagonite, a mixture of amorphous and poorly crystalline clays, iron oxides, and other products formed from the weathering of volcanic rocks.[2]

The terms "dust" and "airborne dust" are used to identify fine particles suspended in the Martian atmosphere. The average grain diameter of airborne dust, as determined from multispectral imaging, is 3.4 microns. For the purposes of this report, dust is characterized as being less than 10 microns in diameter.[3]

The amount of dust in the atmosphere increases during seasonal dust storms, but even in quiet times there is enough suspended dust to impart a salmon color to the sky. There is a consensus that Martian dust has been globally homogenized by the wind, so that its composition is the same everywhere.[4] Although its mineralogy is unknown, magnetic experiments have demonstrated that some dust particles contain magnetic iron oxides. Its red color indicates a high oxidation state.[5]

[1]Clark et al. (1982); Rieder et al. (1997).
[2]Bell et al. (2000).
[3]Tomasko et al. (1999).
[4]McSween and Keil (2000).
[5]Madsen at al. (1999).

a vehicle with very large inflatable tires capable of easily rolling over large rocks might be the appropriate vehicle in which to transport humans. Simply stated, understanding the shape and form of the terrain at the landing site on Mars is a critical requirement.

Finally, knowledge of the distribution of larger rocks is needed to plan traverse routes. The rock distribution will determine if rovers have to surmount objects, that is, roll over rocks that are small enough, or maneuver around them.

The Need for Measurements

To ensure safe landing and operations on the surface of Mars, it is necessary for NASA to fully characterize the landing site and the topography of the anticipated surface operation zone with high-resolution stereoscopic imaging. The operation zone is the area around the landing site defined by the anticipated range of operations of EVAs, including the use of human transport and/or science rovers.

The level of resolution required of this imaging will be determined by the capabilities of the equipment to be used on the surface. Presentations to the committee illustrated human transport rover designs using wheels 1 meter in diameter. Vehicles using standard wheels can typically roll over objects one-third the diameter of the wheel being used. This suggests that if human transport and scientific rovers will use 1-meter wheels, the mission planners will need to know the distribution of rocks one-third of a meter and larger in the landing and operation zone. Imaging rocks this size requires a pixel resolution of 10 cm. The committee anticipates that the three-dimensional mapping would be conducted from Martian orbit.

Recommendation: NASA should map the three-dimensional terrain morphology of landing operation zones for human missions to characterize their features at sufficient resolution to assure safe landing and human and rover locomotion.

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Mobility on the Martian Regolith

The regolith is the complex outer layer of rock and soil on the surface of Mars. The potential hazards associated with the regolith include unstable movement or the inability to move in a timely manner across the Martian surface. These risks will be present when humans walk anywhere or when human transport rovers and critical science rovers are in operation on the surface of Mars.

Stable and Timely Traverse

The greatest threats to the safe movement of humans and critical equipment on the surface of Mars involve the following:

- Degradation of mobility,
- Instability and collision (human or machine),
- Mechanical failure, and
- Rovers that move too slowly.

Each of these hazards is associated with interaction with the Martian regolith and the regolith's ability to support planned rovers and humans. It is necessary to understand these hazards better to permit the design of appropriate systems and machines that will be used on the planet's surface.

Degradation of Mobility

An emergency could arise if humans or equipment become stranded in dunes or other eolian-deposited dust hazards (loose dust deposits that have a consistency of powder snow) because the regolith is unable to support large-mass objects operating on the Martian surface. Rovers could conceivably bog down in loose soil or break through a crusty surface. The power budgets for the movement of rovers and the life support consumables for EVA operations will be based on the designer's understanding of the energy transfer mechanisms involved.

Instability and Collision

An astronaut might fall while on an EVA, and it is more likely that the astronaut would fall on irregular terrain than on smooth terrain. It is also possible that science and human transport rovers might collide with rocks, causing damage to critical systems or injury to astronaut passengers. By understanding the bulk properties of the regolith, NASA should be able to minimize the risk of falling through appropriate design and operational procedures. The characterization of the Martian regolith will also allow science and human transport rovers to be designed so as to minimize unexpected mobility-related events that result in tip-over or collision.

Mechanical Failure

The Martian regolith could induce mechanical failure not only by causing catastrophic collision or tip-over where mechanical parts are broken, but also by abrading or gouging surfaces that contact the regolith. This hazard would be a concern if long-range rovers and extended surface operation times are involved. The vast majority of wear on critical systems will result from rock abrasion in the form of gouging from point contacts on rocks and shear action. Wear in the subsurfaces of materials, resulting from rolling friction, will also be an issue with which NASA must contend. Rock abrasion and wear will impact space suits and rover wheels the most.

For long surface stays with multiple EVAs, space suit boots would be worn down by the process of walking over the Martian regolith. Rock abrasion would probably be more apparent on heavy science and human transport rover wheels, where sharp rocks might gouge grooves in the wheels.

Rovers That Move Too Slowly

A hazard will be introduced if humans or their critical systems cannot move quickly enough on the Martian surface. If there is an emergency caused by an unpredicted solar particle event or a critical system failure, it will be imperative for the astronauts to reach shelter in a timely manner. Critical support rovers need to be able to keep pace with humans walking on the surface. If a critical rover is left behind because it cannot navigate Martian terrain quickly enough, a safety hazard would be introduced and human life might be at risk.

NASA needs to understand the mobility and trafficability characteristics of the Martian surface in order to design systems that can quickly navigate the operations area around the landing site.

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The Need for Measurements

It is necessary to understand the bulk physical properties of the Martian regolith that will interact with the rover vehicles, which in some scenarios are greater than 1,000 kg in mass. In addition to the need to characterize terrain morphology, as mentioned previously, NASA should also characterize the mechanical properties of the Martian regolith at the landing site or comparable terrain and rock properties in the landing and operating area. These properties include the following:

- Rock distribution and shape,
- Rock abrasive properties, and
- Regolith sinkage properties, including shear strength, bulk modulus, yield strength, and internal friction angle.

The experiments required to determine these characteristics must be conducted on the surface of Mars. The rocks that would have to be analyzed are simply too large to return to Earth, and most rocks in the operations zone will be too small to view from orbit. Also, the bulk properties could only be measured in an undisturbed environment.

Recommendation: To ensure that humans and critical rover systems can land on and traverse the Martian surface in a safe, efficient, and timely manner, NASA should characterize the range of mechanical properties of the Martian regolith at the landing site or comparable terrain. Specifically, in situ experiments should be performed to determine the regolith's aggregate strength, stability, and sinkage properties, including bearing strength, bulk modulus, yield strength, and internal friction angle.

Rock Distribution and Shape

If high-resolution orbital imaging is not available, the average rock size distribution and shape can be determined by in situ observations on the surface of Mars as those observations become available prior to human missions to Mars. The committee notes that rock size is currently determined during all precursor lander and rover missions. It is reasonable to expect that this activity will continue to be included in all future in situ missions, whether at the proposed landing site for the first mission or on similar terrain.

Recommendation: NASA should determine, in advance of human missions to Mars, rock size distribution and shapes in situ, at the landing site or on comparable terrain, in order to predict human and rover trafficability.

Rock Abrasive Properties

The abrasive properties of rocks on Mars, including hardness and surface roughness (as dictated by rock grain size and shape), are unknown. The committee believes that, even faced with this lack of knowledge, NASA can still design systems by making certain educated assumptions about the rocks on Mars. Specifically, the committee believes that NASA can adequately design systems by assuming that the rocks on Mars have a worst-case hardness similar to basalt and that NASA can test its systems using rocks with a variety of worst-case surface roughnesses. By such testing, NASA will be able to ensure that astronauts operating on Mars can work safely on a variety of rock surfaces. No further in situ experiments to determine the abrasive properties of Martian rocks are required.

Finding: By testing space suit and rover equipment on Earth using rocks with the hardness of basalt and a variety of worst-case surface roughnesses, NASA does not need to further characterize the properties of rocks on Mars.

Regolith Sinkage Properties

To determine the regolith sinkage properties, including shear strength, bulk modulus, yield strength, and friction angle, NASA must conduct an in situ cone penetrometer or equivalent experiment, which would characterize the aggregate properties of the mixture of rock and soil that composes the Martian regolith. This experiment could be conducted at either the landing site or on comparable terrain. It should be geared to understanding how the Martian regolith would react to the presence of large-mass human transport rovers. Cohesion and friction are intrinsic properties of the most basic soil mechanics models. Friction is commonly expressed as an angle in these models and is referred to as "friction angle."

Airborne Dust Intrusion and Adhesion

Airborne dust presents a potentially significant hazard to human operations on the surface of Mars. The

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ubiquity and pervasiveness of the dust will be a constant source of concern. Dust intrusion and accumulation will need to be continuously monitored and will require well-designed filter systems and periodic housecleaning.

The possible hazards associated with airborne dust accumulation are the following:

- Abrading and wear of mechanical systems,
- Degrading of EVA suit seals,
- Filter clogging,
- Decrease in visibility (optics, space suit visors),
- Changing thermal properties, and
- Accumulating triboelectric charge (from wheel movement or wind).

The first two hazards involve dust intrusion; the next four, dust adhesion.

Dust Intrusion

The ability of dust to penetrate and damage a system is a function of the dust grain size, hardness, and shape. Once dust particles have penetrated a system, especially one with moving mechanical parts, the grains could wear critical moving parts and seals. The hazard presented by dust intrusion is more crucial for long stays on the Martian surface, where critical systems are exposed to the environment for a much longer time.

Dust Adhesion

Airborne dust on Mars will accumulate on surfaces by a wind-driven process abetted by electrostatic adhesion, magnetic attraction, or other adhesive properties such as the adhesion resulting from van der Waals (i.e., intermolecular) forces. The Martian wind, while being a cause of dust deposition, should also help limit the amount of dust that will accumulate on an exposed surface. However, if habitat filters are not designed properly, they could clog from the dust and soil that enter the habitat after an EVA return. Dust accumulation on external communication antennas and solar panel arrays, for instance, could create very hazardous situations by disrupting critical communications or decreasing the efficiency of power generation systems. Dust on optical systems and space suit helmet visors could seriously hinder operations and data measurements. Thermal radiators coated with microlayers of dust will have different heat exchange properties than originally intended as a result of the thermal radiative characteristics of the dust coating. Finally, the triboelectric charge generated by wheel movement in the Martian soil may cause surface soil and dust to clump onto tires, increasing the amount of dust around driveshaft seals and reducing wheel efficiency. While this list is not intended to be all-inclusive, it should give some indication of the far-reaching effects of Martian dust.

The committee does note, however, that the three robot landers that have operated on the surface of Mars to date have all operated successfully in the Martian dust environment by virtue of careful system engineering to prevent many of the effects described above.

The Need for Measurements

After reviewing NASA's experience with dust on the Moon and Mars, the committee is confident that NASA engineers and scientists will be able to design and build systems to mitigate the hazards posed by airborne dust on Mars. Some systems that would be used on the first human mission can be designed either by employing what is currently known about Mars dust or by assuming a worst case scenario in the design process, as described below.

Abrasive Properties of Dust

It is known that the average diameter of airborne dust particles is 3.4 microns. However, little is known of the size distribution, hardness, or shape of the grains. By careful analysis of the abrasive properties of airborne dust, engineers and scientists should be able to design systems that account for the potential for Martian dust to cause abrasive wear of moving parts and seals.

To that end, it would be desirable to know the grain size distribution, hardness, and shape of Martian airborne dust from the analysis of a sample return of airborne dust. However, a sample return is not required. The present Mars soil simulant that has been developed and characterized by NASA for engineering studies (JSC Mars-1: Martian Regolith Simulant) consists of palagonite (glassy volcanic ash altered at low temperature) having a bulk chemical composition similar to that of soils analyzed on Mars. While this simulant is a chemical proxy, it may not represent the physical properties or mineralogy of Martian airborne dust, so it is not adequate for testing mechanical systems for human missions to Mars.

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The committee does not recommend that any precursor in situ measurements be taken on Mars to characterize the mechanical and abrasive properties of airborne dust. Rather, it expects that a simulant having an average particle diameter of approximately 3.4 microns (similar to the average size of airborne dust particles) and a hardness similar to that of basalt, would adequately stress the design of any mechanical and seal systems that will be used during a human mission to Mars.

Basalt is a common surface rock on Mars (Mustard et al., 1997; Bandfield et al., 2000). It is thought to be the material from which Martian soils were formed (McSween and Keil, 2000). Alteration minerals—that is, materials that originated as pure basalt but have been modified in some physical way—would be softer than the minerals comprising basalt. There is no need for a simulant to be harder than basalt, as spectroscopic searches have not detected minerals with greater hardness (e.g., quartz) (Bandfield et al., 2000). Any mechanical system that withstands testing using such a worst-case basalt simulant will in all likelihood be overdesigned for use on Mars.

Finding: The present Mars soil simulant developed by NASA does not adequately simulate physical properties for engineering purposes.

Adhesion Properties of Dust

It is critical to fully characterize soil and airborne dust adhesion properties in order to design systems that minimize the risk of failure resulting from soil and dust accumulation. Also, a full understanding of Martian dust adhesion will allow NASA to predict and plan for maintenance protocols for critical systems such as air filters, solar panels, EVA suit seals, and communications equipment.

The committee recommends that NASA conduct precursor experiments on the surface of Mars to determine the adhesive properties of Martian soil and airborne dust. The alternative to conducting these experiments on Mars is for NASA to develop an accurate simulant that is based on a sample of airborne dust collected from the Martian atmosphere and soil.

Recommendation: NASA should determine the adhesive properties of Martian soil and airborne dust in order to evaluate the effects of dust adhesion on critical systems. This characterization must be conducted in situ by means of experiments to measure airborne dust adhesion.

HAZARDS FROM ATMOSPHERIC DYNAMICS

The physical dynamics of the Martian atmosphere will offer challenges to habitat and system design not encountered on the Moon or here on Earth. NASA engineers will have to predict the effects of electrostatic discharges and high winds to mitigate the hazards caused by these atmospheric phenomena.

Electrostatic Discharge

When an electrically neutral particle collides with another neutral particle, electric charge may be exchanged, so that one particle takes on a positive charge and the other a negative charge of equal magnitude. In Earth's atmosphere, lightning is generated by an accumulation of charges resulting primarily from collisions between ice particles of different size in clouds. As more collisions occur, more charge is built up (Wallace and Hobbs, 1977). The thermodynamics of the changing states of water (solid, liquid, gas) plays the central role in driving the vertical separation of oppositely charged particles within a cloud. The electric potential differences from one region of the cloud to another build up to very large values, producing lightning storms on Earth.

On Mars, the water-driven mechanism for charge separation is not present. Charged particles are expected to be produced by collisions in dust storms, but if the particles are well mixed in adjacent volumes containing many particles, the total positive charge would be essentially the same as the total negative charge in each region. Thus, there would be no large electric potential differences between parts of the cloud and between the dust cloud and the Martian surface (Kolecki and Landis, 1966). Although some electrical activity in Martian dust storms and dust devils should be anticipated, its intensity is not expected to be comparable to that of terrestrial lightning storms. The counterpart of lightning bolts on Earth may be small sparks on Mars.

The two Viking landers were enveloped in a global dust storm soon after landing, and dust devils have been observed many times on Mars by Viking orbiters and landers, the Mars Pathfinder, and the Mars Global Surveyor. Windblown dust appears to be a common condition on Mars and would cause electrostatic charging of astronauts' space suits during operations

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on the surface of Mars, as well as of their equipment and habitat. Despite this phenomenon, there has been no report of electrostatic damage to delicate electronics on any of the surface systems. Furthermore, neither the Viking missions nor the Mars Pathfinder mission experienced any problems due to electrostatic charging.

While it would be useful to learn more about the electrical activity in Martian and terrestrial dust storms and vortices, the committee concludes that such increased knowledge is not essential for planning the first human mission to Mars.

Probably of greater significance is the charging of such objects even in the absence of airborne dust, due to the motion of boots and wheels relative to the surface material and differential motion of different parts of equipment and material. A glove brushing dust from a space suit may cause more dust to cling to both.

The electrical discharge paths between objects at different electric potentials may be through a good conductor, resulting in fast charge neutralization, or through the atmosphere or another poorly conducting material, resulting in a much slower charge dissipation. Objects on moist ground on Earth are said to be grounded since the conducting ground has an almost unlimited capacity to accept either positive or negative charge without changing its electric charge potential from what is essentially zero. Such natural discharge or prevention of charging is not expected to occur on Mars, because there is no near-surface liquid water.

The lack of a local electrical ground on Mars may be so electrically isolating that astronauts operating on the Martian surface would build up large potential differences relative to the equipment they will be using or the habitat in which they will live. For example, an astronaut on an EVA may experience an arc between the space suit and equipment or habitat. Such a discharge, if not properly isolated, could damage sensitive, unprotected electronic components or the space suit. In particular, the committee is concerned with the level of charging that might occur as a result of the high-velocity movement that is likely to take place when using a human transport rover.

The hazards from electrostatic discharge on Mars can range from a simple spark, equivalent to feeling a sting here on Earth after walking on certain types of carpet and reaching for a doorknob, to potentially more potent bursts between astronauts and large equipment or structures on Mars. The principal risk, as the committee sees it, is how these discharges could affect the electronic equipment that is critical for human survival on the planet. Here on Earth, the charge generated from walking across a carpet is usually more than enough to disable and potentially destroy certain electronic components.

The Need for Measurements

The dry conditions and uncertainty about conductivity, charging, and discharging rates in the Mars environment create uncertainties about electrostatic effects on human operations in the Mars environment. However, even given the potential hazards, the committee believes that the risk to humans from electrostatic charging on the surface of Mars can be managed through standard design practice and operational procedures. NASA should design accordingly and assume that no effective local ground is available on Mars.

In one case, the physics of the Martian environment may actually help reduce the risk of electrical discharge to humans or systems. So-called Paschen electrical discharge is likely to mitigate the hazard of differential voltage buildup on humans and systems due to the atmospheric composition and pressure on Mars. Owing primarily to its low pressure, the atmosphere ionizes more easily, which dissipates electrical charges at a lower voltage, minimizing the charge buildup. This means that lower overall electric charge should be present when humans and equipment are working on the surface. For a specific case of parallel plates separated by half a centimeter, on Earth the breakdown voltage is approximately 7,000 volts, as opposed to slightly over 400 volts on Mars.

The committee does not advocate any specific engineering design solution. However, for the sake of discussion, there are many potential solutions for the electrostatic discharge risk. For example, a device that allows discharge through a resistive contact to prevent electrical arcing might be used to mitigate the risk of discharge occurring between an astronaut and the habitat when the astronaut returns from an EVA. A combination of technologies might also be considered, such as point-discharge, needlelike devices or even small radiation sources to prevent charge buildup.

The committee believes that no further in situ measurements are required to characterize the electrostatic properties of the Martian environment, including those properties associated with dust devils, for an initial human mission to Mars. NASA's experience with the Viking and Pathfinder missions supports this conclusion. It should be noted that if or when highly energetic

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(i.e., high-speed) rovers are used, the same might not be true. Such high-speed rovers could conceivably induce very strong charges. While no specific in situ experiments are required at this time, NASA should pay close attention to electrostatic effects on subsequent science rover missions to aid in the design of future fast-moving rovers.

The committee believes it would be helpful for NASA to investigate the design considerations and procedures used at the Siple research station in Antarctica, where there is little to no local electrical ground. Again, as an example of potentially innovative design solutions, two crossed-dipole antennas at Siple, each 21.4 kilometers long, occasionally charged up to the order of 20,000 volts when windborne ice particles passed over them. The danger of discharge was removed by connecting the antennas to the station buildings. The buildings prevented a charge from accumulating on the antenna conductors by acting as large capacitors that stored the charge. The electrostatic voltage on the antennas was reduced to near zero, and since ice is not a perfect electrical insulator, the charge on the buildings dispersed gradually. Sharp conducting points, the needlelike devices referred to above, were also used near the buildings to bleed off the electrical charge.

High Wind Speeds

There has been some concern about the risk to astronauts on the surface of Mars from high-speed wind from either regional or global dust storms or localized dust devils. Global storms are neither reliably seasonal nor predictable. Nor do we know the upper limit on how long these storms may last. Most global storms on Mars start in its southern hemisphere near the beginning of southern summer, when Mars is near perihelion, that is, when it is 17 percent closer to the Sun than at aphelion (Kieffer et al., 1992). The storms occurring at this time usually last several months. The impaired visibility caused by these storms could represent a hazard to astronauts on the surface. However, this phenomenon is well characterized and no further in situ measurements are required.

The strongest surface winds observed by in situ measurements on Mars are believed to be 30 to 50 meters per second (67 to 111 miles per hour) based on eolian deposits at the Viking I landing site. From a terrestrial perspective, these wind speeds appear to represent a significant hazard. However, when the lower atmospheric dynamic pressure on Mars, resulting from a less dense atmosphere than on Earth, is accounted for, the Earth-equivalent wind speeds are much less. Dynamic pressure is proportional to the air density times the square of the wind speed, so that the following comparisons can be made:

- For the same wind speed, the dynamic pressure on Mars is less than on Earth by the ratio of air densities, or a factor of about 82.
- For the same dynamic pressure, the wind speed on Mars must be greater than on Earth by the square root of this number, or a factor of about 9.

Simply stated, the wind must blow nine times faster on Mars than here on Earth to achieve the equivalent dynamic pressure. In the strongest wind case mentioned above, a 30 to 50 meter per second (67 to 111 mile per hour) wind on Mars is roughly equivalent to a 3.3 to 5.5 meter per second (7.4 to 12 mile per hour) wind on Earth.

Another potential hazard associated with wind is abrasion by windblown particles. Suspended dust is so fine that it is unlikely to cause significant abrasion. Although ventifacts (rocks sculpted by windblown particles) were observed at the Mars Pathfinder landing site, these features do not necessarily indicate higher wind speeds. Ventifacts form by saltation—that is, by sand grains bouncing along the surface. Saltation is unlikely to cause abrasion except at or very near ground level, and the time scale of the abrasion that produced ventifacts is certainly much longer than the duration of human Mars missions. Lack of evidence that any Mars landers have been affected by this process suggests that any abrasion by windblown particles can be mitigated by habitat and equipment design.

The Need for Measurements

The committee believes that in light of the relatively low dynamic pressures experienced on Mars, no further characterization of wind speed on Mars is required prior to the first human mission. It believes that the surface winds are sufficiently characterized based on Viking and Pathfinder data and atmospheric dynamic models with regard to speed (based on Viking and Pathfinder experience) and dust devils (based on Pathfinder data) to allow system designers to ensure human safety on the planet by means of robust designs. Therefore, no new in situ experiments to validate global storm or dust devil wind speeds are recommended. The committee

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acknowledges that many precursor lander missions will include meteorological instrument payloads, so additional wind speed measurements will in all likelihood be gathered, which will further aid designers.

Wind may become a factor in certain areas on Mars with large terrain slope changes, such as on the flanks of volcanoes or inside canyons, depending on the time of day. The winds on these slopes may need to be studied more closely if it is determined that humans will be operating in such areas during the first mission to Mars.[1]

Finding: The risk to humans on the surface of Mars from electrostatic discharge and wind can be managed or mitigated through standard design practice and operational procedures.

RADIATION HAZARDS

Astronauts are by definition radiation workers. Radiation exposure in space will be a significant and serious hazard during any human expedition to Mars. There are two major sources of natural radiation in deep space: sparse but penetrating galactic cosmic radiation (GCR) and infrequent but very intense solar particle events (SPEs) associated with solar storms. In addition, many of the scenarios discussed for human missions to Mars involve the use of advanced propulsion systems that use nuclear power sources. In this event astronauts will also have to be shielded from this additional radiation source. While on the surface of Mars, the astronauts will be afforded some protection by the planet itself. Instead of having to contend with radiation from all sides, as in space, the astronauts will have only radiation from above, and that amount will be reduced somewhat by the Martian atmosphere. However, absorption and reradiation by the Martian regolith will alter the spectrum of the radiation environment. The radiation dose received by astronauts on the surface of Mars will be a significant fraction of the total radiation exposure for the mission.

The radiation environment on Mars is the result of complex processes of radiation absorption and reemission. The radiation arriving at the surface of Mars from space is a mixture of ions with a wide range of energies. This radiation interacts with the regolith and the atmosphere to create a shower of secondary particles, including recoil nuclei, nuclear fragments, neutrons, electrons, and subatomic mesons. The radiation impinging from all directions on a point at the Martian surface is influenced by the density and composition of the Martian atmosphere and by the composition of the Martian surface as well as the first few meters of the subsurface.

[1]Ronald Greeley, Arizona State University, e-mail correspondence to the committee, August 10, 2001.

Radiation Effects on Humans

The effects of radiation exposure on humans can be grouped into two basic categories, those effects that occur very soon after exposure and those effects that are apparent months or years after exposure. Acute effects, those that occur very soon after exposure, can range from headaches, dizziness, or nausea to severe illness or death. Acute effects of radiation exposure can have a serious impact on an astronaut's ability to complete the mission. More details on radiation effects can be found in the NRC reports *Radiation Hazards to Crews of Interplanetary Missions*, *The Human Exploration of Space*, and *Radiation and the International Space Station* and in a report by the National Council on Radiation Protection and Measurements, *Radiation Protection Guidance for Activities in Low-Earth Orbit* (NRC, 1996, 1997, 2000; NCRP, 2000). The limits established by NASA for exposure to radiation during missions to low Earth orbit are clearly defined (NASA, 1995).

The severity of delayed effects depends on dose. For the most part, any long-term effects of radiation exposure will not be apparent until well after a mission has returned to Earth. These delayed effects may include the following:

- Cancer,
- Cataracts,
- Nonmalignant skin damage,
- Death of nonregenerative cells/tissue (potentially including the central nervous system),
- Genetic damage,
- Impact on fertility, and
- Suppression of immune function.

The causes of damage from short-term radiation exposure are fairly well characterized. However, the causes of long-term effects are poorly understood. The uncertainty associated with the biological impacts creates problems when trying to quantify the risk of

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radiation exposure on human missions to Mars.[2] A study by the National Research Council found that the uncertainty in biological effects caused by radiation range from 200 to 1,500 percent depending on the specific effect. In addition, the uncertainties surrounding the interaction of galactic cosmic radiation, the interstellar radiation not coming from our Sun, with materials on the surface of Mars are believed to be 10 to 15 percent. Finally, the radiation transport model uncertainties are judged to be on the order of 50 percent (NRC, 1996).

Developing and Validating Three-Dimensional Radiation Transport Models

In examining the radiation hazard, the committee sought to balance the testing capabilities NASA has at its disposal on Earth with experiments that must be conducted in space or on the surface of Mars. There have been no direct measurements of the radiation environment on the surface of Mars. Rather, the radiation environment is estimated using computer codes that model the transport of the deep space radiation through the Martian atmosphere and its interactions with the Martian surface. The committee believes that the models predicting the absorbed radiation dose on the surface of Mars need to be validated before sending humans to Mars. These models will influence the overall design of a Mars mission, including nominal and emergency operation scenarios and habitat design. The committee was primarily concerned with two issues involved in the development and validation of the models:

- Developing models that realistically portray operational scenarios on Mars and
- Establishing the most direct method of validating the absorbed radiation dose models.

The current models that NASA is using to predict astronaut absorbed radiation dose are not designed for detailed three-dimensional analysis of structures (habitats or vehicles) on the Martian surface. As a result, the radiation transport models need to be improved in concert with the development of any in situ measurement instrument and experiment intended to verify radiation transport models. The models must be applicable to a three-dimensional structure in a complex three-dimensional environment. This theory and model development will allow NASA to gain confidence in their predictions of astronaut radiation doses.

Two classes of simulations (Monte Carlo and analytic) are used to model radiation transport. The analytic approach treats the cascade of particles by estimating the average incident particle energy losses as those particles travel along a path and the average buildup of secondary particles. The Monte Carlo models compute the path of representative incident particles and individual secondary particles. Both techniques can be applied to complex shielding geometries. The analytic model computes averages and generates results much faster but employs many approximations. The Monte Carlo model uses fewer simplifications, but because of the large number of particles that must be propagated it is slower and less amenable to systematic trade studies.

Both transport models use approximations to characterize the physics of nuclear scattering. These approximations are necessary because of the inherent complexity of the collisions between large nuclei. To minimize the error introduced by these approximations, experiments are conducted at accelerator laboratories that help to simplify the process by examining specific particles and initial energies that impact some types of sample radiation shielding. The results of such tests provide feedback to the model developers, who, in turn, refine their models. However, practical considerations involving the amount of time it takes to conduct individual experiments and the types of ions and energies available with Earth-based testing limit the number of experiments that can be performed. For these reasons it is not feasible to experimentally measure the effects of all the ion species at all energies on all the shielding conditions that will be experienced on the Martian surface.

In spite of these limitations, researchers anticipate that with continued development of both models, transport codes will be used to simulate the Martian surface radiation environment. These codes will be integral to the design of the space vehicles, surface vehicles, surface habitats, and other shelters. The dose estimates established by these models will be used to set operational rules for surface expeditions. The rules will account for such items as the maximum amount of time

[2]F. Cucinotta and W. Schimmerling, "NASA Strategic Program Plan for Space Radiation Health Research," briefing to the committee, August 2, 2001.

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an astronaut may spend on a surface EVA and the maximum distance from a shelter an astronaut may go.

Effect of Localized Hydrogen and Iron

The effective radiation dose that an astronaut will absorb is strongly affected by the number of secondary neutrons generated when radiation first impacts a material or substance. When radiated material contains hydrogen, neutrons are more readily absorbed: a desirable effect. However, when material contains heavy nuclei, more secondary neutrons are generated: a deleterious effect. There has been some concern that localized concentrations of hydrogen in subsurface ice or hydrated minerals or iron within iron-rich rocks in the Martian regolith could skew the results of in situ testing for absorbed radiation dose if such testing is restricted to a small, localized area. At the committee's request, scientists at NASA Langley Research Center ran model simulations testing the effects of hydrogen and iron concentrations on absorbed dose. The simulations were conducted with varying amounts of hydrogen and iron (Tables 3.1 and 3.2). This preliminary analysis indicates that the current understanding of the elemental composition of Martian soil is adequate for radiation transport calculations through bulk Martian regolith. The analysis further suggests that even substantial variations in the amount of localized hydrogen and iron have little effect on the absorbed dose.

TABLE 3.1 Compositions of Five Different Martian Regolith Scenarios

	Nominal Regolith	High Fe/ High H	High Fe/ Low H	Low Fe/ High H	Low Fe/ Low H
H	0.00	1.00	0.05	1.00	0.05
O	44.56	31.52	32.03	47.55	48.05
Mg	6.48	4.58	4.66	6.91	6.99
Si	27.16	19.21	19.52	28.98	29.30
Ca	5.21	3.69	3.74	5.56	5.62
Fe	16.59	40.00	40.00	10.00	10.00

NOTE: Values are presented in weight percent. The results are from model simulations conducted at the committee's request by Martha Clowdsley at NASA, "Examination of the Sensitivity of Mars Surface Radiation Exposures to Variations in Regolith Composition of Iron and Hydrogen," 2001. The nominal regolith element breakdown represents expected regolith composition, while the other four categories bound extreme range possibilities of iron and hydrogen in the Martian soil.

TABLE 3.2 Effect of Hydrogen and Iron Content on Absorbed Radiation Dose[a]

Shield Thickness	Nominal Regolith	High Fe/ High H	High Fe/ Low H	Low Fe/ High H	Low Fe/ Low H
1 g/cm^2 aluminum 2219	22.9	22.7	22.7	22.6	22.8
10 g/cm^2 aluminum 2219	22.0	21.8	21.7	21.7	21.8

NOTE: Values represent the dose equivalent for blood-forming organs (BFOs). The results are from model simulations conducted at the committee's request by Martha Clowdsley at NASA, "Examination of the Sensitivity of Mars Surface Radiation Exposures to Variations in Regolith Composition of Iron and Hydrogen," 2001.
[a]Compositions from Table 3.1.

The Need for Measurements

Because of the central role that radiation transport and absorbed dose models will perform in the planning and design of human missions to Mars, it is important that the code predictions be validated to verify that the models are providing predictions representative of the real radiation environment on Mars. The committee recommends that NASA conduct a precursor experiment on the surface of Mars to measure total absorbed radiation dose in a tissue-equivalent material. The measurement may take place at one location.

The committee acknowledges that by conducting such an experiment, NASA will only be testing for the validity of the absorbed dose models. This could lead to some ambiguity in the validation test if the experiment design is too simplistic. For example, the model may correctly predict a dose rate that the experiment observes. However, the match between the model and results may be a result of underestimating one component's contribution to the dose and overestimating that of another component, so that the two balance each other. Since, as discussed earlier, the neutron flux is very sensitive to the environment, one way to address this problem would be to require that the experiment be set up to distinguish the radiation dose contribution induced by charged particles from that induced by neutrons. In addition to providing more insight into the source of the absorbed dose, the ability to make this distinction will test the value of the models. This infor-

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mation will provide some assurance that it is not merely coincidence if the models' predicted doses coincide with the measurement made on Mars, but rather that the models are based on sound data.

The full impact of individual variable inputs on model performance will not be resolved with this single experiment. However, if the measurements of total dose and dose contribution from neutrons on Mars agree with model predictions, these variable inputs need not be resolved to conduct the first human mission to Mars.

The in situ test should take place at a location that is representative of potential landing sites for human missions to Mars. Most of Mars appears to have generally the same composition, with the exception of the poles and certain locations with hematite deposits. The average composition of the test site need not exactly match that of the planned landing site.

The experiment should take place at a location with an altitude similar to that of the human missions to Mars. The depth of the Martian atmosphere will play a significant role in astronaut absorbed radiation dose, so the measurement should be made with an atmospheric thickness similar to that which the human missions will encounter.

If practical, it would be beneficial to have the measurements taken at multiple locations separated by tens of meters, such as could be accomplished with a rover. The results of such an experiment could validate the predictions by models that the absorbed dose is relatively insensitive to local variations in the subsurface composition of hydrogen and iron.

Finally, the committee recommends that this in situ test be made a priority in the Mars program and conducted as soon as reasonably possible. Radiation risk mitigation strategies will be an integral part of overall mission design and planning. Should the results of the in situ experiment prove that the radiation transport models are flawed, more time will be needed to adjust the models to account for the differences between the models and the measurement. If the difference is substantial enough to have a significant impact on the design and operation of the mission, further in situ tests may be required.

Habitats designed to protect astronauts against GCR will also protect them against solar particle events. Operational procedures will be necessary to ensure the astronauts have timely access to these habitats or to other, similarly shielded safe havens such as robust, long-range transports. The committee recognizes that the proposed approach would not be adequate to explicitly validate model predictions of the surface dose during solar particle events. While the GCR flux varies slowly within the inner solar system and at Mars, it can be reliably estimated from measurements near Earth. SPEs, however, can be highly localized, and the flux varies significantly with distance from the Sun and location relative to the source of the solar eruption. The flux of particles at Mars during an SPE cannot be determined by measurements taken far from Mars. To directly validate a model prediction during an SPE would require that the surface measurement be supported by a second measurement of the particle flux above the Martian atmosphere.

While it would be valuable during an SPE to directly correlate measurements of dose on the surface if the particle flux is available from an orbiting instrument, the committee believes that a validation of the modeled GCR contribution to dose will add sufficient confidence to the simulations such that they could be used reliably to estimate the surface dose during an SPE. The related (and difficult) task of forecasting SPEs at Mars in a timely fashion is important, but it is outside the purview of this committee.

Recommendation: In order to validate the radiation transport codes, thereby ensuring the accuracy of radiation dose predictions, NASA should perform experiments to measure the absorbed dose in a tissue-equivalent material on Mars at a location representative of the expected landing site, including altitude and bulk elemental composition of the surface. The experiments should distinguish the radiation dose contribution induced by charged particles from that induced by neutrons. These experiments should be made a priority in the Mars exploration program.

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[3]Three NRC reports reprinted in a single volume: *Scientific Prerequisites for the Human Exploration of Space* (1993); *Scientific Opportunities in the Human Exploration of Space* (1994); and *Science Management in the Human Exploration of Space* (1997).

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4

Chemical Environmental Hazards

Chapter 3 presented the hazards from materials on Mars interacting dynamically with humans or critical systems involved in human missions. In Chapter 4, the committee presents hazards associated with the chemical reactivity of materials on Mars. As with radiation exposure standards, NASA standards for astronaut exposure to chemical hazards have only been documented for operation in low Earth orbit (NASA, 1995).

CHEMICAL INTERACTION OF MARTIAN SOIL AND AIRBORNE DUST WITH ASTRONAUTS AND CRITICAL EQUIPMENT

As discussed in Chapter 2, the committee assumed that astronauts will conduct EVAs on the surface of Mars. The following analysis is based on the assumption that some dust and soil will be brought into the habitat through the airlock by returning astronauts, as was the case during the Apollo missions to the Moon. Even though some space suit designs have been proposed that would mitigate the dust and soil intrusion problem, astronauts will inhale some fraction of the dust and fine particle soil entering the habitat.

The committee was faced with the question of whether or not NASA must fully characterize the mineralogy of the dust and soil—that is, the chemical composition and the physical form—prior to the first human mission to Mars. The answer to this question is complicated by the fact that very little is known about Martian airborne dust and soil. The only factual data the committee was able to use during its deliberations was based on the analysis of meteorites from Mars that have landed on Earth (also known as SNC meteorites) and chemical and spectroscopic measurements of Mars soil taken by the Viking and Mars Pathfinder missions.

The committee's goal was to identify, if possible, the level below which particulate concentrations in a habitat must be kept to protect astronauts from dust and soil whose composition is not well known.

Given the unknown nature of the Martian dust and soil, the committee believed it was prudent to err conservatively by assuming a worst-case scenario. In choosing the "worst" toxic chemical hazards to humans, the committee considered inorganic substances separately from organic substances. With respect to inorganic substances, it identified certain toxic metals as the worst threat to humans at the lowest concentrations. The committee addressed organic substances in a different manner, choosing to look first for the presence of organic carbon, which will be discussed below.

The chemical health threat from Martian airborne dust and soil can be considered in terms of acute (short-term) and chronic (long-term) effects. Noncancer acute or chronic effects could result in lung injury in the form of silicosis or in other specific organ damage. Lung tissue could be damaged by the intrusion of acidic dust. Strong oxidants in the soil and dust are also potentially hazardous to astronauts. The effects of such damage would be observable in a short time and could interfere with the completion of a human mission.

Cancer is a potential chronic effect caused by the inhalation of Martian particulate matter containing certain toxic metals, asbestos-like fibers, or organic compounds. The committee concluded that the threat of asbestos-like materials being present in Martian dust and soil is not significant based on inferences about

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dust mineralogy from spectroscopy, measured soil composition, and plausible alteration mechanisms (Morris et al., 1995; Bell et al., 2000).

The committee also concluded that Martian airborne dust could present the same chemical hazards as Martian soil, so soil and dust should be characterized in the same way. In addition, certain soils could contain harmful organic compounds. However, the oxidizing environment at the surface would most likely have destroyed any organic compounds contained in the surface layers of the soil. Notwithstanding these conclusions, in the absence of further data, astronauts should avoid direct skin contact with soil.

Cancer versus Noncancer Risks

Generally, EPA considers that there is no safe threshold (no safe level) for human exposure to certain genotoxic, cancer-inducing compounds. "Genotoxic" refers to the process by which cancer-causing compounds directly interact with DNA. In contrast, there is a defined threshold level above which noncancer effects are induced. An estimate of the safe inhalation concentration is referred to as the reference concentration (RfC). If hazardous compounds are below the RfC threshold, noncancer effects are not expected to occur. If the RfC of a toxic compound is exceeded, there could be harmful health effects. It should be noted that many compounds do not have RfCs established.

An examination of the Integrated Risk Information System (IRIS) provided by the EPA reveals that the allowed safe concentrations for cancer are much more stringent than the safe concentrations that give comparable risk estimates for noncancer effects (Table 4.1 is a representative sample). Therefore, if NASA protects astronauts against the risk of developing cancer in the long term as a result of having been exposed to particulate matter on Mars, NASA will also be protecting astronauts from acute and short-term noncancer effects that could potentially interfere with mission success.

Toxic Metals and Other Inorganic Elements

Airborne dust and soil could contain trace amounts of hazardous chemicals, including compounds of toxic metals that are known to cause cancer over the long term if inhaled in sufficient quantities. Soil analyses conducted by the Viking missions established maximum possible concentration limits for a few toxic elements based on the detection capabilities of the instruments on the landers (Table 4.2), and Mars Pathfinder measurements established that chromium is present in Mars soil. Although analogous measurements have not been made on airborne dust, soil and dust are commonly assumed to have similar chemical compositions (McSween and Keil, 2000).

TABLE 4.1 Representative Listing of Reference Concentrations for Cancer-Causing Compounds and for the Noncancerous Effects of Those Compounds from EPA's IRIS Database (milligrams per cubic meter)

Compound	Reference Concentration (RfC) Safe Dose for Noncancer Effects	Concentration That Gives a Cancer Risk of 1 in 1,000,000[a]
Beryllium	2×10^{-5}	4×10^{-7}
Acrylonitrile	2×10^{-3}	1×10^{-5}
Acrolein	2×10^{-5}	No information given
Acrylic acid	1×10^{-3}	No information given
Aniline	1×10^{-3}	No information given
Antimony trioxide	2×10^{-4}	No information given
Carbon disulfide	7×10^{-1}	No information given
Dichlorobenzene	8×10^{-1}	No information given
Styrene	1×10^{0}	No information given
Chromium VI	No information given	8×10^{-8}
Arsenic	No information given	2×10^{-7}
Cadmium	No information given	6×10^{-7}

[a]Higher dose poses a greater risk.

Based on a survey of Environmental Protection Agency (EPA) exposure risk estimates, the elements that are toxic at the lowest concentrations are hexavalent chromium (Cr VI), arsenic (As), cadmium (Cd), and beryllium (Be) (see Box 2.2).

Hexavalent Chromium

Chromium contained in naturally occurring geologic materials is primarily in the trivalent state (a +3 ion), which is a stable form of chromium and minimally toxic to humans. Hexavalent chromium (Cr VI, a +6 ion), the highly toxic form of chromium, is rarely encountered in natural geologic materials. In fact, hexavalent chromium is only found naturally on Earth in the rare mineral crocoite ($PbCrO_4$) and is more often produced by humans for industrial purposes (ATSDR, 2000).

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TABLE 4.2 Element Detection Capability on the Viking Landers

Atomic Number	Detection Lower Limit	Potentially Hazardous Elements	Note
1 to 11	No detection capability	Be and F	Fluorine amounts may be unusually high on Mars since halogen amounts are generally high.
12 to 28	Variable	Ni, Co, Cr, Si	Consists of major and minor elements.
29 to 42	150 ppm[a]	As, Se, Rb, Sr, Y, Zr, Mo	Bromine (Br) was detected in the 100-150 ppm range.
43 to 75	No detection capability	Cd	No ability to place useful lower limits due to interference from major and minor elements.
76 to 92	300 ppm	Hg, Ti, Pb	

[a]Bromine is an exception. See note in right column.

The committee believes that hexavalent chromium is not present in abundance on Mars but cannot state this with absolute certainty. There are three reasons for being cautious about the presence of hexavalent chromium on Mars.

- Mars Pathfinder APXS (alpha-proton-x-ray spectrometer) data indicate that chromium, in an unknown valance state, is present on Mars in the soil at an average of 0.2±0.1 weight percent (Wanke et al., 2001). If even a modest fraction of this amount is hexavalent chromium, it would pose a serious health threat to astronauts operating on the surface.
- Hexavalent chromium is derived from trivalent chromium by an oxidation process. The surface of Mars is highly oxidizing, which makes it a suitable environment for generating hexavalent chromium.
- Hexavalent chromium reverts fairly easily to the trivalent state in the presence of organic compounds. The surface of Mars appears to be devoid of organic carbon (Biemann et al., 1977). The lack of organic carbon indicates that few or no organic compounds are present, so any hexavalent chromium present may not easily revert to the non-toxic trivalent state.

To offset these concerns to some degree, it should be noted that the only cation known to combine mineralogically with hexavalent chromium on Earth is lead (Pb^{2+}), producing the oxide, crocoite ($PbCrO_4$). Based on SNC meteorite analysis, lead is present on Mars at only about 72 parts per billion (ppb) (Lodders, 1998). Therefore, if the general mineralogy of Mars is similar to that of Earth, as is indicated by all experiments to date, the amount of hexavalent chromium on Mars is likely to be very small.

The physical and chemical weathering processes that would cause rocks on Mars, which the meteorites represent, to be converted into airborne dust and soil could cause an increase in the concentration of certain toxic metals. Even given a thousandfold increase in the concentration of lead (from 72 ppb to 72 ppm) by such weathering processes, the hexavalent chromium that would combine with this lead would not exceed a concentration of about 18 ppm.

For the purposes of this study, the committee made the conservative assumption that hexavalent chromium is present in Martian soil and airborne dust at no more than 150 ppm. This concentration is equivalent to nearly 10 percent of the chromium detected by Pathfinder and well above any expectations for the amount of crocoite present, as discussed above. It must be clear to the reader that all conclusions in this chapter will be based on this assumption and others as discussed shortly. Should the actual concentration of hexavalent chromium become known, the habitat filtration requirements discussed in this chapter will change accordingly, keeping in mind that other toxic elements, such as arsenic, might then be dominant.

Given the severe toxicity and uncertainty of the amount of hexavalent chromium, the committee recommends that NASA conduct an in situ experiment prior to the first human mission to Mars to determine if hexavalent chromium is present in Martian soil and airborne dust at potentially hazardous concentrations. As is shown in Table 4.3, a 2-year exposure to Cr VI at a concentration of 150 ppm in 1 milligram per cubic meter (mg/m^3) airborne particulate matter produces a cancer risk of 5 in 100,000, which is in the middle of

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TABLE 4.3 Toxic Metal Inhalation Risk

Metal	Concentration Equivalent to Lifetime Exposure Representing a Risk of 1 in 1,000,000 (mg/m^3)	Maximum Cancer Risk to Astronauts for 2 Years of Exposure at 1 mg/m^3 Particulate Matter Containing 150 ppm of the Metal, Rounded[a]
Chromium VI	8×10^{-8}	5 in 100,000[b]
Arsenic	2×10^{-7}	2 in 100,000
Beryllium	4×10^{-7}	1 in 100,000
Cadmium	6×10^{-7}	1 in 100,000

NOTE/CALCULATIONS: The concentration of the metal that represents a cancer risk of 1 in 1,000,000 (10^{-6}) is given in the EPA's Integrated Risk Information System (IRIS). For instance, for chromium VI, a risk of 1 in 1,000,000 results from a lifetime exposure (70 years) to a concentration of 8×10^{-8} g/m^3. Risks are linearly related to exposure concentration.

The astronauts will not be exposed to the metal for a lifetime but, in the worst case, for 2 years. Since the risks are proportional to the exposure, one can tolerate a higher concentration for a shorter period of time. The concentration equivalent to 2 years exposure to give a 10^{-6} risk is 70/2 times the lifetime risk.

The following is a sample calculation for arsenic:

- 150 ppm of the metal in the particulate matter in 1 mg/m^3 is 150×10^{-6}, or 1.5×10^{-4} mg/m^3 of metal. This is the (conservative) concentration to which the astronauts could be exposed for 2 years.
- The lifetime cancer risk of 1 in 1,000,000 (10^{-6}) for arsenic is 2×10^{-7} mg/m^3 (from IRIS).
- The concentration equivalent to 10^{-6} for a 2-year exposure is $(70/2) \times (2 \times 10^{-7})$, or 7×10^{-6} mg/m^3.
- The ratio of the exposure concentration to the concentration that gives a risk of 10^{-6} represents the risk times 10^{-6}. For instance, 1.5×10^{-4} (exposure concentration) divided by 7×10^{-6} (exposure that gives a risk of 10^{-6}) $= 0.2 \times 10^{2} \times 10^{-6}$, or 2×10^{-5}, a risk of 2 in 100,000.

[a]Assumptions/methods: (1) the metal is uniformly present in the respirable particulate matter at 150 ppm or less and (2) astronauts could be exposed constantly for 2 years at 1 mg/m^3 particulates in air (maximum). Rounded to nearest whole number.
[b]Risk of contracting cancer is 5 in 100,000.

the acceptable risk range (ARR) established for the exploration of Mars by the committee. Thus, the committee recommends that the measurement quantify hexavalent chromium down to a concentration level that is 150 ppm or less. This measurement can take place at any location on the planet since the airborne dust on Mars is highly mixed and therefore considered to be uniform in composition.

If this measurement cannot be made in situ, a sample of airborne dust and fine particles of Martian soil must be returned to Earth to determine if hexavalent chromium will pose a threat to astronauts operating on the surface of Mars.

Recommendation: In order to evaluate if hexavalent chromium on Mars poses a threat to astronaut health, NASA should conduct a precursor in situ measurement to determine if hexavalent chromium is present in Martian soil and airborne dust at more than 150 parts per million (ppm). This measurement may take place anywhere on Mars where well-mixed, uniform airborne dust is present. If such a measurement is not possible, a sample of airborne dust and fine particles of Martian soil must be returned to Earth for evaluation.

Other Toxic Inorganic Elements

The principal constraint on human missions from other toxic elements in Martian soil and airborne dust is an upper limit on the abundance of arsenic. This limit is based on Viking mission instrument measurement limitations (Table 4.2). Based on ratios of the measured abundances of arsenic, cadmium, and beryllium in Martian meteorites to other elements created by similar geochemical processes, abnormally high concentrations of these elements are not expected in Martian soil and airborne dust (arsenic and cadmium data compiled by Lodders, 1998; beryllium analyzed by Lentz et al., 2001). These elements are generally present at a few tens of parts per billion in Martian meteorites. Martian soils are similar in major element chemistry to the meteorites, except for enrichment in salts (sulfates and chlorides) (Clark et al., 1982). The geochemical process that introduced salts probably also concentrated arsenic and cadmium, but not beryllium, in soils. However, even at concentrations a thousand times greater than the concentrations in meteorites, arsenic and cadmium levels would still be less than 150 ppm.

The Need for Measurements

Based on the predicted concentrations of hexavalent chromium, arsenic, beryllium, and cadmium, as a worst-case scenario, the committee has addressed the risk of astronauts inhaling particulate matter containing 150 ppm of these metals. At this concentration, a 2-year exposure period, and a maximum average particulate

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level of 1 mg/m^3, as discussed below, the committee was able to develop the risk estimates listed in Table 4.3. All of the risks fall within its ARRs. The significance of this result is that no additional measurements of the concentrations of toxic elements in Martian soil and airborne dust, except Cr VI, are necessary as precursors to human exploration. However, this conclusion is dependent on NASA's ability to maintain particulate concentration in the habitat at or below the maximum allowable level discussed in this section of the study.

Instead of determining the concentrations of every toxic element in Martian soil and airborne dust, the committee determined that NASA can design around the potential hazard. Simply stated, if the habitat and/or astronauts are equipped with appropriate air filtration systems, then their health will be protected from the risk of toxic metal exposure as long as the assumptions listed below hold true.

Filtration systems that maintain a maximum average concentration of 1 mg of particulate matter per cubic meter of air will place astronauts in an ARR of between 1 in 10,000 and 1 in 100,000 of getting cancer during their lifetime from exposure to toxic elements in Martian soil and airborne dust (see Table 4.3). As noted in Chapter 2, in the section "Establishing Risk Standards," the committee established the ARR as an appropriate risk for astronauts. The issue is also discussed in Box 2.2.

It is natural that the operation of filtration systems will result in oscillations in airborne particulate matter concentration depending on the loading rate. For instance, when an astronaut returns from an EVA and introduces soil and dust into the habitat, the concentration of particulate matter in the air will go up for some period of time until returning to less than 1 mg/m^3.

It is possible to average a short-term, high-concentration exposure with a low-concentration exposure over a long period of time and obtain an average concentration meeting toxic concentration limits. However, this is not the intent of the specification offered in this report. EPA does not provide short-term or ceiling limits for exposure to chemicals, even though the intention is not to experience high-concentration fluctuations. The National Institute of Occupational Health and Safety (NIOSH) and the Occupational Safety and Health Administration (OSHA), on the other hand, do have short-term exposure limits for many chemicals. For most chemicals, this short-term maximum over a period of 15 to 30 minutes is between 1.5 and 2 times the specified average daily value. The committee believes it is reasonable to adopt this precedent in recommending a maximum concentration of respirable particles to no more than 1.5 times the average concentration for a duration not to exceed 30 minutes per day to protect against toxic elements (NIOSH, 2000).

Assumptions

The committee made the following assumptions in formulating the recommendation that NASA develop a system that filters particulate matter in astronaut habitat air to concentrations of 1 mg/m^3 or less for the first human mission to Mars:

- Astronaut forays outside the habitat will contaminate the environmental living space with material from the surface of Mars.
- Astronauts will primarily be exposed to toxic elements by breathing Martian dust, with only minuscule amounts of soil or dust contaminating food or contacting bare skin.
- Hexavalent chromium, arsenic, cadmium, beryllium, and other toxic metal concentrations are 150 ppm or less in soil and airborne dust.
- There are few or no negative additive or synergistic human health effects of the mixture of toxic metals and other chemicals, including other parameters such as acidity, in Mars soil or airborne dust. Considering metals individually is common practice since the quantification of combined effects with complex chemical mixtures is difficult.
- Radiation exposure in combination with exposure to toxic metals has little negative synergistic effect on human health.
- Toxic metals are not present in higher concentrations in the breathable portion of the airborne dust (small particles less than 1 micron in diameter) than in the Martian soil.
- The dust on Mars is homogeneous with respect to its trace element composition.
- Residence time on Mars for the astronauts will be at least 1.5 years. Acute exposures over a few months are outside the scope of this analysis. If a shorter mission takes place, exposure to toxic metals could be higher and still achieve the same ARR.
- All of the toxic metal is bioavailable—that is, any metals entering an astronaut's body would be

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completely absorbed. If the metals in Martian dust or soil are encapsulated in a coating of a nontoxic material or are otherwise rendered nonbioavailable (e.g., by binding to other chemicals), the risk to astronauts will be reduced.

What If Assumed Filtration Levels Cannot Be Attained?

The committee believes, based on current filtration standards and the capability demonstrated on the International Space Station, that the filtration levels required to protect astronauts are readily achievable. However, if a filtration system cannot be designed to limit the average particulate inhalation exposure of an astronaut to 1 mg of particulate matter per cubic meter of air in the habitat, then a sample of airborne dust taken from the Martian atmosphere and soil must be analyzed to establish concentration levels of all toxic metals. The level of analytical precision required will be dictated by the filtration capability of the astronauts' habitat. Although in situ measurements of Martian dust and soil with a resolution of parts per million are possible in principle, the committee judged that limitations on the ability of robotic instruments to measure trace elements would probably necessitate the return of soil and airborne dust samples to Earth if the specified filtration level cannot be achieved.

The following analyses and/or protocols must be established for the soil and airborne dust samples to ensure astronaut safety on the surface of Mars if appropriate filtration levels cannot be attained:

- Trace element abundance must be measured with parts per million resolution to determine the levels of toxic metals in the soil and airborne dust.
- The chemical and physical form of the toxic metals may need to be determined, depending on their concentrations.
- If the ARR of 1 in 10,000 to 1 in 100,000 due to inhalation of toxic metals cannot be maintained by using filtration systems to reduce airborne particulate concentration, then animal testing should be conducted to determine the integrated effects of soil and dust exposure on living systems. Under these circumstances, the chemical and physical form of the toxic metals should also be determined, since bioavailability could be an issue.

Airborne Respirable Particulate Matter

It should be very clear to the reader that, in the view of the committee, the 1 mg/m^3 specification is the *maximum* acceptable respirable particle average concentration to which astronauts should be exposed. This concentration level will protect astronauts from exposure to toxic metals, which—of all inorganic chemicals—the committee considers to pose the greatest health risk to astronauts. Filtering at or below the recommended 1 mg/m^3 average with a 1.5 mg/m^3 peak concentration should be readily achievable for NASA. The 1 mg/m^3 particulate level is equivalent to very dirty industrial city air and is about 20 times greater than the 0.05 mg/m^3 average standard set for the International Space Station (Green and Lane, 1964; NASA, 2000). Indeed, to minimize risks from exposure, the committee strongly believes that filtering should be implemented below 1 mg/m^3, to as low a concentration as is reasonably achievable in the Martian habitat. The committee notes that there are no risk estimates similar to those presented in the EPA IRIS database for general respirable particulates, so an analysis similar to the one above for toxic metals is not possible. However, maintaining a particulate concentration below 1 mg/m^3 would also be consistent with EPA National Ambient Air Quality Standards (NAAQS). Current and proposed NAAQS for particulate concentrations are shown in Table 4.4.

TABLE 4.4 EPA National Ambient Air Quality Standards for Particulate Concentrations

Pollutant	Measure	Value (mg/m^3)	Type
PM 10—diameter <10 micrometers	Annual arithmetic mean	0.05	Primary and secondary[a]
	24-hour average	0.15	Primary and secondary
PM 2.5 (proposed)—diameter <2.5 micrometers	Annual arithmetic mean	0.015	Primary and secondary
	24-hour average	0.065	Primary and secondary

[a]Primary standards are intended to protect public health in general, including sensitive populations such as children, the elderly, and asthmatics. Secondary standards are intended to protect the public welfare, including protection of animals, vegetation, buildings, etc.

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The mean annual particulate matter (PM) 10 standard (for coarse respirable particles less than 10 microns in diameter) is the same as the International Space Station standard for total particulate concentrations. The lower PM 2.5 standard (for fine respirable particles less than 2.5 microns in diameter) is not currently being enforced by EPA. Although the distribution of Martian dust particle sizes has not been fully characterized, the mean particle diameter of 3.4 microns suggests that a significant fraction of the dust will fall in the coarse respirable PM 10 size category. It is noteworthy that the NAAQS for particulate concentrations are designated to serve as both primary and secondary health standards. Primary standards are intended to protect public health in general, including sensitive populations such as children, the elderly, and asthmatics. Secondary standards are intended to protect the public welfare, including protection of animals, vegetation, buildings, etc. The NAAQS also consider long-term exposure to the hazards. Thus, because the specifications are set to protect sensitive populations over long periods of exposure, NAAQS are conservative for healthy astronauts. It would not be unreasonable for NASA to adopt higher concentration standards for human missions to Mars with durations of 2 years or less.

NASA's Advanced Environmental Monitoring and Control Program has recognized the need for general particulate monitoring in space habitats, recommending that respirable particles less than 10 microns in diameter be quantified in the range 0.01 to 10 mg/m^3 (NASA, 1996). This measurement range is well suited for monitoring particulates at the concentrations the committee has determined are necessary to protect astronauts from exposure to toxic elements. If NASA chooses to limit respirable particulate concentrations to below 1 mg/m^3, the cancer risk from toxic elements will also be reduced, since the relationship between the risk of getting cancer and the allowable concentration of airborne particulate matter is taken to be linear. This means that if NASA allows 10 mg/m^3 of particulate matter in the habitat, the risk range of getting cancer will increase tenfold. On the other hand, if the concentration of particulate matter is one order of magnitude lower, that is, 0.1 mg/m^3, the protection to the astronauts increases by one order of magnitude.

Biological Degradation and Equipment Corrosion

There are high concentrations of sulfur and chlorine in Martian soil (Clark et al., 1982; Wanke et al., 2001). This implies that both the soil and airborne dust might be acidic, which could pose a hazard if they were introduced into an astronaut habitat. When inhaled by astronauts, acidic soil and dust could degrade their lung tissue and, if humidified and allowed to penetrate control units inside the habitat, could corrode sensitive critical equipment, such as control circuits. Even with the filtration systems discussed above, the filtration level may not be stringent enough to protect astronaut health and critical mechanical equipment from dust and soil that are extremely acidic.

On the other hand, strong oxidants detected in Martian soil by the Viking biology experiment would be inactivated by humidification inside the astronaut habitat. It is therefore essential that NASA implement proper humidification in conjunction with the filtration system as part of habitat atmosphere conditioning. The committee concluded that even if strong oxidants are present, if the dust level is maintained at 1 mg/m^3 or less and appropriate humidification systems are in place, there will be negligible risk associated with oxidation on the Martian surface.[1]

The Need for Measurements

The committee recommends that NASA measure the pH and buffer capacity of Martian soil and airborne dust so that mission planners may better understand the potential corrosive effects of the soil and airborne dust on astronauts and critical systems inside the habitat. This measurement could be made on the surface of Mars or from a sample of soil and airborne dust collected from the Martian atmosphere and returned to Earth.

Recommendation: In order to evaluate the potential corrosive effects of Martian soil and airborne dust on humans and critical systems in a humidified environment, NASA should measure the pH and buffer capacity of soil and airborne dust either via an in situ experiment or on Earth with returned samples of soil and airborne dust collected from the Martian atmosphere.

[1]It should be noted that the Viking results were unexpected at the time, and the full nature of the oxidants has not been determined by follow-up experiments.

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As stated above, the committee determined that oxidizing agents in soil and airborne dust do not pose a health hazard to astronauts if proper filtration and humidification levels are maintained. However, if NASA decides not to implement the necessary engineering controls or for other science-related reasons chooses to measure the oxidation properties of Martian airborne dust and soil, then the measurement should be performed on the surface of Mars rather than via a sample return. The committee is concerned that the oxidants might dissipate during a sample return transfer unless the sample is maintained in near-Martian conditions during transit. If NASA chooses to measure the oxidizing characteristics of the Martian environment, the committee recommends exposing a variety of materials, such as space suit material, to the Martian atmosphere and observing the effects of oxidants on the materials by optical or other measurement techniques.

Hazardous Organic Compounds

Organic carbon "includes all compounds of carbon, including straight chain, closed ring and combinations, except such binary compounds as the carbon oxides, carbides, carbon disulfide, etc." (Lewis, 1997). Organic compounds are the proverbial building blocks of life. However, their presence does not necessarily indicate that life is or ever was present. Certain organic compounds can be highly toxic to humans, even if those compounds are not associated with a life-form. This threat should be evaluated in planning the first human mission to Mars.

Organic compounds on Mars, if present, could have come from several sources, including meteorite impact, photochemical synthesis, and Martian biologic activity. At the two Viking landing sites, it was determined that within the limits of the gas chromatography-mass spectrometer experiment, the Martian soil contained no organic compounds to a detection limit of 1 ppb (Biemann et al., 1977). Experimental conditions restricted detection to organic compounds that could be volatilized and/or pyrolyzed (i.e., released from the soil) at up to 500 degrees Celsius. While this constraint precluded the direct detection of living organisms and very high molecular weight materials such as some polymers, the temperature was high enough to volatilize all known organic compounds within the mass detection range of the mass spectrometer (12 to 215 atomic mass units). The temperature was also sufficient to pyrolyze many larger organic compounds into smaller products detectable by the mass spectrometer. Overall, the gas chromatography-mass spectrometer results strongly indicate the absence of appreciable quantities of organic carbon on the Martian surface.

This lack of detectable quantities of organic carbon is most likely a result of the abundance of a strong oxidizing agent on the surface that is produced by ultraviolet radiation from the Sun. Any hazard would most likely come from handling subsurface samples that might contain organic compounds. SNC meteorite samples indicate that there may be very small amounts (in the parts per billion range) of organic compounds in the subsurface, which would not represent a hazard. The committee also believes that there will not be any threat from organic compounds in the airborne dust, because oxidants in the atmosphere would have broken down those compounds.

The Need for Measurements

The committee concludes that if organic carbon is not detected in Martian soil, there is no hazard from organic compounds. If organic carbon is present, it may present a hazard to the astronauts through one of two mechanisms: toxicity or infection from a life-form. The former is discussed in this chapter, while the latter is deferred to the discussion of biohazards in Chapter 5.

From a review of the EPA IRIS database, the committee found that organic chemicals pose a risk similar to that posed by toxic metals at the same concentration. Therefore, the committee concludes that if organic carbon is present at a concentration of more than 150 ppm in soil to which astronauts might be exposed, a possible threat exists. Filtration systems that reduce astronaut exposure to organic carbon to concentrations less than 150 ppm would mitigate this threat.

If experiments determine that organic carbon is present in concentrations greater than 150 ppm, the subsurface soil should be considered a toxic hazard until proven otherwise. NASA must then determine which compounds constitute the organic carbon by returning a sample from that specific location to Earth. The reader will learn in Chapter 5 that the need to assess the potential threat posed by a hazardous life-form consisting of organic carbon requires a more stringent measurement of organic carbon concentration. For this reason, the committee's recommendation on the measurement of organic carbon on Mars is deferred to Chapter 5.

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TOXICITY OF MARTIAN ATMOSPHERIC GASES

Based on previous in situ measurements, the Martian atmosphere has been determined to be composed predominantly of carbon dioxide (95 percent), with nitrogen, argon, and oxygen (all nontoxic) present in abundances greater than 0.1 percent (Owen, 1992). There is a small amount of toxic carbon monoxide (0.07 percent), as well as traces of ozone up to 0.2 ppm. Scientists have used ultraviolet and infrared remote sensing techniques to search for a variety of candidate trace gases in the Martian atmosphere. No organic molecules or toxic gases, such as those containing N, S, P, or Cl, have been detected down to limits of 0.01 ppm (Owen, 1992). Even if a habitat were vented completely to the Martian atmospheric pressure of 0.6 kPa (6 mbar) and then refilled with the habitat's breathable mixture at 100 kPa (1 bar), the dilution factor would be over 160. In this scenario, the astronauts would be exposed to less than 0.6 percent carbon dioxide, 4 ppm of carbon monoxide, and 1 ppb ozone by volume. All of these amounts are well below the current NASA standard for these toxic gases. In addition, the atmospheric revitalization systems on spacecraft include systems for removing carbon dioxide and contaminants. The committee expects that the same capabilities would be provided in a human habitat on Mars. In addition, any highly reactive species, such as hydroxide radicals or other highly oxidizing species, created by photochemical processes in the Martian atmosphere by ultraviolet radiation would quickly evolve to less-hazardous chemical forms upon coming into contact with habitat airlock surfaces. Thus, sufficient knowledge is already available to ascertain that the Martian atmosphere does not pose a toxic risk for astronauts, and no further characterization is required. Long-term oxidizing effects on materials continuously exposed externally is a separate problem, as discussed earlier in this chapter.

If NASA chooses to measure the oxidation properties of the Martian atmosphere, the committee recommends—as it did with respect to measuring the oxidation properties of soil and airborne dust—that this measurement be done on the surface of Mars rather than via a sample return. The committee has the same concerns—that is, that the oxidants might dissipate during a sample return transfer unless the sample is maintained in near-Martian conditions during transit. If NASA chooses to measure the oxidation characteristics on Mars, the committee recommends exposing a variety of materials, such as space suit material, to the Martian atmosphere and to assess the effects of superoxidants or other radicals on the materials.

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5

Potential Hazards of the Biological Environment

The committee was charged with addressing issues of biological risks on Mars from two perspectives: (1) ensuring the safety of astronauts operating on the surface of Mars and (2) ensuring the safety of Earth's biosphere with respect to potential back-contamination by a Martian organism from returning human missions.

The probability that life-forms[1] exist on the surface of Mars (that is, the area exposed to ultraviolet radiation and its photochemical products) is very small. However, as a previous NRC study (NRC, 1997) notes, there is a *possibility* that such life-forms exist there "in the occasional oasis," most likely where liquid water is present, and, furthermore, that "uncertainties with regard to the possibility of extant Martian life can be reduced through a program of research and exploration."

This charge to the committee results in a dilemma. How can NASA use human ingenuity and creativity on Mars to search for life when that life (if it exists) may pose a threat to astronaut health and safety (and therefore to the success of a human mission) as well as to Earth's biosphere?

ENSURING THE SAFETY OF ASTRONAUTS

The committee believes that it is highly unlikely that infectious organisms are present on Mars. The same NRC study (NRC, 1997) that focuses on the possibility that Martian organisms could be agents of infectious disease also states on page 21 as follows: "The chances that invasive properties would have evolved in putative Martian microbes in the absence of evolutionary selection pressure for such properties is vanishingly small. Subcellular disease agents, such as viruses and prions, are biologically part of their host organisms, and an extraterrestrial source of such agents is extremely unlikely." The uncertainty surrounding whether or not life exists on Mars may not be resolved until after astronauts arrive on the planet (NRC, 1997).[2] Of course, if life does exist on Mars, it could represent a biological hazard to astronauts.

[1]Discrete entities that can actively utilize the energy and matter of their environment, react to a stimulus, and modify and propagate themselves.

[2]Some argue that since no life-form, or no conclusive evidence of hazardous life, was identified in meteorites from Mars found on Earth, there is no biohazard threat from Mars. These SNC meteorites are, after all, handled without special precautions in the laboratory. The committee referenced the analysis of the SNC meteorites in Chapter 4 in the discussion of toxic metals on Mars. The use of SNC meteorite data is not appropriate to this argument regarding biohazards on Mars.

Extensive exposure to cosmic rays during a meteorite's travels in interplanetary space, during which the meteorite was exposed to sterilizing doses of radiation, would probably have destroyed any life contained in it (Clark, 2001).

Furthermore, the rocks at the Pathfinder landing site and the soils at all Mars landing sites have quite different compositions from these meteorites. Therefore, the known Martian meteorites are not necessarily representative of all materials on the surface of Mars.

Finally, it must be acknowledged that there have been biological upheavals through the course of paleontological history here on Earth, including millions of species extinctions, with few explanations of cause. It is impossible to determine the cause of these upheavals with absolute certainty, be they physical (meteorite impact) or biological (life introduced onto Earth). While the possibility that life was introduced on Earth from elsewhere is unlikely,

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Martian biological contamination may occur if astronauts breathe contaminated dust or if they contact material that is introduced into their habitat. If an astronaut becomes contaminated or infected, it is conceivable that he or she could transmit Martian biological entities or even disease to fellow astronauts, or introduce such entities into the biosphere upon returning to Earth. A contaminated vehicle or item of equipment returned to Earth could also be a source of contamination.

If an astronaut were infected by a Martian life-form, the infection could potentially be observed and treated, or at least evaluated, before the astronaut lands back on Earth. However, once an astronaut has been directly exposed to such life, it would be very difficult, to the point of being impractical, to determine conclusively that the astronaut would *not* pose a contamination threat to Earth's biosphere. In such an event, NASA might be faced with requiring quarantine and surveillance of returning astronauts until it is determined that a threat no longer exists.

To the degree that NASA has confidence that the life-support systems and habitats can isolate astronauts from hazardous materials, it can more aggressively place those habitats into an environment of unknown constituency. In the extreme, if 100 percent protection were assured by such isolation systems, NASA could send astronauts to an area with known biologic hazards. If 100 percent protection against exposure from the unknown cannot be assured, the hazard must be mitigated by gaining confidence that the environment on Mars poses an acceptable risk.

ENSURING THE SAFETY OF EARTH'S BIOSPHERE

While the threat to Earth's ecosystem from the release of Martian biological agents is very low, "the risk of potentially harmful effects is not zero" and cannot be ignored (NRC, 1997). In light of experience gained during Apollo missions to the Moon, a previous NRC report (NRC, 1993) concludes, "It would, however, be virtually impossible to avoid forward-contamination of Mars or back-contamination of Earth from human exploration." This committee understands that the threat from back-contamination cannot be eliminated with all certainty, but it is confident that if NASA takes the steps outlined in this report, the threat from back-contamination will be minimized.

NASA should assume that if life exists on Mars, it could be hazardous to Earth's biosphere until proven otherwise (NRC, 1997). As such, NASA should ensure proper quarantine or decontamination of equipment that may have been exposed to a Martian life-form.

The Need for Measurements

For the purposes of identifying precursor missions that must take place prior to human exploration of Mars, the committee did not address the general question of how to detect life on Mars at every location. For instance, it does not matter from the standpoint of human safety or Earth ecosystem protection if life exists on Mars in places inaccessible to astronauts, such as in nonfriable layers of rock or in some deep subterranean cavern. It does matter, however, if life exists in any material that the astronauts or their spacecraft and equipment might contact, such as Martian airborne dust and surface or near-surface regolith. With these considerations in mind, the committee recommends that NASA employ the concept of zones of minimal biologic risk (ZMBRs) for astronaut exploration. These zones, operational areas on the surface of Mars, would have been predetermined, to the maximum extent practicable, to be devoid of life or to contain only life-forms that would not be hazardous to humans or Earth's biosphere.

Establishing Zones of Minimal Biologic Risk (ZMBRs)

To protect Earth from contamination by Martian life-forms aboard a returning human mission and astronauts while on the surface of Mars, NASA should first attempt to determine whether life exists (1) at the physical locations where astronauts will be operating and (2) in the Martian material to which astronauts will be exposed.

The establishment of a ZMBR might initially be based on an in situ testing protocol, to be discussed shortly, conducted prior to a human visit. Once a land-

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the uncertainty makes it impossible to prove that meteorites from another planet have never had an effect on Earth's biosphere (NRC, 1997). These considerations, and the consideration that a goal of future human missions will be to search for life-forms in Martian oases, if those oases exist, negate the argument that there is no biohazard threat from Mars based on the existence of sterile Martian meteorites.

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ing site is established as a ZMBR, the astronauts can land and freely operate within it.

The committee recognizes that the requirement to establish and operate in a ZMBR, while intrinsic to the study charter to manage risk to astronauts, may be in conflict with one of the primary goals of the exploration of Mars: to find extraterrestrial life.

As stated above, any and all indigenous materials from Mars must be considered as health hazards and ecohazards and be contained until proven otherwise. If life is discovered on Mars, the committee maintains that such life must be considered a risk to humans as well as Earth's ecosystem until proven otherwise.

A large variety of chemical and microscopy analytical techniques could be used for detecting extant life, including measurements of biomass, use of specific molecular probes, and/or detection of growth, metabolic activity, or the presence of enzymes. A survey on life detection techniques was carried out during an April 2000 workshop sponsored by the NRC but not related to this study (NRC, 2002c). The committee believes that a search for organic carbon might be the quickest way to establish that the landing site is a ZMBR. While some have suggested the possibility of non-carbon-based life on Mars, such as silicon-based life, this committee agrees with assumptions made by previous NRC committees that should hazardous life exist on Mars it would be carbon-based (NRC, 2002a, 2002b).

The committee recommends that NASA conduct a precursor in situ experiment to determine if organic carbon is present at a location as close as reasonably possible to the landing sites selected for human missions to Mars. The committee acknowledges that it will be difficult to land exactly at the location of the anticipated human landing sites. It is beyond the scope of this report to suggest the parameters that would be used in determining the radius of a ZMBR. However, it is conceivable that NASA can establish criteria so that the results of testing one surface material (such as near-surface regolith) can be assumed to apply to all like materials, in like geologic settings, in nearby regions on Mars.

For instance, an in situ test might determine that the uppermost 10 centimeters of regolith are free of any indications of life at one location on a large flat plain on the surface of Mars. NASA could then reasonably conclude that the entire plain is likely to be free of life and therefore a ZMBR. If, on the other hand, the plain is scattered with sizable rocks, the entire plain would not be designated as a ZMBR until tests were conducted in both the open regolith and under representative rocks. In that case, the uppermost few centimeters of regolith and the material sheltered under a rock are like materials (i.e., both are regolith) but are not in like geologic settings, as one portion of the regolith is exposed and the other portion sheltered.

It is generally believed that any life-form retrievable from the surface of Mars, especially any life-form that would be a threat to humans or Earth's ecosystem, would probably be bacterial in nature and size, and possibly similar to bacterial spores. It is highly unlikely that viruses hazardous to terrestrial organisms will be present on Mars since viruses are highly adapted pathogens that infect very specific host organisms and require those specific host organisms for replication and survival (NRC, 1997).

On Earth, certain bacteria form spores when stressed by depletion of critical growth factors such as water or other carbon/nitrogen (food) sources. Bacteria survive for long periods in the spore form until new growth opportunities are available. A typical bacterial spore is 1 to 2 microns in major dimension and is made up of about 1×10^{-12} grams of organic matter. The amount of organic material in ecosystems on Earth in nonliving form, such as foodstock or waste material, is many times greater than the amount of organic material contained in living organisms.

For purposes of illustration, making the generous assumption that there are at least 10 bacteria-size entities containing up to 1×10^{-12} grams of organic material each per gram of soil and that there is 10 times as much extraneous organic material, the concentration of organics in the soil for this life-detection threshold would still be only 0.1 ppb by weight. This is lower than the 1 ppb detection limit for organics possible with the gas chromatography-mass spectrometer instrument flown on the Viking mission (Biemann et al., 1977). The results of those tests were used by many scientists to infer that life could not be present. This life-detection threshold is controversial, however. This committee did not have the necessary expertise to critically evaluate the lower limit of organic carbon needed for life detection. It therefore urges NASA to set an operational value for the life-detection threshold limit through a separate advisory process drawing on a broad range of relevant expertise.

Such a limit should be supported by a rationale for specifying the least amount of carbon that could signify the possible existence of an organism or organism

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activity as discussed above. Certain classes of organic compounds in soil or other samples might be specified at different life-detection threshold levels. Amino acids, for example, would probably be considered more indicative of a possible life-form than highly refractory kerogen-like materials—that is, mixtures of complex organic polymers of high molecular weight similar to petroleum. The presence of excess optically active organic molecules could also be considered indicative of a life-form.

These analyses should be made on a sample or samples from the surface and down to a depth at which astronauts may be exposed. Unless measurement techniques or capabilities are advanced significantly beyond current capabilities, a sample return will probably be required to establish that the planned landing sites are in a ZMBR.

As a further example (and for discussion purposes only), if NASA's mission scenario uses rockets for landing, the exhaust from the rockets will eject the regolith to some depth, exposing subsurface material that the astronauts will be walking on during EVAs. Also, some of the ejected materials will most certainty contact the outside of the return spacecraft, potentially contaminating the vehicle surfaces with some life-form that might exist below the Martian surface. If such a landing scenario is planned, the precursor organic carbon measurement must take place down to the same depth as that from which materials will be ejected.

It is conceivable that NASA might generate a passive soft-landing capability that disturbs the regolith very little. If that is the case, then the precursor in situ organic carbon test needs to be conducted only on the Mars surface and near surface.

NASA will need to establish procedures for astronauts to expand the ZMBR. One such procedure might involve the use of an iterative robotic testing process on the surface and subsurface. In the process of expanding the zones, NASA should take appropriate caution to ensure that astronauts will not come into personal contact with surface and subsurface soil samples before the soil has been fully characterized with regard to the possible presence of Martian life-forms.

Some of the tests used during this pre-excursion process may be fairly straightforward and may only require that the robots determine if organic carbon is present. However, more complex experiments may require human interaction—for example, robots might bring samples back to the habitat laboratory for more critical examination by humans. Astronauts might then use chemistry, microscopy, and biological challenge (interaction with animals, plants, and/or cell cultures) in the testing process to determine if a life-form exists and if that life-form is potentially hazardous to humans or to Earth's biosphere.

A life-detection experimental laboratory in the habitat will be a complex and critical component of Mars exploration, since it must in effect isolate the astronauts from all test materials, using appropriate biological containment techniques (Richmond and McKinney, 1999). The committee suggests that NASA plan for the development, deployment, and design of a facility for conducting life-detection tests when the astronauts land on Mars should the astronauts plan to explore new areas that have the potential to harbor life. Such a life-detection facility would be important since the precursor missions, including in situ and sample return missions, will not conclusively prove that life does not exist somewhere in an oasis on the Martian surface or subsurface. Alternatively, NASA could implement a set of safeguards to ensure that astronauts and return equipment are never directly exposed to new, uncharacterized materials during the entire mission.

Recommendation: The committee recommends that NASA establish zones of minimal biologic risk (ZMBRs) with respect to the possible presence of Martian life during human missions to Mars. In order to do so, NASA should conduct a precursor in situ experiment at a location as reasonably close to the human mission landing sites as possible to determine if organic carbon is present. The measurement should be on materials from the surface and down to a depth to which astronauts may be exposed. If no organic carbon is detected at or above the life-detection threshold, the landing site may be considered a ZMBR. If no measurement technique can be used to determine if organic carbon is present above the life-detection threshold, or if organic carbon is detected above that threshold, a contained sample should be returned to Earth for characterization prior to sending humans to Mars.

If No Organic Carbon Is Detected

If a precursor in situ organic carbon experiment can determine that no organic carbon is present above the life-detection threshold, the committee recommends that NASA judge the near surface on Mars at the landing site to be a ZMBR. Once this initial minimal risk

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zone is established, the human mission may land and operate on the surface in the region around the site of the precursor organic carbon test (with like materials, in like geologic settings) and return to Earth reasonably confident that there is no biological hazard that could harm human health or Earth's ecosystem. In this instance, no sample return is required prior to the first human visit, at least from the perspective of protecting astronauts or Earth's biosphere. It should be noted, however, that there are other scientific reasons for a sample return, as discussed in other NRC reports that call for a sample return (NRC, 2002a).

As stated above, there are currently no measurement techniques or capabilities available for such in situ testing. If such capabilities were to become available, one advantage is that the experiment would not be limited by the small amount of material that a Mars sample return mission would provide. What is more, with the use of rovers, an in situ experiment could be conducted over a wide range of locations.

Positive or Inconclusive Organic Carbon Measurement and Precursor Sample Return

If a precursor in situ organic carbon experiment indicates the presence of organic carbon on Mars above the life detection threshold, the committee recommends that a sample must be returned to Earth from the location and depth where the organic carbon is discovered if no suitable in situ life-form confirmation technologies are available, as is the case now. The returned sample should be considered hazardous, and NASA should follow the same quarantine procedures as outlined in previous NRC studies (NRC, 2002b). These quarantine procedures should be applied to all materials returned from Mars, both precursor samples and samples returned from human missions. However, NASA should also attempt to ensure that any possible life-form in the sample would survive the trip to Earth.

The location and depth of such a sample return would be dictated by NASA mission operations. If NASA determines that rocket exhaust on landing will uncover half a meter of Martian regolith and organic carbon is discovered to exist in material exposed at that depth, then a sample from that depth should be returned to Earth prior to human exploration of Mars.

If a precursor mission sample is returned to Earth subsequent to a positive organic carbon test result, the first priority should be to determine if the organic carbon constitutes a life-form. If the organic carbon is not a Martian life-form, then the location from which the sample was taken may be considered a ZMBR. On the other hand, if the organic carbon in a sample return does contain a life-form, there are varying levels of safety that can be established in the region from which the sample was taken, following a determination of whether such an organism is in fact a biohazard.

The findings and recommendations in this report are relevant to activities represented above the dotted line in Figure 5.1, a decision diagram offered by the committee as a preliminary guideline. If life is indeed discovered on Mars, the strategy for exploiting that discovery will certainly develop based upon the specific nature of the life identified. The open questions that remain below the dotted line can be answered by first testing the life-bearing sample for hazards to humans, such as infectivity, and then evaluating it for hazards to Earth's biosphere. The committee does believe that if a Martian life-form is proven to be harmless to humans and to Earth's biosphere, then the astronauts may operate in the presence of the life-form.

There has been some concern that if a sample return is required, the planning for the first human mission to Mars may be delayed until a sample can be obtained. The committee believes that, even should a sample be required because organic carbon has been found, a baseline plan for a mission to Mars and even hardware development may still proceed under the assumption that a sample return will not find anything significant enough with regard to Martian biology to invalidate the baseline mission plan.

Sample Return: Additional Benefits

The Viking lander experiments were criticized because life-detection tests gave presumably false positive experimental results in some cases and clearly unexpected results in other cases, apparently due to the complex chemistry of the Martian soil. A secondary, though not mandatory, benefit of a precursor sample return mission is that a returned sample would allow researchers to establish effective and reliable testing methods that would reduce the risk of false positive or false negative results. Soil chemical analyses conducted on returned samples would enable improved life-detection protocol testing. False positives or false negatives in testing for life on the surface of Mars could create serious problems for astronauts. For instance, if a test produces a false negative, that is, the test results indicate that Martian life is not present when it actually

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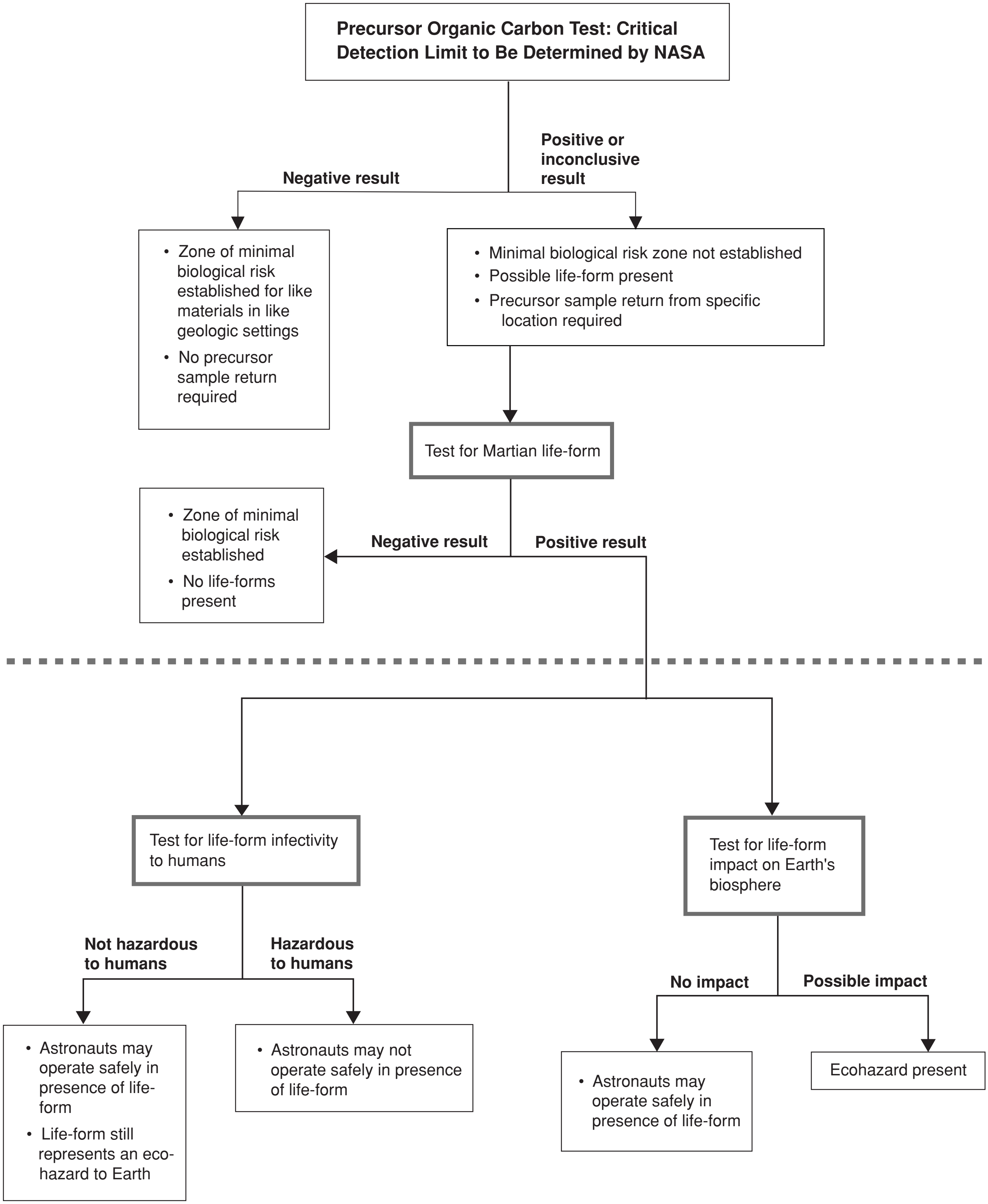

FIGURE 5.1 Mars biology testing protocol.

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is, NASA could improperly establish a ZMBR. In this case, the risk would indeed not be minimal, and astronauts could be exposed to hazardous Martian life-forms. If a false positive is returned, it may be believed that astronauts have been exposed to a Martian life-form when in reality no life-form is present.

RETURN VEHICLE CONTAMINATION

Great care must be exercised to ensure the containment of all material returned from Mars to Earth. All Martian material returned to Earth must be quarantined. There must be a sterile, intermediate transfer conducted in space that ensures that Earth's environment will not become exposed to any Martian material, including dust or soil deposits on the outside surface of the return vehicle. The protocols for such a sterile transfer will be complex and, if the transfer is unsuccessful, may require that the return vehicle be discarded in space and never returned to Earth. Ultimately, however, only contained materials should be transported back to Earth, unless sterilized first (NRC, 1997).

Other protocols may need to be established if, for unforeseen reasons, it is not possible to isolate the return vehicle. In that case, life-detection tests must be conducted within the near-surface Martian regolith that could adhere to the outside of the return vehicle when it lifts off from the Martian surface, unless precursor mission measurements (in situ or sample return) have shown that such material is not biologically hazardous.

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Appendixes

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Appendix A

Statement of Task

The principal objective of the study will be to examine the role of robotic Mars exploration missions in assessing the risks to human exploration of Mars due to possible environmental, chemical, and biological agents on the planet. The fundamental question for the study will be to review the environmental, chemical, and biological risks to humans operating on Mars and to consider how the Mars robotic program can provide answers to mitigate those risks prior to a human mission. In the course of the study, the committee will review:

1. Prior studies by the NRC[1] and others regarding the goals, objectives, and requirements of NASA's Mars exploration activities, both human and robotic;
2. Requirements identified by the NASA Human Exploration and Development of Space Enterprise to be levied on the robotic exploration program;
3. Plans of the robotic Mars exploration program in the context of how it can support preparations for eventual human exploration missions; and
4. NASA plans and requirements for validation of critical technologies in the actual Martian environment prior to committing to a program of human exploration. The review of critical technology validation will emphasize those technological issues that are directly relevant to managing environmental, chemical, and biological risks to humans operating on Mars.

Among the questions that the committee should consider in conducting its review are the following:

- How well are the environmental, chemical, and biological risks to humans on Mars characterized and understood?
- What additional measurements or data from Mars are necessary to properly characterize the risks?
- Are there technologies which must be demonstrated in the Mars environment in order to ensure that environmental, chemical, and biological risks can be managed on a human mission to Mars?
- Must samples from Mars be returned to Earth prior to sending a human mission for any reason, including:
    1. Gaining sufficient confidence in understanding chemical and biological risks to humans on Mars, or
    2. Ensuring the safety of the Earth's biosphere with respect to potential back-contamination from a returning human mission?

[1]Relevant NRC reports:

Microgravity Research in Support of Human Exploration and Development of Space and Planetary Bodies, Space Studies Board (SSB), 2000.

Certification and Curation of Martian Samples, SSB, in review.

Signs of Life: A Report Based on the April 2000 Workshop on Life-Detection Techniques, SSB and Board on Life Sciences, in preparation.

Assessment of the Strategy for Mars Exploration, SSB, in preparation.

Space Technology for the New Century, Aeronautics and Space Engineering Board (ASEB), 1998.

Advanced Technology for Human Support in Space, ASEB, 1997.

Mars Sample Return: Issues and Recommendations, SSB, 1997.

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Appendix B

Biographical Sketches of Committee Members

FREDERICK H. HAUCK (*Chair*) is a member of the Aeronautics and Space Engineering Board and is president and chief executive officer of AXA Space, a company that specializes in providing insurance for launching and operating space systems. Before coming to AXA Space, Mr. Hauck was director of the Navy Space Systems Division in the Office of the Chief of Naval Operations. Before that, he was a test pilot and a member of the astronaut corps. As an astronaut, he flew in space three times and was commander of the first shuttle flight after the Challenger accident. He has been a member or chair of numerous panels and advisory groups on national and international space activities. He holds degrees in physics and nuclear engineering from Tufts University and the Massachusetts Institute of Technology. Mr. Hauck is a fellow in both the Society of Experimental Test Pilots and the American Institute of Aeronautics and Astronautics, and is a national associate of the National Academies.

HARRY Y. McSWEEN (*Vice Chair*) is a professor and former head of the Department of Geological Sciences and Distinguished Professor of Science at the University of Tennessee. He holds degrees from the Citadel, the University of Georgia, and Harvard University (Ph.D.) and has been a member of the University of Tennessee faculty for 23 years. He recently was president of the Meteoritical Society and chair of the Planetary Division of the Geological Society of America and has served on numerous advisory committees for NASA, including the Mars Pathfinder and Mars Global Surveyor spacecraft. Dr. McSween has served as a committee member on the NRC Committee on Planetary and Lunar Exploration from 1995 to 1998 and the Committee on Human Exploration from 1998 to 2000.

CYNTHIA BREAZEAL specializes in robotics and artificial intelligence with an emphasis on human-robotic interaction. Her past work has included behavior-based control for autonomous planetary microrovers, rough terrain locomotion, and fault-tolerant behavior. Dr. Breazeal is currently a professor at the MIT Media Lab. She has published extensively in books, magazines, and journals on a wide range of topics, including autonomous robots, planetary microrovers, legged locomotion, fault-tolerant behavior, visual attention, affective speech recognition, humanoid robotics, computational models of emotion and motivation, expressive speech synthesis, facial animation, behavior arbitration, social interaction between humans and robots, and learning. She has coauthored a graduate text on embodied intelligence and has authored another book, *Designing Sociable Robots,* from MIT Press. Her work has appeared extensively in the popular press, including *Business Week*, *Time*, *U.S. News and World Report*, *Scientific American*, *Wired*, the *New York Times*, and the *Washington Post* and on NBC's *Nightly News* and NPR's *Morning Edition*, as well as in various international publications.

BENTON C. CLARK is chief scientist for flight systems, Lockheed Martin Astronautics (LMA) in Denver, and has over 40 years experience in future mission design, spacecraft design and operations, space science, and development of advanced space instrumentation. He is director of the Advanced Planetary

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Studies group, where flight designs for Discovery and Mars missions are conceived and developed. Dr. Clark has over 55 publications and 90 reports, abstracts and presentations in instrumentation, planetary missions, radiation, space science, planetary geochemistry, exobiology, and other fields of research and development. Dr. Clark has a B.S. in physics from the University of Oklahoma, an M.A. in physics from the University of California, and a Ph.D. in biophysics from Columbia University.

VON R. ESHLEMAN (NAE) is a professor emeritus at Stanford University. His main publications relate to electromagnetic remote sensing, with particular emphasis on spacecraft radio and radar systems. Dr. Eshleman has authored or coauthored approximately 175 publications. He has been a team leader or member for many NASA exploration spacecraft, including Mariner, Pioneer, Viking, Voyager, and Galileo. The missions were designed to study planetary atmospheres, ionospheres, magnetospheres, surfaces, rings, and moons of the solar system. He was also a member of the advisory board for NASA's lunar and planetary missions. Dr. Eshleman received several distinguished alumni awards from George Washington University and Stanford, as well as several NASA medals for exceptional scientific achievement as a result of his work on the atmosphere of Mars in 1965 and the atmospheres of Jupiter, Saturn, and Titan in 1981. He is also a founding member of the Planetary Society.

JOHN HAAS is group leader for the New Technologies Group in Applied Research Associates' New England Division, located in South Royalton, Vermont. Dr. Haas is currently working on the development of sensors and analytical methodologies for process, environmental, biotechnical, and geotechnical monitoring applications, including planetary exploration. Dr. Haas received his Ph.D. in analytical chemistry from the University of Massachusetts and has been principal investigator on nearly two dozen research programs in the areas of field analytical chemistry instrumentation, detection of chemicals of concern to human health, sensor development, geochemistry/geophysics, in situ sampling and measurement techniques, remote fiber-optic sensing, laser spectroscopy, and miniature devices. Among his achievements are the invention of various Raman, fluorescence, absorbance, and refractive index fiber-optic probes, a miniature fluorescence sensor, and a unique Raman spectrograph. Dr. Haas has also developed an array of small chemical, radiation, and geophysical sensors and samplers for use in the cone penetrometer, a subsurface geophysical and geochemical characterization tool. Several of his current research projects are directed at the detection of hazardous chemicals, including biological endotoxins, metallocyanides, perchlorate, and radionuclides.

JON B. REID is a professor at the University of Cincinnati Medical College's Department of Environmental Health. Dr. Reid has over 20 years of experience in toxicology and human health risk. He also works for the National Council on Aging and is assigned to the Environmental Protection Agency's National Center for Environmental Assessment, where his work includes preparation of a methodology for developing a comprehensive pathogen risk assessment procedure. His other consulting activities include research in exposure and risk from chemicals in the environment and the workplace.

JONATHAN RICHMOND is the director of the Office of Health and Safety at the Centers for Disease Control and Prevention in Atlanta, Georgia, and is an international authority on biosafety and laboratory containment design. Dr. Richmond was trained as a geneticist, worked for 10 years as a research virologist, and has been involved in the field of biosafety for the past 25 years. He has authored many scientific publications in microbiology, chaired many national symposia, edited numerous books, and is an international consultant to ministries of health on laboratory safety and training. He also serves as a director of a World Health Organization collaborating center on applied biosafety.

RONALD E. TURNER is a principal scientist at ANSER Corporation. Dr. Turner has extensive experience in radiation effects on humans in space; specifically, he has more than 20 years of experience in space systems analysis, space physics, orbital mechanics, remote sensing, and nuclear and particle physics. His recent research has included risk management strategies for solar particle events during human missions to the Moon or Mars. He has been an invited participant at NASA workshops looking at space radiation/biology missions, life science mission requirements for Mars 2001 and 2003, and the impact of solar particle events on the design of human missions.

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WILLIAM "RED" L. WHITTAKER is the Fredkin Professor of Robotics at the Robotics Institute of Carnegie Mellon University. He is the director of Carnegie Mellon's Field Robotics Center, which he founded in 1986, and cofounder and chief scientist of RedZone Robotics. His research centers on walkers for planetary exploration, mobile robots in unpredictable field environments such as work sites and natural terrain; computer architectures to control mobile robots; modeling and planning for nonrepetitive tasks; complex problems of objective sensing in random or dynamic environments; and integration of complete robot systems. Projects under Dr. Whittaker's direction include unmanned robots to explore planetary surfaces and volcano interiors, automation of mining machines and farm equipment, remote work systems for nuclear facility decommissioning, mobile robots for hazardous waste site investigation, and autonomous land vehicle navigation.

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Appendix C

Acronyms and Abbreviations

APXS	alpha-proton-x-ray spectrometer (experiment on Mars Pathfinder)
ARR	acceptable risk range (for toxic metals)
COT	Committee on Toxicology (NRC)
EPA	Environmental Protection Agency
EVA	extravehicular activity
GCR	galactic cosmic radiation
IRIS	Integrated Risk Information System (EPA)
ISRU	in situ resource utilization
JPL	Jet Propulsion Laboratory (NASA)
MEPAG	Mars Exploration Program/Payload Analysis Group
NAAQS	National Ambient Air Quality Standard (EPA)
NASA	National Aeronautics and Space Administration
NIOSH	National Institute for Occupational Safety and Health
NRC	National Research Council
OSHA	Occupational Safety and Health Administration
PM	particulate matter
ppb	parts per billion
ppm	parts per million
RfC	reference concentration
SMAC	spacecraft maximum allowable concentration
SNC	from Mars having landed on Earth (with reference to a meteorite)
SPE	solar particle event
ZMBR	zone of minimal biologic risk

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