Managing Space Radiation Risk in the New Era of Space Exploration

Committee on the Evaluation of Radiation Shielding for Space Exploration, National Research Council

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Managing Space Radiation Risk in the New Era of Space Exploration

Committee on the Evaluation of Radiation Shielding for Space Exploration

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
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Preface

The risks faced by human explorers will increase significantly as humans expand the exploration realm beyond low Earth orbit to revisit the Moon and venture on to Mars. In addition to the normal risks of mechanical, electrical, and human failure, exposure to the space radiation environment outside the protective magnetic field of Earth presents a risk with which humans have limited practical experience.

My introduction to space radiation came firsthand as a crew member aboard the space shuttle Challenger in April 1984. "What the heck was that?" I blurted out after seeing what looked like a white laser passing quickly through my eyes. "Oh, that's just cosmic rays," said Pinky Nelson, my spacewalking partner and a space physicist. The thought of extremely high energy particles originating from a distant cosmic event passing easily through the space shuttle and subsequently through my head made me think that this could not be all that healthful. The truth of the matter is that it is not.

Other than the short lunar missions of the Apollo program, astronauts and cosmonauts have flown in the relative safety of low Earth orbits, protected by Earth's local presence. NASA is now, however, planning to return to the Moon, establish permanent bases, and gain the experience needed for longer missions to Mars. At the request of NASA's Exploration Systems Mission Directorate, the National Research Council (NRC) assembled the Committee on the Evaluation of Radiation Shielding for Space Exploration to further understanding of the risks of radiation to crews of lunar and martian missions and of how best to protect those crews, and to recommend areas for future technology investments. The statement of task for the committee is given in Appendix A. Based on NASA's current progress in mission planning, this report focuses on exploration of the Moon and touches only on general aspects of Mars exploration. The report covers current knowledge of the radiation environment; the effects of radiation on biological systems, electronic systems, and missions; current plans for radiation protection; and a strategy for mitigating the risks to astronauts. The committee members ranged from space scientists to biologists to architects. Brief biographical sketches appear in Appendix B.

The committee met four times from late 2006 through mid-2007 (see Appendix C for committee meeting agendas and a full list of speakers). During the first three meetings, NASA and the contractor community briefed the committee on the most recent plans for the Constellation program, including the design basis in relation to the galactic cosmic ray and solar particle event environment, current shielding plans, and the latest thinking on the biological impacts of such an environment. This report summarizes the committee's findings on the state of

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the program and presents recommendations on a strategy for mitigating the radiation risks and where to invest to improve technological understanding of the radiation issue. Since the designs for the actual vehicles are in a state of flux, the committee was forced to base its assessments on early designs and implore the community to continue to fund research to verify follow-on designs.

James van Hoften, *Chair*
Committee on the Evaluation of Radiation
Shielding for Space Exploration

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). 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:

Thomas Borak, Colorado State University,
Raymond Colladay, Lockheed Martin (retired),
Louis Lanzerotti, New Jersey Institute of Technology,
Noelle Metting, Department of Energy,
George Paulikas, Aerospace Corporation,
Jeffrey Schwartz, University of Washington,
Margaret Shea, Air Force Research Laboratory (retired), and
Mary Helen Sparks, White Sands Missile Range.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by William M. Beckner, National Council on Radiation Protection and Measurements (retired). Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

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Summary

Space exploration is a risky enterprise. Rockets launch astronauts at tremendous speeds into a harsh, unforgiving environment. Spacecraft must withstand the bitter cold of space and the blistering heat of reentry. The skin of these vehicles must be strong enough to keep the inside comfortably pressurized and tough enough to resist damage from micrometeoroids. Spacecraft meant for lunar or planetary landings must survive the jar of landing, tolerate dust, and be able to take off again. For astronauts, however, there is one danger in space that does not end when they step out of their spacecraft. The radiation that permeates space—unattenuated by Earth's atmosphere and magnetosphere—can damage or kill cells within astronauts' bodies, resulting in cancer or other health consequences years after a mission ends.

The National Aeronautics and Space Administration (NASA) recently embarked on Project Constellation to implement the Vision for Space Exploration—a program announced by President George W. Bush in 2004 with the goal of returning humans to the Moon and eventually transporting them to Mars.[1] To prepare adequately for the safety of these future space explorers, NASA's Exploration Systems Mission Directorate requested that the Aeronautics and Space Engineering Board of the National Research Council establish a committee to evaluate the radiation shielding requirements for lunar missions and to recommend a strategic plan for developing the radiation mitigation capabilities needed to enable the planned lunar mission architecture. Specifically, the Committee on the Evaluation of Radiation Shielding for Space Exploration was asked to do the following (see Appendix A):

1. Review current knowledge of radiation environments on the lunar and Mars surfaces, including radiation types, sources, levels, periodicities, and factors that enhance or mitigate levels. Critical knowledge gaps, if any, will be identified.
2. Assess and identify critical knowledge gaps in the current understanding of the level and type of radiation health risks posed to astronauts during various surface activities—ranging from habitation in the CEV to extended exploration sorties and longer stays in exploration outposts—expected for the lunar and martian environments.
3. Review current and projected radiation shielding approaches and capabilities, as well as other exposure mitigation strategies feasible in the lunar and Mars surface environments.
4. Recommend a comprehensive strategy for mitigating the radiation risks to astronauts during lunar surface missions to levels consistent with NASA's radiation exposure guidelines. The strategy will:
—Be consistent with NASA's current timeline for lunar sortie and outpost habitation plans,

[1]National Aeronautics and Space Administration, *The Vision for Space Exploration,* NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.

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—Recommend research to resolve critical knowledge gaps regarding the lunar radiation environment and risks,
—Recommend a research and technology investment strategy that enables development of the necessary shielding capabilities.

5. The study will provide recommendations on what technology investments (e.g., multifunctional materials, localized shielding, and in situ materials) NASA should be making in preparation for lunar missions, and recommend development timelines to ensure NASA has the appropriate level of shielding in place to meet the planned schedules.

The committee was also asked to consider the likely radiation mitigation needs of future Mars missions and to put emphasis on research and development alternatives that would enhance NASA's ability to eventually meet those future needs. The complete statement of task appears in Appendix A.

The term "shielding" in the charge to the committee reflects a central tradeoff that spacecraft designers and mission planners must take into account. On the one hand, increased mass is required to reduce exposure to radiation; on the other, costs limit the power and energy available for propulsion to put that mass into space and to operate it. At any accepted level of exposure to radiation, the requirement for additional mass may exceed the project costs; and at a given level of cost, exposure to radiation may exceed the acceptable level of risk. In the former case, the dollar, mass, and volume budgets soon come into conflict with the shielding requirements. In the latter case, practical, legal, moral, and political imperatives determine whether such levels of risk may be incurred. The committee agrees that current permissible exposure limits, as specified in NASA radiation protection standards, are appropriate. **The committee strongly recommends that the permissible exposure limits specified in current NASA radiation protection standards not be violated in order to meet engineering resources available at a particular level of funding.**

Although the concept of shielding might be taken to mean no more than the use of materials interposed between a source of radiation—in this case, the space environment—and the individuals who are to be protected, such a definition is exceedingly simplistic. Materials used as shielding serve no purpose except to provide their atomic and nuclear constituents as targets to interact with the incident radiation projectiles, and so either remove them from the radiation stream to which individuals are exposed or change the particles' characteristics—energy, charge, and mass—in ways that reduce their damaging effects.

Spacecraft, structures, and containers in space, and the equipment and instruments that they hold, are made of materials possessing certain mechanical, chemical, electrical, and thermodynamic properties. Whenever designers and engineers can substitute other, multifunctional materials that serve the same purpose equally well but have nuclear and atomic characteristics better suited to attenuating radiation, a gain in shielding results. Similarly, a redistribution of equipment and components may be quite effective in reducing astronauts' exposure to radiation. A well-known example is the modification of the aspect ratio of a structure to reduce the solid angle subtended by the parts with lowest mass. Similarly, concentrating mass around areas where crew members spend much of their time, such as sleeping quarters, can enable the temporal design of a volume more highly shielded from radiation.

The effectiveness of shielding is extremely sensitive to an understanding of the biological mechanisms by which radiation affects human health and performance. At present, such understanding is very incomplete, leading to wide safety margins that dictate substantial shielding requirements and missions of limited duration. Furthermore, the effectiveness of properties of materials in reducing risk depends on the genetics, age, and gender of the exposed individuals and also varies for different components of space radiation. For these and similar reasons, the committee understood its task to extend beyond a focus on the addition and distribution of material, and to require instead a comprehensive consideration of all aspects of protection against radiation in space. The presentations made to the committee corroborated this understanding. Thus, this report addresses issues related to the composition and time-dependence of the space radiation environment, to nuclear propulsion and power, and to physical and biological interactions of radiation with matter, as well as to operational and construction-related aspects of space exploration. **The committee finds that lack of knowledge about the biological effects of and responses to space radiation is the single most important factor limiting the prediction of radiation risk associated with human space exploration.**

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At the present time, and assuming chemical propulsion, the permissible exposure levels would not allow a human crew to undertake a Mars mission and might also seriously limit long-term Moon activity. However, revolutionary progress in the biological sciences in recent years and ongoing breakthroughs could, if continued, substantially reduce the inherent uncertainties in and thus better quantify the risks for humans exposed to radiation in space.

NASA's current Space Radiation Biology Research program attempts to balance mission-oriented research with basic research and to leverage related research at other agencies, nationally and internationally. Such a program is possible only because the NASA Space Radiation Laboratory (NSRL), an essential facility that is unique in the world, can provide beams of particles of energies and charges found in space radiation for use in ground-based experiments in areas that could not be adequately investigated in space. Located within the Brookhaven National Laboratory (BNL), the NSRL is dependent on the existence of the Department of Energy's (DOE's) nuclear and high-energy research program. Accelerators can be and have been closed when the frontier of science moved elsewhere. If DOE determines that the research topics requiring BNL accelerators are no longer a priority, these accelerators will be shut down or reconfigured. It is impossible to predict if or when that might occur; however, a prudent strategy for NASA would be to assume that the BNL accelerators will not be available 15 to 20 years from now, and to plan accordingly. **The committee strongly recommends that NASA's Space Radiation Biology Research program be adequately funded. NASA should perform research at the NASA Space Radiation Laboratory aggressively to take advantage of the existing window of opportunity while this facility is still available. The results of the biological research will thus be able to have an impact on the Project Constellation missions in the short term, as well as provide knowledge essential for the management of space radiation risk in the long term.**

RADIATION ENVIRONMENT

Data from many satellites have enabled the characterization of galactic cosmic radiation (GCR) and solar particle events (SPEs) near Earth, and these results serve to characterize the radiation incident on the surface of the Moon. Knowledge of the secondary radiation, which is produced by galactic cosmic rays and SPEs interacting with material on the lunar surface, is currently based on data from the Apollo, Lunar Prospector, and Clementine missions, and on calculations. The radial extrapolation of the GCR environment from Earth to Mars is well understood, based on measurements made by numerous scientific satellites as they traveled outward through the solar system. To within a few percent or so, the GCR environment at the top of the martian atmosphere is expected to be the same as that near Earth. There are very few simultaneous measurements of SPEs at Earth and at Mars, and current models are inadequate to extrapolate near-Earth measurements of SPEs to Mars. Knowledge of the secondary radiation environment on the surface of Mars is currently based on calculations and measurements taken by spacecraft in Mars orbit.

Other sources of radiation relevant to Project Constellation include astronauts' short trips through Earth's trapped radiation belts, radiation generated by lunar- and martian-surface nuclear power systems, and eventually, perhaps, radiation generated by a spacecraft's nuclear propulsion and power system. On the surface of Mars and, to a lesser extent, on the surface of the Moon, there will be a component of backscattered radiation, mainly neutrons. On Mars, there will also be a component of secondary radiation engendered by interactions with the martian atmosphere.

GCR is a well-characterized background radiation whose level varies gradually over the 11-year solar cycle. SPEs are episodic emissions of high-intensity radiation from the Sun whose frequency also varies over the solar cycle. At solar maximum, there are a large number of SPEs and a relatively low level of GCR. At solar minimum, there are fewer SPEs but a higher level of GCR.

GCR is less intense than the radiation associated with an SPE, but it contains heavy, energetic particles that a reasonable amount of spacecraft shielding cannot completely stop. In fact, as these particles travel through the shielding, they may fragment into secondary radiation. Furthermore, GCR is a constant presence. The committee found that current knowledge of the free-space GCR component of the radiation environment is sufficient to

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support human missions to the Moon. However, human missions to Mars have not yet been sufficiently defined to make a judgment about the effects of the GCR environment on astronauts.

SPEs are very intense but occur over a relatively short period of time (hours to days). Because SPEs generally have energies much lower than those of GCR, their effects can be greatly mitigated with the proper amount of shielding. However, the timing of their occurrence is difficult to predict; an astronaut performing an extravehicular activity could receive an acute or fatal dose of radiation if shelter could not be reached in time.

The committee identified the following requirements to improve the understanding of SPEs:

- Determination of factors that drive SPE variability at energies relevant to astronaut safety;
- Understanding of solar conditions that give rise to large, fast coronal mass ejections;
- Validation of models of the interplanetary medium–solar wind and interplanetary magnetic field; and
- Use of a design-standard SPE in evaluating the adequacy of shielding.

RADIATION-RELATED RISKS

As stated above, the lack of knowledge about biological effects of space radiation is the single most important factor limiting the prediction of radiation-related risk associated with human space exploration. The understanding and interpretation of biological end points such as increased cancer risk and other biological effects are central to designing appropriate and cost-effective shielding. Unfortunately, NASA's space radiation biology research has been compromised by recent cuts in funding, particularly for research addressing noncancer effects.

The major knowledge gaps in radiation-related health risks are in the following areas:

- Carcinogenesis,
- Neurological damage,
- Degenerative tissue diseases,
- Acute radiation syndromes, and
- Immune-system responses.

In addition to health-related risks, radiation can pose additional risks. For example, astronauts may be unable to accomplish prime mission objectives if they are not permitted to leave an outpost because of a radiation storm. To be robust, a mission must include contingencies for emergencies, such as including excess consumables so that the crew can spend extra time on the Moon, if needed.

SHIELDING APPROACHES

NASA and Lockheed Martin presented the committee with an overview of the radiation protection work completed and in progress on Orion, the Project Constellation vehicle that will carry astronauts to the orbit of the Moon. The committee found that the methodology used—ray-tracing analysis combined with state-of-the-art radiation transport and dose prediction codes—is appropriate for estimating dose within the Orion vehicle and can help guide decisions about the amounts and types of spot or whole-body shielding that should be added to provide protection during solar particle events. As presented to the committee, the Orion Radiation Protection Plan appears to meet the minimum radiation protection requirements as specified in the NASA radiation protection standards. But any reduction in the requirements outlined in the Orion Radiation Protection Plan may pose potentially unacceptable health consequences. **The committee recommends that all elements of Project Constellation employ the radiation protection and risk management limits necessary to meet the NASA radiation protection standards presented to the committee.**

Other elements of Project Constellation are still in early concept-development phases, and no detailed radiation analysis or radiation protection design has yet been done. It is expected, however, that design efforts for the other elements will ensure the same level of radiation protection as those for Orion. Ultimately, all designs should meet the NASA radiation protection standards presented to the committee.

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NASA is considering the following radiation protection strategies for the human exploration of the Moon: the use of surface habitat and spacecraft structure and components, provisions for emergency radiation shelters, implementation of active and passive dosimetry, scheduling of extravehicular operation to avoid excessive radiation exposure, and proper consideration of the ALARA (As Low As Reasonably Achievable) principle. These strategies, if properly implemented, are adequate to meet the radiation protection requirements for short-term lunar missions. In addition to the above strategies, longer-duration lunar and Mars missions will require a reduction of the uncertainty in current predictions of radiological risk, plus the possible development of medical countermeasures.

TECHNOLOGY INVESTMENTS

To enable lunar missions with astronauts, the committee recommends the following technology investments, listed in priority order:

- **Radiation biology research.** NASA's Space Radiation Biology Research program should be adequately funded. NASA should perform research at the NASA Space Radiation Laboratory aggressively to take advantage of the existing window of opportunity while this facility is still available. The results of the biological research will thus be able to have an impact on the Project Constellation missions in the short term, as well as provide knowledge essential for the management of space radiation risk in the long term.
- **Testing transport code predictions.** The predictions derived from calculations of radiation transport need to be tested using a common code for laboratory and space measurements that have been validated with accelerator results, existing atmospheric measurements, and lunar and planetary surface measurements as they become available.
- **Research on solar particle events.** NASA should maintain a vigorous basic science program that can clarify the mechanisms that produce SPEs and lead to accurate, quantitative predictions of SPE behavior and identification of observables critical in forecasting SPEs or all-clear periods.
- **Empirical data for shielding design.** NASA should ensure that necessary experimental data in sufficient quantities are collected, analyzed, and managed in a manner appropriate for their use in designing radiation shielding into spacecraft, habitats, surface vehicles, and other components of human space exploration. The data should include information on energy and angular dependence of cross sections for production of nuclear interaction products, and on their multiplicities.
- **Forecasting of SPEs.** Forecasting and warning of SPEs will be an essential part of a comprehensive radiation mitigation strategy. Timely collection of appropriate data and communication of resulting forecasts and warnings will be mission-critical.
- **In situ monitoring and warning.** Warning and monitoring dosimetry, active and passive, is required wherever there is a human presence beyond low Earth orbit.
- **Multifunctional materials.** Where appropriate, replacement of traditional materials with multifunctional materials should be encouraged, with the goal of improving radiation shielding.
- **In situ shielding tradeoffs.** NASA should conduct studies of tradeoffs to determine whether it is more cost-effective to transport prepared shielding materials from Earth or to construct shielding in situ with transported materials and equipment.
- **Review of existing neutron albedo datasets.** The predictions of computer codes developed by NASA Langley Research Center need to be compared with existing data, especially data for secondary radiation and neutron albedo. Existing datasets should also be reviewed to assess their value in determining the extent to which albedo neutrons on the lunar and martian surfaces may constitute a significant component of the radiation environment. Lunar and planetary surface measurements performed in the pursuit of other exploration objectives may become available; if so, the data should be used for statistically significant comparisons with theory whenever appropriate.
- **Surface fission power demonstration—nuclear power for Mars.** NASA could take advantage of the Moon as a testbed for human exploration of Mars by incorporating the development and testing of fission reactor technology into lunar plans.

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OTHER ELEMENTS OF A COMPREHENSIVE PLAN

Exploration is not a one-mission objective; it is not even a few-missions activity. To be sustainable, exploration requires a long-term commitment to radiation risk management: long-term objectives and resources cannot be neglected in favor of short-term expediency. As humans voyage beyond Earth orbit, mission duration will increase, making radiation risk management even more critical. Managing radiation risk is and will continue to be an integral part of exploration mission design and execution.

Radiation experts have been involved in all aspects of the design and development of Orion so far, from hardware to mission operations protocols. However, the committee judges that responsibilities need to be better defined to ensure a continuation of this positive trend. **The committee recommends that an independent radiation safety assessment continue to be an integral part of mission design and operations. On exploration missions, a member of the crew should be designated as the flight crew radiation safety officer. This person would be the point of contact with mission control, monitor on-site dosimetry, and ensure communication and coordination with ground control for the response to radiation warning levels.**

Operational flight rules for human exploration missions are not yet drafted but should be integrated with the lunar architecture planning process. To provide operational space weather support, monitoring and forecasting capabilities should have clear requirements, coordinated not only between the design and operational portions of NASA, but also between NASA and its interagency partners. **The committee recommends that the nation's space weather enterprise integrate its scientific expertise with operational capability through coordinated efforts on the part of NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Department of Defense (DOD). Where multiple end users benefit, NOAA is appropriate as the lead organization in charge of operational forecasts. However, for NASA-unique lunar support requirements, NASA's Exploration Systems Mission Directorate should take a leadership role in defining and providing resources.**

It is often difficult to apply the ALARA principle to radiation risk in a setting in which multiple risks exist, such as a space mission. The committee endorses the application of the ALARA principle to radiation risk management, an approach that further emphasizes the need for radiation safety advocacy as a component of the development team for Project Constellation. At this time, operational plans are not sufficiently advanced and well defined to provide evidence that the ALARA principle has or has not been properly implemented. The design of spacecraft, habitats, and missions should incorporate NASA radiation standards, and an established limit for radiation risk, as incorporated in NASA radiation standards, has to be included in "Go–No-go" decisions for every mission.

Now and in the future, the capability to protect astronauts from the harmful effects of radiation will depend on a continuing supply of world-class knowledge and talent. Due to reductions in the scope of NASA's radiation protection plan, the current pool of intellectual capital will shrink as researchers retire and are not replaced. **NASA should try, perhaps as part of an interagency effort, to attract and engage young researchers and the broader radiation community at a level sufficient to meet the demands for radiation protection of astronauts in lunar mission operations and martian mission planning. This effort should encourage cross-pollination of ideas together with preservation of institutional knowledge by promoting interactions between researchers of different backgrounds and experience levels and by addressing issues that are relevant to, but broader than, space radiation.**

Thus far, NASA has demonstrated a good effort to protect the next generation of space explorers from radiation. It is vital to maintain this effort throughout the design of all Project Constellation vehicles and smoothly transition that expertise as planning and execution of operations proceeds.

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1

Introduction

HAZARDS OF RADIATION

Space is a harsh environment. Nevertheless, engineering technology is capable of protecting astronauts against vacuum, extreme thermal conditions, and micrometeoroid environments. Protection from radiation, however, is much less straightforward.

The radiation environment in space can be very dynamic. While the general climate of galactic cosmic radiation (GCR) varies fairly predictably on an 11-year cycle, solar particle events (SPEs) are unpredictable, both in timing and character. Whereas the radiation hazard posed by episodic SPEs can be managed by providing sufficient shielding, galactic cosmic rays pose a radiation hazard that is distinctly different: (1) galactic cosmic rays are always present, and (2) their energy spectra extend to very high energies with sufficient intensity that the hazard cannot be eliminated by shielding. Moreover, both SPEs and GCR contain not only protons but also heavier nuclei (also known as HZE particles, for "high Z [atomic number] and energy"). Not enough is currently known about the biological effects of HZE particles. Risks cannot be measured directly; they are calculated from measured radiation properties and computer model predictions. Due to all of the unknowns listed above, these risk calculations carry large uncertainties that make it difficult to set requirements and to evaluate potential mitigation efforts. In turn, it is difficult to determine whether levels of risk occurring on lunar outposts and Mars missions will remain within acceptable bounds.

The health risks to be considered are of two kinds: risks to mission success and risks to health following a successful mission. The success of a mission is jeopardized whenever a crew member is unable to perform his or her functions properly, if at all. In such cases, one or more of the mission objectives may be compromised; in extreme cases, the mission may be lost. In terms of radiation, the mission could be compromised by these short-term consequences or "acute effects," which may include headaches, dizziness, nausea, fatigue, and illness ranging from mild to fatal. In addition, mission objectives could be missed because measures to avoid excess radiation exposure might restrict crew activity. Risks incurred during a mission may also extend beyond its successful completion. Severe bone loss, muscle loss, or disorientation may last for a long time after astronauts return to Earth. Radiation risks are of even greater concern; these risks—in particular, the increased risk of fatal cancer—last for the entire life of the crew member. Astronauts may also face other dangers, including cataracts, skin damage, central nervous system damage, and impaired immune systems. Although these effects are not immediate enough to be classified as acute, they have the potential to impact very long missions or an astronaut's future missions.

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Under the Vision for Space Exploration, the National Aeronautics and Space Administration (NASA) is currently planning to return humans to the Moon by 2020 and then to continue on to Mars around 2035.[1] Under NASA's currently planned architecture, early lunar sortie missions will last about 1 week, and with the buildup of infrastructure for lunar base operations missions may eventually lengthen to 6 months. Radiation protection must become a matter of constant vigilance if explorers are ever to be replaced by settlers.

Research may hold many of the answers to these problems. In some cases, there is existing knowledge that simply needs to be transitioned from research grade to a viable product. In other cases, it may take decades of attention before answering a fundamental question or developing an enabling capability. This report identifies some of these key research topics and offers recommendations on how to manage them in order to generate the greatest amount of progress in ameliorating the radiation hazards faced by the Vision for Space Exploration.

STUDY PROCESS

At the request of NASA's Exploration Systems Mission Directorate, the Aeronautics and Space Engineering Board of the National Research Council formed a committee to evaluate the radiation shielding requirements for lunar and martian missions, and to recommend a strategic plan for developing the necessary radiation mitigation capabilities to enable the planned lunar architecture. The Committee on the Evaluation of Radiation Shielding for Space Exploration was tasked to review current knowledge of the space radiation environment, assess the understanding of risks associated with lunar exploration activities, review shielding approaches and capabilities, and recommend a strategy, including technology investments, for reducing these risks. These strategies were expected to address the radiation exposure limits specified by NASA and to be consistent with NASA's current timelines for Constellation Program development. The committee was also to consider the likely radiation mitigation needs of future Mars missions and to place emphasis on research and development alternatives that would enhance NASA's ability eventually to meet those future needs. The committee's full statement of task appears in Appendix A.

The committee held a 2-day meeting in Washington, D.C., during December 2006. At this meeting, it received briefings from NASA on the mission architecture and plans for human exploration of the Moon and Mars, as well as briefings on the current knowledge of the radiation environment, health risks from radiation, and current and projected shielding approaches.

The committee's second meeting took place in Houston, Texas, during February 2007. Representatives from NASA and Lockheed Martin (the Orion[2] contractor) briefed the committee on current plans for the vehicles, habitats, and space suits involved in a lunar mission. The committee also received briefings on space weather monitoring and materials research.

At its third meeting, held in Washington, D.C., in May 2007, the committee completed its information gathering, with presentations on NASA's past and current biological and materials research programs, shielding research at other institutions, operational decision making in the face of radiation events, and possible architectures for a mission to Mars.

A final, fourth meeting was held in Washington, D.C., in June 2007; at that meeting the committee finalized the findings and recommendations contained in this report.

See Appendix C for committee meeting agendas and a full list of speakers.

ORGANIZATION OF THIS REPORT

The first chapter of this report outlines some background information on the Vision for Space Exploration, NASA's work in radiation protection, and permissible radiation exposure limits. Chapter 2 reviews the current knowledge of the radiation environments likely to be experienced by astronauts, as well as the knowledge gaps. Chapter 3 reviews the effects of radiation on biological systems, electronics, and missions. Chapter 4 discusses

[1]National Aeronautics and Space Administration, *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.

[2]See below for a description of the components of the Exploration mission architecture—Orion being the Crew Exploration Vehicle.

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NASA's current mission architecture and current protection plans. Finally, Chapter 5 outlines the committee's risk reduction strategy, including areas where research can have a high impact. Chapter 6 lists all of the report's findings and recommendations.

OVERVIEW OF MISSION ARCHITECTURE

NASA's programs to implement President Bush's Vision for Space Exploration are collectively called the Constellation Systems. "Mission architecture" means the overall structure, the components, and the interrelationships of a mission; it includes a broad range of projects, programs, concepts, and issues. The Constellation Systems mission architecture includes the complete ensemble of launch vehicles, flight vehicles, ground support, support services, and lunar and planetary surface systems. The habitable architecture consists of the flight vehicles and some of the surface facilities that support the astronauts.

The first vehicle to be developed is the Orion Crew Exploration Vehicle (often called the CEV; this report simply uses "Orion"), for which NASA awarded a contract to Lockheed Martin in August 2006. The Orion Block 1 nominally carries four crew members for up to 14 days in low Earth orbit (LEO), with a growth capacity to six crew members. The Orion Block 2 will carry four crew members to lunar orbit and return them to Earth. The Orion cargo variant will also be pressurized but will operate in automated mode to deliver pressurized cargo to the International Space Station. This report does not consider the cargo variant.

The lunar crew in the Orion will rendezvous in LEO with the Lunar Lander. The combined vehicle of Orion, the Lunar Lander, and the Earth Departure Stage (EDS) will inject on a cislunar trajectory. The Lunar Lander performs the lunar orbit insertion burn. In early sortie missions, the crew then transfer to the Lunar Lander to land on the Moon. The crew members perform their surface mission while living in the Lunar Lander descent and ascent stages. The descent stage may include a small living module, as well as an airlock that helps to conserve atmosphere and exclude dust from the crew cabin. When the surface mission is complete, the crew secures the descent stage and launches in the ascent stage to rendezvous with Orion in lunar orbit. In later, outpost missions the crew will transfer to a surface facility composed of habitat and laboratory modules and surface transportation vehicles.

NASA'S SPACE RADIATION PROGRAM

A research and development program is currently underway at NASA to investigate, evaluate, and mitigate the effects of space radiation on astronauts. This program supports several projects, as well as directed research by individual investigators. A vigorous interagency cooperation effort has led to joint support of numerous research and development projects by the Department of Energy (DOE), the National Cancer Institute, and the Armed Forces Radiobiology Research Institute. Through its radiation program, NASA also participates in multi-agency efforts in order to benefit from applications of radiological defense efforts as they evolve.

NASA determines its research portfolio in consultation with the science research community, including the National Council on Radiation Protection and Measurements (NCRP) and the Space Studies Board and other organizations within the National Research Council. Within NASA priorities, the concurrent development of radiation-transport computer codes and of experimental investigations has provided a large, systematic database of shielding properties of materials, tests of shielding calculations, and a toolbox of computer applications used for spacecraft, space suit, and habitat design. Radiobiological research provides a statistically significant determination of the time that individuals may be exposed to radiation in space without exceeding career and mission limits, or so-called "safe days" in space. In the longer term, the scientific consensus is that radiobiological research is the only way to reduce the uncertainties in risk estimation that limit the number of safe days and, eventually, to mitigate risk.

Prior to the Exploration initiative, the Space Radiation program was housed within NASA's Human Systems Research Technology theme. In 2006, the theme consisted of three programs: Human Health and Performance, Human Systems Integration, and Life Support and Habitation, with a total annual budget of $807 million. Between 2006 and 2008, this program was reduced and condensed into one program, Human Research, with a total annual budget of $183 million, of which $36.2 million is for the Space Radiation program (Pawelczyk, 2007). Radiation health research has been reduced, and shielding research has been nearly eliminated. These changes are reflected

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TABLE 1-1 History of the NASA Space Radiation Laboratory

Year	Event
1958	NASA congressional submission calls for a future facility to simulate space radiation on Earth to study the biology and physics of interactions.
1970	Apollo astronaut's retinal light flash observations cause concern for low fluences of GCR—high charge and energy ions.
1973	The National Research Council (NRC, 1973) issues a report concluding, "We recommend most strongly that at least one accelerator be modified to be capable of accelerating particles of atomic numbers up to [26] iron, and preferably higher, with energies of at least 500 MeV/nucleon. Such accelerators . . . must have closely associated facilities to provide support for advanced biological and medical research."
1979-1993	NASA "piggybacks" on the Department of Energy's BEVALAC program at the Lawrence Berkeley National Laboratory.
1991	The Synthesis Group, chaired by T.P. Stafford (1991), concluded that a "multidisciplinary radiation issues research program . . . will have a major influence on spacecraft design, habitats and mission planning."
1995-2002	Limited use of the Brookhaven Alternating Gradient Synchrotron is allowed for radiobiology and physics experiments (nine runs for total of ~1,300 hrs).
1996	The National Research Council recommends that NASA fund a Booster Application Facility to achieve radiation safety goals for the International Space Station and exploration.
1997	Headquarters and Johnson Space Center's Space Radiation Program attend the conceptual design review at the Brookhaven National Laboratory for NSRL.
1998	Space Radiation Program provides first funding for NSRL construction.
2003 (June 30)	NSRL construction is complete.
2003 (July 7)	The first commissioning experiments take place at NSRL.

in the funding of external research: in 2004, NASA selected 28 research projects in biology and materials, at a total of $28 million; in 2007, 16 radiation biology projects were selected at a total of $15 million.[3] The Space Radiation program is led by the NASA Johnson Space Center. A small amount of shielding technology development and demonstration work supports Exploration from within the NASA Langley Research Center's Structures, Materials, and Mechanisms project.

Ground-based simulation of space radiation is an essential, mission-critical element of this program. For that purpose, the NASA Space Radiation Laboratory (NSRL) at the Brookhaven National Laboratory (BNL) in Upton, New York, is used to obtain beams of all particles and energies in the space radiation spectrum. See Table 1-1 for a history of NSRL. In addition, simulations of the complex SPE and GCR spectrum are being developed for the validation of biological risk predictions and materials testing. The $34 million NSRL facility has been operational since 2003. It was built on schedule and under budget; cooperation with the DOE, the operator of BNL, has enabled the leveraging of resources from this $1 billion BNL facility.

The chief health and medical officer of NASA oversees the application and technology transfer of radiation research results to NASA operations and their incorporation into flight rules. Operational and engineering organizations within NASA also collaborate closely with the solar science and space weather community on matters of space radiation warning, monitoring, and environmental measurements.

OVERVIEW OF RADIATION PROTECTION

NASA develops human system standards to ensure an appropriate environment for human habitation, qualified human participants, a necessary level of medical care, and risk mitigation strategies against the deleterious effects of spaceflight. The standards include exposure limits, fitness for duty criteria, permissible outcome limits, and nominal and off-nominal operating bands (intervals of relevant operational parameters within which it is appropriate or not to conduct a mission). The goals of these standards are to ensure mission completion, to limit morbidity, and to reduce the risk of mortality during Exploration-class missions. These standards are established and maintained

[3]See http://www.nasa.gov/centers/marshall/news/news/releases/2003/03-120.html; http://www.nasa.gov/home/hqnews/2006/sep/HQ_06313_radiation_biology.html.

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under the direction of NASA's chief health and medical officer. Research findings, lessons learned from previous space missions and in analogue environments (for example, bed-rest studies), current standards of medical practice, risk management data, and expert recommendations are considered in the process of setting standards. Figure 1-1 shows the historical radiation doses incurred by astronauts, compared with various exposure limits and typical doses related to some terrestrial activities. Figure 1-2 shows astronaut exposure rate by mission year and illustrates the variability of average daily dose rate experience through 2005. This previous human spaceflight experience

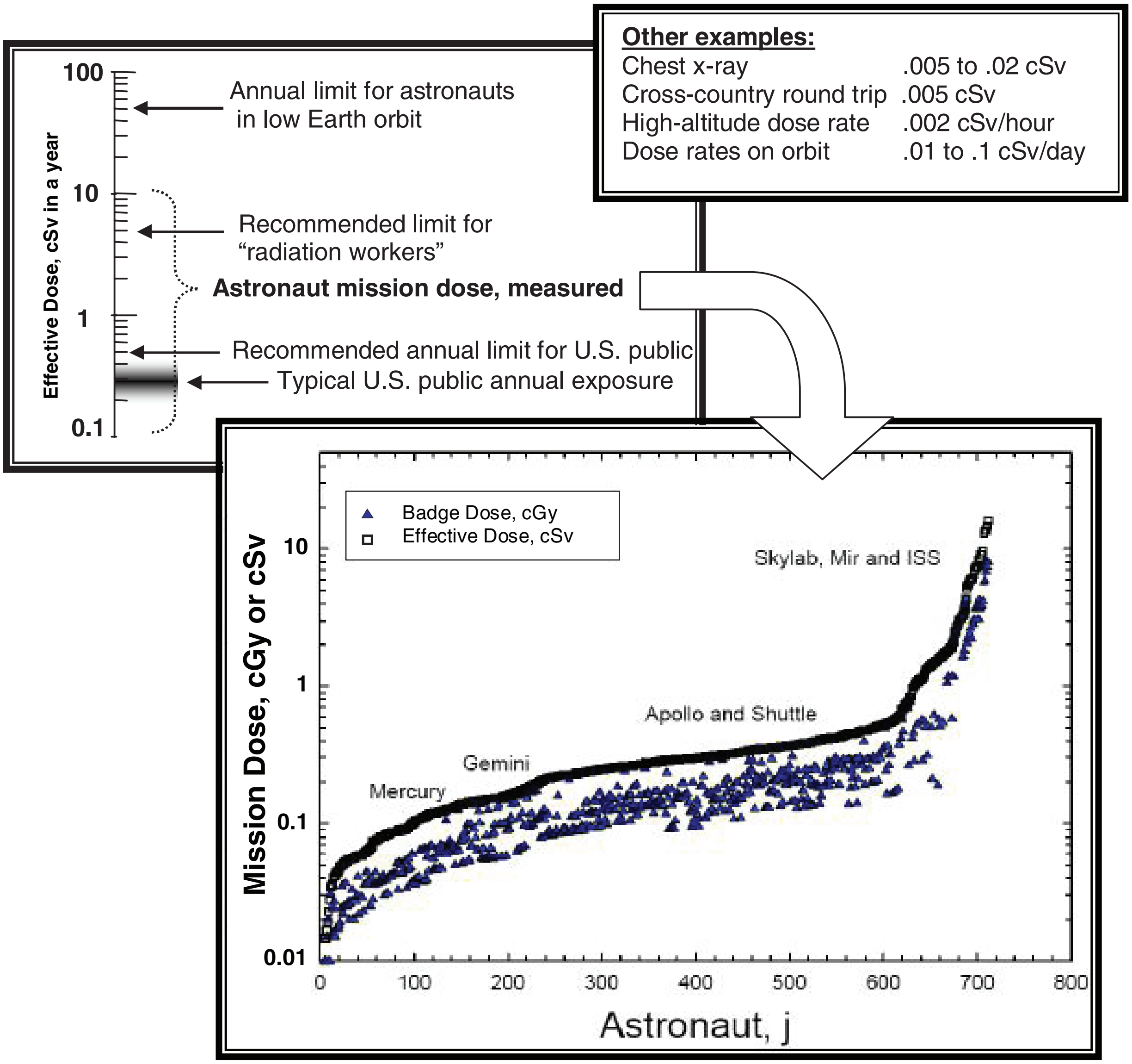

FIGURE 1-1 Radiation doses in context. Astronaut radiation exposure limits and history are compared in this figure with Occupational Safety and Health Administration limits for U.S. radiation workers and for the U.S. public, and with typical public annual exposure, including exposure from medical sources and natural background radiation. Insert on left shows exposures from typical activities. Insert on lower right is a more detailed breakout of U.S. astronaut mission doses through 2002, organized sequentially by astronaut's order of flight. NOTE: cGy, centigray; cSv, centisievert. SOURCE: Modified from Cucinotta et al., 2002.

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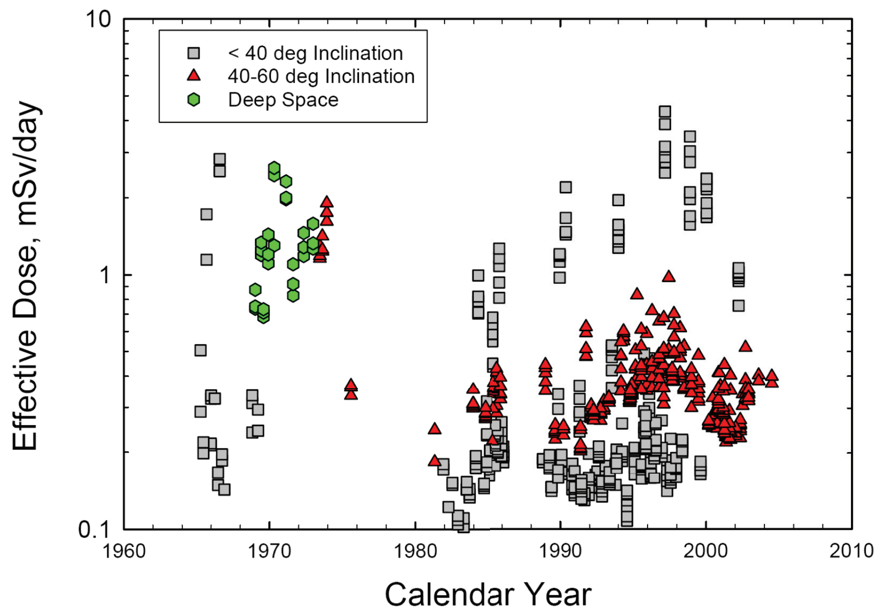

FIGURE 1-2 U.S. astronaut exposure rate history, by mission year, 1962 through 2005. The scatter of the exposure rate is the result of the fact that exposure rate varies as a function of altitude, orbit inclination, time in solar cycle, variations in solar activity, the vehicle shielding, orientation of the vehicle, and location within the vehicle. NOTE: mSv, millisievert. SOURCE: Cucinotta, 2007.

is useful, but it is only partially applicable to the Vision for Space Exploration. Apollo missions were only a few days long, and so the radiation protection involved minimizing travel through the Van Allen radiation belts that encircle Earth in order to avoid solar particle events. There have been longer missions on the space shuttle and the International Space Station, but these took place within the protections of Earth's magnetosphere.

Predicting the risks associated with exposure of biological tissue to a given quantity of radiation is a complicated process. Most of the available data come from studies of Japanese atomic blast survivors, animals, and cell cultures. These data primarily concern high-dose-rate exposures to gamma rays. Since the data available are not ideally suited for determining the effects on a modern American of a long, low-dose-rate exposure to GCR, there is significant uncertainty in these estimations. Risk of exposure induced death (REID) is the currently preferred measure of risk, replacing the mathematically ill-defined "excess relative risk." REID quantifies the risk of an exposed individual dying from a certain cancer as a function of the effective dose. For reference, the American Cancer Society reported that 23 percent of all deaths in 2004 were due to cancer (ACS, 2007).

Permissible exposure limits (PELs) follow recommendations of NCRP Report 132 (NCRP, 2000) with modifications, including new epidemiology and uncertainty assessments, estimates of noncancer risk, and acute effects. There are a number of different PELs—a 30-day limit, a 1-year limit, a career limit, and others. Career limits are based on a REID of 3 percent. This value is based on a comparison with other flight risks, a comparison with the risks faced by workers in less-safe industries (such as mining), and terrestrial radiation limits. The effects of exposures corresponding to this REID vary with age and gender. Furthermore, given the uncertainties in the calculation of REID—both biological and physical—this measure of the risk of exposure is expressed in the form of a probability density function. The PEL is therefore not set to the most probable value of the dose estimate corresponding to a REID of 3 percent. Instead, the PEL is set to the lower 95 percent confidence level of dose estimate, as shown in Figure 1-3. In that way, mission designers are 95 percent certain that REID will be less than 3 percent if the exposure is kept below the PEL.

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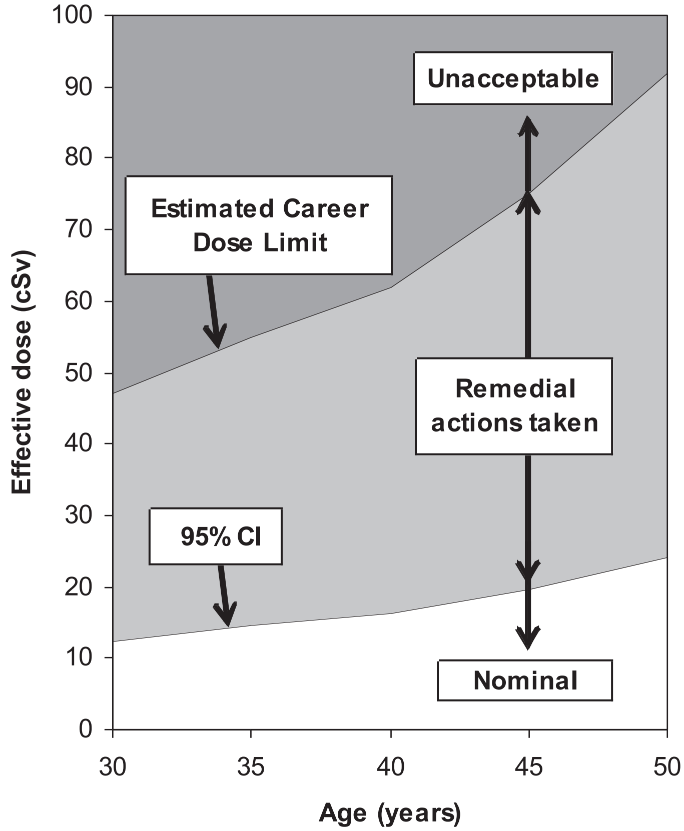

FIGURE 1-3 Permissible exposure limits. Example dose limits for a female astronaut are shown as a function of age. For a selected astronaut (here, a 45-year-old), the expected mission dose falls in the white area. Radiation exposure is measured throughout the mission—if her dose rises to a level represented by the lightly shaded area, mission control decides on various actions that will reduce her dose and ensure that it does not reach the career limit. NOTE: cSv, centisievert; CI, confidence interval.

NASA uses the As Low As Reasonably Achievable (ALARA) principle, a legal requirement applicable on Earth as well as in space, intended to maximize public safety. ALARA is particularly important in space, because the uncertainties associated with space radiation are much higher than those associated with terrestrial radiation. According to ALARA, the PEL should not be considered a "tolerance value" to be used as a design point. Instead, ALARA challenges engineers to include as much radiation protection as possible within the available resources. Setting the PEL to correspond to the lower 95 percent confidence level, as described above, is also in the spirit of the ALARA principle.

The ALARA requirement is implemented at several levels. Launch dates, length of mission, and trajectory may be modified during mission design to take into account solar activity and cosmic ray exposure. Spacecraft may be designed to incorporate different materials and different interior material distributions, including "storm shelters" and extra shielding of crew sleeping quarters, to optimize shielding against solar particle events. Predicted shielding properties of a spacecraft may be validated and their accuracy improved by the partial exposure of components to simulated space radiation on the ground. Extravehicular activities (EVAs) may be scheduled for periods of reduced solar activity and no transit through radiation belts; radiation measurements are used to verify radiation exposure and provide warning for retreat to storm shelters. Once a mission has been designed, it will include an estimated exposure. Crew members are selected so that the sum of their previous radiation exposure and their predicted radiation exposure are below the PELs. If excessive exposures are predicted or do occur, the

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mission may be altered: an EVA may be canceled or the astronauts brought home early. The development of improved early diagnostic methods and radiation effect modifiers, such as radioprotectant pharmaceuticals, will improve the ability to react to unexpected radiation doses. Following a successful mission, medical surveillance and control of further radiation exposures are required.

The thickness of the lightly shaded area in Figure 1-3 is proportional to the mean. Therefore, increasing the career dose limit for an astronaut leads to a higher value of the mean permissible exposure level, but it also widens the distribution, because all the known uncertainties in the calculation of radiation risk are relative errors of the multiplicative factors of a product risk. Thus, accepting a higher career dose limit leads to larger values of uncertainty in terms of radiation exposure and does not necessarily increase the amount of "nominal" area (shown as white in Figure 1-3)—it only widens the shaded region. As a consequence, the most significant gains in the cost-benefit ratio of ALARA application are to be found in the reduction of the uncertainty in the risk calculation, that is, in reducing the width of the 95 percent confidence interval.

This report uses a number of terms common to the field of radiation protection. The most frequently used are defined in Box 1-1; this report also contains a glossary in Appendix D.

BOX 1-1
Common Radiation Terms and Their Definitions

absorbed dose (*D*): average amount of energy imparted by ionizing particles to a unit mass of irradiated material in a volume sufficiently small to disregard variations in the radiation field but sufficiently large to average over statistical fluctuations in energy deposition, and where energy imparted is the difference between energy entering the volume and energy leaving the volume. The same dose has different consequences depending on the type of radiation delivered. Unit: gray (Gy), equivalent to 1 J/kg. As a default, this report uses cGy, because 1 cGy is equal to 1 rad (a deprecated unit still used occasionally).

ALARA (As Low As Reasonably Achievable): a safety principle, as well as a regulatory requirement, that emphasizes keeping doses of and exposure to radiation as low as possible using reasonable methods, and not treating dose limits as "tolerance values"; defined at NASA as limiting radiation exposure to a level that will result in an estimated risk below the limit of the 95 percent confidence level.

biological end point: effect or response being assessed, e.g., cancer, cataracts.

cross section (σ): measure of the probability per unit particle fluence of observing a given end point. Unit: cm^2.

deterministic process: process whereby a given event will occur whenever its dose threshold is exceeded.

dose equivalent (*H*): estimate of radiation risk that accounts for differences in the biological effectiveness of different types of charged particles that produce the absorbed dose. $H = Q \times D$, where Q is a quality factor based on the type of radiation (Q = 1 for x-rays). NASA uses Q as specified in ICRP Publication 60 (ICRP, 1991). Unit: sievert (Sv), equivalent to 1 J/kg. As a default, this report uses cSv because 1 cSv is equal to 1 rem (a deprecated unit still used occasionally).

effective dose (*E*): estimate of radiation risk given in ICRP Publication 60 (ICRP, 1991). It sums the individual effects of all types of radiation present over all of the individual types of tissue in the body. Unit: cSv.

$$E = \sum_{T} w_T \sum_{R} w_R D_{T,R}$$

where w_R is a weighting factor for the type of radiation (NASA uses w_R as specified in ICRP Publication 60; ICRP, 1991); w_T is a weighting factor for the type of tissue; and $D_{R,T}$ is the average dose from radiation R in tissue T.

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OVERVIEW OF GUIDANCE ON RADIATION LIMITS PROVIDED TO NASA

Historical Guidance

A detailed history of space radiation exposure limits can be found in Townsend and Fry (2002). The earliest standards, set in 1970 by a National Research Council (NRC) panel, used the concept of reference risk, which "should correspond to an added probability of radiation-induced neoplasia over a period of about 20 years that is equal to the natural probability for the specific population under consideration." The career limit was set to 400 cSv, with additional limits for bone marrow, skin, ocular lens, and testes (NRC, 1970).

Throughout the 1970s and 1980s, as more data became available, risk estimates for cancer induction per unit dose of radiation began to rise. The National Council on Radiation Protection and Measurements (NCRP) recommended new limits in 1989 in NCRP Report No. 98 (NCRP, 1989), replacing the previous reference risk with 3 percent excess risk of cancer, a quantity comparable to the risks faced by terrestrial radiation workers and workers in other less-safe occupations. In addition, the NCRP limits varied with age and gender. The 400 cSv risk (which had been set for a 30- to 35-year-old male) dropped to 250 cSv. Dose rates for various organs were also set.

fluence, or particle fluence (*F*): number of particles incident on a small sphere centered at a given point in space, divided by the cross-sectional area of that sphere. Mathematically, it is given as d*N*/d*a*, where *N* is the number of particles and *a* is the cross-sectional area. Unit: m^2.

fluence rate (d*F*/d*t*): change in fluence over a given small time interval, or the time derivative of the fluence. Unit: m^2/s.

flux (Φ): term used historically by the nuclear community for fluence rate and also used for particle flux density, but deprecated by the ICRU convention to eliminate confusion between the terms "particle flux density" and "radiant flux." The term "flux" is used in this report because it is common within the space weather and radiation protection communities. See *fluence rate*.

linear energy transfer (LET): measure of the average local energy deposition per unit length of distance traveled in the material. Unit: keV/μm.

permissible exposure limit (PEL): maximum amount of radiation to which an astronaut may be exposed. For terrestrial workers, PELs are legal limits, defined by OSHA. NASA PELs are set by the chief health and medical officer.

relative biological effectiveness (RBE): measure of the effectiveness of a specific type of radiation or particle in producing a specific biological outcome relative to the outcome with the same dose of gamma rays. $RBE = D_{\gamma}/D_{rad\ of\ interest}$.

risk of exposure induced death (REID): measure of risk used by NASA as a standard for radiation protection; reflects a calculation of the probability of death due to exposure to radiation in space.

stochastic process: process whereby the likelihood of the occurrence of a given event can be described by a probability distribution.

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Even as NCRP Report No. 98 (NCRP, 1989) was being released, it was out of date—the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1988) and the BEIR V committee (the Committee on the Biological Effects of Ionizing Radiation) (NRC, 1990) issued reports that included new estimates of risks of stochastic effects of radiation: estimates of excess cancer mortality rose from 1.5 percent per sievert to 5 percent per sievert. These revised risk estimates were used by the NCRP (1993) to set new limits for occupationally exposed individuals in terrestrial occupations; new limits for astronauts followed in 2000 (NCRP, 2000). In addition to the career limits, other short-term limits were recommended in order to avoid deterministic effects in critical organs, such as the skin, ocular lens, and bone marrow.

Space Radiation Research Recommendations of 2006

Because of the unique nature of the space radiation environment beyond LEO, for which no epidemiological data on cancer incidence or mortality exist, guidance on radiation exposures to limit excess cancer mortality to some desired level, such as 3 percent, could not be provided. At the request of NASA, the NCRP published NCRP Report No. 153, *Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit,* in November 2006 (NCRP, 2006). This lengthy report, over 400 pages, provided recommendations on research needs to enable future radiation protection guidance for missions beyond LEO to be developed.

Current Radiation Limits and Guidance

The current radiation exposure limits for NASA, listed in *NASA Space Flight Human Standard Volume 1: Crew Health* (NASA, 2007, p. 65), are as follows:

> *Career Cancer Risk Limits*
>
> Career exposure to radiation is limited to not exceed 3 percent REID (Risk of Exposure Induced Death) for fatal cancer. NASA assures that this risk limit is not exceeded at a 95 percent confidence level using a statistical assessment of the uncertainties in the risk projection calculations to limit the cumulative effective dose (in units of Sievert) received by an astronaut throughout his or her career.
>
> *Dose Limits for Non-Cancer Effects*
>
> Short-term dose limits are imposed to prevent clinically significant non-cancer health effects including performance degradation, sickness, or death in-flight. For risks that occur above a threshold dose, a probability of $<10^{-3}$ is a practical limit if more accurate methods than dose limit values are to be implemented. Lifetime limits for cataracts, heart disease, and damage to the central nervous system are imposed to limit or prevent risks of degenerative tissue diseases (e.g., stroke, coronary heart disease, striatum aging, etc.). Career limits for the heart are intended to limit the REID for heart disease to be below approximately 3 to 5 percent, and are expected to be largely age and sex independent. Average lifeloss from gamma-ray-induced heart disease death is approximately 9 years.

Example age-dependent career effective dose limits for a 1-year mission and calculated days in deep space to stay below permissible exposure limits are shown in Table 1-2.

Dose limits for noncancer effects are listed in Table 1-3. For comparison, Table 1-4 shows the estimated REID for some sample missions.

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TABLE 1-2 Example Age-Dependent Career Effective Dose (E) Limits for a 1-Year Mission and Calculated Days in Deep Space to Stay Below 3 Percent REID with 95 Percent Confidence

	3 Percent REID			
	Males		Females	
Age	E (cSv)	Days	E (cSv)	Days
30	62	142	47	112
35	72	166	55	132
40	80	186	62	150
45	95	224	75	182
50	115	273	92	224
55	147	340	112	282

NOTE: REID, risk of exposure induced death; cSv, centisievert.
SOURCE: NASA, 2007.

TABLE 1-3 Dose Limits for Short-Term or Career Noncancer Effects

Organ	30-day limit	1-year limit	Career
Lens[a]	100 cGy-Eq	200 cGy-Eq	400 cGy-Eq
Skin	150	300	400
Blood forming organs	25	50	Not Applicable
Heart[b]	25	50	100
Central nervous system (CNS)[c]	50	100	150
CNS[c] ($Z \geq 10$)	—	10 cGy	25 cGy

NOTE: Relative biological effectiveness for specific risks is distinct as described in this table.
[a]Lens limits are intended to prevent early (<5 yr) severe cataracts (e.g., from a solar particle event). An additional cataract risk exists at lower doses from cosmic rays for subclinical cataracts, which may progress to severe types after long latency (>5 yr) and are not preventable by existing mitigation measures; however, they are deemed an acceptable risk to the program.
[b]Heart doses calculated as average over heart muscle and adjacent arteries.
[c]CNS limits should be calculated at the hippocampus.
SOURCE: NASA, 2007.

TABLE 1-4 Estimated REID with 95 Percent Confidence Interval (CI) for Sample Exploration Missions

	Solar Minimum		Solar Maximum	
	REID (%)		REID (%)	
Sample Mission	Point Estimate	CI [lower, upper]	Point Estimate	CI [lower, upper]
Long lunar mission, 6 days in deep space, 84 days on surface				
Male	0.28	[0.09, .95]	0.36	[0.12, 1.2]
Female	0.34	[0.11, 1.2]	0.43	[0.13, 1.4]
Mars swing-by, 600 days in deep space				
Male	3.2	[1.0, 10.4]	2.0	[0.60, 6.8]
Female	3.9	[1.2, 12.7]	2.5	[0.76, 8.3]
Mars surface mission, 400 days in deep space, 600 days on surface				
Male	3.4	[1.1, 10.8]	2.4	[0.76, 7.8]
Female	4.1	[1.3, 13.3]	2.9	[0.89, 9.5]

NOTE: Assumes 20 g/cm^2 aluminum shielding and 40-year-old astronauts. Solar maximum includes an August 1972 event in addition to GCR during deep-space portion. REID, risk of exposure induced death. SOURCE: Cucinotta et al., 2005.

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2

Current Knowledge of the Radiation Environment

Astronauts and spacecraft participating in missions to the Moon and Mars will be exposed to a hazardous radiation environment made up of background galactic cosmic radiation (GCR) and punctuated by brief but intense solar particle events (SPEs) (Box 2-1). Accurate and timely information about this environment is required in order to plan, design, and execute human exploration missions. This information consists of estimates or measurements of the time of occurrence, temporal evolution, and spatial distribution of the radiation, as well as the type, maximum intensity, and energy spectrum of the constituent particles. Unfortunately, the prediction and forecasting of solar activity and space weather are severely hampered by incomplete understanding of how the Sun affects interplanetary space and the local environments of Earth, the Moon, and Mars. Scientific progress in this field, leading to accurate long-term and short-term predictions of the space radiation environment, will contribute to the role that solar and space physics scientists can play in human exploration missions.

STATE OF RADIATION ENVIRONMENT KNOWLEDGE

Since the Moon has no atmosphere, deep space measurements are close approximations to the lunar surface environment. Instruments on spacecraft such as the Advanced Composition Explorer (ACE), Solar and Heliospheric Observatory (SOHO), Wind, and Solar Terrestrial Relations Observatory (STEREO) provide data on the energetic-particle environment of deep space. However, these measurements do not provide insight into the surface radiation component from secondary particles created by incident energetic galactic cosmic rays and SPEs. Measurements taken from lunar orbit are closer approximations to the lunar surface environment. Limited orbital measurements have been taken by Explorer 35, Clementine, and Lunar Prospector. Some surface measurements of the lunar radiation environment were made during the Apollo program, but they were generally of short duration with limited resolution. Instruments will be carried on the Lunar Reconnaissance Orbiter mission in late 2008 that will provide additional data on the neutron and charged-particle spectra at the Moon. See Box 2-2 for additional details.

There have been no direct measurements of the radiation environment made on the surface of Mars. Unlike the airless Moon, the thin atmosphere of Mars will stop all protons and alphas with energy less than ~120 MeV per nucleon, and high-Z GCR particles with energy less than about ~0.2-0.6 GeV per nucleon, depending on the species. However, some secondary particles, especially neutrons, will make it to the martian surface. Very energetic protons and galactic cosmic rays will also reach the surface and create secondary particles from collisions with the martian regolith. To model the martian surface environment, one must use transport codes, as has been done by NASA and other researchers.

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BOX 2-1
Main Characteristics of Space Radiation

Solar Particle Events
- Composed largely of protons, generally with low to medium energies (tens to a few hundred MeV per nucleon).
- More likely at solar maximum. Onset, duration, dose rate, and dose are at present unpredictable.
- With adequate warning and access to shelter (>10 g/cm^2 aluminum-equivalent), radiation hazard can be reduced to acceptable levels.
- Biological effects are similar to those from x-rays or gamma rays.
- Major research questions involve the prediction of onset and relevant characteristics and the health risks due to the residual low dose rates when under shielding.

Galactic Cosmic Rays
- Composed of protons, alpha particles, and heavy ions, up to very high energies exceeding tens of GeV per nucleon.
- Steady background varying over the 11-year cycle roughly by a factor of 2.
- Shielding is ineffective because ions penetrate hundreds of centimeters of material and produce secondary radiation.
- Biological effects are poorly understood, with large uncertainties in projections because there are no human data on which to base estimates.
- Major research questions involve solar cycle variations and the need for understanding of mechanisms linking radiation exposure to health risk.

There have been several solar system measurements of the GCR at distances at and beyond Mars, providing confidence in extrapolations of more detailed GCR measures taken near Earth. There have also been limited radiation measurements taken from satellites in orbit around Mars (relevant instruments on Mars Odyssey include the Mars Radiation Environment Experiment [MARIE], the High Energy Neutron Detector, and neutron information from the Gamma Ray Spectrometer; there have also been indirect measurements using instruments on Mars Global Surveyor). Use of these data for estimates of the surface radiation environment requires transport code estimates of particles created in or scattered from the martian atmosphere and calculations of particle transport from the surface through the atmosphere.

The Radiation Assessment Detector (RAD) on the 2009 Mars Science Laboratory will characterize the broad spectrum of radiation at the martian surface. RAD will measure high-energy charged particles coming through the martian atmosphere. In addition to identifying neutrons, gamma rays, protons, and alpha particles, RAD will measure galactic cosmic ray heavy ions up to iron on the periodic table.

Finding 2-1. Current knowledge of the radiation environment on the Moon. Data from many satellites have enabled the characterization of GCR and SPEs near Earth, and these results serve to characterize the radiation incident on the surface of the Moon. Knowledge of the secondary radiation, which is produced by galactic cosmic rays and SPEs interacting with material on the lunar surface, is currently based on data from Apollo, Lunar Prospector, and Clementine and on calculations.

Finding 2-2. Current knowledge of the radiation environment on Mars. The radial extrapolation of the GCR environment from Earth to Mars is well understood, based on measurements made by numerous scientific satellites as they traveled outward through the solar system. To within a few percent or so, the GCR environment at the top of the martian atmosphere is expected to be the same as that near Earth. There are very few simultaneous measurements of SPEs at Earth and at Mars, and current models are inadequate to extrapolate near-Earth measurements of SPEs to Mars. Knowledge of the secondary radiation environment on the surface of Mars is currently based on calculations and measurements taken by spacecraft in Mars orbit.

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BOX 2-2
Radiation Measurements on or near the Lunar Surface

- **Explorer 35** (1967-1973) had a combination of an ionization chamber and Geiger counters. The ionization chamber responded to electrons above 0.7 MeV and protons above 12 MeV. One of the Geiger counters was used for low-energy electrons. The second responded to electrons and protons above 22 keV and 300 keV, respectively.
- **Clementine** was launched in January 1994 and orbited the Moon between February and April 1994. Among its instruments were a charged particle telescope and solid-state dosimeters. The charged particle telescope on Clementine measured the flux and spectra of energetic protons (3 MeV to 80 MeV) and electrons (25 keV to 500 keV). The dosimeters were proton-sensitive static random access memory chips sensitive to protons with energies from a few to more than 20 MeV.
- **Lunar Prospector** collected data in lunar orbit from January 1998 until July 1999. It contained a gamma ray spectrometer (with a fast neutron spectrometer with sensitivity to albedo neutrons with energy up to 8 MeV), a neutron spectrometer (with sensitivity to neutrons with energy less than 1 keV), and an alpha particle spectrometer (detecting alpha particle decay products with energy of a few MeV). Each instrument was optimized to provide information about the lunar surface composition, not the lunar surface radiation environment.
- **Apollo Measurements** The most relevant of the Apollo measurements were made with the Cosmic Ray Detector Experiment, a set of passive glass detectors with sensitivity from 100 keV to 150 MeV per nucleon. The exposure time was limited. Other indirect surface measurements during the Apollo program included the following:

  — The filter glass of Surveyor III (brought back by Apollo 12) was analyzed;
  — The window of the Apollo 12 spacecraft was analyzed for cosmic ray tracks;
  — One helmet on Apollo 8 and three worn on Apollo 12 were used as heavy-particle dosimeters;
  — A control helmet was also exposed to cosmic rays at a balloon altitude of 41 km; and
  — Lunar regolith was analyzed for upper limits on high-energy exposure over the half-lives of long-lived isotopes (thousands to millions of years).

- The **Lunar Reconnaissance Orbiter**, scheduled for launch in late 2008, will have two radiation monitoring instruments: Cosmic Ray Telescope for the Effects of Radiation (CRaTER) and Low Energy Neutron Detector (LEND). The CRaTER telescope consists of three ion-implanted silicon detectors separated by two pieces of tissue-equivalent plastic. It will be sensitive to protons with energy above 20 MeV and energetic high-*Z* particles (iron nuclei with energy greater than 90 MeV per nucleon, for example). The LEND instrument will provide data similar to the Neutron Spectrometer on Lunar Prospector.

GALACTIC COSMIC RADIATION

Interplanetary space is bathed by a low flux[1] (particles per square centimeter per second or particles per square centimeter per steradian per second) of essentially uniformly distributed, highly energetic, and extremely penetrating ions that are believed to be accelerated by supernova shocks in our Galaxy. These ions make up the GCR. The highest-intensity GCR is found between a few tenths and a few tens of GeV per nucleon, where the particles can penetrate tens to hundreds of centimeters of shielding. Every naturally occurring element in the periodic table is present in the GCR: nearly 90 percent are protons (hydrogen), close to 10 percent are helium, and the remaining percentage are elements heavier than helium, with a relative abundance roughly similar to that found in our solar system (Figure 2-1). These subtle compositional differences were a key factor in understanding the origin of GCR and provided the original impetus for the development of heavy-ion transport codes and heavy-ion cross-section libraries that we take for granted today. Galactic cosmic rays also include electrons and positrons, but their intensities are too low to be of practical concern.

The GCR flux outside the solar system is presumed to be constant, at least on timescales of tens of millions of years related to the solar system's motion through the Galaxy (Lieberman and Melott, 2007) and barring a nearby

[1]"Flux" is an older, but not preferred term, which has been replaced by "fluence rate." However, since "flux" is more common within the space weather and radiation protection communities, it is used in this report.

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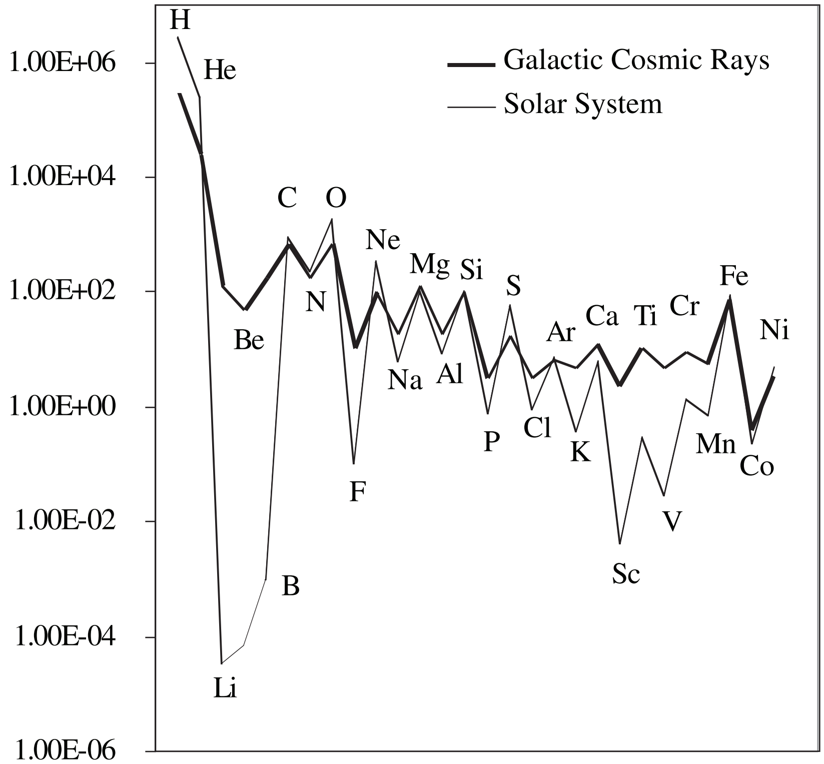

FIGURE 2-1 Relative abundance of elements in galactic cosmic rays and in the solar system. The very large GCR excesses at Li-Be-B and in the sub-Fe elements (Sc-Mn) are the products of spallation interactions during the cosmic rays' journey through the interstellar medium. SOURCE: Based on data from Astrophysics Science Division, NASA Goddard Space Flight Center Web site, available at http://helios.gsfc.nasa.gov/ace/abund_plot.html; http://edmall.gsfc.nasa.gov/99invest.Site/ACE/plot.html.

supernova (Pohl and Esposito, 1998). However, to reach Earth, GCR must penetrate the heliosphere, the magnetic plasma that surrounds the Sun, which suppresses the entry of charged particles from the interplanetary space. The strength of the interplanetary magnetic field increases with proximity to the Sun. As a result, the intensity of the GCR flux is lower around the inner planets than it is in the outer heliosphere. The interplanetary magnetic field varies with the solar activity cycle; the GCR flux near Earth is at a peak near solar minimum (when the interplanetary magnetic field is weak) and at its low point at solar maximum (when the interplanetary magnetic field is strongest) (Cane et al., 1999). This solar-cycle variation in the strength of the interplanetary magnetic field is most likely due to the changing rate of coronal mass ejections (CMEs) (Cliver and Ling, 2001; Owens and Crooker, 2006). The higher rate of CMEs at solar maximum may also impede cosmic-ray access to the inner heliosphere by increasing the level of magnetic turbulence (Newkirk et al., 1981; Bieber et al., 1993) and through coalescence into large magnetic structures in the outer heliosphere (Burlaga et al., 1993; McDonald, 1998; Lara et al., 2005).

The temporal changes in the GCR intensity near Earth varies with the energy of the GCR particles and with the solar maximum in an understood and approximately predictable way, given accurate forecasts of the solar cycle. In the energy range of less than a few GeV per nucleon, the flux decreases from solar minimum to solar maximum by 30 to 50 percent (Figure 2-2). The solar-cycle variation in the GCR intensity near Earth is illustrated in Figure 2-3, which shows the observed count-rate at the Climax Neutron Monitor (NM) for 1951-2006. The Climax NM rate primarily reflects the flux of protons with energies above ~2 GeV. It is the empirical proxy employed to specify the level of solar modulation in Badhwar and O'Neill's GCR model (O'Neill, 2007); alternatively, Nymmik uses

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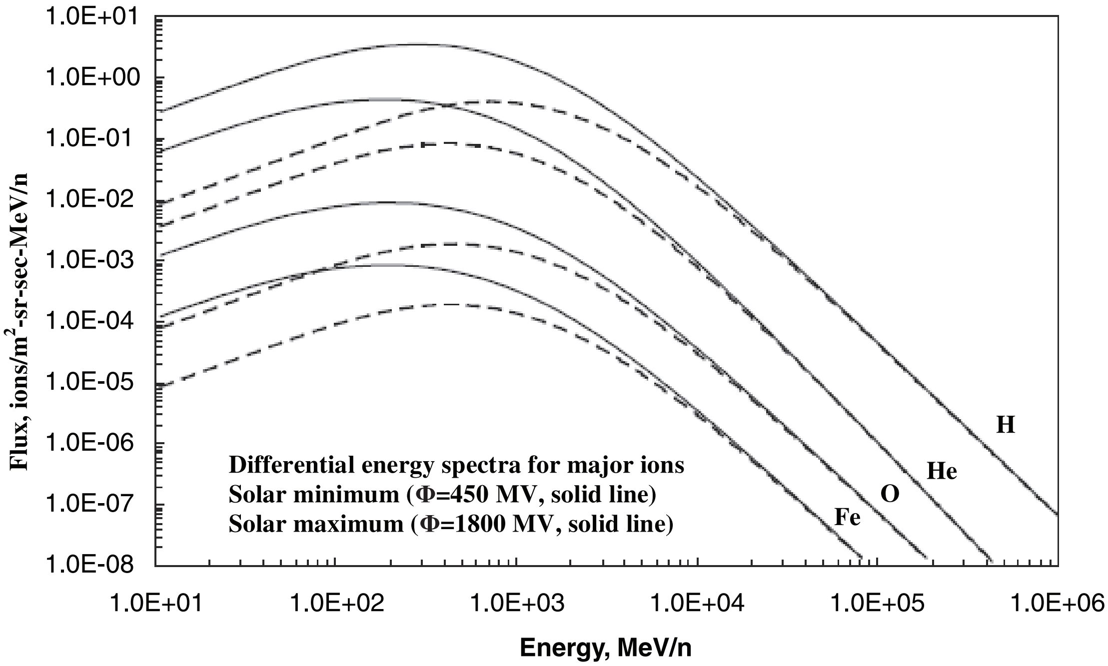

FIGURE 2-2 Differential solar energy spectra at solar minimum and solar maximum. SOURCE: Provided by P. O'Neill, NASA. Generated by data from the Badhwar-O'Neill model (O'Neill, 2007), which incorporates data from the Advanced Composition Explorer satellite, as well as older satellite and balloon data.

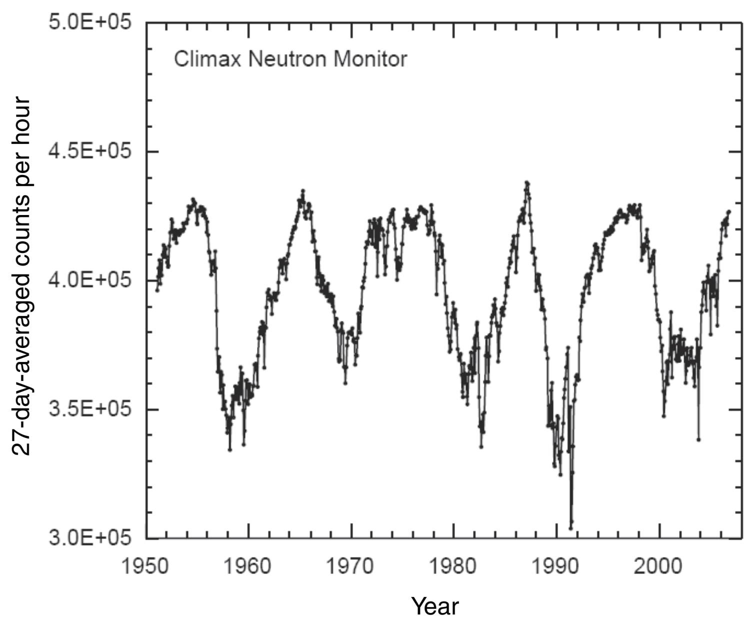

FIGURE 2-3 Solar cycle variation in the count-rate at the Climax Neutron Monitor, 1951-2006. The count-rates have been averaged over the 27-day solar-rotation period. Dates with significant contributions from solar particle events have been excluded from the averages. SOURCE: Based on data provided by the Neutron Monitor Datasets Web site of the University of New Hampshire, National Science Foundation Grant ATM-0339527, available at http://ulysses.sr.unh.edu/NeutronMonitor/neutron_mon.html.

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the smoothed sunspot numbers over the preceding 12 months (Nymmik et al., 1992, 1996). The advantage of the former method is that the NM count-rate is the direct product of GCR interactions on the atmosphere (unless there is a large, high-energy solar particle event in progress). The latter method may have some particular attractions, in that sunspot numbers are a readily available descriptor of solar activity that the solar community attempts to forecast, albeit with limited success. However, McCracken and McDonald (2004) indicate that the long-term variation in GCR intensity, as reflected by ice core data, is poorly correlated to sunspot numbers during some periods of low solar activity prior to the space age.

Figure 2-4 shows the ratio of GCR dose rates from these two models versus depth of shielding. For solar minimum, the Badhwar-O'Neill results are systematically higher by about 10 percent; at solar maximum, they are systematically lower by about 20 percent. The energy dependence in the ratios may be due, at least in part, to differences in the transport codes. The two models were developed using many of the same GCR datasets, except that the Badhwar-O'Neill model also incorporated recent data from ACE. It is therefore not surprising that the results agree relatively well. These remaining discrepancies serve to quantify the level of systematic uncertainty associated with the details of each model's choices in parameterizing the GCR data. For particular year-dates (rather than just the extremes of the solar cycle, as compared in Figure 2-4), the discrepancies between the two models may be somewhat larger.

The discrepancies illustrated in Figure 2-4 are small compared with those that arise from uncertainty in estimations of the biological effects of GCR. One may therefore conclude that the GCR component of the interplanetary radiation environment is known sufficiently well to support the needs of the Exploration missions, at least within the time frame of lunar missions. However, two caveats should be noted.

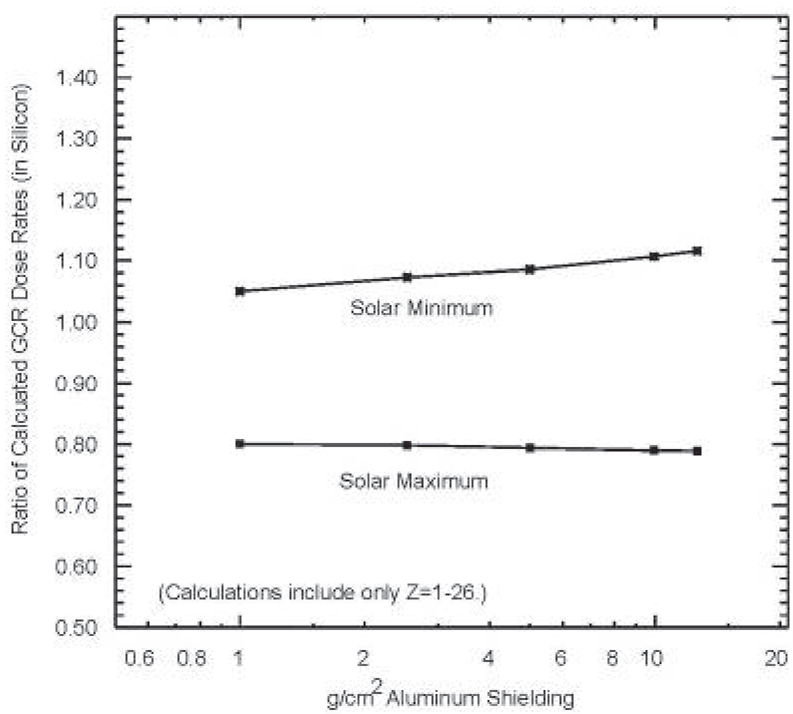

FIGURE 2-4 Ratio of dose rates calculated with the Badhwar-O'Neill model (O'Neill, 2007) and with the Nymmik et al. (1992) GCR model, versus depth of shielding. Ratios are shown for both solar minimum (top) and solar maximum. NOTE: Both of these codes output the dose in silicon, which is related to the radiation dose in electronics. The ratio of doses in water (a better approximation for biology) would be similar. SOURCE: Badhwar-O'Neill dose rates for this comparison were provided for this report by P.M. O'Neill of the NASA Johnson Space Center; the Nymmik et al. (1992) rates were calculated with the CREME96 model, https://creme96.nrl.navy.mil/ and Tylka et al., 1997.

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First, the GCR modulation actually follows a 22-year cycle, related not only to the 11-year sunspot cycle but also to changes in the polarity of the solar magnetic field. ACE, which can, in principle, continue to report GCR measurements until 2025 (Withbroe et al., 2006), is only now beginning its observations of the second half of this 22-year cycle. ACE measures GCR with unprecedented precision. It will therefore be beneficial to see if the reported accuracy of the Badhwar-O'Neill and other GCR models continues over the coming decade.

Second, all of these statements about the reliability of the GCR models are predicated on our experience during the space age. But, as discussed later in this chapter, there are indications from polar ice cores that solar modulation levels were lower and GCR fluxes concomitantly higher for extended periods of time during the past 1,150 years (McCracken and McDonald, 2004). It is impossible to say how reliable the GCR models might be if it were to become necessary to extrapolate them into this unknown regime.

Finding 2-3. Lunar GCR environment. Given the far larger uncertainties in biological effects, the committee finds that knowledge of the composition, energy spectrum, and temporal variation of the "free space" GCR component of the interplanetary radiation environment is sufficient to support the needs of the Constellation lunar missions. Nevertheless, it will be useful to benchmark GCR models against measurements reported by ACE in the upcoming second half of the 22-year GCR modulation cycle.

Because the GCR flux inversely follows the solar cycle (peaking at solar minimum, lowest at solar maximum) and because the rate of solar events is reduced at solar minimum, a significant gap in long-term forecasts of the radiation environment is in the area of forecasting the solar cycle. The current challenge in this area is illustrated by a recent effort by a National Oceanic and Atmospheric Administration (NOAA)/NASA panel to forecast the next solar cycle, Cycle 24 (Figure 2-5). The expert panel assembled to make the forecast noted that the end of Cycle 23 is later than anticipated by up to a year, and it could not reach consensus on whether the next solar cycle would be larger or smaller than an "average" solar cycle. This further translated into uncertainty over the timing of the next solar maximum, with the panel agreeing that the next solar maximum would occur between October 2011 (for a cycle larger than average) and August 2012 (for a cycle smaller than average).[2]

SOLAR PARTICLE EVENTS

Energetic particles, occasionally with energies exceeding several GeV, are accelerated in sporadic events at the Sun associated with solar activity. These energetic particles are produced by processes whose details are still being studied. SPEs occur intermittently throughout the solar cycle, although much less frequently near sunspot minimum. At the present time, the occurrence and intensity of SPEs cannot be predicted. In addition to the particles themselves, signatures of SPEs also include significant increases in solar radio emissions, x-rays, and, occasionally, detectable levels of gamma rays and neutrons from the Sun.

A large body of research in the 1980s led to the classification of SPEs into two types, "gradual" and "impulsive" (Reames, 1990; Cliver and Cane, 2002; Tylka and Lee, 2006). These terms are now generally understood as shorthand for two distinctive particle-acceleration mechanisms. In gradual SPEs, which have large intensities at energies relevant to astronaut radiation safety, shocks driven by fast CMEs are the dominant accelerator. The particle acceleration in impulsive SPEs, however, is believed to be due to magnetic reconnection processes, similar to those that go on in solar flares. Compared with gradual SPEs, impulsive SPEs are characterized by small intensities, short durations, low energies that do not penetrate typical shielding, and observability only over a narrow range of solar longitudes that are well connected to the spacecraft. Impulsive SPEs are also characterized by distinctive patterns of enhancements in heavy ions (Reames, 2000a; Reames and Ng, 2004; Mason et al., 2004). Impulsive SPEs are unimportant to astronaut safety because of their low particle fluxes. However, impulsive SPEs contribute indirectly to the SPE radiation hazard by enriching the suprathermal seed population from which CME-driven shocks accelerate particles to high energies. All further discussion of SPEs in this report refers to gradual SPEs.

[2]See NOAA Space Environment Center, Solar Cycle 24 Prediction, available at http://www.sec.noaa.gov/SolarCycle/SC24/index.html.

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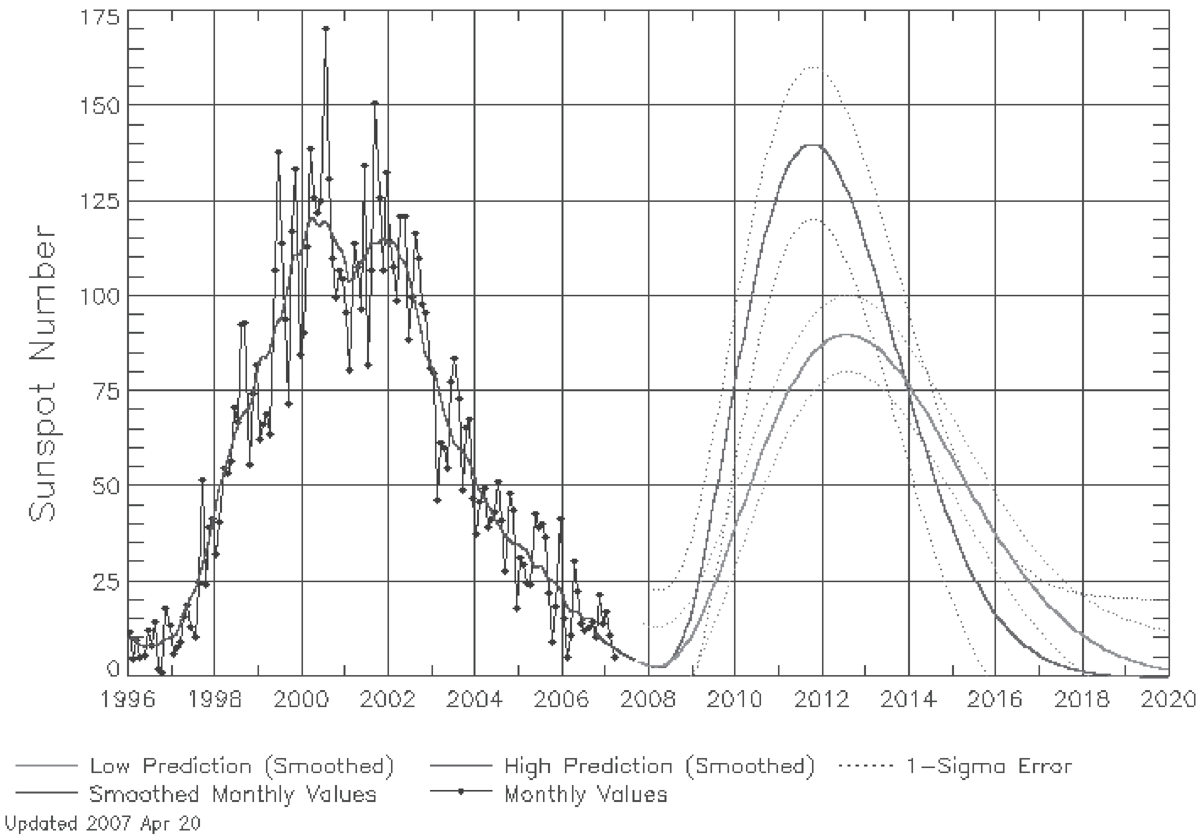

FIGURE 2-5 National Oceanic and Atmospheric Administration/NASA Solar Cycle 24 prediction panel results, showing two potential outcomes for the next solar maximum (data through March 31, 2007). SOURCE: NOAA Space Environment Center, "Solar Cycle 24 Prediction," available at http://www.sec.noaa.gov/SolarCycle/SC24/index.html.

Dramatic increases in the intensity of penetrating particles (with ranges of millimeters up to tens of centimeters) can begin within minutes to tens of minutes of the onset of solar activity. During these early minutes, the particle flux is generally "anisotropic," meaning that more particles come from one direction than from another. The peak direction is not necessarily toward the Sun but generally lies along the direction of the interplanetary magnetic field, which varies. The flux becomes essentially isotropic (with no preferred direction) within tens of minutes to hours, depending on particle energy. Peak flux may occur minutes to days after onset, also generally depending on energy. The flux can be quite large throughout the event, although the flux at energies above several hundred MeV is generally not a significant contribution to the total fluence (flux integrated over the event).

Figure 2-6 shows examples of the time evolution of some very large SPEs from Cycle 23. SPEs typically persist for hours to days, depending on energy. The observed time profiles and energies produced by the CME-driven shock are determined by the evolving nature of the shock, the sweep of the observer's magnetic connection point across the shock front as the shock moves outward from the Sun, and the properties of the interplanetary medium through which the shock and the energetic particles propagate. Many of the largest SPEs are part of multi-event episodes, produced as a single solar active region rotates across the face of the Sun. These episodes have the potential to constrain operations for many successive days. Although high-energy particles are generally produced when the CME-driven shock is still far from Earth, some SPEs have a substantial secondary peak when the CME-driven shock passes over the Earth (typically 18 to 30 hours after event onset). These secondary increases

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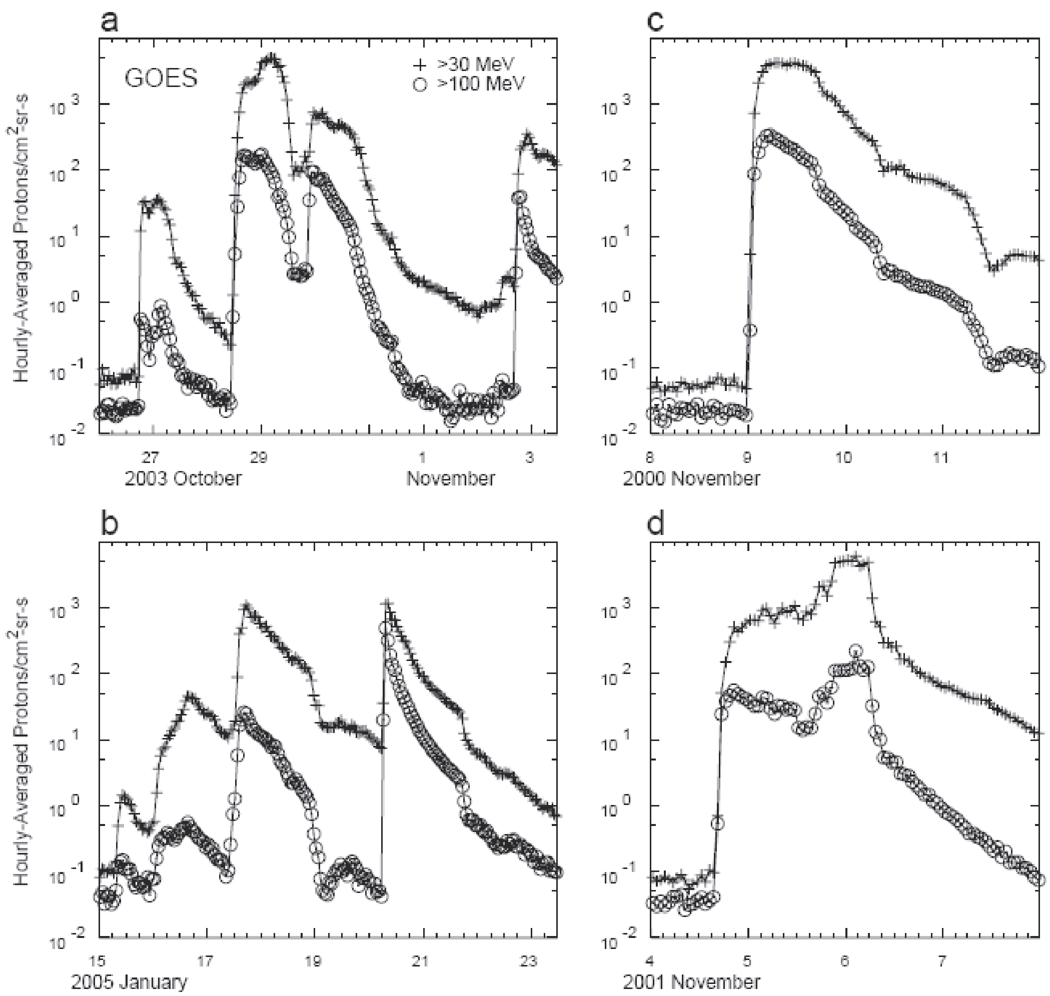

FIGURE 2-6 Examples of solar proton timelines from the Geostationary Operational Environmental Satellite (GOES) at >30 MeV and >100 MeV. Panels (a) and (b) show multi-event episodes. Panels (c) and (d) show single events. The second increase in panel (d) is an example of an energetic storm particle (ESP) event, associated with the arrival of a powerful coronal mass ejection-driven shock at Earth. SOURCE: National Geophysical Data Center.

are often referred to as energetic storm particle (ESP) events. In most cases, ESP events are seen only at energies that do not pose a radiation hazard. But a few times per solar cycle, the shock's arrival at Earth also brings very large fluxes at very high energies, extending beyond ~100 MeV. These rare, powerful events are the most severe transient radiation environment to which Exploration astronauts may be exposed.

Energy Spectra

The energy distribution also varies substantially from event to event. In general, the most significant energy range is from a few tens of MeV to a few hundred MeV. The drop in the energy spectrum is an important feature. "Soft" events have a larger proportion of particles with lower energy. "Hard" events have more than the average proportion of high-energy particles. Figure 2-7 shows the proton energy spectrum from two events illustrating the

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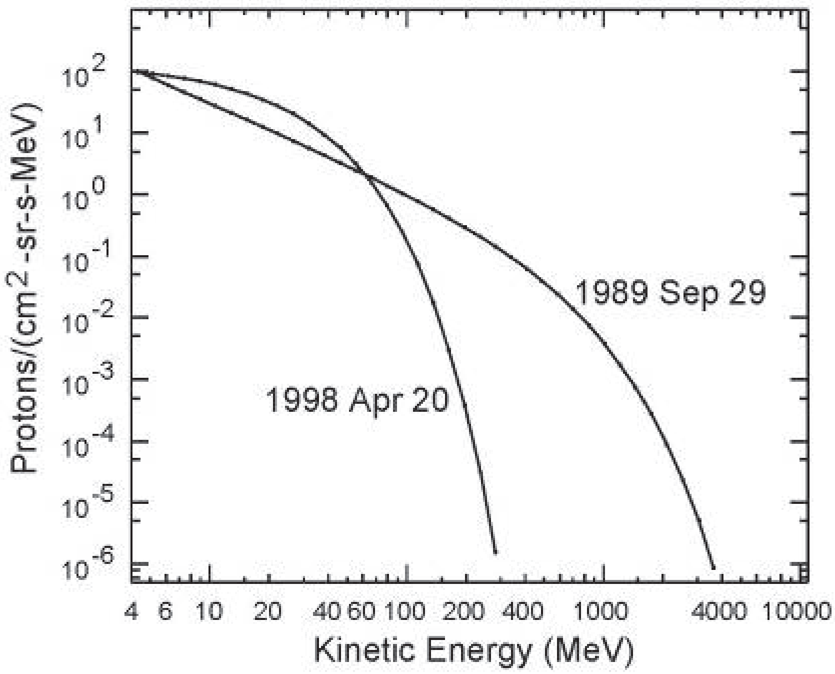

FIGURE 2-7 Examples of "soft" (1998 April 20) and "hard" (1989 September 29) solar proton spectra. SOURCE: Reames, 2000b. Copyright 2000; used with permission from the American Institute of Physics.

difference between hard and soft spectra. Both SPEs were associated with fast CMEs (~1,800 km/s) on the Sun's west limb. Behind 10 g/cm^2 aluminum shielding, the soft event (April 1998) would contribute approximately 0.02 cGy per hour, while the hard event (September 1989) dose-equivalent rate would have been 1.0 cGy per hour (neglecting body self-shielding and secondary neutrons produced in the shielding).

Composition

On average, protons comprise more than 90 percent of the energetic ions produced in an SPE. For this and other reasons, protons are the primary concern when evaluating potential SPE radiation hazards. However, the processes that accelerate protons to high energies also accelerate heavier ions. Moreover, the relative abundances of the various heavy-ion species vary significantly from event to event, as well as with energy and with time during an event. These abundance variations have proven to be powerful probes of the acceleration and transport processes by which SPEs are produced.

As an example of this variability, Figure 2-8 shows the energy-dependence of the event-integrated Fe/O (iron/oxygen) ratio in two very large SPEs associated with ostensibly similar flares and CMEs. Whereas the two events are nearly identical out to ~10 MeV per nucleon, at the highest measured energies the Fe/O ratios differ by nearly two orders of magnitude. Various hypotheses have been put forward to explain the behavior in Figure 2-8. However, analysis and modeling of observations like these are contributing to an emerging consensus on the way in which flares and CMEs contribute to the production of large SPEs: whereas CME-driven shocks are the ultimate energy source for potentially hazardous solar energetic particles, the reconnection processes associated with flares provide a distinctive contribution to the seed particles that are promoted to high energies by the action of the shock (Mason et al., 1999; Desai et al., 2003, 2006; Tylka et al., 2001, 2005; Lee, 2007). Strong correlations have also been found between heavy-ion characteristics and spectral shapes (such as those of Figure 2-7), and recent work

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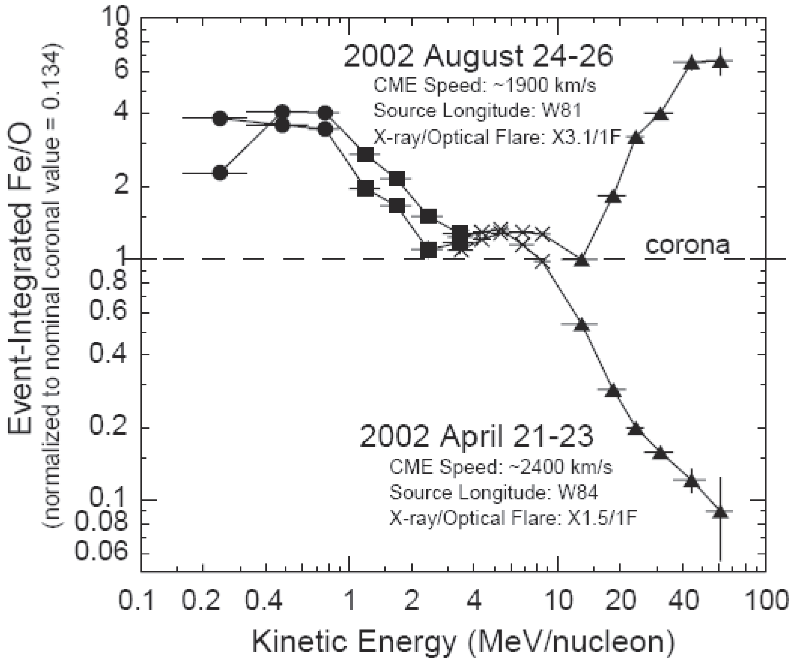

FIGURE 2-8 Event-integrated Fe/O ratio versus kinetic energy in two very large solar particle events. The data are normalized to the nominal coronal value given by Reames (1995). Different symbols distinguish measurements from various instruments on the Advanced Composition Explorer and Wind. Coronal mass ejection (CME) speed, longitude of the source of the flare, and x-ray/optical flare size are also noted for each event. The source longitude is the angular distance from a standard meridian (0 degrees heliographic longitude), measured from east to west (0 degrees to 360 degrees) along the Sun's equator. Optical flares in H-alpha are usually accompanied by radio and x-ray bursts and occasionally by high-energy particle emissions. The optical brightness and size of the flare are indicated by a two-character code called "importance." The first character, a number from 1 to 4, indicates the apparent area; the second character indicates relative brilliance: B for bright, N for normal and F for faint. (See http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarflares and http://www.spaceweather.com/glossary/flareclasses_optical.html.) X-ray flares are classified in three categories: X-class flares are big; they are major events that can trigger planetwide radio blackouts and long-lasting radiation storms. M-class flares are medium-sized; they can cause brief radio blackouts that affect Earth's polar regions. Minor radiation storms sometimes follow an M-class flare. Compared to X- and M-class events, C-class flares are small, with few noticeable consequences here on Earth. (See http://www.spaceweather.com/glossary/flareclasses.html.) SOURCE: Tylka et al., 2006.

suggests that these correlations can be understood in terms of the evolving nature of the CME-driven shock as it moves outward from the Sun (Tylka and Lee, 2006; Sandroos and Vainio, 2007). As a result, insights derived from heavy ions show promise for explaining and eventually modeling the event-to-event variability that lies behind the engineering and operational challenges of the SPE radiation hazard.

Because of the higher rate of energy deposition of heavy ions when traversing matter, it is important to assess whether solar heavy ions might pose a significant radiation hazard in themselves. As a starting point for this discussion, it should be remembered that heavier ions must have higher initial energies in order to penetrate a given depth of shielding. For example, to penetrate 1.0 g/cm^2 of aluminum, protons and iron nuclei must have energies of ~30 MeV and ~100 MeV per nucleon, respectively. Given that SPE spectra at the skin of the spacecraft generally fall steeply with increasing energy, the higher-penetration thresholds go a long way in suppressing the dose from solar heavy ions.

For a few SPEs, heavy-ion spectra have been measured out to well beyond minimal penetration energies. Tylka and Dietrich (1999) reported measurements of solar heavy ions out to nearly 1 GeV per nucleon. Kim et al.

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(1999) used these results in an analysis of proton and heavy-ion contributions to astronaut radiation exposure in the September 29, 1989, event. They found that for most of the organs and shielding thicknesses that they considered, the total dose equivalents in this event would have exceeded the 30-day exposure limits from NCRP Report No. 98 (NCRP, 1989). In some cases alphas contributed as much as 10 to 40 percent of the dose equivalent. Ions heavier than alphas contributed no more than a few percent to the total dose equivalent.

These calculations suggest that solar heavy ions, apart perhaps from alphas, do not make a significant contribution to the SPE radiation hazard for astronauts. However, it should be emphasized that the biological effect of HZE (high atomic number and energy) particles is at present not well understood (see Chapter 3). As this understanding evolves, it may become necessary to revisit this conclusion about the potential relevance of solar heavy ions.

If solar heavy ions are found to have a potential biological impact, their time structure should also be considered. At energies relevant to a given depth of shielding, the time-intensity profiles for protons can rise much more slowly that that of heavier ions, especially iron. In the event considered by Kim et al. (1999), the relevant proton fluence built up gradually over the course of more than a day, whereas about half of the relevant Fe fluence arrived in just the first few hours of the event. Thus, if solar heavy ions pose a radiation hazard to astronauts, that hazard will generally occur in the first few hours of the event—just at the time when astronauts might be caught "outside" and under minimal shielding.

Finally, even if solar heavy ions are a negligible radiation hazard for astronauts, it should be noted that they can have significant impacts on spacecraft electronics. This topic is discussed more thoroughly in Chapter 3.

Frequency of Events

The NOAA Space Environment Center (SEC) declares that an SPE is underway when the number of protons with energy greater than 10 MeV exceeds 10 cm^2 per second per steradian (4π steradians is a full sphere). During most of the solar cycle there are roughly 10 SPEs per year meeting this criterion. Each event will require the attention of those responsible for astronaut radiation hazards. Some will turn out to be too low in peak flux or total fluence to be an issue for the astronauts. Most will be large enough to have some impact on concurrent lunar missions: from delaying or shortening an EVA up to aborting the mission. One to three times per solar cycle there will be an extremely large event (top 5 percent in peak flux or total fluence).

Catalogs of SPEs are tabulated on the basis of either peak flux or event-integrated fluence above some relevant energy thresholds. Both peak flux and fluence are needed to assess radiation hazards for spacecraft systems. For human radiation exposure, however, fluence is generally the relevant quantity. Figure 2-9 shows the frequency of events for recent solar cycles organized by the fluence of all particles with energy greater than 30 MeV.

Near-Term Forecasts and Nowcasting

There are two classes of SPE forecast tools currently available to support human spaceflight: near-term and "nowcast." Near-term forecast tools provide estimates of the probability of an event within the next few hours to days. Nowcasts attempt to forecast the energy spectrum and time evolution of the expected flux. Of these, the time to maximum flux and the event duration are of greatest importance for an ongoing mission, because they are used to project how quickly and for how long astronauts must take shelter. The energy spectrum is needed for depth-dose calculations. Finally, the total expected dose is proportional to the total event fluence, given by the integral of the flux over the event duration.

The NOAA SEC and the United States Air Force (USAF) are responsible for providing space weather forecasts. Each center has developed operational software to prepare SPE forecasts and alerts. The USAF's projections serve specialized Department of Defense (DOD) needs, but its forecasts are also available to NASA through the NOAA SEC. The NOAA SEC provides SPE forecasts to U.S. domestic civil users, including the Space Radiation Analysis Group (SRAG) at the NASA Johnson Space Center, and the International Space Environment Service. NOAA also directly supports the NASA SRAG with Geostationary Operational Environmental Satellite (GOES) measurements. The NASA SRAG combines the GOES data, NOAA forecasts, and operational models of Earth's magnetic field to predict doses inside the space shuttle and the International Space Station (ISS).

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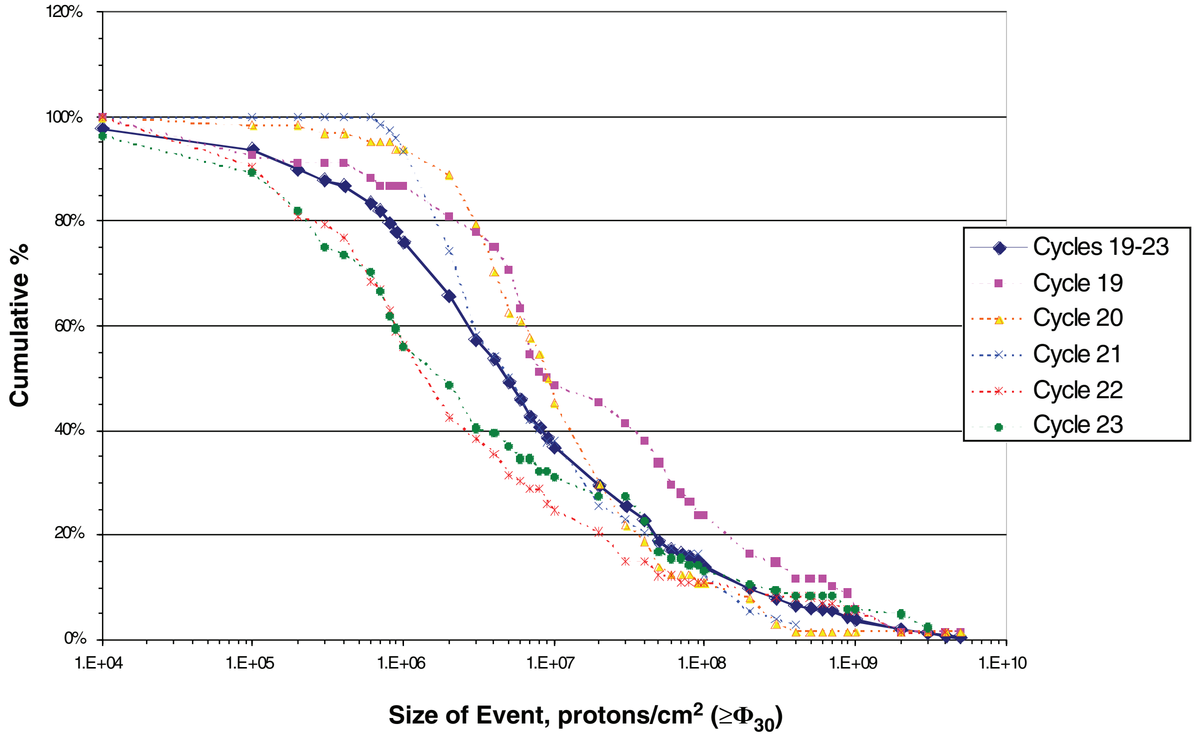

FIGURE 2-9 Cumulative distribution of solar particle events. SOURCE: F. Cucinotta, NASA, "Radiation Risk Assessments for Lunar Missions-Shielding Evaluation Criteria," presentation to the committee December 12, 2006.

When no particle event is underway and when there are no significant x-ray events, neither the SEC nor the USAF has a quantitative model or algorithm to produce multiple-day forecasts for SPEs. NOAA provides a 1- to 3-day probability estimate of energetic-particle activity (along with estimates of the probability of significant x-ray flares and other geomagnetic activity). The particle event forecast is based on qualitative observations of ongoing solar activity and solar active regions and their history. Long-lived active regions occasionally have a pattern of multiple eruptions. NOAA may upgrade the potential for a particle event when a region that produced a particle event on a previous solar rotation (with a period of about 27 days) returns. The lack of multiple-day prediction severely limits risk management alternatives for human spaceflight. In effect, a crew on a spacecraft or a team of astronauts at a remote site on the Moon must react to an event after it begins, limiting the time and options for evasive actions, if warranted, to a few hours.

Even after an SPE has been observed to be underway, forecasts of peak flux are good only to within an order of magnitude or worse. The two operational models in use are the NOAA PROTONS model and the USAF's Proton Prediction System (PPS). Both of these empirical models were developed before the central role of fast CMEs in producing large solar energetic particles was widely recognized. These models predict and characterize SPEs starting from soft x-ray and microwave proxies, as well as optical information on the location of the active region. The use of these proxies contributes to the limited reliability of these models. Nevertheless, these models continue to be essential simply because real-time CME observations are not routinely available. The NOAA PROTONS model predicts the probability of an SPE exceeding its threshold criterion (peak intensity >10 protons/cm^2 per steradian at >10 MeV), and the time of occurrence and the value of the peak intensity. The USAF PPS predicts time, intensity, and spectra.

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Statistical Analyses of SPEs

There are now more than 40 years of solar particle event observations outside the mitigating influence of Earth's magnetic field. These data have been used to compile several statistical models of SPE frequency and intensities, for example in works by Feynman et al. (1993), Xapsos et al. (1998, 2000), and Nymmik (1999). These models are not meant to predict or characterize individual events. Instead, they are very useful in spacecraft design for approximating the number and type of SPEs that may be encountered during a given mission. Various versions of these trend analyses address peak proton flux and total proton fluence, but they do not adequately capture statistics on the spectral hardness of events, the probability of correlated successive events, or the distribution of "all-clear" periods—consecutive days with no solar event underway.

SPACE RADIATION CLIMATOLOGY

Nearly all of our knowledge of the space radiation environment comes from the past 50 years of the space age. All of our experience and "rules of thumb" for operating in this environment—from the slow, nearly constant rate of single-event upsets caused by GCRs, to lifetimes of solar panels that are continually degraded by the accumulated fluence of solar protons, to the probability and duration of all-clear periods—are based on this era. It is tempting to assume that the experience of the past 50 years is typical of the space radiation climate.

But there is one dataset—albeit more indirect than the satellite measurements of the space age—that offers a longer-term perspective: ice cores, which trap the products of reactions of GCR (McCracken and McDonald, 2004) and solar energetic particles (McCracken et al., 2001a,b) with constituents of Earth's atmosphere. Painstaking measurements and analysis of this unique archive have pushed the knowledge of the space radiation climate back more than 1,000 years. This long-term record offers three cautionary notes: (1) the experience of the space age is not typical, (2) there were periods in the past when the space radiation environment was significantly harsher and thus would have presented a much more challenging environment for the design and operation of Exploration systems, and (3) significant changes in the space radiation climate can occur on the timescale of decades, the same timescale envisioned for the Exploration initiative.

Ice-Core Results on Galactic Cosmic Radiation

To quantify the potential implications of changes in the level of GCR modulation, Figure 2-9 shows dose-depth calculations from four different runs of the Badhwar-O'Neill GCR model (O'Neill, 2007). In two of the runs, the modulation parameter was set at values typical of solar maximum and solar minimum in the space age. In the third run, the modulation parameter was reduced to 20 percent of the solar-minimum value, so as to correspond roughly to the highest GCR intensities inferred from the ice-core studies (McCracken et al., 2004). Finally, in the fourth run, the estimated local interstellar GCR spectrum (LIS), without any modulation whatsoever, was used. This run provides an upper limit on how severe the GCR exposure might become (barring a nearby supernova!): Figure 2-10 suggests that the dose rate from GCRs—even under substantial shielding—could be ~2 to ~8 times more severe than current expectations if the GCR level were to rise to the levels indicated by the ice cores.

Ice-Core Results on Solar Particle Events

McCracken et al. (2001a,b; see also Shea et al., 2006) have presented a comprehensive study of very large SPEs in ice-core nitrates since 1561 AD. Among the conclusions from their study:

- In the past 450 years, there have been SPEs in which the >30 MeV proton fluence was more than twice as large as the value given by King (1974) for the August 1972 event. (NASA has chosen the King description of the August 1972 event as the design standard for SPE radiation protection for astronauts.)
- The rate of such very large SPEs has been six to eight times larger in the past than what has been observed in the space age.

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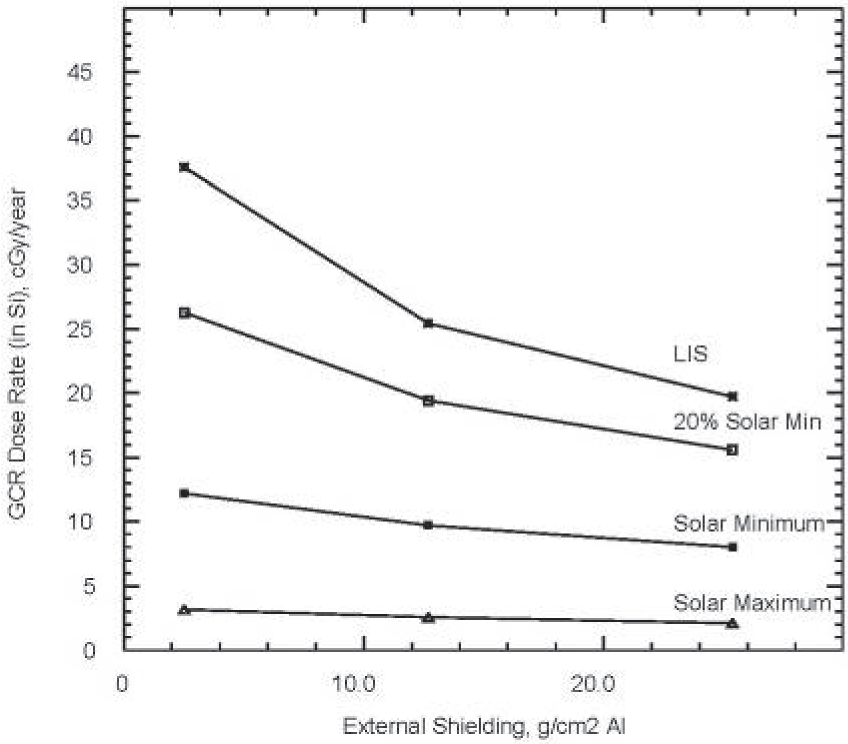

FIGURE 2-10 Dose rate versus depth of shielding from the Badhwar-O'Neill GCR model (O'Neill, 2007), under four different assumptions about the level of solar modulation. These calculations used a simplified transport code that did not include the dose contribution from projectile and target fragments produced in the shielding. NOTE: Dose rates are at 1 AU; LIS, local interstellar GCR spectrum. SOURCE: Provided by P.M. O'Neill, NASA Johnson Space Center, for this committee.

- The rates of these very large SPEs appear to have an ~80-year periodicity, corresponding to the so-called Gleissberg cycle in sunspot numbers.
- The space age has coincided with a minimum in the Gleissberg cycle and in SPE production.

McCracken and McDonald (2004) summarize the implications of their studies by saying:

> We predict that the frequency of large solar proton events may increase from its present low value by a factor of 6 to 8, commencing perhaps in Solar Cycle 24. Should this prediction be correct, the Earth will experience substantially more solar proton events and ground level events than has been our experience since 1950. This will have major implications for space flight and engineering.

It is worthwhile to see how Solar Cycle 23, which is just now drawing to a close, compares with previous experience from the space age. Figure 2-11 shows the cycle-integrated >10 MeV and >30 MeV solar proton fluences[3] for Cycles 19-23. These results show that Cycle 23 has had the largest >10 MeV solar proton fluence since the start of the space age. This is also true at >30 MeV, although the increment over Cycle 19 is small and probably within the systematic uncertainties. In any case, at both energies, the Cycle 23 fluences are clearly higher than those in Cycles 20 and 21.

[3]Total proton fluence is a more robust measure than "number of events," since many "events" actually comprise multiple outbursts, and there are no universally agreed criteria for how to count "events" in these circumstances.

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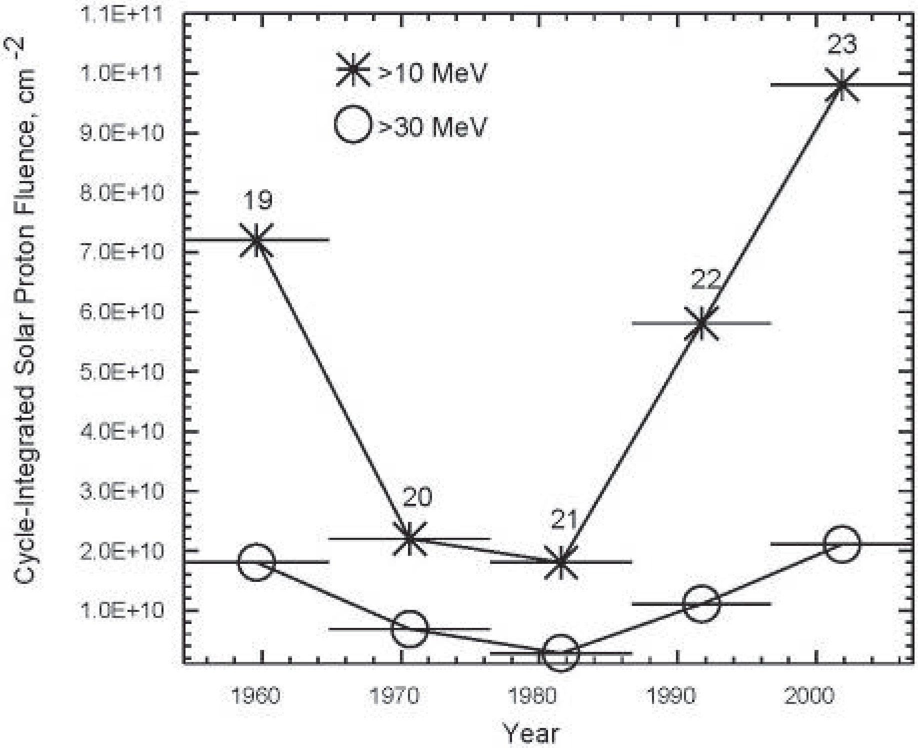

FIGURE 2-11 Cycle-integrated solar proton fluences >10 MeV and >30 MeV for Solar Cycles 19-23. Fluence numbers for Cycles 19-22 come from Shea and Smart (1990, 1999). Cycle 23 fluences were derived from the Geostationary Operational Environmental Satellite proton data available at the National Geophysical Data Center.

Are these upswings a statistical outlier? Or are they perhaps the first harbingers of the changes predicted by McCracken and McDonald (2004)? At this point, it is impossible to say with certainty. However, Feynman et al. (1993) present a statistical model of solar proton exposures, which quantifies the probability of observing a particular solar proton fluence in a given mission duration, based on the SPE database from 1963-1991. For each of these energies, that model[4] suggests only a ~7 percent probability for observing cycle-integrated fluences at least as large as those reported for Cycle 23.

Finding 2-4. Space radiation climate. Ice-core studies indicate that the past ~50 years may have coincided with a comparatively benign space radiation climate, in terms of both GCR modulation levels and the frequency of very large SPE events. Of particular concern is the possibility of a six- to eightfold increase in the number of very large SPE events, perhaps starting within the next decade. If such an increase were to occur, it would have a major impact on the design and operation of Exploration systems.

Recommendation 2-1. Planning for long-term changes in space climate. NASA must ultimately judge how much weight to assign to the cautionary findings from ice cores on a potentially more severe space radiation climate in the future. Given that the Exploration initiative envisions a commitment of the nation's resources that spans decades, NASA should ensure that the mission architecture has sufficient flexibility and margin to cope with such changes, should they occur.

[4]The relevant figures in Feynman et al. (1993) are Figure 4c and 4d. Note that the fluence on the horizontal axis of these figures has been mislabeled. The units should be cm^{-2}, not cm^{-2}-sr^{-1} (J. Feynman, personal communication with A. Tylka).

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At present, it is unclear whether or not this is the case. NASA should make an assessment of the potential impact of these radiation-climate changes on Exploration missions.

Knowledge Gaps

Coronal Mass Ejections

There is only a partial understanding of what causes a CME to erupt from the Sun and of the necessary and sufficient conditions by which a large, fast CME produces high intensities of high-energy particles of potential relevance to astronaut safety. The broad range of coordinated observations from a fleet of scientific satellites in the past 10 years has yielded substantial progress and focused attention on key unresolved issues. These issues encompass questions about the detailed physics of solar eruptions, particle acceleration, and transport processes, and the conditions under which they transpire. These questions can only be answered by new science missions that will sharpen and broaden our view of these phenomena. The planned Solar Dynamics Observatory will reveal the solar-magnetic topologies that give rise to CMEs. The recently launched STEREO satellites will provide the first three-dimensional view of CME eruptions; they will also map, for the first time, the longitudinal structure of large SPE events, something that is essential for developing predictive SPE capabilities for Mars. The proposed Sentinels mission (Lin, 2006) will provide in situ observations of the radial evolution of SPEs between the Sun and Earth, thereby providing unique data for developing physics-based SPE models. Modeling efforts, such as Boston University's Center for Integrated Space Weather Modeling, will incorporate these new sources of data into physics-based numerical simulations.

Current SPE prediction models make no utilization of what is already known about the role of fast CMEs in producing SPEs. A significant empirical correlation between CME speed and SPE intensity has long been known. Recent work has shown that the scatter in this correlation is tightened by identifying those CMEs for which another CME has erupted from the same active region in the previous day (Gopalswamy et al., 2004; Kahler and Vourlidas, 2005). At present, forecasters do not take advantage of these potential predictors, simply because routine real-time CME observations are not available to them. NASA and NOAA are presumably moving aggressively to alleviate this deficiency in preparation for Exploration missions. In the meantime, SPE-prediction algorithms incorporating this knowledge can be developed and tested using the extensive database acquired over the past decade.

One- to 3-day forecasts will require substantial improvements in our understanding of the physical causes of CMEs, the particle acceleration and transport mechanisms, the role of a "seed population" in generating very high energy particles, and the dynamics of the ambient solar wind. These investigations will need a focused effort and will involve a wider community of researchers. Note that there are additional reasons, beyond NASA, to acquire this understanding, as the CMEs and other space weather effects lead directly to other impacts at Earth.

The PROTONS and PPS models were developed under the paradigm that the particle acceleration occurred at the site of the associated x-ray flare. However, there is little correlation between the time, location, and magnitude of a flare and the time, location, and speed of an associated CME eruption other than a general relationship that very active solar regions generate large CMEs and big flares. Hence, current forecasting models do badly in predicting extreme events, and extreme events represent the greatest danger to human spaceflight crews. Observational data on the source CME and associated shock are available only from science platforms, and these data do not often have an operationally useful cadence or timeliness. Another weakness of each of these models is an inability to predict enhancements to the proton flux when a strong shock moving with the CME passes over Earth—potentially the most dangerous period to a human in space. Operational forecasts also do not include high-energy heavy ions, which may potentially impact spacecraft electronics.

There is general recognition within the NOAA SEC and the USAF that a more physics-based model of SPEs is needed to improve on these predictions. Nonetheless, a modest effort to identify better proxies or indicators of SPEs could offer some potential to marginally improve phenomenological SPE forecasts. Examples under investigation include the direct detection of interplanetary or solar surface shocks and x-ray spectral signatures that may presage SPEs. It may be possible to monitor the local arrival of energetic solar electrons as a precursor to large solar proton events, with an advanced warning of tens of minutes (Posner, 2007).

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Methods involving artificial intelligence, Bayesian inference, and locally weighted regression have demonstrated promise in providing nowcasting capabilities after energetic particles begin to arrive. These methods are capable of predicting, with reasonable accuracy, total doses and the future temporal evolution of the dose as particles arrive very early in the evolution of the event. Typically the forecasts are within 10 to 20 percent error of the actual profile before half of the event dose was received. However, sometimes one parameter was not adequately forecasted, which causes the event to be either over- or underpredicted (Hoff et al., 2003; Hines et al., 2005; Neal and Townsend, 2005). However, these methods are at present unable to forecast event fluence levels and their associated doses until after particles begin to arrive. Hence, they could provide a much-needed short-term capability for mission operations, but in a merely stopgap role. Computer codes implementing these models are currently research codes and not in the form of operational tools that are usable by mission operations personnel. However, operational tools using these codes are currently under development with funding provided by the NASA Living With a Star Targeted Research and Technology program.

Significant new capability exists within the space physics community—observations from ACE, SOHO, STEREO, and Wind, and the establishment of multiple interdisciplinary space weather modeling consortia such as the Center for Space Environment Monitoring at the University of Michigan or the Community Coordinated Modeling Center, a partnership of government agencies centered at Goddard Space Flight Center—provide a substantial opportunity to advance the state of the art in CME forecasting and thus better SPE forecasts. The STEREO mission and the planned Solar Dynamics Observatory will also contribute to the understanding of CMEs and SPEs. This knowledge in turn may help in two ways. First, it may help interpret the climatological data on SPEs, including the distribution of SPEs within the solar cycle and whether there are physical limits on the worst-case SPE. Second, a better understanding of the physics of CMEs and the particle acceleration process may lead to longer-term forecasts of all-clear periods, periods of hours to days when it is extremely unlikely for a significant event to occur.

Choice of the Design-Standard Solar Spectrum

NASA has adopted the proton spectrum of the August 1972 event, as parameterized in King (1974), as the standard for assessing the ability of shielding to reduce astronaut radiation exposure to acceptable levels during an SPE (NASA, 2006). This proton spectrum is shown in Figure 2-12. Also shown in Figure 2-12 is the spectrum of the October 1989 SPE, as given by Xapsos (2000). Both of these events were the product of three successive solar eruptions over a period of 6 days, as solar rotation carried an active region across the face of the Sun (Simnett, 1976; Sauer, 1993). In both cases, each successive eruption produced particle spectra that extended to higher energies, as observed at Earth. There are significant differences in the time structure of the two episodes, primarily associated with the arrival of a powerful shock at Earth on October 20, 1989, something for which there is no comparable feature in August 1972. Nevertheless, the reported event-integrated proton fluences below ~100 MeV are the same in these two events to within a factor of two.

Both of these events are very rare; there is no reason to regard either of them as intrinsically "less likely" than the other and therefore less appropriate as a standard for shielding design. There may be engineering reasons for adopting August 1972 as the design-standard event. But in terms of radiation safety, there is no reason to give it greater weight than the October 1989 event.

The critical difference between the two events becomes apparent when the spectra are examined above ~100 MeV, where the October 1989 spectrum is harder: it falls off much more slowly with increasing energy than the exponential form given by King for August 1972 (King, 1974). The potential implication for shielding is illustrated in Figure 2-13, which shows the dose from each of these spectra at the center of a spherical shell of aluminum, as a function of the shell's thickness. In these calculations, the aluminum shielding is followed by 8 g/cm^2 of water to crudely represent the body's self-shielding. The dose calculations in Figure 2-13 do not include the production of secondary neutrons in the shielding and are therefore lower limits on the dose. Although these calculations are highly simplified compared with NASA's state-of-the-art calculations for realistic spacecraft and habitat configurations, the results in Figure 2-13 nevertheless illustrate the reason for potential concern. If, for example, the objective were to reduce radiation exposure to 20 cGy (corresponding to roughly 30 cSv for a proton quality factor of 1.5), this level could be achieved for the August 1972 spectrum with about 8 g/cm^2 aluminum-

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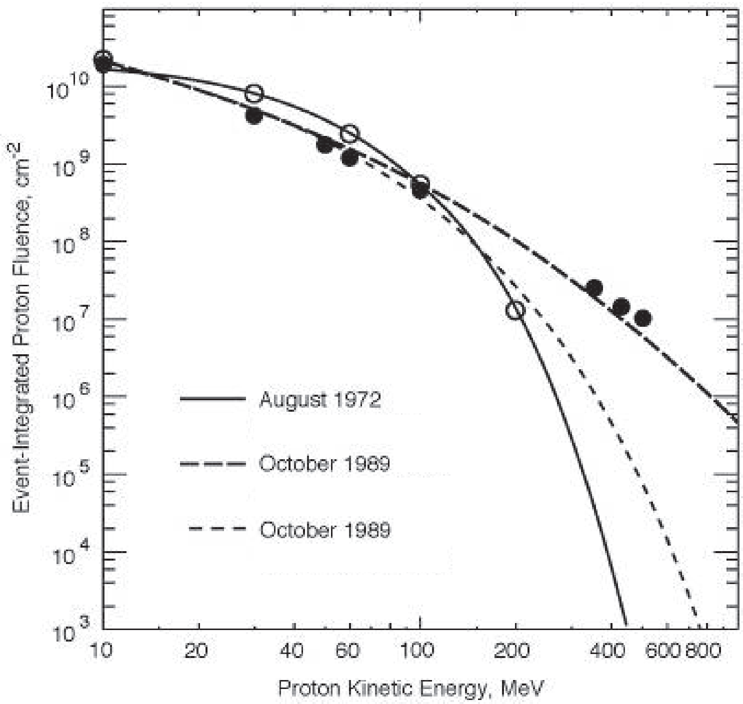

FIGURE 2-12 Representations of the event-integrated proton spectra for August 1972 (from King, 1974) and for October 1989 (from Wilson et al., 1999, and Xapsos, 2000). Measured data points (open circles of August 1972; filled circles for October 1989) are also shown, as discussed in the text.

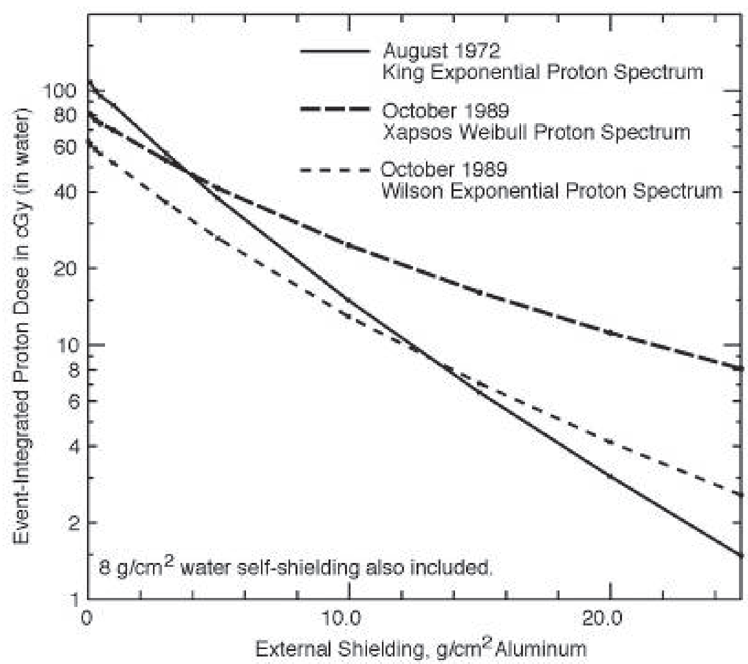

FIGURE 2-13 Dose-depth curves corresponding to the proton spectra in Figure 2-12. See the text for details.

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equivalent shielding. For the October 1989 spectrum, the shielding thickness required to reduce exposure to the same level would need to be roughly 50 percent larger, at about 12 g/cm^2. A more rigorous simulation of realistic shielding distributions will produce different numbers, but the relative magnitude of results from the two events may very well be on this order.

There is also another reason for hesitancy in adopting the King spectrum (King, 1974) as the final word in assessing the adequacy of astronaut radiation shielding. The data points in Figure 2-12 show the actual proton fluence measurements that were used in generating the King (1974) and Xapsos (2000) fits. All of these measurements come from satellites except for one: the highest-energy data point in the August 1972 event at 200 MeV. This data point, which largely determines the shape of the spectral fit, comes from a series of stratospheric balloon launches (Bazilevskaya et al., 1973). One cannot foreclose the possibility of significantly larger systematic error in the balloon data point. If that were the case, the King spectrum might not be a reliable representation of what actually occurred in August 1972, at least not above ~100 MeV.

It is also important to use the correct spectral form when making radiation calculations. The King spectrum for August 1972 (King, 1974) is exponential in energy. The Xapsos (2000) spectrum for October 1989 is a Weibull function in energy. Figure 2-12 also shows an older representation of the October 1989 spectrum (Wilson et al., 1999), which appears to be derived from an exponential fit in rigidity to GOES data points below 100 MeV (Townsend and Zapp, 1999). This older parameterization[5] is clearly inadequate in that it falls below the >300 MeV GOES data points by more than an order of magnitude. As a result, this alternative form is closer to the August 1972 spectrum at high energies and, as shown in Figure 2-13, leads to roughly comparable dose levels under ~10 g/cm^2 or more of spacecraft shielding. *Any comparative study of radiation exposure that has used an exponential-in-rigidity for the October 1989 spectrum is potentially invalid, especially for shielding thicknesses greater that ~5 g/cm^2. Any conclusions drawn from such studies should be re-examined.* These same concerns pertain to published spectra for the September 1989 SPE and perhaps other events as well.

Spectral extrapolations used in radiation-shielding calculations can be cross-checked against existing proton measurements in the range of ~200-500 MeV. There are several potential sources of such data that may not have been adequately exploited to date. NASA's Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) satellite provides solar proton measurements out to ~400 MeV for events since 1992 (Mewaldt et al., 2005a,b). Several GOES satellites have carried the High Energy Proton and Alpha Detector (HEPAD), which provided the data points above 300 MeV in Figure 2-12; data are available for most large SPEs since 1986. However, the HEPAD data are difficult to work with owing to uncertainties in the calibration and background-subtraction procedures (Smart and Shea, 1999) and poor documentation for the online HEPAD data available from the National Geophysical Data Center. Finally, neutron monitors can provide proton fluence measurements above ~500 MeV, as a check on whether a functional form falls too steeply at high energies. However, most published studies of neutron monitor observations to date have not included the absolute proton fluences that are required for radiation calculations.

Uncertainty in the spectral form of SPE protons has important implications for onboard particle detectors. These detectors will be an essential component of the radiation protection program for Exploration missions. They should be sized so as to measure the solar proton spectrum accurately out to ~500 MeV. They must also be designed so that dead-time effects and other data-rate limitations, which often plague particle instruments in very large SPEs, do not significantly compromise the reliability of the measurements.

Finally, the committee notes that the October 1989 SPE has been used as a design standard elsewhere in NASA. In particular, NASA has twice designated the Cosmic Ray Effects on Micro-Electronics (1996 revision) (CREME96) SPE model (Tylka et al., 1997) as the standard for electronics design in Exploration vehicles (NASA, 2006). This model is based on measurements of the October 1989 event, and its proton spectrum is essentially identical to that of Xapsos (2000). The factor of two is intended to raise the event to the level of a "worst case." CREME96 also includes solar heavy ions, since spacecraft electronics are potentially vulnerable to both solar protons and solar heavy ions.

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[5]This older representation was first developed when there were still substantial uncertainties about the reliability and potential relevance of the high-energy GOES measurements. The committee notes in passing that this erroneous spectrum for October 1989 has been reproduced in other comparisons of SPE spectra (e.g., Turner, 1999; Mewaldt et al., 2005a; NCRP, 2006).

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Finding 2-5. The King spectrum as a design standard. Although the committee recognizes the advantages of adopting a specific solar proton spectrum as the design standard, NASA's current strategy of evaluating the efficacy of an SPE shielding configuration using only the August 1972 King spectrum is not adequate. Under typical depths of shielding for Exploration vehicles, the level of radiation exposure produced by other large events in the historical record could exceed the exposure of August 1972.

Finding 2-6. Spectra data fitting. There is no theoretical basis for *any* of the published spectral fits to large SPEs. The extrapolation to energies beyond 100 MeV must therefore be guided by data. Solar proton spectral forms based on data that do not extend to ~500 MeV may very well give misleading results in evaluations of the efficacy of radiation shielding for astronauts.

Recommendation 2-2. SPE design standards. The dose levels made possible by a shielding design should also be calculated using the observed proton spectrum from other large events in the historical record, even if it is not feasible to modify the shielding design as a result. The October 1989 event is particularly important in this regard.

Recommendation 2-3. Uncertainties in spectra data fitting. NASA should make use of existing data to re-evaluate the spectra beyond 100 MeV in large events in the historical record and should assess the impact of uncertainties in the high-energy spectra on the adequacy of radiation shielding designs.

Solar Wind Models

As noted in the National Research Council report *Space Radiation Hazards and the Vision for Space Exploration* (NRC, 2006), reliable predictions of SPE onset and severity require an understanding of the heliospheric environment through which the energetic particles propagate. The ability to characterize the solar wind and interplanetary magnetic field accurately during and after the passage of CMEs is improving. The standard model in use operationally today is the Wang-Sheeley-Arge model (Arge and Pizzo, 2000), an empirical model based on observations of the solar magnetic field. More physics-based three-dimensional models are under development (e.g., Riley et al., 2001; Roussev et al., 2003). These models have not yet been validated with adequate spatial and temporal in situ observations. Data from NASA's current STEREO mission (to explore longitudinal structure at 1 AU) and NASA's proposed Sentinels mission (to explore radial dependencies inside of 1 AU) will be particularly valuable in this regard.

TRAPPED RADIATION

In addition to galactic cosmic rays and solar energetic particles, particles trapped in Earth's magnetic field comprise the third major component of the near-Earth ionizing radiation environment. The trapped particles in these "radiation belts" that surround Earth include electrons, protons, and heavier ions. At Earth, the trapped electron spectra extend out to about 10 MeV, and trapped proton spectra extend to hundreds of MeV. The trapped proton intensities near Earth are among the highest proton intensities potentially encountered by manned Exploration missions. Trapped protons are an important design consideration for all spacecraft operating in near-Earth orbits. Measurements to date indicate that the energy spectra of the heavy ions are soft and that their intensities above a few tens of MeV per nucleon are too small to be of practical concern.

The trapped particle models in current use are the AP-8 for protons and the AE-8 for electrons (Sawyer and Vette, 1976). Although the AP-8/AE-8 models are still widely used for spacecraft design, it is recognized that they are severely outdated because of the secular changes in Earth's magnetic field since the era when the measurements underlying the models were made. It is also now recognized that radiation belts vary on timescales shorter than just the solar maximum/solar minimum levels described in the AP-8/AE-8 models (e.g., Blake et al., 1992; Li et al., 1993). NASA's Living with a Star program's Radiation Belt Storm Probes, which are scheduled for launch in 2012, are expected to provide measurements that will be the basis for new models. In the meantime, there are also efforts aimed at extending the capabilities of existing models and improving their accuracy through re-analysis of

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TABLE 2-1 Average Radiation Doses of the Apollo Mission Flight Crews

Apollo Mission	Skin Dose (cGy)
7[a]	0.16
8	0.16
9[a]	0.2
10	0.48
11	0.18
12	0.58
13	0.24
14	1.14
15	0.3
16	0.51
17	0.55

[a] Low-Earth-orbit missions—did not go to the Moon. SOURCE: Bailey, 1975.

existing datasets (Ginet and O'Brien, 2007; Ginet et al., 2007). Beta versions of the new models (designated AP-9 and AE-9) are scheduled for release in the 2009-2010 time frame. Efforts at improving models of Earth's trapped radiation are important for other NASA missions, as well as for DOD and for the commercial use of space.

The magnetic fields on the Moon and at Mars are vestigial; they are too weak to sustain any trapped-particle population. Accordingly, trapped radiation will not be considered further in this report, except to note that the exploration vehicles must pass through Earth's radiation belts when departing from and returning to Earth. Unlike crews on the space shuttle and the ISS, whose orbits just clip the lower reaches of the radiation belts, crews on exploration vehicles can potentially be exposed to much larger doses while transiting Earth's radiation belts. In fact, as shown in Table 2-1, the largest radiation exposure of the Apollo era occurred on Apollo 14, when the return trajectory carried the spacecraft through an intense region of trapped protons. Although the additional dose in the case of Apollo 14 was less than 1 cGy, mission planners should bear this experience in mind. Avoidance of such an exposure is an example of the purpose of attention to the As Low As Reasonably Achievable (ALARA) principle.

SECONDARY RADIATION

Whenever the local space radiation environment in deep space impinges on the shell of the spacecraft, the solar and galactic cosmic rays penetrate the spacecraft structure and shielding and their physical characteristics are altered by atomic and nuclear collisions with the constituent atoms of the structural and shielding materials. The physical changes in these radiation fields as they pass through bulk material shielding (and through body tissues overlying critical organs) include energy losses, mainly due to atomic collisions and nuclear elastic and inelastic collisions, and changes in particle identities resulting from nuclear fragmentation reactions that produce secondary neutrons, protons, mesons, and heavier charged particles. Fragmentation occurs in both the projectile, which is usually moving at high speeds, and in the target, which is usually stationary or nearly so. Hence, the more energetic secondary radiations are generally produced from the projectile nuclei. These alterations in the composition of the radiation fields as they pass through the spacecraft and crew members' bodies are described by radiation transport codes, which must include the effects of spacecraft and human geometries. Biological damage, and the concomitant risk to crew members, result from interactions of the altered, transported radiation environment at the local organ or tissue site. This local radiation environment will be some mixture of primary and secondary radiations, which vary depending on the material composition and thickness of the target materials. Figure 2-14 depicts the complexity associated with these internal radiation fields, where the external radiation interacts with the spacecraft structure creating an internal environment that is different in composition from the external one. As the thickness of the spacecraft walls increases, the differences between the internal and external environments

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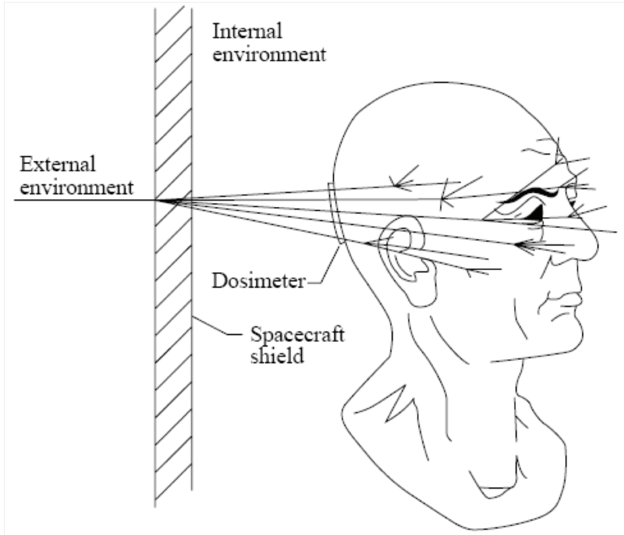

FIGURE 2-14 Schematic of the space radiation protection problem. SOURCE: Wilson et al., 1997.

increase as well. Because of self-shielding of internal body organs by overlying tissue, the local radiation fields at the internal organs are different from the internal environment within the spacecraft. Dosimetric quantities, such as dose, dose equivalent, and effective dose, which are presumed to be related to biological risk, can then be estimated from the calculated local particle fluxes and energies, in the tissue or organ of interest. These radiation transport methods can also be used to assess damage to spacecraft electronics.

One representative calculation of the percentage variation in organ dose-equivalent contributions from incident galactic cosmic rays and their secondary radiations, produced by projectile and target fragmentation processes, is displayed in Table 2-2. The calculations assumed spacecraft aluminum shielding of the indicated area density,

TABLE 2-2 Percentage Contributions to the Annual Total Dose Equivalent, Rounded to the Nearest Whole Percent, from Surviving Incident Galactic Cosmic Rays, Their Projectile Fragmentation Products, and Target Nuclear Fragments for Various Organs and Several Thicknesses of Aluminum Shielding

Type Contribution	Skin (g/cm^2)	Ocular Lens (g/cm^2)	Bone Marrow (g/cm^2)
No aluminum shielding			
Incident ions	89	86	65
Projectile fragments	9	11	30
Target fragments	2	3	5
5 g/cm^2 aluminum shielding			
Incident ions	90	79	62
Projectile fragments	6	17	35
Target fragments	4	4	3
30 g/cm^2 aluminum shielding			
Incident ions	56	56	49
Projectile fragments	39	39	45
Target fragments	5	5	5

SOURCE: Townsend et al., 1992. Reprinted with permission from the Radiation Research Society.

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and employed the Computerized Anatomical Man model of human geometry. Note that even with no external shielding, secondary radiation fields produced by the overlying body tissue will be responsible for about one-third of the bone marrow dose equivalent, and more than 10 percent of the skin and eye dose equivalents. As the spacecraft shield thickness increases, the increased production of secondary radiations results in an increase in their percentage contributions to the organ dose equivalents. Note that most of the organ dose equivalent behind 30 g/cm^2 aluminum shielding results from secondary radiations produced in the spacecraft structure and overlying body tissues of the astronauts.

Figure 2-15 displays the dose equivalent (*H*) in water (a surrogate for tissue) for an incident galactic cosmic radiation spectrum (1977 solar minimum) after passage through the indicated thickness (area density) of aluminum and an additional 10 cm of water. These dose equivalents are fairly representative of bone marrow values. Note that the contribution from ions heavier than neon (Z = 10) decreases rapidly as the shield thickness increases, as does the contribution from lighter ions ranging from lithium (Z = 3) through fluorine (Z = 9). This rapid decrease in the contributions from ions heavier than helium (Z = 2) is due to a combination of their rapid energy losses from Coulomb scattering with atomic electrons and to their breakup (fragmentation) into lighter ions with smaller atomic numbers as they penetrate the shield. Low-energy, heavy particles stop very quickly owing to their large stopping powers. Hence, the values for *H* are large for thin shields. If the heavy ions did not fragment, the dose from them would increase as they slowed. However, as the higher-energy particles penetrate, they break up into

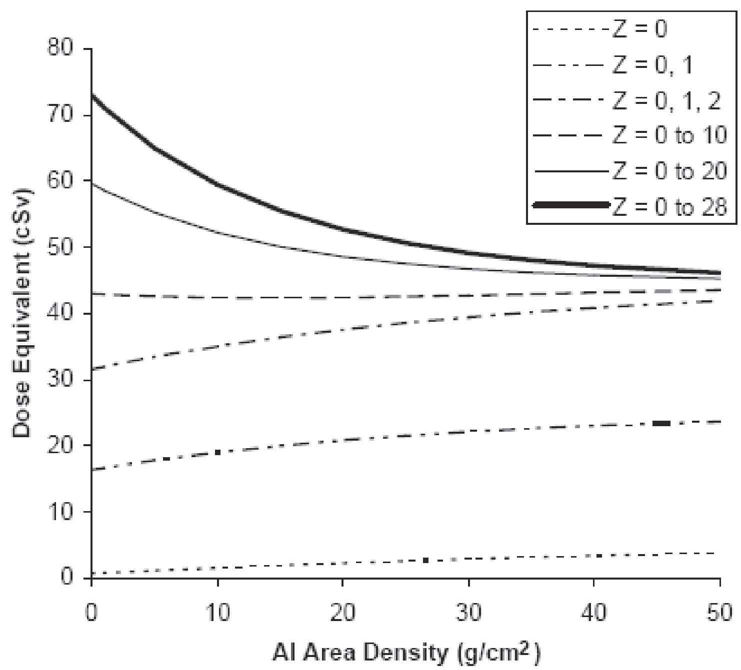

FIGURE 2-15 Annual dose equivalent in centisieverts (cSv) for the 1977 GCR solar minimum spectrum of Badhwar and O'Neill as a function of aluminum shielding area density plus 10 cm of water (to approximate body self-shielding for bone marrow). The bottom curve (labeled Z = 0) displays the contribution due to neutrons. The curve labeled Z = 0, 1 displays the cumulative contributions due to protons and neutrons (The difference between the two curves is the contribution due solely to protons). The curve labeled Z = 0, 1, 2 displays contributions resulting from adding the Z = 2 particles to the Z = 0, 1 results. The spectrum builds until all contributions for Z = 0 through 28 have been included (top curve). Note that the contributions from Z = 0, 1, and 2 gradually increase as the Al area density increases, whereas the contributions from the heavy ions (Z > 2) decrease with increasing Al area density because they are removed by fragmentation (breakup) processes in the Al shield and in the overlying body tissue. SOURCE: Generated with HZETRN (see Appendix D), quality factors from ICRP (1991).

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lighter fragments, which have smaller stopping powers (less dose per particle) and also lower *Q* values per particle. As they continue to penetrate, they fragment into smaller ions and eventually no longer contribute to $Z > 2$; instead they now contribute to the $Z = 1, 2$ spectra. The total dose equivalent versus depth curve then decreases much more slowly, as the shield thickness increases, because of the large numbers of neutrons, hydrogen nuclei (mainly protons), and helium nuclei (mainly alpha particles) produced by fragmentation. The hydrogen and helium spectra are mixtures of primary and secondary particles. The neutron spectra are all secondary neutrons since there are no neutrons in the incident spectrum. These lighter particles have ranges and collision mean-free paths that are much larger than the more highly charged parent nuclei that produced them, which accounts for this slowly decreasing trend in the dose-equivalent versus shield-thickness curves.

Knowledge Gaps

There is a serious concern about the purely one-dimensional nature of the space radiation transport codes used to estimate shielding requirements and potential biological risks to crews on deep-space missions, including planned lunar missions. Based on presentations to the committee by John Wilson from the NASA Langley Research Center ("Current and Projected Radiation Shielding Approaches and Capabilities," December 12, 2006) and on the report of the shielding workshop held at the center in January 2007 (NASA/NIA, 2007), significant attention has been paid to "fragmentation" cross sections (i.e., probability of interaction). There has also been some work reported on "charge-changing cross sections." However, there were no references to dependence on angle or energy of the fragments. For an incident-GCR projectile and any material target nuclei, there will be one or more fragments coming out of any nuclear interaction, at different energies and into different directions. The data necessary for calculations of GCR shielding come in various levels. In the presentations to the committee, "fragmentation" was used to denote the probability of one given fragment, of any energy, being emitted into a small cone pointed in the forward direction (at 0 degrees). This is useful but limited information. For shielding materials that are not too thick, most of the fragments will continue in a fairly narrow cone in the forward direction, so not much is missed by detecting them with a small detector. However, the fragments' energies at any point inside a shielding material will depend on the interaction location where they were made. As the shielding material gets thicker, some of the fragments will be made by second, third, and further generations of interacting particles. For that reason, measurements of the energy of the outgoing particle in thick shielding are an essential test of the contribution of intermediate reaction products to the final mix. At that point, angular distributions begin to be important. Finally, when a galactic cosmic ray projectile undergoes a nuclear reaction, it breaks up into many pieces, not just one or two. As a result, several fairly heavy fragments may come out close together, at the same time. The number of fragments, or "multiplicity," is an important component of knowledge about the reaction.

RADIATION FROM NUCLEAR GROUND POWER

Under its technology development program, NASA is developing fission reactors for potential use during Exploration missions. Such reactors will be particularly valuable on nonpolar locations on the Moon and will also be particularly valuable on Mars, since solar power will not be sufficient in either location. Presented below is a review of the knowledge of radiation environments associated with nuclear reactors. The engineering challenges associated with the safe operation of nuclear reactors are discussed in Chapter 4.

Development and Use of Nuclear Ground Power

Although discovered in 1939, the nuclear fission chain reaction was not harnessed until the 1950s for commercial use in nuclear reactors. The first electricity-generating nuclear power plant was the Experimental Breeder Reactor-I, at the National Reactor Testing Station in Idaho. It initially produced nearly 100 kW, enough to power the equipment in the small reactor building (Fischer, 1997). To date there are 436 nuclear power plants in the world, operating in 32 countries, with a total capacity of 370,000 MW, providing 16 percent of total electricity generation. Terrestrial nuclear engineering and technology proved safe and accurate, and nuclear engineers gained tremendous

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experience in building and using smaller nuclear reactor units for research, training, education, materials testing, and the production of radioisotopes for medicine and industry, and for propelling ships and submarines. There are 284 research reactors, operating in 56 countries, and more than 220 submarine reactors.

Radiation from Terrestrial Nuclear Ground Power Plants

The principal concerns and fear regarding the operation of nuclear power plants arise from perceived risk associated with potential exposure to radiation and effects of radiation on health. More than 50 years of nuclear power development and usage have resulted in only two major accidents, the Three Mile Island (TMI) (in the United States in 1979) and Chernobyl (in Ukraine in 1986). The sequence of certain events including equipment malfunctions, design-related problems, and worker errors led to a partial meltdown of the TMI-2 reactor core, but only very small and insignificant off-site releases of radioactivity.[6] The experience from this accident, based on decades-long measurements and analysis, shows that radioactive material was not readily mobilized beyond the immediate internal reactor structure, and thus has helped create better understanding of the predictions related to radioactive releases in the environment. Apart from the Chernobyl accident that released significant amount of radioactive isotopes into the environment, no single nuclear worker or member of the public has died due to radioactive exposure from civil nuclear power plant operation.

Most of the radiation exposure for the average person dwelling in the United States comes from natural background radiation (55%), while the main remaining exposure comes from medical procedures (15%), cosmic radiation (8%), and soil (8%) (NCRP, 1987[7]). The accumulated experience in using nuclear technology shows that the overall risk from the normal operation of nuclear power plants (including the fuel cycle and probabilistic prediction of potential design-basis accidents) will contribute around 0.05 percent of the total dose.[8] Several large studies in the United States, Canada, and Europe have found no evidence of any increase in cancer mortality among people living near nuclear ground power plants. For example, the National Cancer Institute of the National Institutes of Health has reported in a fact sheet (available at http://www.cancer.gov/cancertopics/factsheet/Risk/nuclear-facilities) on the results of a survey that evaluated mortality from 16 types of cancer and found no increased incidence of cancer mortality for people living near 62 power plants in the United States, and also no increase in the incidence of childhood leukemia mortality (Jablon et al., 1991).

Radiation Shielding and Control

Nuclear reactors are carefully designed with a number of engineering barriers that prevent the release of radioactive material and ensure safe and reliable isolation from the environment. The main safety design criteria are intended to reduce the chance of release of radioactive materials into the environment during normal operation and accidents. Besides a number of primary and backup systems employed to monitor, control, and support the safe operation of a plant, each of the reactors has a well-designed series of engineering and physical barriers with the ultimate goal of preventing discharge of radioactive materials.

Regulations and Policy

The U.S. Nuclear Regulatory Commission (U.S. NRC) is the federal agency that establishes the policy and controls the radioactive release from nuclear ground power into the environment. The U.S. NRC's mission is "to protect public health and safety and the environment from the effects of radiation from nuclear reactors, materials, and waste facilities," including nuclear materials used in commercial nuclear ground power.[9] The U.S. NRC requires

[6]See U.S. NRC, Fact Sheet on TMI Accident, available at http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html.

[7]A committee of the National Council on Radiation Protection and Measurements (NCRP) is currently compiling an update of these statistics. Although updated statistics were not available in time for this report, it is known, for example, that the exposure due to medical procedures has increased by 650 percent (Mettler, 2007).

[8]See IAEA Power Reactor Information System, available at http://www.iaea.org/programmes/a2/index.html.

[9]See U.S. NRC Web site, http://www.nrc.gov/about-nrc/radiation.html.

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that the plant operator monitor the environmental impact of the nuclear power plant by measuring airborne and liquid radioactive effluents and taking radioactivity readings from the air, water, animals, and plants surrounding the facility (U.S. NRC, 2002). Since the attacks on September 11, 2001, the U.S. NRC has strengthened the regulations on nuclear reactor security.

Finding 2-7. Knowledge of radiation from nuclear ground power. Experience with nuclear power on Earth has provided sufficient knowledge to create this capability on the Moon. The remaining challenges are engineering problems, not scientific problems. Experiments to show the operational safety of space and planetary-surface fission power systems, including unique design features such as compactness, light weight, and heat transport and heat rejection in reduced gravity, will be important.

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3

Radiation Effects

EFFECTS ON HUMANS

Some Elementary Concepts in Radiation Biology

In order to understand the mechanisms by which human beings are threatened by exposure to radiation, one must consider a living organism as any other system, in terms of its parts and how well they work together. An airplane, which is one of the more complicated achievements of engineering, could be described as 50,000 parts flying in formation. A human being is approximately 10^{14} parts, not only flying in formation but also engaged in parallel processing and generation of information. An airplane cannot safely miss any parts (bolts, wires, seats) or parts of systems (metal skin on wings, fuel tank hoses, computers); similarly, an organism cannot safely miss too many cells in its brain or its heart, nor survive the loss of essential tissues and organs. Furthermore, while understanding the effect of a given scenario on one airplane can be reasonably extended to other airplanes, the effects of radiation on human beings are different from person to person. Radiation biologists must take into consideration interindividual differences, as well as determine if effects on individual systems in isolation are consistent with the effects on an organism as a whole. However, an airplane cannot repair itself, reproduce itself, or decide where it wants to fly. A human being can do all those things, and many more.

The parts of a living organism are the cells and their aggregation into correlated groups, that is, tissues and organs. Two minimal conditions must be met for the organism to be healthy: all the critical parts must be there, and they all must function together properly. The number of cells required for proper tissue and organ function is determined by the ability of cells to divide and maintain their structure. The function of tissues and organs is determined by the ability of constituent cells to keep sending and receiving the required signaling molecules. In a healthy organism, all the required cells are there, and talk to each other in a timely and businesslike manner. All of these aspects of living systems can be perturbed, in many cases permanently, by exposure to radiation, as summarized in Figure 3-1.

When an organism is exposed to radiation, the energy from the radiation is deposited at the cellular level by interactions between the radiation and the electrons of molecules making up the cells. As a consequence, the carbon, oxygen, nitrogen, and other atoms that make up complex molecules may lose the electron bonds that tie them to the rest of the molecule. In many cases, they don't move very far, and other electrons can be used to re-establish the chemical bonds. In some cases, however, the molecule does not recover. In the case of template molecules such as deoxyribonucleic acid (DNA), this changes the cell's ability to manufacture the proper signals at the proper time.

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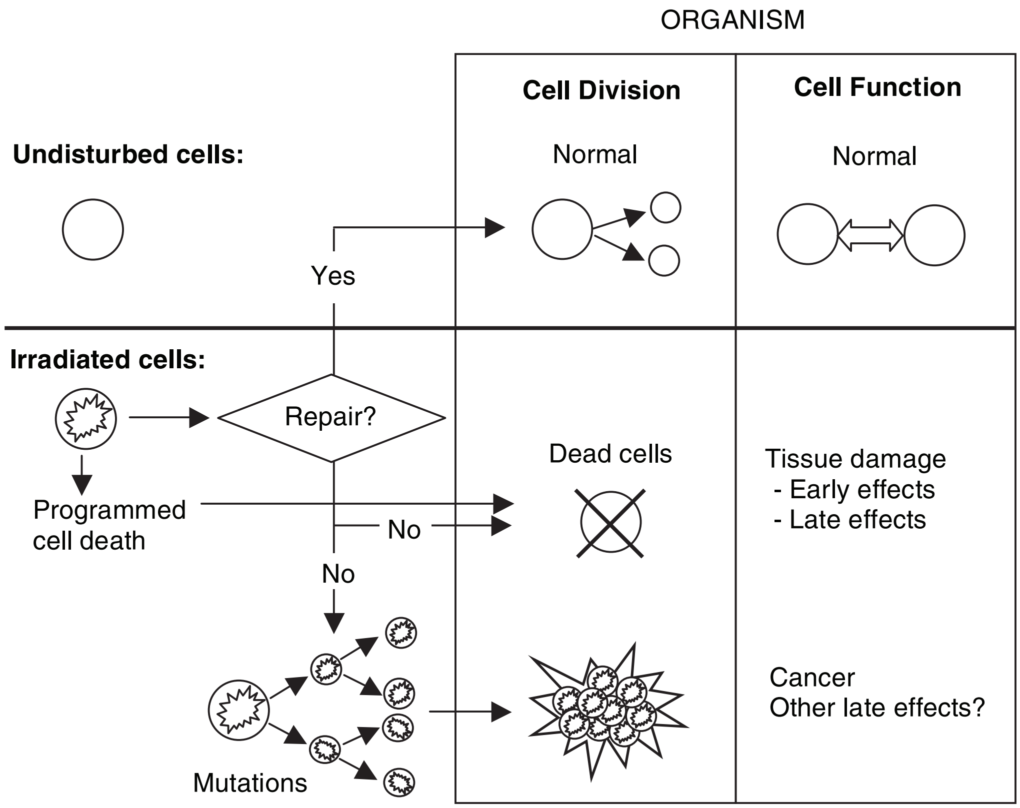

FIGURE 3-1 Pathways of biological damage produced by exposure to radiation.

An irradiated cell may be able to repair any damage that it has suffered, using one or more of several chemical pathways available in nature. If it repairs itself correctly, then, by definition, it is indistinguishable from a normal cell and goes back to its undisturbed state. If the cell does not repair the damage, it may die. In that case, it is removed from the system. In principle, this is a good thing, because a dead cell cannot become a cancer cell. However, if too many cells of a tissue die, organ function will be compromised. If sensitive cells, for example, cells in the gut, die in large enough numbers, then the gut cannot absorb food or maintain electrolyte balance. This is why, after a dose of radiation killing a large enough number of cells, nausea and vomiting set in. However, if the radiation dose is delivered over a period of time that is long compared with the repair time constant of the cells, the cells can repair and maintain, or delete and replace, a sufficient number of cells for function to be undisturbed. These different radiation time courses are referred to as "early" and "late," to describe how the body responds to different dose rates.

Cellular repair mechanisms are not always fully successful. In some cases, repair can leave the cell in sufficiently good shape to limp through another few cell divisions, thus maintaining the number of cells for a while. However, the daughter cells will inherit some of the original, incompletely or poorly repaired damage and die off or lead to dying or aberrant cells in subsequent divisions. This unstable state of the cell and its progeny is often called genomic instability, but is not fully understood and is likely to encompass a much broader range of phenomena, including possible responses to molecular signals from nearby damaged cells. In any case, the eventual death of cells is also good for the organism, again since dead cells cannot initiate cancer. However, just as in the case of acute effects, the loss of too many cells will compromise tissue and organ function, possibly leading to serious consequences and even death. While these effects are similar to acute effects, the fact that they do not

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occur more or less immediately during or after irradiation means that other biological processes can be significant, and thus the consequences can be different. Chronic effects of radiation appear to involve the induction of a cytokine cascade as a response to tissue damage. This often leads to the replacement of a functional cell type with fibrocytes, thus causing fibrosis and other dysfunctional processes. Other undefined mechanisms may also contribute to late effects.

However, ionizing radiation injures normal cells through various molecular pathways. In general, the radiation sensitivity of a given tissue, and in turn of a given organ, depends on the radiation sensitivity of the key cells in the system, although there appears to be much interaction among the tissues, so that effects on one tissue can have impact on other organ systems in the body. Also important in understanding radiation sensitivity studies are several physical and biological variables: dose size, dose mode (internal or external), dose rate, fractionation (division of the total dose into small doses administered at intervals), the size of the irradiated field, the time of observation after exposure, and the condition of the stroma and vascular supply. If full repair of cells fails, but not to the point of leading to the death of subsequent generations of cells, damaged cells may survive and transform into cells that can become cancer precursors or change further and develop into tumors. Even if a damaged cell does not evolve into cancerous tissue, its communication with other cells may be impaired to the point that it cannot provide adequate limiting or stimulating signals for proper function within a given tissue. For example, most higher organisms carry a complement of reserve cells. These "stem" cells can differentiate into cells of any description, and can replace them. If stem cells are damaged, they may not properly differentiate and learn to function in a given tissue. For instance, cells in blood vessels in the brain may lose properties required to keep blood contained, possibly leading to stroke. The use of stem cell replacement therapy, especially for bone marrow, has been considered by NASA for many years, but the difficulties associated with performing such procedures in space have been considered too great to overcome.

The delayed effects of radiation are not independent of the initial events, as any damage to cells may take time to manifest, after they have reproduced, interacted with other cells, and undergone evolution of whole-tissue responses. Figure 3-2 shows the time course of radiation injury for somatic cells, thus excluding genetic and hereditary aspects, which are less well understood but also can be assumed to follow their own, complex time course.

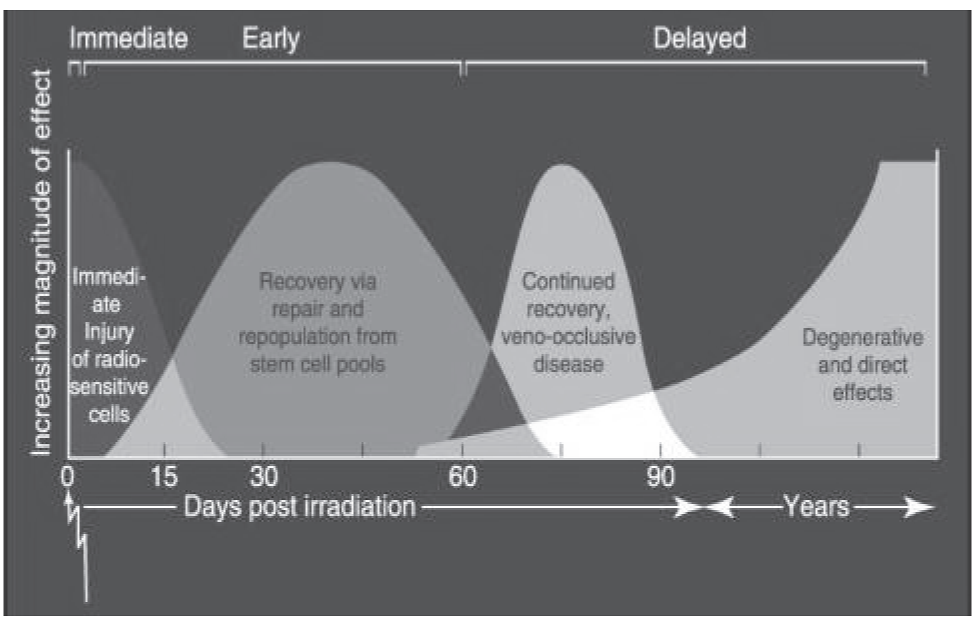

FIGURE 3-2 Temporal relationships among somatic effects. SOURCE: Fajardo et al., 2001. Copyright 2001; reprinted with permission from Oxford University Press.

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Finally, it is useful to distinguish between effects on the properties of cell systems, such as tissues and organs, and the consequences of modifying single cells. The function of tissues and organs persists to some extent, even when cells are lost. It is only when a substantial number of cells are missing that the tissue structure or the organ function cannot continue. Thus, tissue and organ effects are characterized by a threshold beyond which the loss of function is irreversible. The threshold will be characterized by a step function with a slope that depends on the number of cells required for minimal function, their replacement, the rate of loss of support structure and fluids, external intervention, and so on. The term for these effects is "deterministic," to indicate that they will occur inevitably once a certain dose of radiation is delivered. As an example, Figure 3-3 shows the calculated probability of radiation exposure leading to death as a function of radiation dose and medical treatment. The acute response curves in the figure show that thresholds are generally quite sharp, so that any uncertainty in the dose (or in conversion of the dose into a biological common scale) is quickly amplified by the response probability, and a small probability may, in actual fact, be significantly larger.

To the contrary, the degree of repair and the transformation of a single cell are stochastic variables, described by a probability distribution. Particularly at the lowest doses of radiation, which are of greatest interest for the consideration of occupational radiation exposure and where no deterministic effects are likely to be observed, radiation exposure may lead a cell to the initial stage of cancer, or may lead a cell to induce another cell to do so. These processes are modeled probabilistically, which indicates their vastly different scientific complexity. Figure 3-3 shows an estimated nonzero probability even for the smallest doses.

Cancer risks are not measured but calculated using absorbed dose from radiation, following prescriptions such as are given in NCRP Report 132 (NCRP, 2000). Such calculations are a function of a multitude of factors, and the uncertainties in the knowledge of these factors propagate to result in uncertainties in the calculated risk. Thus, the risk is given by a probability distribution function (PDF) and not by a point estimate. The uncertainties in these calculations can be estimated and the PDF evaluated for various radiation environments (NCRP, 1997; Cucinotta et al., 2001) to obtain probability distributions for the risk incurred at a given dose. As an example, Figure 3-4

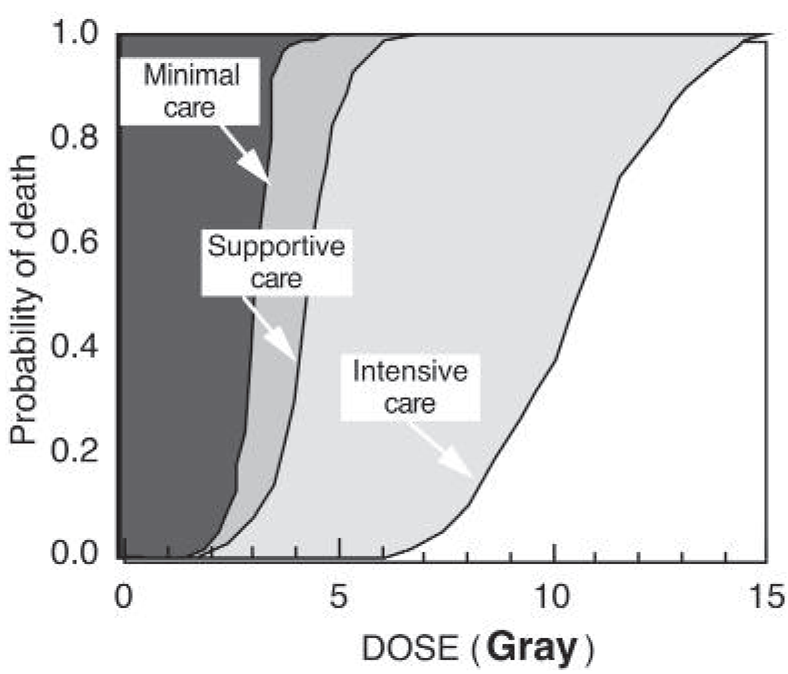

FIGURE 3-3 Risk versus dose for different levels of medical treatment. NOTE: Although this figure is based on work of the National Council on Radiation Protection and Measurements (NCRP), advances in supportive care have dramatically changed the shape of the supportive curve. It is much closer to that seen for intensive care. SOURCE: Adapted from NCRP, 1989.

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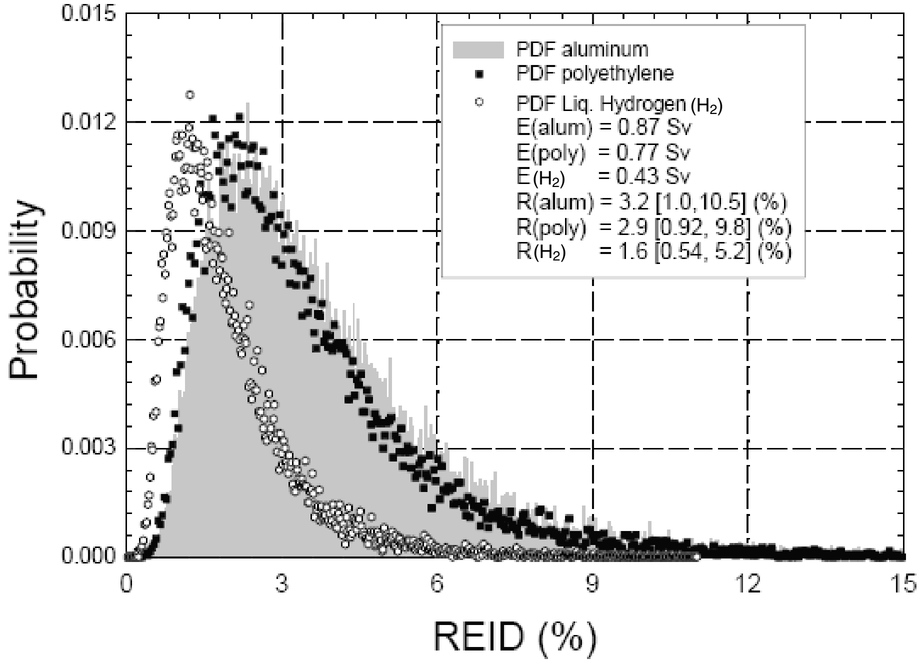

FIGURE 3-4 Probability density functions (PDFs) for 40-year-old males on a solar minimum Mars swing-by mission behind 20-g/cm^2 shields of aluminum, polyethylene, or liquid hydrogen. Effective doses, point estimates, and 95 percent confidence interval for risk of exposure-induced death (REID) are shown in the inset. SOURCE: Cucinotta et al., 2005.

shows the PDFs representing uncertainties in projecting fatal cancer risk (in the form of risk of exposure induced death; REID) associated with a Mars swing-by mission (600 days), for three different kinds of shielding. The area under the curve represents the cumulative probability of that value for REID. In the case of aluminum, half the area under the curve lies to the left of REID = 3.2% (the other half lies to the right); only 5% of the area under the curve lies to the right of REID = 10.5%, making that the 95% confidence-level upper limit. Similarly, only 5% of the area lies to the left of REID = 1.0%, making that the 95% confidence-level lower limit. These PDFs are generated by using Monte Carlo methods to propagate risk from the component biological and physical uncertainties through the risk estimate process.

Similar calculations have been made for GCR at various dose levels (Cucinotta et al., 2001), using quality factors and extrapolation from low-linear-energy-transfer (LET) epidemiology studies, and on mechanistic insights from ground-based studies conducted at facilities such as the NASA Space Radiation Laboratory (NSRL). The use of a linear extrapolation without a threshold, as is customary in the interpretation of the atomic bomb survivor data on which epidemiological dose response is based, means that, at any given dose, there is a definite probability of incurring a fatal cancer, even if the mean (or any other point estimate) may correspond to a minor risk. At higher values of LET, the mean risk of fatal cancer increases, following the rise of the quality factor. Only at the highest values of LET, or for high doses at any LET, the mean risk begins to decrease, as a consequence of the decreasing survival of highly irradiated cells. However, very high values of LET for high atomic number and energy (HZE) particles do not necessarily translate to decreased cell survival. Because of the track structure at large velocities (i.e., $\beta = 0.88$ for Fe with a LET of 150 keV/μm), many cells may only receive small doses of electrons (delta rays) that are not necessarily fatal.

Despite recent progress made in the area of space radiobiology, especially in studies relevant to carcinogenesis, many uncertainties remain about the specific biological effects of extended GCR and solar particle event (SPE)

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exposure. An example of estimates of the probability of REID, presented by NASA, is found in Table 1-4, where the uncertainty ratio (the ratio between the upper end of the confidence interval and the mean risk prediction) is generally around 3.

Much of what is known of the biological effects of space radiation has come out of NASA's Space Radiation Biology Research program. The strategy of this research program was based on a rational calculation that breakthroughs in biology have occurred at a rapid rate, reflecting the status of biology as the cutting edge of science. Early in the program's conception, Curtis et al. (1995) estimated the radiation risk uncertainty ratio to be 4-15×. A National Research Council (NRC) report (NRC, 1996) estimated that the likely time for reducing these uncertainties would require a timescale extending beyond the working lifetime of program scientists. Accordingly, the program budget and level of effort were increased so that, based solely on work within this program, the uncertainty could be halved within 10 to 15 years. However, the calculation that breakthroughs would occur inevitably in a fast-moving, revolutionized science field like biology led to the expectation that even greater reductions are possible within that time frame. In the year 2000, the uncertainty ratio was recalculated to be as high as 6× for a 1,000-day mission to Mars (Cucinotta et al., 2001). Several uncertainty ratio reduction curves are shown in Figure 3-5. The curve corresponding to the uncertainty ratio dropping by half over 30 years (representing the progress before the program was accelerated) is shown together with a curve assuming that the uncertainty ratio can be halved in 15 years under continuous progress, as estimated for the increase in funded research. However, using an assumption, for illustrative purposes, that breakthroughs that can help reduce the uncertainty by a factor of 2 occur about once every 5 years, it may be seen that a reduction in the uncertainty ratio to 1.5× would be achievable around 2015; 1.5× (meaning that risk is estimated to within ±50 percent) is an estimate of the best that one could expect to do about the risk uncertainty; once this level is attained, research can be more productively focused elsewhere. Some examples of breakthroughs, available in 2005, were as follows:

- Cancer susceptibility genes for which genetic testing is available have been discovered; examples include the gene for hereditary retinoblastoma, the breast cancer genes BRCA1 and BRCA2, genes associated with some types of colon cancer, and a gene that is involved in susceptibility to cancer development and is associated with radiation sensitivity—the gene for ataxia telangiectasia.
- Signal transduction pathways have been defined that link cellular communication systems and result in altered gene expression and altered cellular phenotypes; new information on such pathways is being obtained on an almost daily basis.

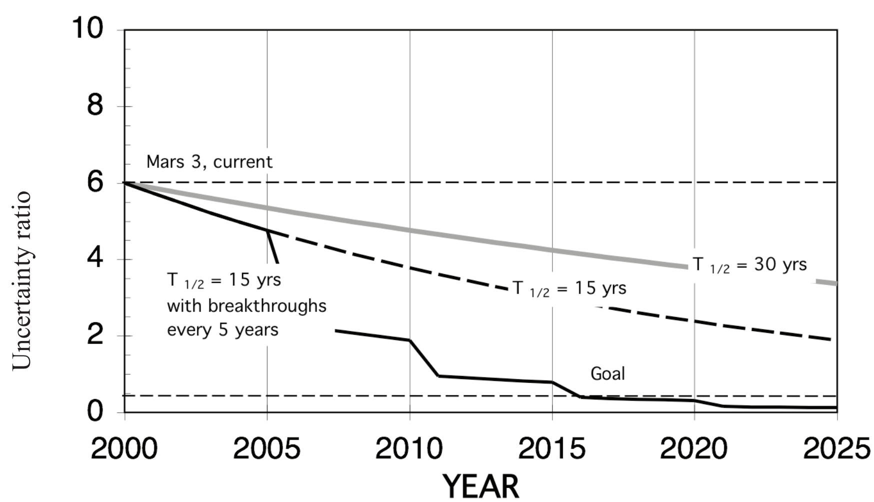

FIGURE 3-5 Evolution of risk uncertainty for Mars exploration. SOURCE: Adapted from NASA, 1998.

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- Mechanisms associated with the tumor suppressor gene TP53 have been discovered, including apoptosis or programmed cell death. Modulation of the cell cycle in mammalian cells by cyclin-dependent kinases and a general understanding of DNA damage checkpoints at the phase boundaries of the cell cycle have drastically improved our understanding of the response of cells to radiation.

It is not possible to predict when breakthroughs such as those listed above will occur, but it is possible to predict that they will happen, based on current experience in the biological sciences. NASA can ensure that these breakthroughs are applied in a timely and cost-effective manner to the space radiation problem by ensuring the existence of a scientific community with a critical mass of investigators who are active at the cutting edge of the field, who understand the nuances of space radiation biology, and who know NASA needs well enough to leverage discoveries.

Considerable progress has been made by NASA in several areas:

- Substantial increments in GCR data and the development of accurate models have reduced the uncertainty in predictions of the interplanetary GCR environment to an estimated 10 to 15 percent (Cucinotta et al., 2005).
- The acquisition of data on the physics of nuclear interactions, in combination with refinements in transport codes, has led to an uncertainty in shielding calculations estimated to be 30 to 50 percent (NRC, 1996; based on Schimmerling et al., 1987, 1989; and Shavers et al., 1993).
- Data obtained in laboratory radiation research, leading to a better understanding of quality factors; continuing analyses of health effects on cohorts exposed to radiation; and refinements in the probabilistic analysis of space radiation risk seem to indicate that NASA is roughly on course in its strategy to reduce uncertainty along the lines of the curve labeled "$T_{1/2}$ = 15 years with breakthroughs every 5 years" in Figure 3-5 (Cucinotta et al., 2005).

However, at the present time it is premature to make numerical estimates of decreased risk uncertainty with time, given the knowledge gaps listed below. Recent radiation biology research has demonstrated that there are still fundamental responses of cells and tissues to radiation that are not clearly understood and that might affect risk assessments. Rather than uniformly decreasing the uncertainties associated with risk estimates, some discoveries may reduce the uncertainties and may even reveal that the risks are currently overestimated; conversely, some new discoveries may reveal increased risks, or increased uncertainty about risks thought to be well understood at present. For example, in the past several years investigators have identified a bystander effect to radiation, where unirradiated cells in the neighborhood of irradiated cells in cell cultures show responses including genetic instability, chromosomal abnormalities, and the induction of radiation response genes. The mechanism(s) responsible for this bystander effect have not yet been elucidated, but they clearly involve damaging consequences to unirradiated cells that could impact cell survival, mutation induction, and thus tissue responses.

While the bystander effect has been detected following exposure to both alpha particles and low-LET radiations, it is also likely to be induced by GCR and SPEs. For HZE exposure, the notion of bystander cells needs to be modified slightly, to refer to cells that are either irradiated by the extended distribution of delta rays (i.e., cells not directly traversed) as well as cells participating in subsequent biochemical signaling pathways. In the situation of low-fluence particle exposures, bystander responses could contribute significantly to overall risk by effectively increasing the number of cells subject to damage far above the number of cells directly traversed by a particle. Nearly all bystander experimental research has been done in cell culture. Biological responses such as these have yet to be demonstrated to occur in normal tissues, and conclusions drawn from cell culture research should be validated in a normal tissue context where possible. Further research in this area and other poorly understood biological responses (such as delayed mutation induction) may continue to complicate our understanding of radiation responses, possibly leading to further increases in uncertainties before these uncertainties can be decreased.

Knowledge Gaps

As noted above, the risks incurred as a consequence of exposure to space radiation are not measured; instead, they are calculated using available information. This information may consist of measured or archived data on the

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radiation environment and the physical properties of its components, as well as knowledge about the consequences of particular levels and microscopic patterns of energy deposition in human tissues and organs. As a consequence, the expression of the uncertainties in risk prediction depend on and incorporate uncertainties in the particular theoretical framework—the model—used in the calculation.

The model generally used for establishing radiation limits is based on the detailed epidemiological and medical observations of atomic bomb survivors, supplemented, where appropriate, with data from occupational radiation, medical, and accidental radiation exposures. Dose-response curves from atomic bomb survivor data, mainly survivors exposed to relatively high doses of instantaneously delivered gamma rays, are used in conjunction with other information to extrapolate the probability of health effects to lower doses, delivered over long periods of time, to peacetime populations other than Japanese survivors, and to other kinds of radiation. Significant improvements in the accuracy of risk prediction at low doses are not likely in the context of this phenomenological and epidemiological modeling alone. Compilations of data for radiation workers or radiation accidents have not yet provided a level of quality comparable to the data on Japanese survivors. Radiation workers generally receive very low exposures, so that epidemiological studies are hampered by poor statistics even more than studies of Japanese survivors. Dosimetry for victims of radiation accidents, especially individuals with low doses, is often extremely uncertain. Much of the low-dose data is from laboratory experiments and not for cancer epidemiology. However, various learned bodies, such as the NCRP and the Biological Effects of Ionizing Radiation (BEIR) study groups follow the development of databases by the U.S. Department of Energy and other agencies and may eventually be able to use such data to improve epidemiological estimates based on Japanese survivors. However, this is not yet the case.

Improvements in risk prediction, especially for space radiation, could be made by linking mechanisms of cellular and molecular processing of radiation damage to macroscopic processes at the tissue, organ, and organism levels. There are a finite number of biological functions in cells, and nature is economical—it tends to use the same chemical reactions in many different contexts rather than devise a new chemical process for every occasion.

Completion of the human genome sequence and the rise of methods for massively parallel expression experiments have enabled the development of systems biology, a new approach to biological problems that seeks to understand the whole organism through integrating information about all of its biochemical processes and gene and protein network interactions. This systems biology approach is being developed as an alternative to current molecular models and may provide the next major breakthrough in biological science. These studies are likely to complement ongoing experimental studies by providing additional models for understanding molecular events in the context of whole organisms. In the short term, the same insights from cellular and tissue radiobiology that are laying the basis for systems biology also impact the existing models of radiation injury and are required to address existing knowledge gaps. In the long term, integrating the explosive development of systems biology into epidemiological studies and space radiation risk management will depend on the support of a science community of investigators at institutions where this work is proceeding. Results of this research will be important in securing the sustainability of a space research program beyond the first few missions.

The knowledge gaps fit into five categories:

1. *Carcinogenesis: Excess lifetime morbidity and mortality risk from radiation-induced cancers.* Radiation quality and susceptibility are likely to be factors in the epidemiological modeling of cancer incidence. Population-averaged values do not account for dispersion due to genetic factors (familial, high-and low-penetrance genes, single-nucleotide polymorphisms). However, genetic susceptibility dependence of radiation risks may be invariant to radiation quality. Neutron carcinogenesis studies show relative biological effectiveness (RBE) variations across mouse strains for the same tissue; however, similar studies do not exist for HZE. Radiation susceptibility, by which certain individuals are more likely than others to develop cancer in response to radiation exposure, is unlikely to be due to the same mechanism in all individuals concerned. Different factors may lead to different injury end points. It is well known that some individuals have genetic predispositions for breast cancer, others for colon cancer, and so on. An understanding of the various cellular signal pathways leading to cancer in different tissues and organs might enable the selection of diagnostic techniques for earlier detection or for more successful intervention, in both cases reducing the career risk.

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2. *Neurological damage (central nervous system, CNS): acute or late modifications to neurological performance, fatigue, or increased Alzheimer's or other late effects.* One aspect of CNS exposure that has been suggested is a possible link between a loss of stem cells and compromised recovery from trauma. In addition, several studies have shown that there are CNS effects for which the relationship between LET and RBE is complex or nonexistent. Therefore, current risk assessments for such effects may be invalid (Rabin et al., 2007; F. Cucinotta, NASA. "Radiation Risk Assessments for Lunar Missions—Shielding Evaluation Criteria," presented to the committee on December 12, 2006). Recent studies suggest that contrary to previous assumptions, the CNS may be a relatively radiosensitive organ, on the same order as the gastrointestinal tract. The CNS may even be affected in the absence of direct irradiation when other tissues have been irradiated.

3. *Degenerative tissue diseases related to accelerated aging: including death from heart, circulatory, and digestive diseases, or morbidity from these diseases, cataracts, and others diseases.* Very few of these degenerative diseases are being actively examined from a research perspective, although increasingly more information is pointing to the importance of radiation in affecting these organ systems.

The question of a dose-threshold for degenerative tissue effects has not been resolved. Although some earlier studies by Yang and Ainsworth (1982) showed no threshold for HZE ions, the atomic bomb studies have shown cardiovascular disease effects at doses at 50 cSv as well as dose-response effects on various immunological markers of inflammation. In addition, there remain serious questions about modeling noncancer risks. Using epidemiological models, it is not as clear as with cancer how risks transfer across populations, whether there is a dose and dose-rate dependence, and what the quality factors are for specific risks. Even if these characteristics can be modeled satisfactorily, there remains the vexing question of how cancer and noncancer mortality effects should be weighted if they lead to different amounts of life-loss.

A number of studies on cataract induction have raised concerns about the accelerated onset of cataracts and the possible consequences for very long term missions. While dose thresholds have been established based on medical exposures, there is some evidence that cataracts have features that are similar to stochastic effects.

4. *Acute radiation syndromes leading to nausea, vomiting, or death that could occur following a solar particle event.* Acute radiation effects generally have a threshold, corresponding to relatively high radiation dose, as may be seen in Table 3-1. Note that Table 3-1 refers to absorbed doses and not to dose equivalent, showing the lack of information required to convert such acute-effect data from low-LET x-rays and gamma rays to charged particles. The NCRP has attempted to deal with this problem in NCRP Report No. 132 (NCRP, 2000) by prescribing a tabulated set of LET-dependent "RBE" factors, to be multiplied by absorbed dose in acute irradiation, leading to a "Gy-equivalent" quantity to be used for limiting acute radiation risk. These radiation levels are likely to be exceeded only during activities involving minimal shielding, as would be expected during an extravehicular activity or in a rover. The dose rates likely to lead to acute effects are expected only for SPEs. The cumulative effect of exposure to penetrating, hard-to-shield GCR is most likely to lead to cancer, CNS, and degenerative risks. Acute radiation effects and cancer risks are expected to be the most important consequences of SPEs.

TABLE 3-1 Thresholds for Radiation Effects

Effect	Absorbed Dose (cGy)
Blood-count changes	20-50
Vomiting or nausea	100
Death	
Minimal care	320-360
Medical treatment	480-540
Autologous bone marrow transplant	1,100
Permanent sterility	
Males	350
Females	250
Cataracts	200-500

SOURCE: NCRP, 1989, Table 5-1.

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5. *Immune system responses: Exposure to the space environment is known to alter cellular-mediated immune system functions such as cytokine production and lymphocyte proliferation and trafficking.* While such responses during spaceflight are generally thought to be due to microgravity effects, the complex processes involved, including any direct contribution by radiation, are not yet fully understood. The potential interactions of the altered immune system with radiation responses have also not been thoroughly studied. For instance, decreased immune surveillance may allow more efficient radiation-induced carcinogenesis. Such potential interactions between radiation and other aspects of the space environment require further research, and are likely to become increasingly important to astronaut health as mission durations increase.

In addition, hematopoietic stem cells are among the most radiosensitive cells in the body, and acute radiation effects include a marked depression of lymphocytes at doses near 100 cSv within the first 6 hours following radiation exposure. Effects of radiation exposure at much lower doses have been observed, suggesting a possibility for radiogenic immune dysfunction in astronauts during the time frame of their spaceflight. This could hamper astronaut function and lead to poor performance during missions. Further studies are needed to elucidate the nature and mechanisms of immune responses following exposure to high-LET radiation.

Finding 3-1. Uncertainty in radiation biology. Lack of knowledge about the biological effects of and responses to space radiation is the single most important factor limiting the prediction of radiation risk associated with human space exploration.

Finding 3-2. Funding cuts to radiation biology research. NASA's space radiation biology research has been compromised by the recent cuts in funding, particularly in research addressing noncancer effects.

EFFECTS ON MATERIALS AND DEVICES

Space is a harsh environment for hardware as well as for humans. The radiation hazard for humans is the focus of this report. Accordingly, only a brief review of radiation effects on materials and devices is offered here, for the sake of completeness. In general, NASA has broad experience in coping with space radiation effects on materials and devices, and the committee expects that that expertise will be brought to bear on the design and operation of Exploration vehicles.

Radiation effects limit the lifetime of spacecraft, limit the regions of space in which spacecraft can operate, and increase the risk of spacecraft failure. At this time there are four general classes of radiation-induced mechanisms that affect space systems: (1) permanent degradation, (2) transient damage, (3) single-event effects (SEEs), and (4) spacecraft charging, including both surface charging and internal (or so-called deep dielectric) charging.

Permanent degradation of materials and microelectronics results from prolonged exposure to particle radiation. This degradation can result from ionization and displacement of atoms in a crystalline lattice, often referred to as a displacement kerma or as a non-ionizing energy loss (NIEL) (Leroy and Rancoita, 2007). Ionizing dose affects a wide class of materials and devices, whereas NIEL is typically only relevant in minority carrier semiconductors, such as bipolar technology devices, and in optical materials, such as detectors, solar cells, and optocouplers where changes in carrier lifetime affect device performance. For solar panels on interplanetary spacecraft—or on the Moon—the cumulative effect of displacement damage during large SPEs can be the limiting factor in their lifetime.[1] Total ionizing dose is the dominant concern for majority carrier devices such as complementary metal oxide semiconductor technology devices and is often the limiting degradation mechanism for spacecraft electronic performance (van Lint et al., 1980; Messenger and Ash, 1986). At very high doses, greater than 100 kGy, a range of other non-electronic materials can begin to show serious degradation such as a color change, polymer cross-linking, cracking, material flaking, and embrittlement. Teflon is an example of a material that is very sensitive to radiation damage and can change its mechanical and electrical insulating properties when irradiated to high levels.

[1]In the very large SPE of July 14, 2000, the current output from the solar panels on the SOHO spacecraft suffered a decrease in current output that was the equivalent of a year's normal exposure (Brekke et al., 2005).

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Transient damage refers to the radiation damage component that is only present during the irradiation or that anneals out during normal environmental conditions. Transient effects include dose-rate effects, for example, photocurrents, as well as the annealing of transistor gain due to displacement damage effects. Dose-rate effects track the incident radiation rate, typically a gamma background level, and refer to a continuum effect rather than to ionization associated with a single heavy particle. Displacement damage can inject a severe degradation in the gain of a semiconductor that anneals out in the period as early as 1 microsecond and extending out to several months after the irradiation with, approximately, an exponential time constant (Messenger and Ash, 1986).

SEEs refer to a class of effects in which the damage results from a *single* ionizing particle traversing a microelectronic device rather than the accumulated impact of a large number of particles. SEEs are disruptions of normal circuit response that occur as a result of electron hole pairs being generated along the path of the incident ionizing particle (Messenger and Ash, 1997). Both the total collected charge and the rate of charge collection can be important in triggering the disruptive effect. The particle source can be "primary" from the GCR or SPE particle populations or a secondary spallation product, generated from the nuclear interaction between a primary particle and nuclei of microelectronics materials. Even thermal neutrons can affect unhardened parts that include boron[2] as a doping material in the semiconductor or in the glass passivation layer. SEEs range from the relatively benign bit flips (single-event upsets) that can be circumvented by engineering, to temporarily disruptive latchups (where the power must be cycled to reset the circuit), to catastrophic burnouts (where the induced parasitic current flows lead to permanent and irreversible circuit damage). A particular concern in the space-microelectronics community is emergent technologies with smaller feature sizes, for which single protons and neutrons can deposit enough charge directly to cause SEEs in radiation-hardened semiconductors. With older technologies, SEEs were caused by either heavy ions or by heavy spallation fragments.[3] This increased vulnerability of the emerging technologies violates some of the assumptions that underlie commonly-used methodologies for estimating SEE rates in space.

Spacecraft surface charging and deep dielectric charging result from exposure to low-energy electrons (typically from a few electron volts to a few kiloelectronvolts) in plasmas and high-energy electrons (typically >100 keV), respectively. In hot plasmas, spacecraft surfaces cannot maintain a current balance, and large potentials can build up causing a discharge. Higher-energy electrons can penetrate spacecraft structures and bury themselves in dielectric materials until the dielectric breakdown level is reached and a discharge is released into circuits. Discharges result in background interference on instruments and detectors, biasing of instrument readings, physical damage to materials, upsets, physical damage to electronics, increased current collection, the re-attraction of contaminants, and ion sputtering that leads to an acceleration of the erosion of materials. Deep-dielectric charging requires very large electron fluences, on the order of 10^{10}-10^{11}/cm^2, collected over the timescale set by the dielectric leakage rate. Such electron intensities are not found in interplanetary space, and deep-dielectric effects have generally been a concern for satellites exposed to transient increases in radiation belt electrons while operating in low Earth and geostationary orbits (Barth, 2002).

As already mentioned, NASA has broad experience in dealing with space radiation effects on materials and devices. However, there is one area of potential concern where NASA has little experience: radiation effects on materials near ground nuclear power stations or near nuclear space propulsion systems. The radiation degradation considerations for materials near a reactor core go beyond the normal concerns over the degradation of electronic equipment and can involve changes in the mechanical and thermal properties of the material. The nuclear industry has experience in this area that can be applied to the NASA designs. A combination of distance and shielding are generally applied to lower the radiation levels at locations of sensitive equipment. Careful material selection and material testing are used for materials near the reactor. The reactor itself is generally designed with intrinsic feedback mechanisms, for example, thermal expansion, that ensure safe operation under all reasonable scenarios. The reactor control systems generally have some electronic components that are located several meters from the core itself in order to use distance and shielding to reduce the radiation environment. The material degradation of

[2]The relevant reaction is $^{10}B(n,\alpha)^{7}Li$.

[3]The larger feature size and critical charge required for an upset made them immune to the charge delivered by the interaction of a single proton or neutron.

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the reactor materials themselves balances the radiation damage against the high-temperature material properties and corrosion and oxidation considerations for materials in the working environment. The ground station power conversion system, such as a Brayton engine, may be located close to the reactor and must take radiation degradation mechanisms into account—for example, degradation of seal materials and material embrittlement. Shielding of the reactor neutron/gamma radiation often uses high-atomic-number materials to attenuate the gammas and a combination of material rich in hydrogen together with boron and lithium-containing materials to attenuate the neutron flux. The hydrogen in the materials thermalizes the neutrons and the ^{10}B or ^{6}Li absorbs the neutron. An important consideration in the shield design is the generation of neutron-induced secondary gammas within the shield material itself. For thick shields, the neutron-induced secondary gammas are typically the most important radiation consideration on items inside of the shield.

EFFECTS ON MISSION

It is important that NASA carefully consider the potential for mission failure, in addition to health impacts, while establishing a radiation shielding strategy. While there is a very small possibility that an acute dose could render an astronaut unable to perform his or her duties, missions may also fail because they are restricted by flight rules. Radiation limits are chosen to reduce the long-term health effects on astronauts, effects that may not manifest until years after the mission has been completed. The principle of As Low As Reasonably Achievable (ALARA) is implemented through flight rules to ensure that astronauts do not approach these limits and to reduce the risk of exposing the astronauts to acute radiation effects. Among these flight rules will be a requirement to return to the most heavily shielded shelter if the radiation flux exceeds a predetermined dose-rate threshold. Because SPEs are unpredictable, the threshold will necessarily be conservative and well below a life-threatening dose rate. While the peak flux of severe SPEs may be limited to a few hours, the flux above an action level may persist for several days. The initial missions to the Moon will last only 1 or 2 weeks, and the ability to extend the mission to account for time lost to an SPE will be limited by consumables and orbital mechanics. Therefore, it is possible that the astronauts will be unable to accomplish prime mission objectives because they were not permitted to leave the outpost or, depending on the event timing, even land on the lunar surface in the first place.

There are several courses of action available to NASA at this early stage in operational planning to reduce the risk of mission failure due to SPEs that in due course stay below a fluence that approaches radiation limits. First and foremost, when creating the flight rules, NASA could consider the probability that an event will occur that exceeds a certain threshold flux level, in addition to a threshold fluence level.

The radiation shielding strategy could be made robust against long-duration, low-flux events. The simplest solution may be to include additional consumables and operational flexibility to extend the mission stay. This has the dual benefit of supporting extended stay for any number of additional contingencies that may delay a return to Earth (more time needed to complete objectives, unanticipated discoveries, broken or faulty equipment, and so on). However, NASA could also consider providing additional shielding for the astronauts on surface excursions and limiting the time exposed on the surface in a space suit. Emergency procedures that can be executed away from the outpost for limited periods should be explored and evaluated against returning to base. These could include provisions for prepositioned shelters or the ability to construct adequate shelter from available resources.

Improved forecasting or nowcasting may also have a substantial value. If forecasters are able to reliably ensure all-clear periods of up to 8 hours, or if the projected fluence of ongoing events can be reliably forecast for 8 or more hours, then the dose-rate action level could be adjusted. A cost-benefit analysis or identification of cost-benefit metrics would help to quantitatively measure the value of enhancement to SPE or all-clear forecasts.

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4

Shielding Approaches and Capabilities

BASIC SHIELDING CONCEPTS

In principle, there are three ways to reduce a dose from external radiation:

- Increasing the distance from the source,
- Minimizing the time of exposure, and
- Using shielding.

Increasing the distance from the source is often the simplest to implement for terrestrial radiation protection (e.g., the use of tongs to minimize exposure to hands, moving work spaces farther away from sources). In deep space, however, the spacecraft and crew are immersed in the radiation environment. Using distance from the source as a means of mitigating exposure is not possible.

Limiting the time that the crews are exposed to a radiation field was used in the early space program. During the Apollo era, human missions to the Moon used this method of minimizing exposure to the Van Allen radiation belts on the transits to and from the Moon. Transit times to Mars, however, may be driven by other considerations, such as available means of propulsion and spacecraft trajectory.

The most commonly used means of protecting terrestrial radiation workers is through the use of shielding (i.e., the placement of material between the human and the radiation source in order to reduce the intensity of the radiation field at the human's location). In principle, shielding alone should be able to reduce exposure by attenuating the radiation and reducing the dose rates. For deep space missions, however, shielding alone cannot guarantee protection in all situations owing to the very high energies of the incident ions and the production of highly penetrating secondary particles, such as neutrons and light ions, coupled with mass constraints on the spacecraft and the large uncertainties in biological risk.

SHIELDING FOR PROJECT CONSTELLATION'S ORION

For operations within Earth's geomagnetic field, little or no supplemental shielding is needed to ensure astronaut safety in a capsule or habitat. However, upon leaving this protective geomagnetic shield, the astronauts are subjected fully to the natural GCR environment and susceptible to serious radiation fluxes from solar particle events (SPEs).

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The return to the Moon plan for the Constellation program is quite similar to that of the Apollo program. However, Constellation will use a two-launch method. The Ares V Heavy Lift Launch Vehicle will launch the Earth Departure Stage (EDS) containing the propulsion system and the Lunar Lander. The four-member crew will be launched in the Orion Crew Exploration Vehicle to low Earth orbit (LEO) using the Ares 1 Crew Launch Vehicle, which will then dock with the EDS before heading to the Moon. Once the combined vehicle is in lunar orbit and systems checks have ensured a "Go" for landing, the Lunar Lander will separate from the Orion and initiate the lunar landing.

The Orion Block-2 design requirements respond to two major mission scenarios:

- Supporting crew and cargo transportation to the International Space Station (ISS) in LEO and returning them to Earth, and
- Transporting crew to low lunar orbit (LLO) and returning them safely to Earth. As part of the lunar missions, the Orion will rendezvous and dock with the Lunar Lander (already mated to the EDS) in LEO, and will provide piloting, guidance, and navigation to the combined cislunar spacecraft.

On both of these missions, the Orion capsule would be the principal shielded volume; that is, it would be either the only volume, or it would be the most likely shielded module from which the crew could fly the mission and still benefit from a level of protection. The requirements provided by NASA to Lockheed Martin are as follows (T. Shelfer, Lockheed Martin, "Crew Exploration Vehicle Requirements—Contractor's Perspective," presented to the committee on February 21, 2007):

> - Orion shall provide radiation protection, consistent with the principles of ALARA [As Low As Reasonably Achievable], to ensure that the tissue-averaged effective dose to any crew member does not exceed 15 cSv for the worst-case SPE, defined as the King parameterization of the August 1972 event.
> - The vehicle shall continuously measure and record the external fluence of particles of $Z < 3$, in the energy range 30 to 300 MeV per nucleon and particles of $3 \le Z \le 26$, in the energy range 100 to 400 MeV per nucleon and integral fluence measurement at higher energies, as a function of energy and time, from a monitoring location that ensures an unobstructed free space full-angle field of view 65 degrees or greater.
> - The vehicle shall provide an omnidirectional, portable system that can continuously measure and record the dose equivalent from charged particles with linear energy transfer 0.2 to 1,000 keV per micrometer, as a function of time, at an average tissue depth of at least 2 mm.

Preliminary analyses by NASA and Lockheed Martin indicate that the Orion capsule provides adequate shielding from its structure, avionics, life support, other hardware, consumables, and waste storage such that lower-energy SPEs would not be a threat. However, for the rarer, higher-energy events, doses could accumulate beyond the acceptable limit. For this reason, the Orion capsule itself must either incorporate sufficient shielding or else have the capability to reconfigure shielding and functional hardware to provide a radiation storm shelter for the astronauts. The duration of the most hazardous portion of an SPE or a close series of SPEs can be hours to a few days. Thus, the Orion capsule must be capable of providing the storm-shelter capability for a somewhat extended period of time, and astronauts must have access to food, water, and minimum hygiene facilities. Although it will be permissible to leave the radiation storm shelter for short periods (minutes to fractional hours) to meet personal needs or perform a task required for mission success, the astronauts should spend the duration of an SPE inside the shelter. As stated above, protection is accomplished by time, distance, and shielding. In this case, the astronauts can safely leave the shielded area if they return quickly. Lockheed Martin designers considered several solutions: hull shielding, deployable water shielding, shielding integrated into seats, and a deployable, high-density polyethylene (HDPE; defined by a density of greater than 0.94 g/cm^3). At the time of this writing (summer 2007), the Orion project plans to provide 2.5-cm-thick slabs of HDPE for use by the astronauts to configure an in-space shelter inside the Orion capsule itself. The HDPE shield was the only one that could feasibly provide the necessary amount of shielding. The shielding would be 2.5 cm thick and would be stowed on the floor of the Environmental Control and Life Support System when not in use. At the time of this analysis, Orion was still in its first design cycle. More detailed radiation analyses and shielding configurations are planned in future iterations (T. Shelfer,

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Lockheed Martin, "Crew Exploration Vehicle Requirements Contractor's Perspective," presented to the committee on February 21, 2007).

Two instruments will be used to meet the monitoring requirements: the Radiation Assessment Detector (RAD) and the Tissue Equivalent Proportional Counter (TEPC). The RAD will be based on the instrument of the same name discussed in Chapter 2, used to monitor the martian radiation environment, in order to decrease development cost and leverage another currently planned project. The TEPC will be based on a design from Texas A&M University. Both of these instruments will take advantage of the ISS as a testing and evaluation environment (T. Shelfer, Lockheed Martin, "Crew Exploration Vehicle Requirements Contractor's Perspective," presented to the committee on February 21, 2007).

LUNAR LANDER

The Lunar Lander will be a highly specialized vehicle designed for operation in LLO, from LLO through terminal descent and landing, and then ascent from the lunar surface to rendezvous with Orion back in LLO. As described in the Exploration Systems Architecture Study (NASA, 2005) and NASA's May 2006 Lunar Lander request for information (NASA, 2006), the Lunar Lander consists of three pressurized, habitable volumes: the Ascent Stage, the Descent Stage Habitat, and the Extravehicular Activity (EVA) Airlock. The airlock is discussed later in this chapter.

All three portions of the Lunar Lander will travel from LLO to the Moon's surface. The Descent Stage will carry the habitat for the crew to use during the surface segment of the mission, baselined at 16 m^3 (NASA, 2004). The crew would live primarily in this module during their stay on the surface, and they would retain access to the designated 10 m^3 volume in the Ascent Stage. The Descent Stage and the Airlock would be left on the surface when the astronauts return to LLO in the Ascent Stage. The Ascent Stage represents the highest cost in total system mass, so it places the greatest premium on lightweight construction and will likely offer minimal shielding. However, the amount of time that crew members spend exclusively in the Ascent Stage will be quite limited, on the order of hours (G. Yoder, NASA, "Lunar Architecture Team Overview," presented to the committee December 12, 2006.)

The habitat is the most suitable module to afford radiation protection to the crew. Although the weight restrictions are stringent, they may allow the provision of some radiation shielding in addition to the basic pressure-vessel structure, and thermal and micrometeoroid protection. The advantage of making the habitat serve as a radiation storm shelter is that it already contains the habitability accommodations to sustain the crew in relative comfort over the course of a solar storm. These habitability accommodations include life support, food systems, hygiene and waste management systems, sleep stations, and stowage for clothing and personal articles.

The process used in the Orion capsule—developing a three-dimensional computer-aided design shielding model and a crew-radiation-exposure assessment based on some of the historical large SPEs—is also appropriate and reasonable to replicate for the various components of the Lunar Lander.

SURFACE INFRASTRUCTURE

In the past 2 years, NASA has published several versions of the lunar exploration timelines. Table 4-1 displays the timeline presented at the 2nd Space Exploration Conference (Lavoie, 2006), which was also presented at the committee's first meeting by Geoffrey Yoder, NASA. The findings and recommendations of this report are still applicable to missions with slightly different timelines (such as those in NASA, 2004, 2005, 2006).

Table 4-1 shows that in early years, missions will be short. The crew will need to bring along just about everything they need. However, the long-term goal is to gradually build up an outpost capable of supporting longer and more complex missions. The surface infrastructure, therefore, plays a significant role in controlling the total mission radiation dose.

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TABLE 4-1 Potential Durations of Lunar Exploration Mission

Mission Type	Duration
Outpost buildup, years 1-2	7 days
Outpost buildup, year 3	14 days
Outpost buildup, years 4-5	30 days
Outpost occupancy	6 months
Total/maximum mission duration	>6 months

SOURCE: Lavoie, 2006.

Habitats

Most space habitats, such as Skylab, Soyuz, Mir, and ISS modules, have been cylindrical, disk-shaped, or, in rare cases, spherical. Curved shapes provide the minimum thickness of the module walls for a given pressurized volume, responding to the need for minimizing mass (and therefore cost) of transportation into space. For the approximately isotropic incidence of space radiation, spherical shields provide the minimum mass for a given volume; however, a long cylinder is superior, presenting the minimum shielding at the ends, where it subtends the smallest solid angle; and that incoming radiation will have to traverse an increased amount of material, seen at an angle. These examples are for modules in free space, but the same will be true for habitat modules to be deployed to the Moon or to the surface of Mars. The difference is in shielding priorities. In free space, the only mass available for shielding is the construction of the module itself, equipment, and supplies. Orion, on its longer missions, may be afforded a small amount of shielding-dedicated mass. However, on the surface of a planet, a habitat does not need to provide shielding in all directions; the planet itself grants 180° of protection, making a half-cylinder or dome more efficient as well as more practical. If the habitat is intended to provide the major component of radiation shielding during transit to the Moon, it may be useful to place the ascent and/or descent stages on the weakly shielded bottom of the habitat.

Robots

A menagerie of robotic concepts has been proposed to assist astronauts on lunar or planetary surfaces. A robotic assistant could carry a mobile, deployable solar-particle storm shelter with a mass of several hundred kilograms, accompanying an astronaut team or buddy pair on an EVA excursion. In the event of an SPE at a time when the crew is far from the base, crew members could unfold and deploy this shelter and wait out the storm for the few hours of greatest intensity. This strategy depends on the amount of life-support consumables carried by the crew (typically on the order of 8 to 12 hours, possibly increased by the robot's carrying capacity) as well as their own comfort spending long hours immobile in the EVA space suit.

Unpressurized Rover

The unpressurized Lunar Rover Vehicle (LRV) used during the Apollo 16 mission proved a safe and reliable vehicle for the lunar crews. The rover extended the area of exploration outside the lunar module from meters to kilometers, allowed a greater mass of samples to be returned, and beamed images back to Earth. The LRV transported astronauts to places they never could have reached on foot. However, the astronauts were limited in their traverses by the available water and oxygen in their personal life support system (PLSS) backpacks. In the event the LRV broke down, the astronauts would need enough air and water to return safely to the Lunar Module. Unpressurized rovers will still be used in Constellation for short jaunts and trips around the outpost complex. They could still carry some portable radiation shielding in case of a breakdown, but their range is already limited, so it is likely that an astronaut could return to the outpost in time to avoid significant SPE exposure.

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Pressurized Rover

Several initiatives during the 1980s and 1990s considered larger, pressurized lunar rovers that could carry greater quantities of consumables for the astronauts of post-Apollo missions. A pressurized vehicle for lunar exploration was seen as the next logical step. Several universities, NASA centers, and NASA contractors produced a number of pressurized lunar rover designs.

A notional pressurized lunar rover (PLR) considered by Anderson et al. (2006) has a mass of about 5,150 kg and a traverse range of several hundred kilometers. Like the space suits that it supports, the pressurized rover would essentially be a complete spacecraft in which the crew could live while exploring the lunar surface. The rover could incorporate fuel cells to provide mobile power and water for the life-support system on long journeys. These cells produce water and electrical power by combining lunar oxygen and hydrogen brought from Earth.

With this enhanced mobility, the crew can service remote facilities, such as lunar telescopes, and conduct long-range geological traverses while making geological surveys and sample collections. The lunar south pole is at the edge of the largest crater in the solar system, approximately 2,500 km across. Exploring areas this large will require traveling for weeks on end. However, extending the EVA time also increases the probability that it will coincide with an SPE. Because it is mobile, the pressurized rover—like the other rovers—could not depend on in situ shielding at the outset of an SPE unless it found a convenient, naturally occurring “garage” in a lunar lava tube or cave. Therefore, this pressurized rover would need to carry its own radiation shielding to protect a crew throughout an SPE. A three-dimensional computer-aided design radiation shielding model could be developed for the pressurized rover, and parametric SPE radiation analyses be performed to ascertain the intrinsic shielding capability of the pressurized rover. If needed, it could also carry deployable radiation shielding materials, such as the polyethylene shields carried by Orion.

In Situ Shielding

Bringing all the radiation shielding all the way from Earth to the lunar or martian surface poses a substantial mass penalty. The most popular ideas for mitigating this mass penalty involve using surface resources to provide shielding. These resources include regolith, lava tubes, caves, and other landforms.

Regolith Shielding

In situ shielding made from regolith is an appealing possibility because regolith is found everywhere on the lunar surface and certainly will be available at the south pole where NASA’s Outpost-First Strategy plans to establish the first lunar base. The poles tend to resemble the highlands more than they resemble the maria, so it is less likely that explorers can find a lava tube or cave at the eventual location of choice for the outpost site.

Regolith consists of dust, rocks, and pulverized rock, all typically composed of aluminosilicates and iron oxide minerals. Approximately one-half of the mass in such materials is oxygen, and because of this the average atomic number of the material is as low as or lower than aluminum ($Z = 13$). Although not as optimal as high-hydrogen-content materials in terms of shielding effectiveness per unit of mass, regoliths are nonetheless as least as effective as aluminum (Zeitlin et al., 2002).

The simplest approach to shielding using regolith is to place the module on or as close as possible to the ground and to construct a simple embankment by piling material against the module to shield in the azimuthal directions. Using regolith to shield in the zenith direction can be aided by providing a simple scaffolding or flat-roof structure on which to load additional material. The ends of the modules, where airlocks may be located, can be effectively shielded by creating a blocking berm at a standoff distance. As long as the line of sight to space is blocked, there is no requirement to providing a contiguous shield. The regolith can be loose, or converted into convenient forms such as sandbags or pressed blocks. Habitat designs that consist of a module on long legs (e.g., the Apollo lunar module) or a landing truss could be much more difficult to shield using regolith because of the challenges of raising tons of material to the necessary heights and providing sufficient support.

Simonsen (1997) describes a method for determining an appropriate regolith thickness. First, one selects a radiation environment scenario—a combination of GCR and SPE exposure representing “worst-case conditions.”

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(See Chapter 2 for further discussion on this topic.) Next, the radiation transport codes HZETRN and BRYNTRN are used to compute the effective dose behind a slab of regolith as a function of thickness. This curve is used to identify a candidate thickness or thicknesses that would keep effective dose below the permissible exposure limit (PEL). Then, the HZETRN and BRYNTRN analyses are repeated, this time using the selected thickness of shielding over the actual geometry of the shielded habitat. If the resulting effective doses are below the PEL, then the shielding thickness is acceptable; otherwise, the shielding thickness must be increased.

The following example will give a rough idea of the amount of mass involved. In a basic but realistic analysis, Simonsen (1997) estimates that 90 metric tons of regolith is adequate to shield a cylindrical habitat 12.2 m in length and 4.6 m in diameter with 50 g/cm^2 thickness of regolith.

Analyzing the required thickness for a habitat of Mars is basically similar, although the radiation design environment will be slightly different, the PELs will be lower (since the overall mission is longer), and the regolith has a different composition. There is also one additional step: modeling the propagation of the radiation through Mars's atmosphere, which offers a substantial degree of dose reduction. (More detail on this method can be found in Simonsen [1997]). Simonsen points out that for short stays on the martian surface, it may make sense not to use any regolith shielding at all, because the construction would add length and risk to the mission, negating the additional protection of the shielding.

The process detailed above will generate a design that meets standards, but not one that satisfies the ALARA principle. Since regolith is abundant, the goal might be "the thicker, the better." As thicknesses are increased to exceed a few meters, a practical limit is reached, however, because of structural load factors even in the low lunar gravity, the diminishing marginal shielding associated with large thickness, and the efforts and safety risks for construction. Implementation becomes a matter of the economies of scale.

Substantial masses of equipment will be required to excavate and move surface material; to sort, crush, or condense it for packaging; to package it by pressing it into bricks or packing it into bags; to move these packaged units to the construction site; and finally to build the protective structure over the habitat. Because astronaut time is expensive and the crew will have many higher priorities than "filling and stacking sandbags," this construction will most likely require automated and teleoperated machinery to extract and process regolith, and robotic systems to move and emplace it. The equipment might resemble skid-steer loaders or compact excavators but would be designed for operation in a low-gravity space environment. It will weigh at least several metric tons—a very significant payload for the Lunar Lander—and also require significant amounts of power from the solar-power generators, which are also large payloads. Thus, the economy of scale becomes a system tradeoff of how much of this equipment it is feasible to deliver to the lunar surface and when to deliver it. For example, if there is not sufficient power generation and transmission capability in place yet, it does not make sense to deliver the regolith-handling equipment that will exceed the available capacity.

For sortie missions, it is likely that regolith shielding will not be practical. However, as missions lengthen, the utility of the shielding increases. Furthermore, constructing an outpost means that the cost of shielding construction is amortized over the duration of the program. This will be true of either sculpted regolith or of shielding that has been brought from Earth but left behind when the Lunar Lander departs.

Geomorphology-Dependent Shielding

Lava tubes, caves, tunnel borings, and other shielding solutions based on existing lunar formations offer the potential to reduce but probably not eliminate the need for heavy construction equipment. Lava tubes are believed to exist in the maria, where the rills appear to be collapsed lava tubes. Caves may exist in crater walls or tumbled boulder fields. In the most basic scenario, the outpost would be located next to a steep hill or cliff (perhaps the side of a crater), cutting off some portion of the line of sight. In the ideal scenario, explorers would find a lava tube of sufficient size and structural stability to contain the outpost and its proximity operations.

Theoretically, missions could include equipment to dig down into the regolith instead of piling it on top of a habitat. The resulting "shield thickness" would be very large, but such construction is more energy-intensive and complex. This concept is not being currently considered within the scope of Project Constellation.

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Extravehicular Activity

Space Suits

An astronaut performing an EVA is primarily shielded by the planetary body on which he or she is standing. Clowdsley et al. (2005) calculated a point estimate that the maximum daily effective GCR dose for an astronaut in an EVA suit exposed on the lunar surface is 0.085 cSv (about half of the calculated amount for free space). The 1977 solar minimum environment was used as a worst-case GCR environment. This estimate neglected the minimal radiation protection capabilities of the EVA suit itself. Further protection can be added through operational planning, the use of portable shelters, and possibly pressurized rovers. Space suits are not intended to provide significant protection. Since mass is tightly constrained during space suit design, any mass taken up solely by shielding could otherwise be used to store more oxygen, enable a thicker thermal shield, or make the suit less cumbersome. Like many parts of Project Constellation, space suits are subject to risk leveling: finding that an extra kilogram is available, a designer will figure out how that kilogram could be used to provide the greatest reduction in risk. However, space suits do also provide some minimal degree of radiation protection. Therefore, it is useful to quantify their shielding properties and to incorporate the ALARA principle into their design (Wilson et al., 2006).

Current space suit concepts encompass three main types: the soft suit, the hard suit, and the hybrid suit. Each of these three broad categories covers a range of advantages and disadvantages for general and specific applications and criteria.

- *Soft suit:* a space suit in which the only rigid component is typically the helmet and perhaps the soles of the boots. The potential of the soft suit as a tight-fitting pressure envelope is to minimize mass while maximizing flexibility. The Mercury, Gemini, and Apollo suits were all soft suits.
- *Hard suit:* a space suit in which all the components of the pressure enclosure are made from a rigid torso, joints, spacers, and sizing rings. The pressure-sealed joints turn on circular ball bearing races. Although NASA has explored a few concepts, they have proven too heavy, uncomfortable, and expensive to be used on missions. A hard suit offers the potential for the fabrication of its parts from carbon composite, a better material for radiation shielding than aluminum or fiberglass is.
- *Hybrid suit:* a space suit that combines hard and soft components, typically a hard upper torso and the rest soft goods. The space shuttle and ISS extravehicular mobility units (EMUs) are hybrid suits.

Other features are generally standard across suit design, updated as each model incorporates the technology available at the time. Helmet visors are coated to protect the astronauts' eyes from certain wavelengths of harmful light; they also reduce the dose of ionizing radiation to the eyes, therefore also lowering the risk of cataracts. The personal life support system (PLSS) backpack contains oxygen, water, and batteries. It provides a fair amount of radiation shielding over a limited area through its mass. Gloves are usually fairly thin, given the need for dexterity and manipulation.

The layer of material closest to the skin is the liquid cooling and ventilation garment (LCVG). It supports a network of small, water-filled tubes used for convective cooling. The LCVG is contained by a bladder and restraint to maintain the suit's pressure. The outermost layer is the thermal micrometeoroid garment (TMG), which actually consists of several layers of insulation and ripstop fabric.

In 2003, NASA published a collection of radiation studies that had been performed on the EMU and the Orlan-M, the space suit used by the Russians on the ISS (Cucinotta et al., 2003). These studies included beamline experiments using electrons with an energy (6 MeV) typical of those in Earth's Van Allen radiation belts and protons with energies representative of SPEs and Van Allen belts (up to 232 MeV). Validation of the BRYNTRN space radiation transport code, which was developed at NASA Langley Research Center and typically used for estimating doses from SPE and Van Allen protons was also carried out. Some relevant findings from this group of studies included the following:

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- When doses were measured behind swatches of space suit material for a beam of 60 MeV protons, secondary radiation caused the dose to actually increase by 10 to 40 percent for the suits and helmets owing to the increased slowing down of the protons, resulting in greater energy deposition rates (Benton et al., 2003).
- Beam-line experiments were also performed on a phantom torso (a human mock-up, designed to provide the same shielding as a human body; it can be outfitted with dosimeters at various organ locations). The proton beam energy was set to 232 MeV in order to penetrate the torso. The torso was instrumented with TLD-600 and TLD-700 dosimeters, positioned to measure doses and dose equivalents in the eye, brain, lung, stomach, and thigh. The eye and brain were shielded by the helmets; the lung, stomach, and thigh were shielded by the suit fabric. Overall, the helmets were found to reduce the doses by 22 to 27 percent for the eye and by 13 to 21 percent for the brain. Dose-equivalent reductions ranged from 14 to 25 percent for the eye and less than ~8 percent for the brain. For the lung, stomach, and thigh, dose reductions ranged from <1 percent (thigh) to 13 percent (stomach). Dose-equivalent reductions ranged from 0 percent (thigh) to 14 percent (lung) (Benton et al., 2003).
- The BRYNTRN radiation transport code was found to model proton exposures accurately when compared with measured doses taken in a beam line (Zapp et al., 2003). Typical differences between calculated and measured doses were less than 6 percent for the various organs.
- Space suits have components that do provide some measure of radiation protection. Certain minor changes in the EMU design, for example, adding a thin layer of material to the dorsal side of the glove, could yield gains in radiation protection (Moyers et al., 2003).

Note that the beam experiments involved protons and electrons at energies similar to those found in LEO. Constellation astronauts will have to pass through these regions, but the bulk of their time will be spent in deep space or on a lunar or planetary surface, where the contributions of electrons are negligible but GCR and SPEs play a much more prominent role. Despite the differences, these measurements, methods, and computational models can serve as a starting point for evaluating new space suit designs. Wilson et al. (2006) suggest some other possible design changes inspired by the analysis of ISS suits: replacing the water tubes of the LCVG with a solid water jacket, using a thin layer of polyethylene as part of the suit layup, and redesigning the PLSS so that the mass of its components are more evenly distributed around the body.

The Johnson Space Center EVA Systems Project Office issued an EVA Systems Architecture and Reference Suit System Approach briefing (Dutton and Johnson, 2006) that has been approved by the Constellation program. Like the EMU, the Constellation suit will be fairly modular; it will have two configurations: an emergency suit (for launch, entry, and abort and for contingency EVA) and a sortie EVA suit. These two suits will share many components, although they will have different soft upper torsos, TMGs, and visors. A third configuration may eventually be designed for outpost EVA; it will use many of the same components.

The Constellation TMG will evolve out of the TMGs used in the Apollo program, substituting modern, advanced materials such as hydrogen-rich radiation shielding. The TMG will have to be redesigned for martian missions owing to atmospheric requirements. During the design of the EMU, materials with radiation shielding properties were used, but certification only required that the materials could stand up to the environment (e.g., 50 EVAs), not that they would guarantee a certain amount of protection. In addition, the visors of the helmet will be subject to a variety of requirements on transmittance and reflectance of certain wavelengths of light. Although dose limits for the Constellation suits have not yet been set, designers are expecting them to be similar (S. Cupples, NASA, "EVA Suit Radiation Attenuation," presentation to the committee on February 21, 2007). The setting of requirements, and the efforts of the space suit designers to incorporate radiation shielding early in the process are both very positive signs.

Airlock

The *Exploration Systems Architecture Study* (NASA, 2005) and request for information (NASA, 2006) both include an EVA airlock to enable the safest and most efficient means of transit between the pressurized cabin of the lander or habitat and the vacuum of space. The EVA airlock may offer an alternative module for a radiation storm shelter, particularly if NASA implements a requirement for a hyperbaric capability, such as on the ISS (Barratt,

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1996). In this case, the airlock could be operated at 6 atmospheres, allowing the airlock to serve as a recompression chamber in case of decompression sickness. An airlock that holds 6 atmospheres (and will be pressure-tested to 12) will be significantly more robust and thicker in its primary structure than one that operates at 1 atmosphere and tests to 2. This thicker structure and material would afford a de facto shielded module.

However, outfitting the EVA airlock to serve as a solar storm shelter poses some significant penalties. The most obvious is that a primary purpose of the airlock is to provide a buffer for the living quarters to exclude, mitigate, and control the intrusion of lunar dust, which the Apollo astronauts found highly irritating for breathing and on the skin, and which also may prove toxic. Secondly, the airlock would become cramped during an SPE lasting several days. A crew taking shelter in the airlock would need to bring their sleeping arrangements from the habitat with them into the airlock, as well as food, water, first aid, laptops, and other necessities. The crew would need to leave the airlock to use the hygiene facilities in the habitat. Because of these drawbacks, it may be preferable to provide some shielding in the habitat so that the airlock would only need to be used during the highest flux peak of the event.

Portable Shielding

The purpose of a portable radiation shield would be to provide temporary shielding in a contingency situation—for example, the sudden onset of an SPE. The portable radiation shield is envisioned to be a rapidly deployed and easily transported "blanket-design" made of a lightweight material that exhibits good radiation-mitigating properties, such as high-density polyethylene. The "blanket" could be transported on a lunar rover or a multipurpose trailer. In the event of an SPE, it would be advisable for the EVA crews to seek out terrain that would provide additional shielding, such as a high rock or cliff formation. It is also envisioned that mission controllers would direct the crew when to seek shelter and to use the portable shielding, and also when an "all-clear" period was reached and it was permissible to continue the EVA or to return to a base location. Another design could be for individual use, such as a hooded, poncho-type shield arrangement that the crew member could slip into quickly. The thickness of these portable shields would be dictated by how much radiation mitigation would be warranted.

Concept of Operations

Operational protocols will be critical to radiation safety during any EVA beyond the protective influence of Earth's geomagnetic shield. These protocols will involve gathering two kinds of data: solar activity indicators and actual radiation dose as experienced by the astronauts conducting the EVA. The second can only be accomplished by including one or more active dosimeters on their persons or on nearby equipment, such as a rover or robotic assistant.

When solar activity is observed that could result in an SPE, the EVA will likely have specific contingency plans already in place for seeking shelter or for using available shielding, much as there are contingency procedures for anomalous launch or other hazardous operational situations. During EVA, access to shielding on a timescale of less than 1 hour, and preferably only minutes, is desired in order to avoid possible excessive exposure. For the most expedient mitigation, astronauts might use a two-tiered approach. Dose rate will build up over a period of time, so that immediately taking on even a small amount of strategic shielding (e.g., covering the torso) prior to reaching a more substantial shelter area would be effective in reducing the total exposure received.

Nuclear Power

Space missions usually rely on solar panels and/or fuel cells to provide electricity. However, as anticipated by NASA, the future long-term missions to the Moon and Mars would require a power source on the order of 1 MW that can reliably supply electricity and provide heat for a few decades. Nuclear reactors are the most efficient method of generating this power (Figure 4-1). Presented here is a discussion of the engineering challenges associated with the safe operation of fission reactors in space. Not only must the reactors have adequate shielding to protect astronauts during nominal operation, but they must have enhanced safety and reliability as well.

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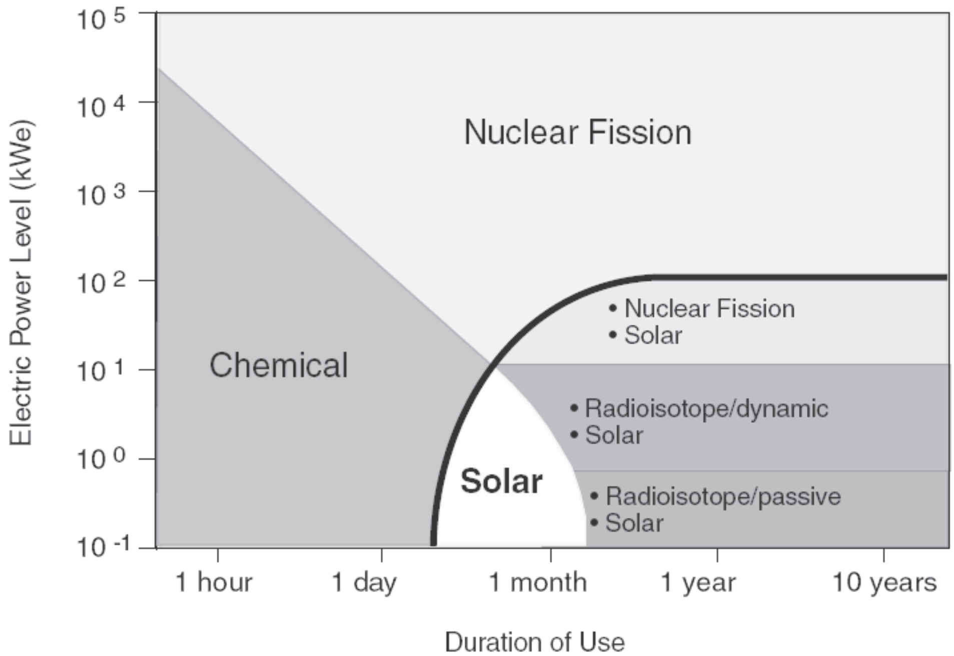

FIGURE 4-1 The relative applicability of various space-based sources of electrical power. SOURCE: NRC, 2006.

Under the present plan for the lunar architecture (Lavoie, 2006), the Shackleton Crater Rim is selected as the outpost site location. The average monthly illumination at the outpost location is in excess of 70 percent, which would allow the outpost to be powered entirely by solar-power generation. The Solar Standard Power Unit will generate 10 kW of daytime power and 2 kW of eclipse power. In combination with two Make-up Power Units, the system will deliver 6 kW of continuous day/night power. The Make-up Power Unit primarily includes a self-contained proton exchange membrane regenerative fuel cell subsystem with gaseous H_2/O_2 storage.

The Prometheus Power and Propulsion program, originally tasked to investigate nuclear propulsion for long-duration missions to the outer planets, was restructured to support the long-duration stays on lunar and martian surfaces called for by the Vision for Space Exploration. This program's primary focus is nuclear fission surface power (FSP) systems. The FSP is the most credible solution for power generation at levels of tens of kilowatts to support lunar surface operation independent of day/night cycle or lunar surface location. The FSP is similarly enabling for the poorly illuminated surface of Mars.

The FSP module contains main components that are intended to generate and at the same time to control the thermal power and reactor-induced radiation for the lunar or martian habitat. These components include the following:

- Reactor core and reflectors,
- Primary heat transfer,
- Radiation shield,
- Reactor instrumentation and control, and
- Power conversion and radiator.

According to NASA's investigations and missions planning, the power requirements for human-tended outposts are projected to range from 25 to 100 kW in the early stages, with the requirements approaching 1 MWe following

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the lunar base development. The power level and life for the current reference design of each FPS are 40 kW and 8 years, respectively. The FPS radiation shield component provides the attenuation of the reactor-induced radiation to the rest of the FPS module (J. Nainiger and L. Mason, NASA, "Plans for Affordable Surface Fission Power," presentation to the committee on December 12, 2006).

The radiation protection measures and systems designs for fission power on Earth are well known. However, when applied to remote planetary destinations, direct transfer of the existing technology becomes difficult, if not impossible. The heavy shielding used on Earth is too massive to transport to the Moon. Unlike terrestrial radiation workers, astronauts will have to live within a certain range of the reactors. As noted in Chapter 2, solving these problems will require engineering solutions rather than more research. NASA is currently considering two fission surface power system (nuclear reactor) shielding approaches:

- *Emplaced configuration:* The light-material-shielded reactor will be placed in an excavated cavity so that external shielding is provided by lunar or martian regolith (Figure 4-2A). Unless a convenient crater can be located, this will require astronauts to be involved in excavation, construction, and the installation of the reactor. The overall effect of using regolith as a shield is a reduction of the neutron and gamma-ray doses from the reactor by five and three orders of magnitude, respectively. (See also the discussion in the subsection "In Situ Shielding" earlier in this chapter.)
- *Landed configuration:* A reactor equipped with an above-grade, 4π shield made of Earth-delivered materials will be placed on the regolith surface. The landed configuration requires very large mass and volume of high-Z and low-Z materials to reduce the neutron and gamma-ray dose to the levels equivalent to those provided by underground emplacement of the reactor module (Figure 4-2B).

The main sources of radiation are neutron and gamma rays from the fissions in the reactor, prompt gamma emission from neutron interactions with the regolith, and gamma rays emitted by the decay of activated regolith and other external shielding materials. The activation of the soil near the reactor will reach near-equilibrium during the 10- to 20-year lifetime of the surface station. The activity following reactor shutdown will be dominated by Na^{24}, with a half-life of roughly 15 hours; soil activation will decrease within days. For the reference below-grade excavated configuration, the total radiation dose is less than 5 cSv/yr at a radial distance of 100 m from the reactor axis. For the above-grade configuration, the 4π shield reduces the dose at the habitat area that is 1 km away from the reactor axis to less than 5 cSv/yr, and for nonhabitat areas to less than 50 cSv/yr (J. Nainiger and L. Mason, NASA, "Plans for Affordable Surface Fission Power," presentation to the committee on December 12, 2006).

The radiation rate from the reactor core is dependent on its power. The power generation expected for this mission is easily attainable with current technology; therefore, other aspects could be optimized: the weight and type of the shielding materials and the distance from the habitats to the reactor. Optimization methodologies and computer simulation tools needed for this sort of analysis are already available. On Earth, where weight is a much lower concern, there has been limited attention to the development of very lightweight shielding. On a mission to the Moon, NASA will be limited to available lightweight shielding materials or materials from the lunar surface.

Engineering challenges in the development of the fission surface power system design studies and technology demonstrations include the following:

- *Fission surface power system and balance-of-plant design:* Conceptual studies that would lead toward technology demonstration would require analysis of the reactor design, technology selection, and material shield design development and demonstration.
- *Microgravity:* Analysis of microgravity effects would need to be carried out, with selected experiments to verify the operational safety of the ground fission power system—for example, effects on the flow of coolant through pipes.
- *Autonomous operation:* Lunar surface power systems cannot be constantly attended to and thus they will require more complex, robust, self-contained control systems.

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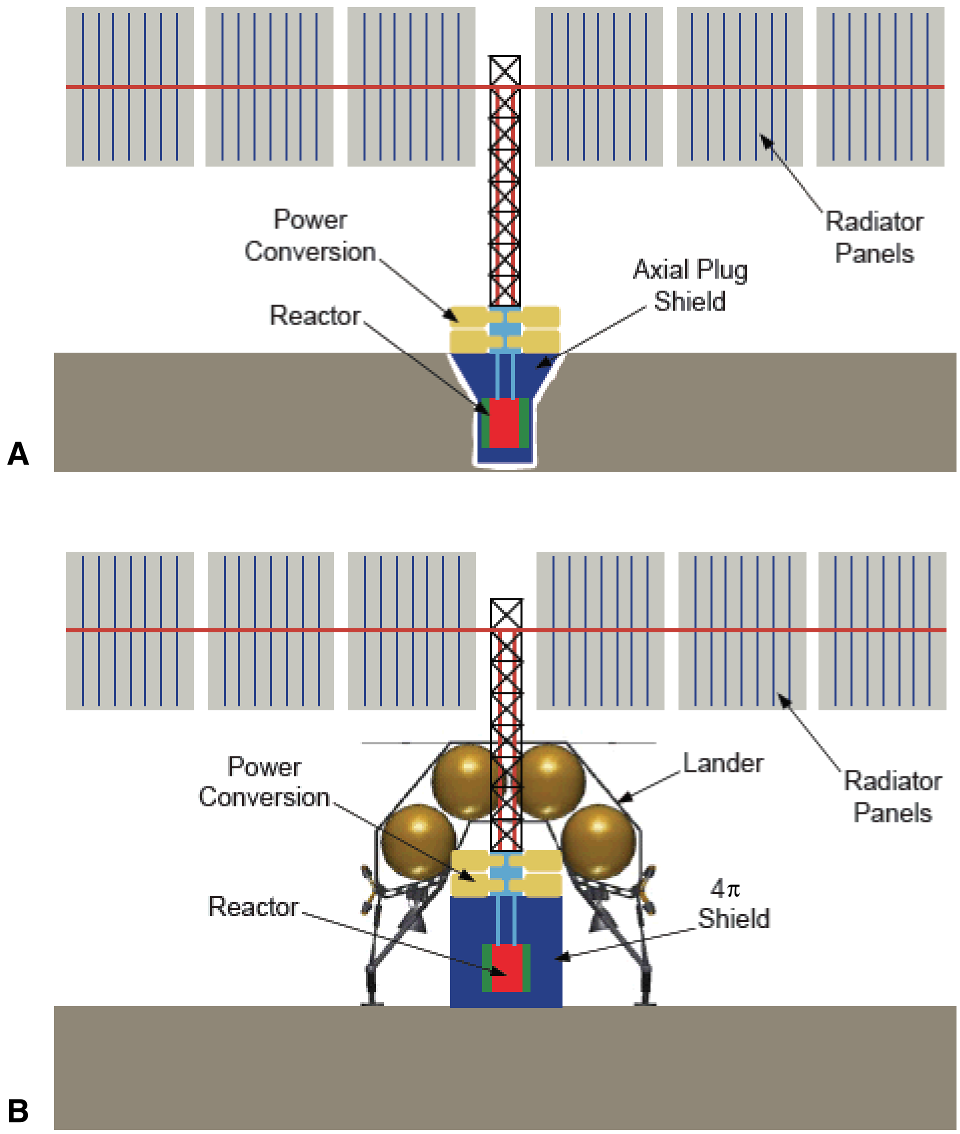

FIGURE 4-2 (A) Reactor power module in excavated cavity (emplaced configuration). (B) Reactor power module on landed configuration with external 4π shield. NOTE: This is a conceptual figure for illustrative purposes only. It does not imply a finalized design, nor the committee's endorsement of the concept pictured. SOURCE: J. Nainiger and L. Mason, NASA, "Plans for Affordable Surface Fission Power," presentation to the committee on December 12, 2006.

- *Shielding:*
  —What is the optimized lightweight shielding design for the expected range of the fission surface power systems?
  —What is a safe distance from the fission surface power systems to ensure acceptable annual exposure, including the variations of power and shielding from the base-design when added to the natural radiation exposure on the lunar surface?

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— What course will be taken in case of accidents in the presence of the crew? What would be the expected exposures to the crew? Would crew intervention be required, and what additional dose would that confer? Would these considerations necessitate additional shielding?
— For the case of accidents not in the presence of the crew, once the crew returns, what action is required and what dose would that involve?
— What would be done with the reactor core at the end of life? What shielding requirements would that pose and what dose levels may be expected? Further analyses are needed to understand the best policy on planetary and space pollution with radioactive materials.

• *Launching criteria, requirements, and technology:* NASA has never launched a nuclear reactor into space. The risks associated with launching a reactor, its transport and extreme environmental constraints on the Moon and Mars can be addressed through research in the following areas.

— Launch payload: optimization of weight and size regarding the shielding.
— Hazardous material safety consideration: safety protocols.
— Operational lifetime: continuous power generation for life support and shielding material durability.
— Environmental constraints and effect on shielding: safe operation with intact shielding.
— Shielding in case of accidents: “breakup” during launch or reentry; water-immersion accident in which the reactor falls into water and becomes moderated; compression in the case of an impact; individual component failures.

NUCLEAR PROPULSION

NASA has not yet decided on an approach to providing propulsion to Mars, so it is unknown if nuclear propulsion will be employed. Therefore, this section provides only an overview of some of the pluses and minuses associated with the topic.

Nuclear propulsion includes a broad range of propulsion methods that use nuclear reaction as a primary source of power. Nuclear propulsion is usually divided into two categories, depending on the *source* of propulsion.

1. Radioisotope decay has been a main source of electricity and propulsion for numerous missions in the past four decades. Russia has flown more than 30 reactors and numerous radioisotope systems. The United States flew the SNAP-10A in 1965 and has flown dozens of radioisotope systems (most recently on the New Horizons mission to Pluto). Energy is released from the radioactive decay of the selected radioisotope (in most cases plutonium-238) providing a continuous, reliable, and proven source of power. The energy released in radioactive decay of the isotope in the device called a radioisotope thermoelectric generator (RTG) is converted into electrical power that is used to accelerate and eject propellant at a speed high enough to boost the spacecraft. The major limitation of such a system is its low power. RTG is usually applied for long-term (i.e., low-acceleration) missions or missions to the outer planets, where solar power is inadequate. This approach currently represents the safest space nuclear propulsion system with the lowest requirements for the shielding, as long as the container holding the radioisotope does not leak. The environmental impact study for the Cassini-Huygens probe launched in 1997 (NASA, 1997) for Saturn estimated the probability of contamination accidents at various stages in the mission. For example, the probability of an accident to cause radioactive release from one or more of its three RTGs during the first 3.5 minutes following launch was estimated at 1 in 1,400; the probability of a release later in the ascent into orbit was 1 in 476; after that, the likelihood of an accidental release fell off sharply to less than 1 in 1 million.
2. Thermal nuclear propulsion in submarines is an industry with developed, proven technology and more than 50 years of accumulated knowledge and experience. However, there has not yet been an analogous system that propelled spacecraft into space. There have been ideas to develop nuclear power in space since the earliest days of the space program. A nuclear thermal rocket and chemical rockets operate by the same basic principles—namely, the expansion of hot gas (propellant) through a rocket nozzle to provide thrust. The propellant flows through coolant channels of the solid-fuel reactor core where it is heated to very high temperatures (>3,000 K proposed for pseudo-ternary carbides). To achieve high performance, the fuel is required to operate at very high temperatures. Hydrogen has been used as a propellant during all rocket reactor tests and is preferred because it has the lowest

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molecular weight. However, hot hydrogen can react with the fuel, resulting in corrosion and mass loss. Furthermore, mission cost constraints require a compact, lightweight reactor necessitating high power densities (high neutron flux) with associated radiation damage and increased susceptibility to fracture.

Because of its high performance potential, nuclear thermal propulsion could be used for human exploration missions and cargo transport to the Moon or Mars, for outer-planet robotic explorations, and for Earth-orbit transfers of satellites. The main benefit of nuclear propulsion is that it can provide a greater specific impulse, or the amount of thrust provided per unit mass of propellant. Producing the same thrust with less required fuel creates two complementary possibilities. First, one could have a spacecraft of the same weight but with more shielding. Second, one could have a lighter spacecraft, with a higher velocity that could reduce the transit time and radiation dose. In reducing mission length, nuclear propulsion will reduce the risk to astronauts from cosmic radiation in addition to the other health, psychological, and operational benefits associated with shorter mission durations. Although this would be offset in part by the radiation of the reactor itself, Nealy et al. (1991) found that cosmic radiation was more dominant. It is estimated that nuclear propulsion could reduce the length of a short human-exploration mission to Mars from a year and a half (using chemical propulsion) to under a year (NASA, 1989). Nuclear propulsion could also reduce the total time of a longer-duration mission by 50 to 100 days for the low-Earth-orbit mission (Bennett and Miller, 1991). A comparison of two similar missions is shown in Figure 4-3; in addition to a shorter mission length, the nuclear mission includes a longer stay on Mars, which raises the value of the mission as well as reducing the total radiation exposure. Figure 4-4 shows the tradeoffs between mission masses and travel times for a long-duration mission launching between 2008 and 2011.

ALTERNATIVE METHODS

Active Shielding

The use of active shielding that involves the generation of an electromagnetic field to deflect or capture the incoming radiation particles and thereby protect the crew has been proposed. However, there are many practical and technical difficulties with implementing such a method of defense. First, the active shield may require large amounts of power. Second, such powerful electromagnetic fields can have disruptive effects upon the onboard microelectronics. Third, possible exposure of the crew to such powerful electromagnetic fields may carry additional unknown health effects. There are also technological challenges that need to be addressed including the safe dissipation of the stored energy in the event of a spontaneous quench of the magnet, refrigeration of the coils to 2.1 K on a long space mission, and the development of new superconducting cables.

Electromagnetic shields often seem attractive when compared with bulk shielding. However, a true comparison between the efficacy of the two must include the following:

1. Complete and realistic representations of radiation environments expected in deep space (SPEs *and* GCR), which consist of particle types ranging from protons through iron nuclei with energies up to several GeV per nucleon. It is not sufficient to choose one particle type and energy for the analyses and then base the conclusions of the study on that limited environment.
2. It is not possible to deflect all of the incident particles, since many will have energies above the cutoff energy of the electromagnetic field. Just as it is not possible to stop all of the particles in a bulk shield; some particles will be transmitted through both types of shielding. Estimates of the shield effectiveness must include detailed calculations of the biological risks from those transmitted particles, both primary and secondary. Thus, dose and dose-equivalent comparisons between active and passive shields should include detailed transport analyses that consider all relevant secondary particle production mechanisms. Estimates of bulk shield mass requirements based on simple range-energy relationships are not adequate for choosing between passive bulk shielding and proposed alternative shield configurations.

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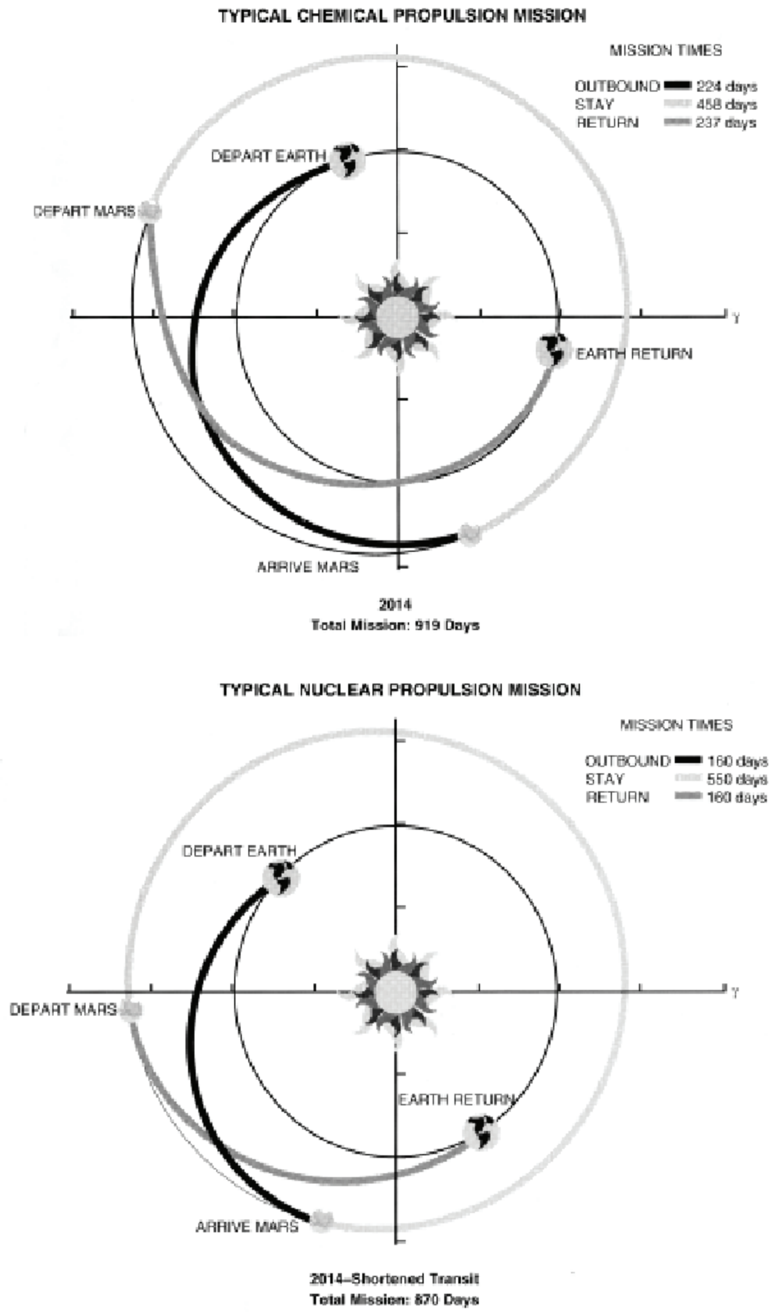

FIGURE 4-3 Mars mission duration for chemical and nuclear propulsion. SOURCE: Stafford, 1991.

Finally, there is a difficulty that is ubiquitous to the lunar surface: lunar dust. The lunar dust contains nanophase iron inclusions that give it electromagnetic properties. Creating a powerful electromagnetic field could loft dust over the outpost. The Apollo crews found the dust to be irritating to the skin and respiratory system during their short 2- to 3-day stays on the lunar surface. Since the dust is highly abrasive to machinery and probably hazardous to the crew's health, levitating the dust could create additional threats to the crew and mission.

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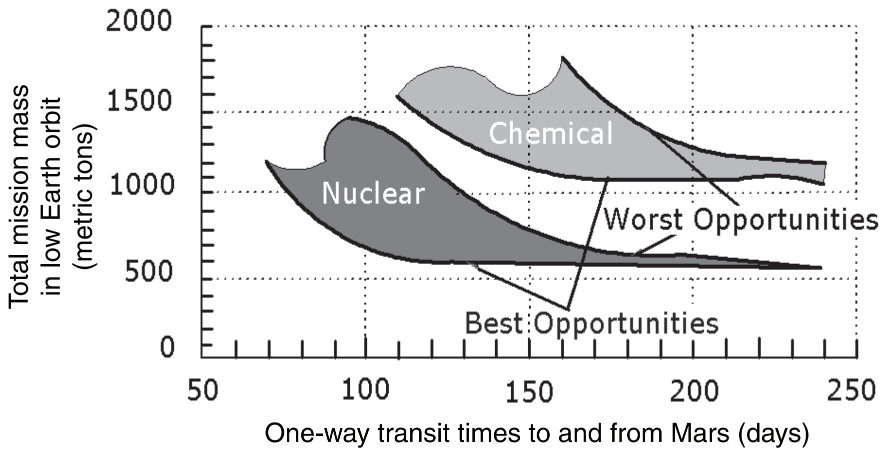

FIGURE 4-4 Comparison of transit times for a long-duration Mars mission using either a chemical or a nuclear propulsion system. Shorter-duration missions require more propellant and thus a higher mission mass. SOURCE: Stafford, 1991.

Radioprotectants

The only radioprotectant that has been approved for use in humans at this time is amifostine (ethyol), which has a dose-reduction factor (ratio of dose of radiation to cause an effect in the presence of the drug to the dose of radiation to cause the same effect in the absence of the drug) of 1.8 to 2.7 when the drug is administered prior to an exposure. The dose-reduction factor varies with the amount of time that has passed since exposure. This drug was originally developed by the Walter Reed Institute (and called WR2721) as a thiol-containing compound with free-radical scavenging capabilities (Hall and Giaccia, 2006). Amifostine is used clinically to prevent late tissue toxicities (such as salivary gland damage) in patients who are being treated for head and neck cancers.

The drug has been available to NASA for several decades, predominantly because of its ability to inhibit the induction of mutations following radiation exposure, thus suggesting the possibility of reducing stochastic effects (cancer) following radiation exposure. There is some confusion in the literature on the ability of amifostine to protect against damage from high-LET (linear-energy-transfer) types of radiation such as those encountered in space (Hall and Giaccia, 2006). On the one hand, the free-radical scavenging activity of amifostine should allow it to protect against indirect damage to DNA (induced by free radicals, predominantly following low-LET exposures) rather than direct damage to DNA, which predominates following high-LET exposures. On the other hand, there are several studies demonstrating that amifostine reduces cancer induction in mice when administered prior to exposure either to low-LET gamma rays or to high-LET neutrons (Grdina et al., 2002a,b), although the mechanism is still to be elucidated (Grdina et al., 2000). Nevertheless, its use as a chemoprevention agent is limited by toxicity, which includes hypotension.

Various other radioprotectors have been examined in the literature, including phosphanol, Mn-SOD mimetic drugs, and others (Greenberger and Epperly, 2007). None has been shown to have the same level or as broad a level of protection as amifostine. During the past 2 or 3 years, in an effort to protect against possible radiation attacks coming from terrorists and others, the National Institutes of Health has invested in several large center grants to develop a better understanding of radiation effects, including the development of new protectors. NASA participates, along with other agencies, in the continuing evaluation of these developments, and it is well placed to take advantage of any breakthroughs in radioprotectant developments as they occur.

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SUMMARY

Finding 4-1. State of radiation protection plans for lunar missions. The use of surface habitat and spacecraft structure and components, provisions for emergency radiation shelters, implementation of active and passive dosimetry, the scheduling of EVA operations, and proper consideration of the ALARA principle are strategies that are currently being considered for the Constellation program. These strategies, if implemented, are adequate for meeting the radiation protection requirements for short-term lunar missions.

Recommendation 4-1. Strategic design of Orion. As the design of Orion continues to evolve, designers should continue to consider and implement radiation protection strategies.

Finding 4-2. State of radiation protection plans for Mars missions. For longer-duration lunar and Mars missions the currently large uncertainties in radiological risk predictions could be reduced by future research. Without such research, it may be necessary to baseline large shielding masses and reduced-length missions, and/or delay human exploration missions until uncertainties in risk prediction and radiobiological methods of risk management have advanced to the point that they can be conducted within the limits of acceptable risk.

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5

Strategy for Radiation Risk Mitigation

TECHNOLOGY INVESTMENTS TO ENABLE LUNAR MISSIONS

A comprehensive radiation risk management strategy is based on an understanding of the biological effects of radiation exposure and includes physical shielding, radiation monitoring and forecasting, and operational flight rules. Because this strategy is science-based, it will lead to risk mitigation methods, such as accurate space radiation environment forecasts, improved spacecraft design, and methods of biological intervention.

The recommendations listed below are roughly in priority order, but they are considered essential elements of a single group. Together, they are necessary and sufficient to implement an effective strategy for risk reduction leading to operational management of radiation risk. The committee considered Mars application as a factor that gave additional weight to a given research topic, but it did not prioritize technologies that have application only to Mars. The lone exception is the tenth topic listed below, Surface Fission Power Demonstration—Nuclear Power for Mars. It should be considered separate from the priority list, because it is not essential to lunar exploration (although it may be useful). However, it was listed because the Moon provides a unique technology development opportunity; in order to take advantage of that opportunity, this research should be included in NASA's research plan.

The prioritization process considered impact (payoff), time-urgency, current understanding versus gaps to fill, the probability of successful outcomes, and an estimate of the time and resources necessary to substantially meet the recommendations. Those efforts that must be implemented immediately to have a substantial impact have the highest priority—for example, challenges that impact the Orion configuration or will be difficult and costly to "retrofit" later. Therefore, challenges in Orion development received a high priority, as did research objectives with high payoff but long-term commitment.

1. Radiation Biology Research

The rapid progress in our understanding of cancer mechanisms at the molecular level and the impact of radiation on these mechanisms should allow for more precise estimates of human cancer risk. Biological understanding has also grown more complex with newer concepts of genomic instability, bystander effects, and genetic susceptibility. It is essential that these breakthroughs in molecular understanding be tested in and translated to a better understanding of cancer in the whole organism and the impact of radiation types and energies on these mechanisms. The radiation effects need to be understood quantitatively as well as qualitatively. Through the application of sys-

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tems biology and risk modeling, quantitative cancer risks to humans will therefore be more precisely estimated for various radiation exposure scenarios.

From a better understanding of the radiation spectra that the astronauts are predicted to experience, cancer risk models will identify those radiation types and energies that are the most significant and least precisely understood from a human-risk standpoint. This should guide the experimental biology research work, including possible future whole-animal studies. In this way the overall uncertainty in the estimated cancer risk to the astronauts can be minimized.

The knowledge with regard to latent cancer effects from radiation greatly exceeds that of other potential chronic effects, especially cardiovascular disease and central nervous system effects. Researchers are just beginning to realize the potential importance of these other effects in relation to radiation exposures. There is a great need to understand their biological effects so that risk estimation is possible with reasonable precision for both acute and chronic exposures. The committee is concerned that these emerging adverse health effects are not receiving appropriate attention by NASA.

The NASA Bioastronautics Roadmap (NASA, 2005), as well as the recent National Council on Radiation Protection and Measurements report (NCRP, 2006), provides worthwhile guidance to the research issues. There is just sufficient time to reduce the radiation risk uncertainties before the lunar mission, but not enough time to impact design for the first missions. Because of the much greater radiation risks associated with a journey to Mars, it is also essential that research be increased now in order to make rational decisions on the feasibility of such an endeavor. In order to meet these goals, ongoing cell and animal studies need to be expanded and oriented toward an understanding of the mechanisms responsible for radiation risk, including cancer as well as the noncancer risks thought capable of having a significant impact on astronaut health.

One of the key enablers to reducing this uncertainty is the NASA Space Radiation Laboratory (NSRL), located at the Department of Energy's (DOE's) Brookhaven National Laboratory (BNL). Its combination of atomic number, energy, and flux makes the NSRL unique because it provides nearly the full range of particles and energies that constitute GCR, at fluxes that can go from a few particles per square centimeter per second to 100 million particles per square centimeter per second. Furthermore, the NSRL facility is dedicated to providing several thousand hours of beam time exclusively for NASA. The National Research Council's (NRC's) *Radiation Hazards to Crews of Interplanetary Missions* (NRC, 1996) stated that 3 months of beam time per year would be required to make progress on high-priority research questions. There is one other heavy-ion facility in the world (the Schwerionen Synchrotron Accelerator in Darmstadt, Germany) that can deliver the same range of particles and energies as NSRL, but it is fully dedicated to nuclear physics and can provide only occasional beam for space radiation experiments. Another handful of facilities (such as the cyclotron at DOE's Lawrence Berkeley National Laboratory, the Proton Therapy Facility at Loma Linda University, and the Heavy Ion Medical Accelerator in Chiba, Japan) deliver a partial range of particles and/or energies, but are also fully dedicated to physics or radiation therapy programs, with restricted availability for space science experiments. These other facilities may prove to be cost-effective in providing ions and beam time for certain classes of experiments, but they cannot be seen as a substitute for NSRL. Finally, because NSRL is almost fully dedicated to NASA service, space-specific modifications can be obtained that are not available elsewhere, such as broadband beams, rapid changes between beams (e.g., iron to protons), large beam spots, in-beam incubators, laboratory facilities for on-line biochemical analyses, animal holding facilities, and dosimetry and data-acquisition services.

DOE's Brookhaven National Laboratory has an annual budget of $500 million. NSRL is a relatively small part of a much larger accelerator complex that serves the high-energy, the nuclear physics, and the heavy-ion physics communities. That support can be expected to last as long as the research conducted by these communities continues to be cutting edge and vital. However, accelerators can be and have been closed when the frontier of science moved elsewhere. If DOE determines that the research topics requiring BNL accelerators no longer are a priority, they will be shut down or reconfigured. It is impossible to predict if or when that might occur; however, a prudent strategy for NASA would be to assume that the BNL accelerators will not be available 15 to 20 years from now and plan accordingly.

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Finding 5-1. The NASA Space Radiation Laboratory. The entire Space Radiation Biology Research program is critically dependent on the availability of the NASA Space Radiation Laboratory. This facility is dependent on the DOE heavy-ion physics program and may not be available if the needs of this program change. There are no other facilities available that meet the requirements for high atomic number and energy (HZE) space radiation biology research, worldwide.

Recommendation 5-1. Radiation biology research. NASA's Space Radiation Biology Research program should be adequately funded. NASA should perform research aggressively at the NASA Space Radiation Laboratory to take advantage of the existing window of opportunity while this facility is still available. The results of the biological research will thus be able to have an impact on the Project Constellation missions in the short term, as well as provide knowledge essential for the management of space radiation risk in the long term.

2. Radiation Protection in Orion

At the time of this study, the radiation protection planning for Orion and other elements of the Constellation program was in its beginning stages. As noted in the findings and recommendations below, much of what will be needed is currently being addressed. However, the development program for this system is proceeding at a rapid pace, and design changes occur frequently. Because Orion eventually must operate away from Earth's protective geomagnetic field, it will be critically important for NASA to incorporate radiation protection at the systems engineering level from the earliest stages and to vigilantly continue throughout all phases of mission development and execution. Nominally, these design efforts will be needed out to 2013, when Orion is scheduled to be completed.

Finding 5-2. Dose estimation in the Orion crew module. The use of ray-tracing analysis combined with state-of-the-art radiation transport and dose codes is an appropriate method for estimating dose within the Orion crew module, and can be used to guide decisions on the amounts and types of spot or whole-body shielding that should be added to provide protection during solar particle events.

Finding 5-3. Orion Radiation Protection Plan. The Orion Radiation Protection Plan, as presented to the committee, appears to meet the minimum radiation protection requirements as specified in NASA's radiation protection standards. Any reduction in the Orion Radiation Protection Plan may pose potentially unacceptable health risks.

3. Validation and Verification of Transport Calculations

Code validation is a series of tests intended to provide evidence that a given transport calculation method correctly describes the radiation field as modified by material volumes in a given experimental arrangement. This is a falsifiable hypothesis that cannot be proven true for all circumstances with a finite set of tests. However, critical predictions can be tested by statistically significant comparisons with experimental data and with the results of other computer codes. The latter type of comparison allows for the evaluation of the precision, stability, and reliability of the computational methods; it also establishes the relative practical advantages of different methods, such as computational speed, ease of use, and flexibility.

However, the validation and accuracy of the calculations can only be ascertained by comparison with independent experimental data. The experimental data may be taken from archives or obtained in experiments designed to test particular features of a specific code. Data may not be available for all interactions of interest. In this case, extrapolation schemes may be used, based on available experimental or theoretical results for particular interactions of radiation with matter (stopping power, range, nuclear cross sections).

A variety of radiation transport codes are currently in use. The codes used to analyze laboratory data were developed for beams with a narrow distribution of energies. Conversely, the versions of the transport codes that are used for shielding in space were developed for incident galactic cosmic rays with a broad distribution of energies. This difference causes computational problems that prevent validation of galactic cosmic ray codes with laboratory data.

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Finding 5-4. Existing transport data. New measurements do not need to be taken solely for the purposes of code validation. In addition, structure in the energy dependence of relevant fragmentation yields for heavy charged particles is considered to be sufficiently small to have a negligible impact on interpolation schemes. One exception is that additional data on production of light ions (Z = 1, 2) and neutrons may be required.

Recommendation 5-2. Testing transport code predictions. The predictions derived from calculations of radiation transport need to be tested using a common code for laboratory and space measurements that have been validated with accelerator results, existing atmospheric measurements, and lunar and planetary surface measurements as they become available.

4. Research on Solar Particle Events

Operations planning support to lunar and future Mars missions will require forecast tools that estimate the probability of a solar particle event (SPE) within the next few hours to days. Real-time mission operations support will substantially benefit from predictions of the expected peak flux, time to peak flux, total fluence, and duration of ongoing events within the first hour of event onset.

However, today these tools are still limited. SPE predictions 1 day to several days in advance first require the operational capability to predict the onset or character of the source coronal mass ejections (CMEs) or the near-Sun ambient plasma characteristics where the most significant particle acceleration occurs. Even after an SPE has been observed to be underway, forecasts of peak flux are only good to within an order of magnitude at best. The National Oceanic and Atmospheric Administration (NOAA) and the U.S. Air Force provide current operational space weather forecasts. However, their models are inherently limited by the fact that they are fundamentally based on x-ray flare proxies to the SPE.

Significant advances in near-term forecast capability will require the development of a physics-based model that builds on current understanding of the relationship between CMEs and SPEs and incorporates new information expected from ongoing science missions over the next 10 years. Such models could reasonably be expected to exist in time for the human return to the Moon in 2020. In the nearer term, over the next few years, significant improvements could be made by incorporating elements of the cutting-edge SPE research models into more operations-oriented prediction codes. In addition, a better understanding of the precursor conditions necessary for a significant solar particle event could be applied to reliably predict periods when a severe solar storm is extremely unlikely. These “all-clear” forecasts would be valuable to mission operations and mission planning.

Finding 5-5. SPE prediction. At present, the ability to predict an SPE and to project its evolution once underway does not exist. Such a capability will play an important role in managing the SPE radiation hazard.

Recommendation 5-3. Research on solar particle events. NASA should maintain a vigorous basic science program that can clarify the mechanisms that produce SPEs and lead to accurate, quantitative predictions of SPE behavior and identification of observables critical in forecasting SPEs or all-clear periods.

5. Empirical Data for Shielding Design

Although much of the experimental data collected by the NASA measurements consortium has been analyzed and is available online, some data remain to be analyzed. However, these data, collected over more than 10 years, may not be adequate because they do not include information on energy-, angle-, or multiplicity-dependence of the fragments produced from nuclear interactions. In addition, only a partial set of the experimental data obtained by heavy-ion investigators throughout the world over the past several decades has been collected, cataloged, and put into databases accessible to NASA. Validations of transport codes with empirical transport data have been limited. In particular, comparisons with laboratory measurements of fluence spectra (number of fragments of each produced species as a function of energy and angle) cannot be made using deterministic versions of NASA’s space radiation transport codes, since they were developed for incident galactic cosmic ray and SPE spectra, which have

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a broad distribution of energies. Hence, published comparisons have been between predictions of different codes, or between code and space-based dosimetry measurements.

The use of accelerator measurements is critical if adequate statistics are to be obtained with a sufficient number of beam and target combinations. That being said, great value can be gained from a carefully chosen but limited set of new laboratory experiments. The uncertainties currently attributed to physics are minor compared with the biological uncertainties, and NSRL beam time should be prioritized accordingly.

Finding 5-6. Experimental data for designers. NASA has not made an adequate effort to collect, catalog, and categorize existing experimental data obtained by the worldwide heavy-ion research community and to make it available in appropriate form to the shielding engineering community.

Recommendation 5-4. Empirical data for shielding design. NASA should ensure that necessary experimental data in sufficient quantities are collected, analyzed, and managed in a manner appropriate for their use in designing radiation shielding into spacecraft, habitats, surface vehicles, and other components of human space exploration. The data should include information on energy and angular dependence of cross sections for production of nuclear interaction products, and on their multiplicities.

6. In Situ Monitoring and Warning

A comprehensive strategy for radiation protection goes well beyond the selection and arrangement of material to be incorporated in Orion, Lunar Lander, and elements of the lunar outpost. NASA will ultimately establish a system, or architecture, that incorporates various components beyond the physical barriers to radiation. The broader architecture is discussed in the report *Space Radiation Hazards and the Vision for Space Exploration* (NRC, 2006) and is illustrated by Figure 5-1, reprinted from that report. The architecture will include the following:

- *Solar monitoring:* What is going on at the Sun to observe activity that may lead to an SPE?
- *Heliospheric monitoring:* What is the state of the solar wind, interplanetary magnetic field, and fluctuations in the nominal solar wind to be able to predict the propagation of accelerated protons from the source to the astronauts?
- *Energetic-particle monitoring:* What is the solar proton and ion flux in the region near the astronauts?
- *Real-time astronaut dose and dose-rate monitoring:* What will the dose be, as measured under any shielding available to the astronaut?
- *Communications and data fusion:* What are the issues that may affect the ability to get the right data to the right place in a useful format?
- *Flight rules and procedures:* How will the mission react to sudden changes in the radiation environment to avoid overexposure and follow the principle of As Low As Reasonably Achievable (ALARA)?

Each element has contributing components: observations, models, procedures, and so on. For example, radiation exposure forecasts will rely on in situ dosimetry (which will also be available to the crew) as well as transport models that start with the forecast or observed radiation environment and convert the external radiation field into estimates of the astronaut's exposure. Mission impact will consider the exposure forecast, the flight rules, the mission manifest, and crew exposure histories. Recommended actions to minimize radiation exposure will be considered in the context of mission objectives and competing risks.

Often overlooked or incorporated late in the design, the communication infrastructure is an important factor to consider from the outset in the construction of a total radiation protection architecture. For example, real-time telemetry from radiation monitors on the International Space Station are transmitted to Earth through antennas that are subject to being shut down during high radiation events. For a lunar architecture, some of the elements of a radiation shielding strategy may be located far from Earth and may require multiple round trips between the Moon and Earth before actionable advice is delivered to the astronauts. Tradeoffs are needed to determine optimal distribution of measurements, models, and decision making, particularly for surface excursions when an SPE may

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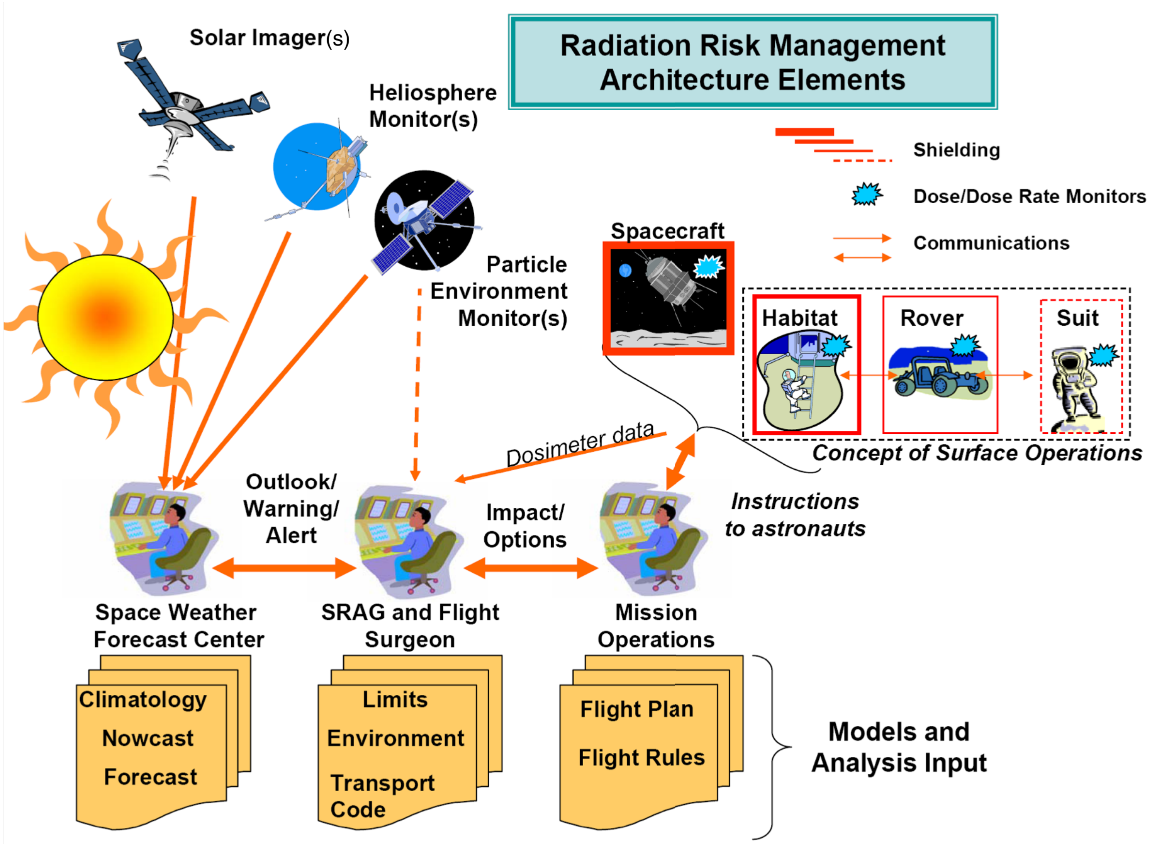

FIGURE 5-1 Operational elements of a radiation risk management architecture. SOURCE: NRC, 2006.

disrupt communications. There may be times when the crew will have to make decisions without input from ground control. On a Mars mission, the communication to the astronauts will take up to 20 minutes to arrive from Earth. Data collectors may also be up to 20 minutes away from Earth and Mars (see Figure 5-2). Since the highest-energy particles move with speeds close to the speed of light, techniques are needed to ensure that warnings and support are provided in a timely fashion.

During every spaceflight, radiation dosimeters will be required to determine the exposure to astronauts and to confirm compliance with regulations, as well as to indicate if exposure rates require the postponement or termination of a particular mission. The response of space dosimeters must conform to the biological risk for the broad spectrum of incident radiation. This is no easy task and research in this field should be performed along with research into the biological effects of radiation.

Incorporation of in situ warning and dosimetry into Orion must begin immediately. Provisions for active and passive dosimeters into the Lunar Lander and outpost components (including all surface transportation elements) should be included in every iteration of the design, from the very earliest stages. If NASA's Exploration Systems Mission Directorate establishes a formal working relationship with NASA's space science community and with the NOAA Space Environment Center over the next 3 years, the proper elements of a comprehensive operational warning system can be in place when humans return to the Moon. The Geostationary Operational Environmental Satellite (GOES)-R and -S spacecraft, which are expected to become operational in 2017 and 2020, respectively, will have an extensive complement of operational space environment monitors. These spacecraft are already well into development, with instruments to be delivered as early as 2011. However, there will be a need for additional

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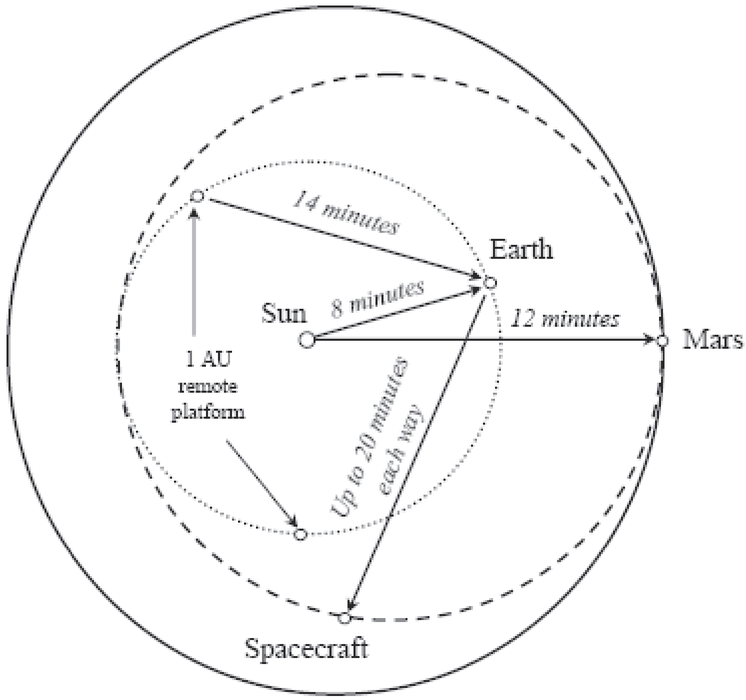

FIGURE 5-2 One-way communication times between elements of Mars mission will be measured in the tens of minutes. SOURCE: Turner and Levine, 1998.

solar, solar wind, and particle environment monitors and communications elements. If there is to be an acquisition plan for additional exploration-specific space weather elements in place by 2020, a comprehensive requirements analysis should be completed by 2012.

Finding 5-7. Forecasting of SPEs. Forecasting and warning of SPEs will be an essential part of a comprehensive radiation mitigation strategy. Timely collection of appropriate data and communication of resulting forecasts and warnings will be mission-critical.

Recommendation 5-5. Flight crew radiation safety officer. On exploration missions, a member of the crew should be designated as flight crew radiation safety officer. This person would be the point of contact with mission control, monitor on-site dosimetry, and ensure communication and coordination with ground control for the response to radiation warning levels.

Recommendation 5-6. In situ monitoring and warning. Warning and monitoring dosimetry, active and passive, is required wherever there is a human presence beyond low Earth orbit.

7. Multifunctional Materials

Materials development is not an overnight process. Developing a brand-new material typically takes 15 to 20 years of research; a research program started today would have results available to designers after Mars mission planning had already begun. There are a number of carbon and polymer composites, however, that have been under investigation for years. Some of these materials would have a dual advantage of reduced weight and increased

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radiation protection. While they are not yet ready to be used for flight hardware, a 5- to 10-year research program could bring them to maturity in time to influence lunar outpost design, as well as removable equipment carried aboard Orion. However, the longer such a research program is delayed, the less benefit the end product will be able to provide to the Exploration Vision.

Radiation shielding does not need to come in the form of thick plates attached to the bulkhead of a spacecraft. Everything inside—food, water, furnishings, equipment, and even other astronauts—provides additional shielding. Clever material selection and placement of objects such as shelving, lockers, and electronics can give the astronauts increased protection, resulting in a reduced need for heavy external shields. This is not necessarily a dedicated project, but something that should be considered and incorporated into the ALARA process for all Constellation elements.

Finding 5-8. Multifunctionality. Multifunctionality presents a way to increase the ability to shield against radiation by taking advantage of the mass of materials already included in the spacecraft design. Low-Z spacecraft materials offer some shielding advantages over conventional, higher-Z metallic structures.

Recommendation 5-7. Multifunctional materials. Where appropriate, replacement of traditional materials with multifunctional materials should be encouraged, with the goal of improving radiation shielding.

8. In Situ Shielding Tradeoffs

Using lunar or martian regolith to shield a habitat seems like a way to provide radiation shielding without adding launch weight. However, even lunar soil is not free. If astronauts spend the time to construct shields by hand, it could reduce the overall value of the mission. If robotic or remotely operated machines are used to construct the shields, they must be transported to the site. These machines may or may not be applicable to other tasks required by the outpost. Finally, the Orion crew module would still need shielding for the transit period, particularly on a Mars mission.

In situ shielding is a viable idea that offers potential benefit to Project Constellation. However, its benefits will vary based on the mission architecture. It will not be obvious whether it is more practical to carry terrestrial shielding or to dig in upon arrival. Analysis of the tradeoffs, concurrent with the development of the outpost architecture, will be valuable in determining the correct path.

Recommendation 5-8. In situ shielding tradeoffs. NASA should conduct studies of tradeoffs to determine whether it is more cost-effective to transport prepared shielding materials from Earth or to construct shielding in situ with transported materials and equipment.

9. Review of Existing Neutron Albedo Datasets

One radiation source that may not have been sufficiently considered on the Moon and on Mars is the secondary radiation (primarily neutrons and gamma rays, often referred to as “albedo”), produced by the interactions of GCR and high-energy solar protons with matter in the martian atmosphere or the surface of Mars or the Moon. The gamma-ray albedo is not believed to be a significant radiation hazard. Existing estimates of the total effective dose from lunar albedo neutrons indicate that they contribute approximately 10 percent of the dose on the lunar surface. If a complete investigation of the available data confirm this conclusion, it is not necessary to make any further measurements of lunar albedo neutrons for the purposes of radiation protection.

Of potentially greater importance on Mars is the neutron albedo because of the extra neutrons generated by atmospheric nuclear interactions. The NASA Langley Research Center has developed computer codes to model secondary neutron production and has carried out extensive calculations for the Moon and for Mars, using GCR and the August 1972 SPE as the progenitors. It may be possible to validate these albedo-production codes with data from Mars Odyssey (e.g., Evans et al., 2006) and future lunar and Mars missions. However, opportunities to validate these codes with data from closer to home can be exploited. In particular, terrestrial measurements of the

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neutron albedo are available from aircraft (Goldhagen et al., 2004), at sea level (Nakamura et al., 2005), and at various altitudes in between (Kowatari et al., 2005). Sato and Niita (2006) have recently reported on modeling these observations using Monte Carlo techniques and the CREME96 model (Tylka et al., 1997) of the galactic cosmic rays. They will not, of course, address the aspects of the code that are tied to assumptions about the composition and structure of the lunar and martian surface and the martian atmosphere. For more information, see Adams et al. (2007), Harris et al. (2003), Petry (2005), Share and Murphy (2001), Share et al. (2001, 2002), and Wilson et al. (1989, 2004).

Recommendation 5-9. Review of existing neutron albedo datasets. The predictions of computer codes developed by the NASA Langley Research Center need to be compared with existing data, especially data for secondary radiation and neutron albedo. Existing datasets should also be reviewed to assess their value in determining the extent to which albedo neutrons on the lunar and martian surfaces may constitute a significant component of the radiation environment. Lunar and planetary surface measurements performed in the pursuit of other exploration objectives may become available; if so, the data should be used for statistically significant comparisons with theory whenever appropriate.

10. Surface Fission Power Demonstration—Nuclear Power for Mars

As discussed in Chapter 4, long-term missions to Mars cannot depend on solar power alone. Nuclear reactors are the best candidate for these conditions and are an established, mature technology. Most of the necessary work will involve modifying current technology for space, particularly martian operation. Not only must the reactors have adequate shielding to protect astronauts during nominal operation, but they must have enhanced safety and reliability as well. Many of the constraints on Mars are also present, to a lesser degree, on the Moon. There is harmful dust on the Moon, but it exists in a vacuum; Mars has atmospheric gas and windblown dust, which has corrosive and electrostatic effects as well as affecting a susceptibility to high-voltage breakdown. Lunar reactors would have to be somewhat autonomous, since astronauts cannot constantly attend to them, although they could potentially be controlled from Earth. Martian reactors would have to be very autonomous, because the communications delay makes teleoperation infeasible. In preparation for future missions to Mars, NASA can leverage the unique environment of the lunar surface to move beyond conceptual studies into a technology demonstration of space nuclear systems. On the Moon, solar power is also feasible, meaning that astronauts' lives would not be dependent on the success of a reactor design. Furthermore, fission surface power would be necessary for a lunar settlement at a location other than the poles, should one become desirable.

One year before a Mars mission, the fission surface power systems should be well demonstrated. The terrestrial use of nuclear power systems has gained substantial experience that can be leveraged in developing, demonstrating, testing, and manufacturing the prototype space reactor and space fission surface power system. A demonstration would require national support, in the form of a joint program including national laboratories and universities helping the NASA specialists to design and demonstrate successful nuclear space technology. Commercial nuclear entities will also be needed for fuel production. The particular challenges are as follows:

- *Nuclear reactor design:* Develop the reactor design, build the full-scale end-to-end prototype, and develop and test the reactor performances in simulated environments of the Moon and Mars; perform irradiation materials tests on the nuclear fuel, primary loop materials, and shielding.
- *Software and database review for radiation transport modeling:* Review the cross-section database for materials of interest under lunar and martian environmental conditions; review the existing computational tools for radiation transport modeling.
- *Materials testing:* Evaluate radiation effects under different environmental conditions (temperature, pressure, gravity) and fill in the gaps in the radiation-thermal-mechanical materials property database.
- *Power conversion and heat-rejection technology:* Develop the technology to demonstrate the best power conversion system and the heat-rejection components and systems.

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- *Shielding:* Develop the series of tests for the optimal shielding packing and weight versus radiation attenuation effectiveness under constraints on minimal weight for transit to the surface and maximized multipurpose use of the materials involved in the shielding design.
- *Instrumentation and remote control systems:* Demonstrate the technology to support potentially required innovations in instrumentation and remote control systems, both hardware and software.
- *Launching nuclear reactor into space:* Develop the technology for safe launching of the nuclear reactor.

While lunar reactors should be designed with martian operation in mind, additional development and testing will still be required for martian reactors. The Moon is not a perfect analog for Mars, but can be a valuable stepping-stone.

Finding 5-9. Reactor shielding. Significant research is required before nuclear fission can be used for surface power on Mars or to support exploration at a nonpolar location on the Moon.

Recommendation 5-10. Surface fission power demonstration—nuclear power for Mars. NASA could take advantage of the Moon as a testbed for human exploration of Mars by incorporating the development and testing of fission reactor technology into lunar plans.

STRATEGIES FOR KEEPING RADIATION RISK WITHIN NASA GUIDELINES

Combined with the technology investments outlined above, the following recommendations constitute a comprehensive strategy for mitigating radiation risk to Constellation astronauts.

Transition from Research to Operations

There is a significant gap between operational SPE forecast tools and the improved understanding of these events that has developed over the past decade. The slow transition of research to operations is a well-documented issue in this field; it has been discussed in numerous recent studies (NRC, 2000, 2003, 2006; OFCM, 2006).

Space weather research and forecasting is inherently interdisciplinary and increasingly interagency. Support to lunar missions will build on existing capabilities but will have unique requirements as well. Improved forecasting of SPEs in support of human activities at the Moon in turn will have a benefit to terrestrial users of space weather forecasts. There needs to be a strategy for integrating knowledge, needs, and satellite requirements so that the agencies involved (NOAA, the National Science Foundation, NASA, and the Department of Defense) can work together to improve monitoring and forecast capabilities.

This recognition of the interagency flavor to space weather is not new to this committee. The decadal research strategy in solar and space physics (NRC, 2003, pp. 19-20) contained the following recommendations:

> The principal agencies involved in solar and space physics research—NASA, NSF, NOAA, and DOD—should devise and implement a management process that will ensure a high level of coordination in the field and that will disseminate the results of such a coordinated effort—including data, research opportunities, and related matters—widely and frequently to the research community.
>
> For space-weather applications, increased attention should be devoted to coordinated NASA, NOAA, NSF and DOD research findings, models, and instrumentation so that new developments can quickly be incorporated in the operational and applications programs of NOAA and DOD.

Recommendation 5-11. Agency partnerships in space weather. The nation's space weather enterprise should integrate its scientific expertise with operational capability through coordinated efforts on the part of NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Department of Defense (DOD). Where multiple end users benefit, NOAA is appropriate as the lead organization

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in charge of operational forecasts. However, for NASA-unique lunar support requirements, NASA's Exploration Systems Mission Directorate should take a leadership role in defining and providing resources.

Human Capital Infrastructure

Intellectual Capital

A research program establishes the intellectual capital that medicine, engineering, and management apply to accomplish an agency mission. During the Apollo era, ample intellectual capital was available from research in metallurgy, semiconductors, computers, and aerodynamics, largely performed under the auspices of agencies and institutions other than NASA.

The critical element in space exploration is the human. No comparable research legacy is available now to draw on in order to ensure the health and performance of humans in space and their subsequent quality of life. The overwhelming majority of current biomedical and radiation physics research is focused on issues that do not allow easy application to the NASA mission.

One of the vital strategic roles of having a research program is the availability of a science community able to recognize, develop, and apply breakthroughs to the NASA mission. However, it takes 5 to 15 years before the state of the art in biology results in substantial breakthroughs with applications to the NASA missions. Nevertheless, incremental progress in radiation risk management is possible, and has been significant over the past 15 years. To be successful, a multidisciplinary, mission-oriented research program requires several components:

- Critical mass,
- Stability,
- Credibility,
- Accountability, and
- Integration.

These components are not independent. A critical mass of investigators is required to maintain credibility, to provide mechanisms of accountability such as reviews, and to provide wide enough coverage of research areas to make integration possible. Stability of research support is required by the life cycle of scientific research, which incorporates the duration of graduate and postdoctoral study and research and generates the commitment of sufficient time and effort to make measurable progress. In biology, an additional constraint is posed by the life scales of experimentation. Cells in culture need to be established, maintained, and characterized before and after experiments. Animals need to be bred, housed, and selected before irradiation. Radiation effects may not become apparent for many cycles of cell division, whether in cell culture or in an animal tissue. Especially for validation of hypotheses, it may be necessary to wait for a significant fraction of an animal's life before a statistically significant result can be ascertained. For this reason, the timescale of meaningful advances in biology can be estimated as being 5 to 15 years.

Critical Mass

To illustrate these concepts, in 1990, all of the radiation research at NASA consisted of about a dozen scientists, and the entire budget for radiation biology, physics, and transport code development was approximately three-quarters of a million dollars. An expansion of the budget was planned but, as a consequence of years of neglecting research, NASA found itself faced with the fact that it takes time to build up a science community. The current NASA radiation research community was built up slowly and painfully, one scientist at a time. It was somewhat easier to find individuals able and willing to review research proposals, but the scores given to most proposals were poor, reflecting the fact that, initially, many outstanding and very capable scientists were disinterested in responding to a NASA Research Announcement. Hence, it was only the occasional graduate student or bright postdoctoral student, attracted by a stipend, who improved the quality of the field. These younger people

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had the ability to attract brighter students in turn, and the development of interesting research areas brought in scientists from related fields, who had not theretofore taken an interest in radiation (much less in heavy charged particle radiation).

The turning point in the radiation biology program came when NASA and the National Cancer Institute embarked on a joint, 5-year program to support research in genomic instability. This is a key concept in the understanding of cancer progression, and high-energy heavy ions turned out to be a very useful tool in its study. As a consequence, studies related to genomic instability became part of the mainstream of radiation research related to cancer, as well as in space radiation research. A wide variety of investigators in many related areas became interested in this type of problem and added to the ranks of the growing science community. A similar interagency collaboration, with the DOE's Low Dose Program, continues to this day, leveraging the research of both agencies.

Concerning the development of necessary nuclear models and databases and the completion of the radiation transport codes needed for shielding and risk assessment, the cadre of radiation physics expertise available within the larger space radiation protection community has been and continues to be very small and is shrinking. NASA needs experts in radiation transport who are also experts in the nuclear interactions of heavy charged particles. It is generally true that most of the developers of transport codes are within the reactor engineering community and have little or no understanding of charged-particle transport as applied to high-energy heavy ions. They are also generally unfamiliar with the nuclear models and databases needed to carry out HZE particle transport for space applications. Within the field of nuclear physics, the areas of current investigation, interest, and expertise are far removed from the needs of the space radiation transport community. Few nuclear physicists are knowledgeable about radiation transport methods and codes. Thus, there needs to be an effort by NASA to maintain an adequate level of available expertise and knowledge, both intramural and extramural, in space radiation transport and interactions. The intramural expertise is needed to ensure that in-house knowledge is available to design engineers, tool developers, and mission planners. Since space radiation physics and transport, as applied to space radiation protection, are not typically part of any university curriculum, extramural expertise and research personnel are needed, particularly at universities, to provide training of new, knowledgeable personnel to replace existing scientists and engineers as they retire.

Finding 5-10. Intellectual capital. Due to reductions in the scope of NASA's Radiation Protection Plan, the current pool of intellectual capital will shrink as researchers retire and are not replaced.

Recommendation 5-12. Engaging young researchers. NASA should try, perhaps as part of an interagency effort, to attract and engage young researchers and the broader radiation community at a level sufficient to supply the demands for radiation protection of astronauts in lunar mission operations and martian mission planning. This effort should encourage cross-pollination of ideas together with preservation of institutional knowledge by promoting interactions between researchers of different backgrounds and experience levels and by addressing issues that are relevant to, but broader than, space radiation.

Integration of Radiation Protection into Design of Vehicles and Missions

Managing radiation risk is an integral part of exploration mission design and execution. As humans leave Earth orbit and mission duration increases, it becomes even more critical. This is not something that can be added the day before liftoff. Truly effective radiation shielding requires the interaction of multiple disciplines—materials, biology, space physics, and communications. Furthermore, the concept of radiation shielding must then percolate into the design of Constellation vehicles and missions. A model of a successful radiation protection process is shown in Figure 5-3. At this time, the path from research to radiation protection standards seems to be well established, although the quality of the research is threatened by current budget cuts. Similarly, the process to provide dosimetry for monitoring, validating, and recording the radiation environment and the processes to engender forecasts and warnings of high radiation levels are both understood; the content of these activities is being developed in various ways.

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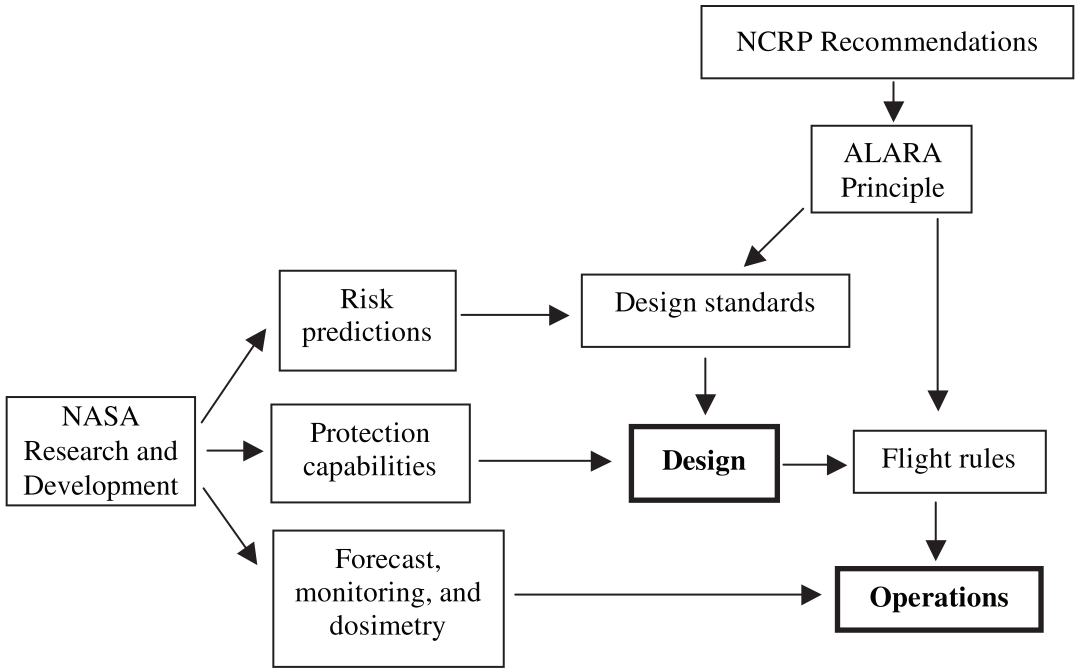

FIGURE 5-3 Suggested risk management process. NOTE: NCRP, National Council on Radiation Protection and Measurements; ALARA, As Low As Reasonably Achievable.

However, space systems designers have many more concerns than radiation. If radiation safety is not embedded into the approval process, portable polyethylene shielding could be removed from the design at the last minute in order to meet weight requirements. Alternatively, if the designers realize at a late stage that they have not used enough protection, they may have to add a layer of parasitic shielding, causing a science experiment or a spare part to be removed. Clever shielding designs—particularly those that include multifunctional components—can provide adequate protection for a relatively low weight cost, but only if they are integrated early on.

Finding 5-11. Radiation-incorporated design. It is often difficult to apply the ALARA principle to radiation risk in a setting in which multiple risks exist, such as a space mission. Radiation experts have been involved in all aspects of the design and development of Orion so far, from hardware to mission operations protocols.

Finding 5-12. Risk leveling. NASA uses "risk leveling" to optimize its developments, taking into account all risks, not just a single risk or group of risks. This is an inexact science, however, because estimates of virtually all risks involve some uncertainties, and most risks have different end points or outcomes, ranging from latent to acute effects and from trauma to the risk of death. A diversity of expert specialties is required as inputs to make these decisions.

Recommendation 5-13. Risk management. NASA should continue its current approach to radiation protection and risk management on Orion. Radiation safety advocacy should be continued throughout the design process to ensure that this protection is available in the final embodiment of the Orion Block-2.

Finding 5-13. Operational implementation of the ALARA principle. Operational plans for NASA are not sufficiently advanced and well defined to provide evidence that the ALARA principle has or has not been properly implemented.

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Finding 5-14. Constellation Radiation Protection Plan. There is not yet a radiation protection plan for elements of Project Constellation other than Orion.

Recommendation 5-14. Radiation protection in other Constellation elements. All elements of Project Constellation should employ the radiation protection and risk management limits necessary to meet the NASA radiation protection standards presented to the committee.

At the request of the National Aeronautics and Space Administration, the Institute of Medicine recently examined the process by which NASA establishes spaceflight health standards for human performance. The standards-setting process is currently designed to address acceptable levels of risk for three categories of in-flight health concerns, including space permissible exposure limits (e.g., radiation exposure standards). The committee found that the initial standards-setting process developed by NASA is a carefully designed evidence-based process that involves input from relevant stakeholders.

The flight rules—or even the processes of developing flight rules—have yet to be started. Whether or not space radiation risk can be efficiently managed hinges on these rules. Imagine that a CME erupts from the Sun, preceding an SPE. A new monitoring satellite detects the CME and sends a message to Earth. NASA's Space Radiation Analysis Group calculates a nowcast, predicting exactly when and for how long the astronauts need to stay inside. The lunar module provides sufficient radiation shielding to protect the crew. However, it is the flight rules and operational procedures that allow (and require) mission control to reconfigure the day's tasks so that the astronauts are safe. Furthermore, it is not sufficient to create overly conservative procedures. Although there is no loss of life, a mission can still fail because an astronaut sits huddled in a shielded room when it is actually safe for him or her to be drilling for samples outside. Designing flight rules that maximize the safety of the crew and of the mission will require taking advantage of the expertise available in the space radiation research and design community.

Recommendation 5-15. Role of standards in design. Permissible exposure limits specified in current NASA radiation protection standards should not be violated in order to meet engineering resources available at a particular level of funding. To ensure that the design of spacecraft habitats and missions implement NASA radiation protection standards,

- An independent radiation safety assessment should continue to be an integral part of mission design and operations, and
- An established limit for radiation risk, as incorporated in NASA radiation protection standards, needs to be included in "Go–No-go" decisions for every mission.

Radiation risk management is one of the major challenges of solar system exploration. The Exploration Vision is NASA's first mission that intends to truly face it head-on. It is not an impossible problem, but neither can it be taken lightly. Every vehicle, every mission must take radiation into account at some level—either it provides sufficient protection, or there is an operational procedure which ensures that the crew is able to get to a protected place. Reaching this goal will require research, technology development, and a great deal of cooperation.

Finding 5-15. Long-term commitment. Exploration continues beyond a single mission and requires a long-term commitment to radiation risk management.

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6

Findings and Recommendations

A complete list of the committee's findings and recommendations from Chapters 1 through 5 appears below, in the order in which they appear in the report.

Finding 2-1. Current knowledge of the radiation environment on the Moon. Data from many satellites have enabled the characterization of GCR and SPEs near Earth, and these results serve to characterize the radiation incident on the surface of the Moon. Knowledge of the secondary radiation, which is produced by galactic cosmic rays and SPEs interacting with material on the lunar surface, is currently based on data from Apollo, Lunar Prospector, and Clementine and on calculations.

Finding 2-2. Current knowledge of the radiation environment on Mars. The radial extrapolation of the GCR environment from Earth to Mars is well understood, based on measurements made by numerous scientific satellites as they traveled outward through the solar system. To within a few percent or so, the GCR environment at the top of the martian atmosphere is expected to be the same as that near Earth. There are very few simultaneous measurements of SPEs at Earth and at Mars, and current models are inadequate to extrapolate near-Earth measurements of SPEs to Mars. Knowledge of the secondary radiation environment on the surface of Mars is currently based on calculations and measurements taken by spacecraft in Mars orbit.

Finding 2-3. Lunar GCR environment. Given the far larger uncertainties in biological effects, the committee finds that knowledge of the composition, energy spectrum, and temporal variation of the "free space" GCR component of the interplanetary radiation environment is sufficient to support the needs of the Constellation lunar missions. Nevertheless, it will be useful to benchmark GCR models against measurements reported by ACE in the upcoming second half of the 22-year GCR modulation cycle.

Finding 2-4. Space radiation climate. Ice-core studies indicate that the past ~50 years may have coincided with a comparatively benign space radiation climate, in terms of both GCR modulation levels and the frequency of very large SPE events. Of particular concern is the possibility of a six- to eightfold increase in the number of very large SPE events, perhaps starting within the next decade. If such an increase were to occur, it would have a major impact on the design and operation of Exploration systems.

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Recommendation 2-1. Planning for long-term changes in space climate. NASA must ultimately judge how much weight to assign to the cautionary findings from ice cores on a potentially more severe space radiation climate in the future. Given that the Exploration initiative envisions a commitment of the nation's resources that spans decades, NASA should ensure that the mission architecture has sufficient flexibility and margin to cope with such changes, should they occur.

Finding 2-5. The King spectrum as a design standard. Although the committee recognizes the advantages of adopting a specific solar proton spectrum as the design standard, NASA's current strategy of evaluating the efficacy of an SPE shielding configuration using only the August 1972 King spectrum is not adequate. Under typical depths of shielding for Exploration vehicles, the level of radiation exposure produced by other large events in the historical record could exceed the exposure of August 1972.

Finding 2-6. Spectra data fitting. There is no theoretical basis for *any* of the published spectral fits to large SPEs. The extrapolation to energies beyond 100 MeV must therefore be guided by data. Solar proton spectral forms based on data that do not extend to ~500 MeV may very well give misleading results in evaluations of the efficacy of radiation shielding for astronauts.

Recommendation 2-2. SPE design standards. The dose levels made possible by a shielding design should also be calculated using the observed proton spectrum from other large events in the historical record, even if it is not feasible to modify the shielding design as a result. The October 1989 event is particularly important in this regard.

Recommendation 2-3. Uncertainties in spectra data fitting. NASA should make use of existing data to re-evaluate the spectra beyond 100 MeV in large events in the historical record and should assess the impact of uncertainties in the high-energy spectra on the adequacy of radiation shielding designs.

Finding 2-7. Knowledge of radiation from nuclear ground power. Experience with nuclear power on Earth has provided sufficient knowledge to create this capability on the Moon. The remaining challenges are engineering problems, not scientific problems. Experiments to show the operational safety of space and planetary-surface fission power systems, including unique design features such as compactness, light weight, and heat transport and heat rejection in reduced gravity, will be important.

Finding 3-1. Uncertainty in radiation biology. Lack of knowledge about the biological effects of and responses to space radiation is the single most important factor limiting the prediction of radiation risk associated with human space exploration.

Finding 3-2. Funding cuts to radiation biology research. NASA's space radiation biology research has been compromised by the recent cuts in funding, particularly in research addressing noncancer effects.

Finding 4-1. State of radiation protection plans for lunar missions. The use of surface habitat and spacecraft structure and components, provisions for emergency radiation shelters, implementation of active and passive dosimetry, the scheduling of EVA operations, and proper consideration of the ALARA principle are strategies that are currently being considered for the Constellation program. These strategies, if implemented, are adequate for meeting the radiation protection requirements for short-term lunar missions.

Recommendation 4-1. Strategic design of Orion. As the design of Orion continues to evolve, designers should continue to consider and implement radiation protection strategies.

Finding 4-2. State of radiation protection plans for Mars missions. For longer-duration lunar and Mars missions the currently large uncertainties in radiological risk predictions could be reduced by future research. Without such research, it may be necessary to baseline large shielding masses and reduced-length missions, and/or delay human

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exploration missions until uncertainties in risk prediction and radiobiological methods of risk management have advanced to the point that they can be conducted within the limits of acceptable risk.

Finding 5-1. The NASA Space Radiation Laboratory. The entire Space Radiation Biology Research program is critically dependent on the availability of the NASA Space Radiation Laboratory. This facility is dependent on the DOE heavy-ion physics program and may not be available if the needs of this program change. There are no other facilities available that meet the requirements for high atomic number and energy (HZE) space radiation biology research, worldwide.

Recommendation 5-1. Radiation biology research. NASA's Space Radiation Biology Research program should be adequately funded. NASA should perform research at the NASA Space Radiation Laboratory aggressively to take advantage of the existing window of opportunity while this facility is still available. The results of the biological research will thus be able to have an impact on the Project Constellation missions in the short term, as well as provide knowledge essential for the management of space radiation risk in the long term.

Finding 5-2. Dose estimation in the Orion crew module. The use of ray-tracing analysis combined with state-of-the-art radiation transport and dose codes is an appropriate method for estimating dose within the Orion crew module, and can be used to guide decisions on the amounts and types of spot or whole-body shielding that should be added to provide protection during solar particle events.

Finding 5-3. Orion Radiation Protection Plan. The Orion Radiation Protection Plan, as presented to the committee, appears to meet the minimum radiation protection requirements as specified in NASA's radiation protection standards. Any reduction in the Orion Radiation Protection Plan may pose potentially unacceptable health risks.

Finding 5-4. Existing transport data. New measurements do not need to be taken solely for the purposes of code validation. In addition, structure in the energy dependence of relevant fragmentation yields for heavy charged particles is considered to be sufficiently small to have a negligible impact on interpolation schemes. One exception is that additional data on production of light ions ($Z = 1, 2$) and neutrons may be required.

Recommendation 5-2. Testing transport code predictions. The predictions derived from calculations of radiation transport need to be tested using a common code for laboratory and space measurements that have been validated with accelerator results, existing atmospheric measurements, and lunar and planetary surface measurements as they become available.

Finding 5-5. SPE prediction. At present, the ability to predict an SPE and to project its evolution once underway does not exist. Such a capability will play an important role in managing the SPE radiation hazard.

Recommendation 5-3. Research on solar particle events. NASA should maintain a vigorous basic science program that can clarify the mechanisms that produce SPEs and lead to accurate, quantitative predictions of SPE behavior and identification of observables critical in forecasting SPEs or all-clear periods.

Finding 5-6. Experimental data for designers. NASA has not made an adequate effort to collect, catalog, and categorize existing experimental data obtained by the worldwide heavy-ion research community and to make it available in appropriate form to the shielding engineering community.

Recommendation 5-4. Empirical data for shielding design. NASA should ensure that necessary experimental data in sufficient quantities are collected, analyzed, and managed in a manner appropriate for their use in designing radiation shielding into spacecraft, habitats, surface vehicles, and other components of human space exploration. The data should include information on energy and angular dependence of cross sections for production of nuclear interaction products, and on their multiplicities.

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Finding 5-7. Forecasting of SPEs. Forecasting and warning of SPEs will be an essential part of a comprehensive radiation mitigation strategy. Timely collection of appropriate data and communication of resulting forecasts and warnings will be mission-critical.

Recommendation 5-5. Flight crew radiation safety officer. On exploration missions, a member of the crew should be designated as flight crew radiation safety officer. This person would be the point of contact with mission control, monitor on-site dosimetry, and ensure communication and coordination with ground control for the response to radiation warning levels.

Recommendation 5-6. In situ monitoring and warning. Warning and monitoring dosimetry, active and passive, is required wherever there is a human presence beyond low Earth orbit.

Finding 5-8. Multifunctionality. Multifunctionality presents a way to increase the ability to shield against radiation by taking advantage of the mass of materials already included in the spacecraft design. Low-Z spacecraft materials offer some shielding advantages over conventional, higher-Z metallic structures.

Recommendation 5-7. Multifunctional materials. Where appropriate, replacement of traditional materials with multifunctional materials should be encouraged, with the goal of improving radiation shielding.

Recommendation 5-8. In situ shielding tradeoffs. NASA should conduct studies of tradeoffs to determine whether it is more cost-effective to transport prepared shielding materials from Earth or to construct shielding in situ with transported materials and equipment.

Recommendation 5-9. Review of existing neutron albedo datasets. The predictions of computer codes developed by the NASA Langley Research Center need to be compared with existing data, especially data for secondary radiation and neutron albedo. Existing datasets should also be reviewed to assess their value in determining the extent to which albedo neutrons on the lunar and martian surfaces may constitute a significant component of the radiation environment. Lunar and planetary surface measurements performed in the pursuit of other exploration objectives may become available; if so, the data should be used for statistically significant comparisons with theory whenever appropriate.

Finding 5-9. Reactor shielding. Significant research is required before nuclear fission can be used for surface power on Mars or to support exploration at a nonpolar location on the Moon.

Recommendation 5-10. Surface fission power demonstration—nuclear power for Mars. NASA could take advantage of the Moon as a testbed for human exploration of Mars by incorporating the development and testing of fission reactor technology into lunar plans.

Recommendation 5-11. Agency partnerships in space weather. The nation's space weather enterprise should integrate its scientific expertise with operational capability through coordinated efforts on the part of NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Department of Defense (DOD). Where multiple end users benefit, NOAA is appropriate as the lead organization in charge of operational forecasts. However, for NASA-unique lunar support requirements, NASA's Exploration Systems Mission Directorate should take a leadership role in defining and providing resources.

Finding 5-10. Intellectual capital. Due to reductions in the scope of NASA's Radiation Protection Plan, the current pool of intellectual capital will shrink as researchers retire and are not replaced.

Recommendation 5-12. Engaging young researchers. NASA should try, perhaps as part of an interagency effort, to attract and engage young researchers and the broader radiation community at a level sufficient to meet

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the demands for radiation protection of astronauts in lunar mission operations and martian mission planning. This effort should encourage cross-pollination of ideas together with preservation of institutional knowledge by promoting interactions between researchers of different backgrounds and experience levels and by addressing issues that are relevant to, but broader than, space radiation.

Finding 5-11. Radiation-incorporated design. It is often difficult to apply the ALARA principle to radiation risk in a setting in which multiple risks exist, such as a space mission. Radiation experts have been involved in all aspects of the design and development of Orion so far, from hardware to mission operations protocols.

Finding 5-12. Risk leveling. NASA uses "risk leveling" to optimize its developments, taking into account all risks, not just a single risk or group of risks. This is an inexact science, however, because estimates of virtually all risks involve some uncertainties, and most risks have different end points or outcomes, ranging from latent to acute effects and from trauma to the risk of death. A diversity of expert specialties is required as inputs to make these decisions.

Recommendation 5-13. Risk management. NASA should continue its current approach to radiation protection and risk management on Orion. Radiation safety advocacy should be continued throughout the design process to ensure that this protection is available in the final embodiment of the Orion Block-2.

Finding 5-13. Operational implementation of the ALARA principle. Operational plans for NASA are not sufficiently advanced and well defined to provide evidence that the ALARA principle has or has not been properly implemented.

Finding 5-14. Constellation Radiation Protection Plan. There is not yet a radiation protection plan for elements of Project Constellation other than Orion.

Recommendation 5-14. Radiation protection in other Constellation elements. All elements of Project Constellation should employ the radiation protection and risk management limits necessary to meet the NASA radiation protection standards presented to the committee.

Recommendation 5-15. Role of standards in design. Permissible exposure limits specified in current NASA radiation protection standards should not be violated in order to meet engineering resources available at a particular level of funding. To ensure that the design of spacecraft habitats and missions implement NASA radiation protection standards,

- An independent radiation safety assessment should continue to be an integral part of mission design and operations, and
- An established limit for radiation risk, as incorporated in NASA radiation protection standards, needs to be included in "Go–No-go" decisions for every mission.

Finding 5-15. Long-term commitment. Exploration continues beyond a single mission and requires a long-term commitment to radiation risk management.

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Appendixes

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A

Statement of Task

Based on mission requirements (e.g., specific mission architecture and total radiation dose limits) provided by NASA, the committee will evaluate the radiation shielding requirements for lunar missions and recommend a strategic plan for developing the necessary radiation mitigation capabilities to enable the planned lunar architecture. Specifically the committee will:

1. Review current knowledge of radiation environments on the lunar and Mars surfaces, including radiation types, sources, levels, periodicities, and factors that enhance or mitigate levels. Critical knowledge gaps, if any, will be identified.
2. Assess and identify critical knowledge gaps in the current understanding of the level and type of radiation health risks posed to astronauts during various surface activities—ranging from habitation in the CEV to extended exploration sorties and longer stays in exploration outposts—expected for the lunar and martian environments.
3. Review current and projected radiation shielding approaches and capabilities, as well as other exposure mitigation strategies feasible in the lunar and Mars surface environments.
4. Recommend a comprehensive strategy for mitigating the radiation risks to astronauts during lunar surface missions to levels consistent with NASA's radiation exposure guidelines. The strategy will:
   —Be consistent with NASA's current timeline for lunar sortie and outpost habitation plans,
   —Recommend research to resolve critical knowledge gaps regarding the lunar radiation environment and risks,
   —Recommend a research and technology investment strategy that enables development of the necessary shielding capabilities.
5. The study will provide recommendations on what technology investments (e.g., multifunctional materials, localized shielding, and in situ materials) NASA should be making in preparation for lunar missions, and recommend development timelines to ensure NASA has the appropriate level of shielding in place to meet the planned schedules.

In developing this strategy for lunar missions, the committee will also consider the likely radiation mitigation needs of future Mars missions and give higher priority to research and development alternatives that will enhance NASA's ability to eventually meet those future needs. "Critical knowledge gaps" are defined as gaps that prevent the development of any risk mitigation strategy capable of fulfilling mission needs while meeting reasonable criteria (e.g., cost, schedule and effectiveness).

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B

Biographies of Committee Members

JAMES D.A. VAN HOFTEN, *Chair*, recently retired as a senior vice president and partner of the Bechtel Corporation. He was also the managing director of Bechtel's Aviation business in London. Dr. van Hoften received a B.S. with honors in civil engineering from the University of California, Berkeley, and an M.S. in hydraulic engineering from Colorado State University (CSU). Following tours in Southeast Asia as a Navy pilot, he completed his Ph.D. in hydraulic engineering at CSU and then became an assistant professor of civil engineering at the University of Houston. In 1978, he was selected as a member of the first dedicated space shuttle astronaut group. He led testing and analysis for the astronaut team for the entry software development and later headed the astronaut support group for these early missions. He flew on two very successful space shuttle flights. Dr. van Hoften joined the Bechtel Corporation in 1986 where he focused on complex infrastructure programs in the civil, military, and aerospace arenas. Dr. van Hoften is on the board of directors of two public international energy companies. He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), was awarded the President's Medal from the American Society of Civil Engineers (ASCE), was named an outstanding alumnus of the University of California, Berkeley, and received the Arnold E. Morgan Award as the outstanding graduate of CSU. Dr. van Hoften was one of the first members of the Commercial Space Transportation Advisory Committee for the Department of Transportation and has also served on the board of advisors to ASCE's Civil Engineering Research Fund.

SALLY A. AMUNDSON is an associate professor of radiation oncology at the Center for Radiological Research at Columbia University. Her research interests include functional genomics of responses to ionizing radiation and other stressors, signal transduction in DNA-damage and stress responses, radiation biodosimetry and molecular responses to low doses of ionizing radiation and to high linear energy transfer radiation. She is active in the Radiation Research Society, which awarded her the Michael Fry Research Award in 2004, and she is a member of the National Council on Radiation Protection and Measurements. She received a B.A. from Hamline University and an Sc.D. in radiation biology from Harvard University, and then pursued postdoctoral studies at the Los Alamos National Laboratory and the National Cancer Institute.

SAMIM ANGHAIE is a professor of nuclear and radiological engineering at the University of Florida, where he also is director of the Innovative Nuclear Space Power and Propulsion Institute. He has been a professor at the University of Florida since 1986, before which he was an assistant professor at Oregon State University for 2 years. His research interests include thermal hydraulics; computational fluid dynamics and heat transfer; high-

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temperature nuclear fuels and materials; inverse radiation transport methods; advanced reactor design; direct energy conversion; and space nuclear power and propulsion. Dr. Anghaie received a B.S. in physics in 1972 and an M.S. in physics in 1974, both from Pahlavi University, Shiraz, Iran. He received his Ph.D. in nuclear engineering from Pennsylvania State University in 1982.

WILLIAM ATWELL is a technical fellow with the Boeing Company and currently supports the AeroThermal Group. Mr. Atwell has 40 years of experience in the areas of the space radiation environment, high-energy particle transport through materials, active and passive dosimetry, spacecraft, satellite, and anatomical modeling/shielding analysis, radiation detection instrumentation, biological and physical effects, and data analyses. He is one of the original members of the NASA Johnson Space Center (JSC) Space Radiation Analysis Group. Recently, his interests and support activities have been in space radiation research projects for NASA, the European Space Agency, and the German Space Agency. He has been on the science teams for the 2001 Mars Odyssey Martian Radiation Environment Experiment and the Boeing Jupiter Icy Moons Orbiter Phase A study. He provides support to the NGC/Boeing Crew Exploration Vehicle proposal effort and the JSC-requested Radiation Trade studies. Mr. Atwell was a chair of the AIAA Life Science and Systems Technical Committee and is chair of the AIAA Life Sciences and Space Processing Technical Committee and a member of the AIAA Public Policy Technical Committee. Mr. Atwell is the recipient of the Astronaut's Silver Snoopy Award, Rockwell International Space Systems Division (now Boeing) President's Award, and numerous NASA, NATO, and AIAA awards and commendations. He received the 2001 Special Space Flight Achievement Award from JSC for his scientific support, modeling efforts, and space radiation analyses of the Phantom Torso Experiment (1998) and the International Space Station Increment 2 (2001). Mr. Atwell has authored more than 200 technical and scientific publications. He has an M.S. and a B.S. in physics/mathematics from Indiana State University and was a Ph.D. candidate at the University of Florida.

BENTON C. CLARK is chief scientist for Space Exploration Systems, Lockheed Martin Astronautics in Denver, Colorado, and has more than 40 years of experience in future-mission design, spacecraft design and operations, planetary science, space radiation, and development of advanced space instrumentation. He is the senior member of the Advanced Planetary Studies group, where flight designs for Discovery, New Frontiers, and Mars missions are conceived and developed. Dr. Clark has more than 80 publications and 120 reports, abstracts, and presentations in instrumentation, planetary missions, radiation, space science, planetary geochemistry, exobiology, astrobiology, and other fields of research and development. He has served on numerous advisory panels for NASA, AIAA, and the National Research Council (NRC). He has received the NASA Public Service Medal, the Wright Brothers Award, the Air Force Service Medal, the Rotary International Stellar Award, and the Lockheed Martin Nova Award; he is an inductee to the Aviation and Space Hall of Fame, and has been selected Inventor and Author of the Year for Martin Marietta Corporation. Dr. Clark has a B.S. in physics from the University of Oklahoma, an M.A. in physics from the University of California, Berkeley, and a Ph.D. in biophysics from Columbia University.

MARC M. COHEN is a licensed architect who has more than 20 years of experience in space architecture design research and development, specializing in space living, working environments, and human factors. He recently took early retirement from the NASA Ames Research Center to join Northrop Grumman Integrated Systems. Dr. Cohen has an extensive record of accomplishment in developing architectural concepts for space stations, interplanetary vehicles, and lunar and martian surface habitats. He conducts advanced materials research and quantitative modeling of habitat designs. He is an associate fellow of the AIAA, founded the AeroSpace Architecture Subcommittee, and currently chairs the AIAA's Design Engineering Technical Committee. He has an A.B. from Princeton University, an M.Arch. from Columbia University, and an Arch.D. from the University of Michigan.

PATRICK J. GRIFFIN is a Distinguished Member of the Technical Staff in the Applied Nuclear Technologies Department at Sandia National Laboratories and was chair of the NRC Panel on Assessment of Practicality of Pulsed Fast Neutron Analysis for Aviation Security. He was named a National Affiliate of the National Academies in recognition of his service to the NRC's National Materials Advisory Board on several committees. At Sandia National Laboratories, he performs research in the areas of radiation modeling and simulation, neutron-effects

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testing, radiation dosimetry, and radiation damage to materials. He has more than 20 years of experience in the areas of neutron dosimetry and radiation shielding, has been guest editor for the *Journal of Radiation Effects*, gave the keynote address at the 10th International Symposium on Reactor Dosimetry, and has received several awards, including the 2006 Sandia National Laboratories' Meritorious Achievement for Individual Technical Leadership and the 2007 National Nuclear Security Administration Award of Excellence for significant contributions to the Stockpile Stewardship Program. He is active in the standardization community and is the current chair of the American Society of Testing and Materials Subcommittee E10.05 on Nuclear Radiation Metrology. Dr. Griffin received a B.S. in physics in 1973 and a Ph.D. in theoretical nuclear physics in 1979, both from Ohio University.

DAVID G. HOEL is Distinguished University Professor in the Department of Biostatistics, Bioinformatics and Epidemiology at the Medical University of South Carolina, Charleston. He has a B.A. in mathematics from the University of California, Berkeley; a Ph.D. in mathematical statistics from the University of North Carolina, Chapel Hill; and postdoctoral training in preventive medicine from Stanford University. Dr. Hoel was at the National Institute of Environmental Health Sciences of the National Institutes of Health for more than 20 years as director of the Division of Environmental Risk Assessment, which was responsible for developing methods for quantitatively estimating health risks from low-dose chemical exposures. He has particular interests in estimating the health effects of radiation exposures and has spent a total of 3 years working at the Radiation Effects Research Foundation in Hiroshima as one of the program directors. His current research is focused on low-dose adverse health effects of gamma, neutron, and alpha radiation as well as plutonium in particular. His research support is from the Department of Energy and NASA. Dr. Hoel has served on numerous government and NRC committees, including the Science Advisory Board of the Environmental Protection Agency and the Food and Drug Administration's transmissible spongiform encephalopathies (mad-cow disease) advisory committee. International committees on which he has served include a radiation exposure advisory committee for the UN's International Atomic Energy Agency and the World Health Organization's International Agency for Research on Cancer. He is a member of the Institute of Medicine and a fellow of the American Association for the Advancement of Science.

TATJANA JEVREMOVIC is an associate professor in the School of Nuclear Engineering at Purdue University. She is the director of the Laboratory for Neutronics and Geometry Computation and leads the Purdue Breast Cancer Research Group. She also holds an associate professor position in the School of Health Sciences (by courtesy) and is an adjunct professor in the Division for Environmental and Ecological Engineering. Formerly, she was the chief engineer for the Nuclear Fuel Division of NFI, Ltd., Tokai, Japan, and a lecturer at the University of Tokyo. Dr. Jevremovic's research interests include computational reactor physics and radiation transport, neutron capture therapy, microbeam studies, and radiation shielding for space applications. She is a member of the American Nuclear Society and Women in Nuclear. She has authored more than 90 conference and journal papers and a textbook, *Nuclear Principles in Engineering*. She has B.S. and M.S. degrees in engineering physics/nuclear engineering from the University of Belgrade and a Ph.D. in nuclear engineering from the University of Tokyo.

WALTER SCHIMMERLING is the former program scientist for NASA's Space Radiation Health Program, Bioastronautics Research Division. Dr. Schimmerling served as a research biophysicist and senior research scientist at the Lawrence Berkeley National Laboratory from 1972 to 1989. He also served as a NASA visiting senior scientist at the Jet Propulsion Laboratory, as manager of the Radiation Health Program at NASA Headquarters, and as program director of the joint NASA-National Cancer Institute research project on genomic instability. He is the author of numerous publications on high-energy heavy-ion physics and mitigating the health effects of radiation during spaceflight. He was also the chief scientist of the Space Life Sciences Division of the Universities Space Research Association.

LAWRENCE W. TOWNSEND is a professor in the Department of Nuclear Engineering at the University of Tennessee. Between 1970 and 1977 he served in the U.S. Navy as a nuclear submarine engineering officer. From 1981 until 1995 he held positions as research scientist and senior research scientist at NASA Langley Research Center. Dr. Townsend received numerous scientific awards, including NASA's Exceptional Scientific Achievement

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Medal for outstanding contributions to the understanding of nuclear interactions of cosmic radiation with matter and its implications for space radiation exposure and shielding. He is a council member of the National Council on Radiation Protection and Measurements and a fellow of the American Nuclear Society and of the Health Physics Society. His research interests include space radiation transport code development, space radiation shielding, theoretical modeling of secondary neutron production cross sections and spectra from energetic proton and heavy-ion interactions with thin and thick targets, modeling production of radioactive and stable heavy nuclides from nuclear spallation, and the design of neutron sources, including cold sources, for use in radiography, radiotherapy, neutron activation analysis, and materials studies. He was the principal investigator and leader of the Space Radiation Transport Code Development Consortium from 2002 to 2007. He is the author of approximately 525 publications, including 145 research articles in refereed journals.

RONALD E. TURNER is a fellow at Analytic Services, Inc. (ANSER). Dr. Turner has more than 20 years of experience in space systems analysis, space physics, orbital mechanics, remote sensing, and nuclear and particle physics. He also has extensive experience in radiation effects on humans in space. His recent research on the Mars Odyssey mission included risk management strategies for solar particle events during human missions to the Moon or Mars. He has been a participant at NASA workshops looking at space radiation/biology missions, life science mission requirements for several Mars initiatives, and the impact of solar particle events on the design of human missions. Dr. Turner served on the NRC *Safe on Mars* study in 2002. He was the senior science adviser to the NASA Institute for Advanced Concepts. Dr. Turner received a Ph.D. in physics from the Ohio State University, an M.S. in physics from the University of Florida, and a B.S. in physics from the University of Florida. He was also chair of the NRC Human Health and Support Systems Panel reviewing the NASA capabilities roadmap and is a member of the Space Studies Board Committee on Solar and Space Physics.

ALLAN J. TYLKA is a research physicist in the High Energy Space Environment Branch of the Space Science Division of Naval Research Laboratory (NRL). Dr. Tylka's work has focused on using satellite data to investigate and model acceleration and transport processes in solar energetic particle events. He led development of CREME96, a revision of NRL's Cosmic Ray Effects on Micro-Electronics code, that is widely used in the aerospace industry to assess space radiation impacts on satellites. He is a fellow of the American Physical Society and a member of the American Geophysical Union, the American Astronomical Society, the International Astronomical Union, and the American Association for the Advancement of Science. Dr. Tylka received an Alan Berman Research Publication Award, an NRL Technology Transfer Award, an NRL Invention Award, and the 2005 Editors' Citation for Excellence in Refereeing for the *Journal of Geophysical Research-Space Physics*. Dr. Tylka holds a B.A. in physics and mathematics from Washington and Jefferson College and an M.S. in physics from the University of Maryland. Following his study of high-energy particle physics at the Deutsches Elektronen-Synchrotron in Hamburg, Germany, Dr. Tylka received his Ph.D. in physics from the University of Maryland.

GAYLE E. WOLOSCHAK is currently a professor in the Department of Radiology, Feinberg School of Medicine, Northwestern University. Her interests include studies of the molecular biology of lymphocyte and motor neuron abnormalities in DNA-repair-deficient mice, studies of radiation-inducible nanoparticles, and analysis of molecular mechanisms of oncogenesis in radiation-induced tumors. She received her Ph.D. in medical sciences (microbiology) from the Medical College of Ohio and did postdoctoral training in the Departments of Immunology and Molecular Biology at the Mayo Clinic. Dr. Woloschak was a senior molecular biologist and group leader of the Biosciences Division, Argonne National Laboratory, and a senior fellow at Nanosciences Consortium, Argonne National Laboratory-University of Chicago. She has served as a member on the National Institutes of Health's radiation study section and on the NRC's Committee on Radiofrequency Radiation, and chaired NASA's peer review radiation biology committee.

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C

Committee Meeting Agendas and Speakers

The National Research Council appreciates the efforts of and the information provided by the following individuals, who volunteered their time to speak at the meetings of the Committee on the Evaluation of Radiation Shielding for Space Exploration.

DECEMBER 12, 2006

9:45 a.m. Welcoming Remarks
James van Hoften, Committee Chair

10:00 *NASA Strategy for Implementation of Vision for Space Exploration*
Carl Walz, Director, Advanced Capabilities Division, NASA Headquarters

11:00 *Architecture to Date, Our Near and Mid Term Plans, and Technology Investment Priorities*
Geoffrey Yoder, NASA Headquarters

12:00 p.m. Lunch

1:00 *Plans for Affordable Fission Surface Power Systems*
Joseph Nainiger and Lee Mason, NASA Glenn Research Center

2:00 *Radiation Environment of Moon and Mars and In-Between*
Patrick O'Neill, NASA Johnson Space Center

3:15 *Health Risks to Astronauts in Exploration Missions*
Francis Cucinotta, NASA Johnson Space Center

4:15 *Current and Projected Radiation Shielding Approaches and Capabilities*
John Wilson, NASA Langley Research Center

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5:15 Closing Remarks, Announcements

5:30 Adjourn

DECEMBER 13, 2006

8:30 a.m. Welcome

8:45 *Space Radiation Hazards and NASA's Vision for Space Exploration: A Workshop*
Ron Turner, Committee Member

10:00 Closed Session

3:00 p.m. Adjourn

FEBRUARY 21, 2007

8:00 a.m. Closed Session

9:00 *Human Exploration Vehicle Requirements NASA's Perspective*

Overview of the Constellation Program and Landers
John Connolly, NASA Johnson Space Center

—*Lunar Habitats*
Larry Toups, NASA Johnson Space Center
—*Lunar EVAs*
Scott Cupples, NASA Johnson Space Center

12:00 p.m. Lunch

1:00 *Crew Exploration Vehicle Requirements Contractor's Perspective*
Tad Shelfer, Lockheed Martin Mission Services

3:15 *Radiation Shielding Design Process, and Status of NASA Structures and Materials Program*
Lisa Simonsen, NASA Langley Research Center

4:15 Closing Discussion and Questions

5:30 Adjourn

FEBRUARY 22, 2007

8:00 a.m. Welcome

8:15 *Solar Forecasting*
Joseph Kunches, NOAA

9:15 *Space Operations—Responses to Solar Weather Enhancements*
Mark Weyland, NASA Johnson Space Center

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10:15 Wrap-up Open Session

10:45 Closed Session

4:00 p.m. Adjourn

MAY 10, 2007

7:30 a.m. Closed Session

12:00 p.m. Lunch and Discussion

12:30 *Radiation on Mars*
Francis Cucinotta, NASA Johnson Space Center
Martha Clowdsley, NASA Langley Research Center

2:00 *Radiation Shielding Materials*
Jeffrey Johnson, Oak Ridge National Laboratory

3:00 *Structures, Materials, and Mechanisms Group*
Sheila Thibeault, NASA Langley Research Center

3:45 *Operational Decisions for Radiation*
David Liskowsky, NASA Office of the Chief Medical Officer
Francis Cucinotta, NASA Johnson Space Center

4:30 *Prioritization for Shielding and Biology at NASA*
Frank Sulzman, NASA Johnson Space Center

5:30 Closing Remarks
James van Hoften, Committee Chair

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D

Glossary and Acronyms

absorbed dose (*D*): Average amount of energy imparted by ionizing particles to a unit mass of irradiated material in a volume sufficiently small to disregard variations in the radiation field but sufficiently large to average over statistical fluctuations in energy deposition, and where energy imparted is the difference between energy entering the volume and energy leaving the volume. The same dose has different consequences depending on the type of radiation delivered. Unit: gray (Gy), equivalent to 1 J/kg.

ACE: Advanced Composition Explorer

acute effects: short-term biological effects of exposure to radiation, including headaches, dizziness, nausea, and illness that can range from mild to fatal

ALARA (As Low As Reasonably Achievable): A safety principle, as well as a regulatory requirement, that emphasizes keeping doses of and exposure to radiation as low as possible using reasonable methods, and not treating dose limits as "tolerance values"; defined at NASA as limiting radiation exposure to a level that will result in an estimated risk below the limit of the 95 percent confidence level.

albedo: secondary radiation produced by interactions of galactic cosmic rays and high-energy solar protons with matter in the atmosphere or on the surface

alpha particle: An energetic charged nucleus consisting of two protons and two neutrons. This particle is identical to the ^{4}He nucleus.

apoptosis: A specific mode of cell death (also known as programmed cell death) that can be triggered by exposure to radiation, especially in cells of lymphoid/myeloid or epithelial lineage. Extensive apoptosis contributes to the hematopoietic and gastrointestinal symptoms seen in acute radiation syndrome.

Ares V/Heavy Lift Launch Vehicle: the Constellation system vehicle that will deliver cargo from Earth to low Earth orbit

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ascent stage: The pressurized upper stage of the Lunar Lander in which the crew pilots the lander from lunar orbit to the lunar surface and return. The ascent stage takes off from the descent stage, leaving the latter behind on the surface.

AU: astronomical unit

AX-2: NASA Ames Research Center Experimental Suit 2, designed during the Apollo program as a lunar surface hard suit to bend at the waist and rotate in the torso so that the crew member can reach down to the ground with one hand. Fabricated from fiberglass.

AX-5: NASA Ames Research Center Experimental Suit 5, designed during the Space Station Advanced Development program to provide a durable hard suit for extended operations in zero gravity. Fabricated from numerically milled aluminum forgings.

BEIR: Committee on Biological Effects of Ionizing Radiation

BEVALAC: An early, high-energy synchrotron accelerator constructed in the 1950s at Lawrence Berkeley National Laboratory and used to discover the antiproton. Closed in 1992.

biological end point: effect or response being assessed, e.g., cancer, cataracts

bipolar device: a type of semiconductor whose operation is based on both majority and minority carriers

BNL: Brookhaven National Laboratory

BRYNTRN: a computer code for simulating baryon transport

carbon composite: A structural material that can substitute for aluminum and other metals in the construction of many parts of a spacecraft, notably the pressure vessel shell. Composite may incorporate boron, epoxy, polyethylene, hydrogen, or other materials that enhance radiation shielding properties.

cargo habitat: a crew habitat that the Lunar Lander carries for delivery to the Lunar Outpost as a key part of the "Outpost-first" strategy

CHMO: chief health and medical officer

chronic effects: long-term effects of exposure to radiation; includes cancer, cataracts, and nervous system damage

CI: confidence interval

CME: coronal mass ejection, an explosion of plasma released from the atmosphere (or corona) of the Sun

CNS: central nervous system

computerized anatomical male/female: a model of human geometry used to evaluate radiation doses at various points inside the body

Constellation system: the complete ensemble of launch vehicles, flight vehicles, ground support, support services, and lunar and planetary surface systems associated with the Vision for Space Exploration

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CRaTER: Cosmic Ray Telescope for the Effects of Radiation

CREAM96: Cosmic Ray Effects on Micro-Electronics (1996 revision), a computer code

cross section (σ): Measure of the probability per unit particle fluence of observing a given end point. Unit: cm^2.

descent stage: The lower stage of the Lunar Lander that includes the descent and landing engines and propellant tanks to serve them. The crew ascending back to lunar orbit in the ascent stage leaves the descent stage behind on the lunar surface.

descent stage habitat: in the descent stage, a pressurized crew habitat in which the crew would live during sortie missions

deterministic process: process whereby a given event will occur whenever its dose threshold is exceeded

DNA: deoxyribonucleic acid

DOD: Department of Defense

DOE: Department of Energy

dose: The average energy deposited by radiation per unit mass of material. Total dose refers to a combination of both ionizing and non-ionizing dose. See *NIEL*.

dose equivalent (*H*): Estimate of radiation risk that accounts for differences in the biological effectiveness of different types of charged particles that produce the absorbed dose. $H = Q \times D$, where Q is a quality factor based on the type of radiation ($Q = 1$ for x-rays). NASA uses Q as specified in ICRP Publication 60 (ICRP, 1991). Unit: sievert (Sv), equivalent to 1 J/kg.

EDS: Earth departure stage

effective dose (*E*): Estimate of radiation risk given in ICRP Publication 60 (ICRP, 1991). It sums the individual effects of all types of radiation present over all of the individual types of tissue in the body. Unit: cSv.

electron volt (eV): a unit of energy equivalent to 1.602×10^{-19} joules

EMU: Extravehicular mobility unit, the space suit developed for space shuttle crews that also serves on the ISS. The EMU features a hard upper torso and soft lower torso, arms, and legs over the pressure bladder. The entire EMU except the helmets and boots is covered by the thermal micrometeoroid garment.

ESP: energetic storm particle

EVA: extravehicular activity

excess risk: the probability of a certain effect on an individual who has been exposed to a given dose of radiation compared with the baseline probability of that effect

extravehicular activity (EVA): activity that occurs when a crew member moves from a spacecraft or habitat to the vacuum of space in a space suit

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fluence, or particle fluence (*F*): Number of particles incident on a small sphere centered at a given point in space, divided by the cross-sectional area of that sphere. Mathematically, it is given as d*N*/d*a*, where *N* is the number of particles and *a* is the cross-sectional area. Unit: m^2.

fluence rate (d*F*/d*t*): Change in fluence over a given small time interval, or the time derivative of the fluence. Unit: m^2/s.

flux (Φ): Term used historically by the nuclear community for fluence rate and also used for particle flux density, but deprecated by the ICRU convention to eliminate confusion between the terms "particle flux density" and "radiant flux." See *fluence rate*.

FSP: fission surface power

galactic cosmic rays: Essentially isotropic distribution of highly energetic particles from within and beyond our Galaxy. These rays are made primarily of hydrogen and helium but contain traces of all the elements.

GCR: galactic cosmic radiation

GOES: Geostationary Operational Environmental Satellite

HDPE: high-density polyethylene, defined as having a density greater than 0.94 g/cm^3

HEPAD: High Energy Proton and Alpha Detector

HZE: high atomic number and energy

HZETRN: a transport code developed specifically for high-charge, high-energy particles that is widely used for space radiation shielding and design calculations

ISS: International Space Station

kerma: Kinetic energy released in materials, the sum of the initial kinetic energies for all charged particles released by uncharged ionizing radiation in a small sample of material divided by the mass of the sample. Kerma is the same as dose when charged particle equilibrium exists.

latchup: a condition in a semiconductor in which the device is transformed into an anomalous state that no longer responds to input signals

LCVG: liquid cooling and ventilation garment

LEND: Low Energy Neutron Detector

LEO (low Earth orbit): the environment in which most recent space missions have been concentrated, where the magnetic field of Earth provides protection against much of the radiation that would be encountered on more distant exploration missions

LET (linear energy transfer): Measure of the average local energy deposition per unit length of distance traveled in the material. Unit: keV/μm.

LIS: local interstellar GCR spectrum

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LLO: low lunar orbit

LRV: lunar rover vehicle

Lunar Lander: the Constellation system vehicle that will travel between the Orion and the surface of the Moon

MARIE: Mars Radiation Environment Experiment

NASA: National Aeronautics and Space Administration

NCRP: National Council on Radiation Protection and Measurements

NIEL: Non-ionizing energy loss, also called displacement kerma. The total kerma can be divided into an ionizing component and a displacement, or NIEL, component.

NIH: National Institutes of Health

NM: neutron monitor

NOAA: National Oceanic and Atmospheric Administration

Nowcasting: prediction of total doses and the future temporal evolution of the dose once a solar particle event has begun

NRC: National Research Council

NSF: National Science Foundation

NSRL: NASA Space Radiation Laboratory

Orion Crew Exploration Vehicle: The Constellation system vehicle that will carry passengers in low Earth orbit, or from low Earth orbit to the Moon or Mars, and then back to Earth. Often referred to as CEV; in this report referred to as the Orion crew module.

PDF: probability density function

PEL (permissible exposure limit): Maximum amount of radiation to which an astronaut may be exposed. For terrestrial workers, PELs are legal limits, defined by OSHA. NASA PELs are set by the chief health and medical officer.

PLR: pressurized lunar rover

PLSS: personal life support system

PPS: Proton Prediction System

Q: quality factor

RAD: Radiation Assessment Detector

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RBE (relative biological effectiveness): Measure of the effectiveness of a specific type of radiation or particle in producing a specific biological outcome relative to the outcome with the same dose of gamma rays. RBE = $D\ /D_{\text{rad of interest}}$.

regolith: Abundant loose material found on the surface of a moon or planet. Colloquially known as dirt.

REID (risk of exposure induced death): Measure of risk used by NASA as a standard for radiation protection; reflects a calculation of the probability of death due to exposure to radiation in space.

RFI: request for information

RTG: radioisotope thermoelectric generator

SAMPEX: Solar Anomalous and Magnetospheric Particle Explorer

SEC: Space Environment Center

secondary radiation: radiation that has been generated by the passage of a primary particle through a material

SEE (single-event effect): a class of effects in which damage results from a single ionizing particle traversing a microelectronic device, rather than the accumulated impact of a large number of particles

sievert (Sv): The SI unit of effective dose. It is the product of the absorbed dose and a radiation weighting factor.

SOHO: Solar and Heliospheric Observatory

Solar cycle: The roughly 11-year cycle of solar activity, as reflected, for example, by variation in the number of sunspots (see Figure 2-5). The extrema of this cycle are known as "solar maximum" and "solar minimum." At solar maximum, the numbers of sunspots, flares, CMEs, and SPEs are high; at solar minimum, they are low. The intensity of galactic cosmic rays near Earth varies inversely with the solar-activity cycle, being highest at solar minimum and lowest at solar maximum (see Figure 2-4).

solar flare: a burst of energy released from the atmosphere (or corona) of the Sun

Space Radiation Analysis Group (SRAG): the radiation protection body of NASA responsible for radiation monitoring, projecting exposures, and ensuring adherence to principles of ALARA

spallation: A high-energy nuclear reaction in which a high-atomic-number target nucleus is struck by a high-energy, light particle (typically a proton); this causes the target nucleus to break up into many components, releasing many neutrons, protons, and higher Z particles.

SPE (solar particle event): Large fluxes of energetic particles produced by the Sun that can last from a few hours to a few days. Signatures of solar energetic-particle events may include significant increases in types of electromagnetic radiation such as radio waves, x-rays, and gamma rays.

SRAG: Space Radiation Analysis Group

STEREO: Solar-Terrestrial Relations Observatory

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stochastic process: process whereby the likelihood of the occurrence of a given event can be described by a probability distribution

TEPC: tissue equivalent proportional counter

TMG: thermal micrometeoroid garment

TMI: Three Mile Island

trapped radiation: Ionized particles held in place by Earth's magnetic fields. Also known as the Van Allen belt.

U.S. NRC: U.S. Nuclear Regulatory Commission

USAF: United States Air Force

Wind: a NASA spacecraft that observes the Sun and solar wind

Z: atomic number, the number of protons in the nucleus of an atom

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