Radiation Hazards to Crews of Interplanetary Missions

Biological Issues and Research Strategies

Task Group on the Biological Effects of Space Radiation

Space Studies Board

Commission on Physical Sciences, Mathematics, and Applications

National Research Council

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Foreword

Astronauts who venture beyond the protection of Earth's atmosphere and magnetosphere risk exposure to levels of radiation far exceeding those on Earth. Of all the risks they face, this one is probably the most straightforward to control-by providing adequate shielding. However, because shielding adds weight, cost, and complexity to space vehicles, it is very important for designers to have a good, quantitative understanding of the true risk and its degree of certainty.

This report assesses our understanding of radiation hazards in space. It also considers the additional research needed to reduce the areas of uncertainty, research that must be completed prior to undertaking the detailed design of a vehicle carrying crew members into space for periods of extended exposure. The report finds that it will take more than a decade of research to answer even the narrowest set of key questions, although happily the needed studies can all be conducted on the ground rather than in space.

The nation has backed away from a specific timetable for human exploration of the moon and Mars. Yet it seems plausible that such expeditions will be mounted sometime in the first quarter of the 21st century, especially given the recent resurgence of interest in possible life on Mars from the study of meteorites. It becomes clear, when the lengthy time scale of the research is also taken into account, that the present report is indeed timely and should receive prompt consideration by NASA planners.

Claude R. Canizares, *Chair*
Space Studies Board

Preface

The study that is the subject of this report was initiated as a result of a series of discussions between the leaders of NASA's Office of Life and Microgravity Sciences and Applications (OLMSA), NASA's Life and Biomedical Sciences Division (LBSAD), and the Space Studies Board's Committee on Space Biology and Medicine (CSBM). In order to address concerns within NASA and CSBM regarding the many uncertainties in the understanding of radiation hazards to the crew of long-duration missions in space, CSBM formed an expert task group on radiation biology and physics whose members had no direct involvement with NASA's radiation programs. A CSBM member with the appropriate expertise was appointed to lead the group.

The Task Group on the Biological Effects of Space Radiation (TGBESR) was asked to review current knowledge on the effects of long-term exposure to radiation in a space environment and to consider NASA radiation shielding requirements for orbital and interplanetary spacecraft. The task group was charged with assessing the adequacy of NASA planning for the protection of humans from radiation in those environments and with making recommendations regarding needed research and/or new shielding requirements. Where feasible, the task group would also provide NASA with radiation safety guidelines.

Early in the study the task group was informed by NASA that plans for the international space station were at such an advanced stage that any recommendations affecting shielding of orbital craft could not be implemented by the agency. The task group therefore decided to concentrate on the radiation hazards of interplanetary missions. Further, at the urging of NASA, the task group has attempted to provide reasonable estimates of time lines for completing the radiation research it has recommended.

Although the recommendations of the task group are published here as a separate and independent report of TGBESR, it is the intent of CSBM that this report will also form the basis of a section in a space life sciences strategy report being prepared by CSBM for publication at a later date.

During the course of this study the task group was briefed extensively by representatives of OLMSA and LBSAD regarding NASA's planning for deep-space missions and projections for radiation shielding. The task group also received in-depth technical briefings on the status of NASA's radiation research and the agency's current understanding of radiation hazards, and it consulted a wide range of technical documentation . When verification or additional details of prior research were needed, task group members made direct queries to the pertinent investigators in the radiation research community.

A number of individuals who assisted the task group by supplying information deserve special thanks for their contributions: Harry Holloway, Frank Sulzman, and Walter Schimmerling of NASA headquarters; John Wilson of NASA Langley Research Center; Amy Kronenberg of Lawrence Berkeley National Laboratory; and Gregory Nelson of the Jet Propulsion Laboratory.

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Executive Summary

NASA's long-range plans include possible human exploratory missions to the moon and Mars within the next quarter century. Such missions beyond low Earth orbit will expose crews to transient radiation from solar particle events as well as continuous high-energy galactic cosmic rays ranging from energetic protons with low mean linear energy transfer (LET) to nuclei with high atomic numbers, high energies, and high LET. Because the radiation levels in space are high and the missions long, adequate shielding is needed to mini mize the deleterious health effects of exposure to radiation.

The knowledge base needed to design shielding involves two sets of factors, each with quantitative uncertainty-the radiation spectra and doses present behind different types of shielding, and the effects of the doses on relevant biological systems. It is only prudent to design shielding that will protect the crew of spacecraft exposed to predicted high, but uncertain, levels of radiation and biological effects. Because of the uncertainties regarding the degree and type of radiation protection needed, a requirement for shielding to protect against large deleterious, but uncertain, biological effects may be imposed, which in turn could result in an unacceptable cost to a mission. It therefore is of interest to reduce these uncertainties in biological effects and shielding requirements for reasons of mission feasibility, safety, and cost.

This report of the Task Group on the Biological Effects of Space Radiation summarizes current knowledge of the types and levels of radiation to which crews will be exposed in space and discusses the range of possible human health effects that need to be protected against (Chapters 1 and 2). It points out that recent reductions in facilities for radiation research raise concerns about how best to acquire needed new knowledge. The report goes on to suggest other steps to be taken and the types of experiments needed to reduce significantly the level of uncertainty regarding health risks to human crews in space (Chapter 3). In Chapter 4 the task group recommends priorities for research from which NASA can obtain the information needed to evaluate the biological risks faced by humans exposed to radiation in space and to mitigate such risks. It outlines, in general terms, the commitment of resources that NASA should make to carrying out these experiments in order to design effective shielding in time for a possible mission launch to Mars by 2018, which would allow for energetically favorable flight trajectories. Chapter 5 addresses additional issues pertinent to carrying out studies on the effects of radiation, and the appendixes provide additional details and clarification as appropriate.

Summarized below are the task group's conclusions, its recommendations for future experiments, and its estimates of the time needed to carry out these experiments. The data from these experiments should permit NASA to design cost-effective shielding to protect astronauts from the deleterious effects of radiation in space.

1. The principal risks of suffering early effects as a result of exposure to radiation in space arise from solar particle events (SPEs). It is not too difficult a task to provide appropriate shielding or storm shelters to protect against exposure during SPEs, but surveillance methods to predict and detect solar particle events from *both* sides of the sun relative to a spacecraft must be improved.

2. The kinds of biological effects resulting from exposure to the ionizing radiation encountered in deep space do not differ from those resulting from exposure to x rays. However, the quantitative difference between the risks posed by x rays (low-LET radiation) and by heavy high-energy nuclei (high-LET radiation) may be large, and the magnitude of the human biological effects is largely unknown. An understanding of these effects-including cancer induction, central nervous system changes, cataract formation, heritable effects, and early effects on body organs and function-as well as of the shielding necessary to mitigate these effects for crew members, is essential for the rational design of space vehicles built for interplanetary missions.

3. The task group members generally agreed that the potential late effects of radiation are the major concern in estimating risks to crew members. Of the known late effects, cancer is currently considered to be the most important. However, experimental data suggest that exposure to high-atomic-number and high-energy (HZE) particles may also pose a risk of damage to the central nervous system (CNS). Since it is estimated that during a 1-year interplanetary flight each 100-μm^2; cell nucleus will be traversed by a primary energetic particle of atomic number greater than 4,[1] further experimentation is essential to determine if CNS damage is a significant risk.

4. To estimate the cancer risk posed by exposure of humans to radiation such as HZE particles, for which no human data are available, it is necessary to use data on the Japanese atomic bomb survivors exposed to acute low-LET radiation and then extrapolate, based on experimental data, to estimate the risks posed by high-LET radiation. At present, the only comparative data for cancer are for studies on the induction of Harderian gland tumors in mice. Additional research is required to reduce the uncertainties of the assumptions inherent in this approach. To calculate risks associated with exposure to low-fluence-rate HZE par ticles, it is assumed, based on cell and animal studies, that there is not a large dose-rate effect.

5. Biophysical models and data for cell killing and mutagenesis indicate that as the LET increases, the biological effect of the radiation increases to a maximum near a LET of 100 keV/µm and then decreases at higher LET. (See, for example, NCRP Report No.98.[2]) However, no such decrease was observed in the one animal tumor for which data were obtained using a number of heavy ions with increasing LET.[3] This discrepancy creates uncertainties in estimates of risks associated with exposure to particles at these higher LETs. To resolve these uncertainties, additional systematic studies are needed on the induction in animals of other radiobiologically well characterized cancers, such as leukemia and breast cancer. From a practical point of view, sufficiently accurate data can only be obtained from ground-based experiments using acute doses.

6. The background frequencies of the heritable changes in humans, which might be increased by

exposure to radiation, range from ~ 10^{-5} to 3×10^{-3} per genetic locus.[4] The minimum chronic dose that would double these values is ~ 4 Sv,[5] a value greater than that given in NASA's current lifetime exposure guidelines. Hence, the genetic risk-the absolute increase in the frequencies of heritable changes-to an astronaut will be low. The risk to the gene pool of the overall human population will of course be far lower due to the relatively small number of space-faring humans.

7. The doses of radiation to which crews are exposed in space are not expected to induce early deterministic effects, with the possible exception of skin damage and a temporary reduction in fertility. Skin damage is likely only following exposure at high doses outside the spacecraft. Experimental studies in dogs indicate that any reduction in fertility per unit dose of radiation may be greater for low-dose-rate, protracted exposure than for acute exposure.[6]

8. The space vehicles used for missions of short duration in low Earth orbit have required minimal optimization of radiation shielding for crew protection purposes. In contrast, optimization of shielding for prolonged interplanetary trips will be a major factor in the design and cost of space vehicles. It will be necessary to know, for protons and HZE particles, the basic nuclear cross sections for interactions and fragmentation in shielding. Such data will be used to calculate the particle distributions and energies present behind different types of shielding as a result of the incident radiation passing through the shield material. Such transport calculations must be verified by ground-based experiments.

9. A knowledge of the particle types and energies present behind types of shielding should be used, with appropriate risk models, to calculate biological effects-cell killing, mutations, chromosomal changes, and tumor induction-in animals exposed to radiation. NASA investigators should also obtain parallel experimental data for the same radiation types and energies and compare these to the results calculated with models. This research is best accomplished at ground-based facilities.

10. Microgravity has little effect on the responses of simple cellular systems to radiation,[7] and uncertain ties about the effects of microgravity seem negligible compared with the other uncertainties regarding risk (see 11 below). Doing cell biology and cancer induction experiments in space is costly and difficult and would require that a source of radiation be carried in the spacecraft. Because only a limited number of animals could be investigated, the results would not be statistically significant. Hence, for the study of living systems, radiation experiments in space should have a very low priority compared with ground-based research.

11. The estimated overall uncertainty in the risks of radiation-induced biological effects ranges from a factor of 4- to 15-fold greater to a factor of 4- to 15-fold smaller than our present estimates because of uncertainties both in the way HZE particles and their spallation products penetrate shielding (particle

transport) and in the quantitative way in which these types of radiation affect biological functions.[8] In the absence of precise data and calculations, the shielding would have to protect crew members against the higher, but uncertain, estimated risk. The cost of this possibly unnecessary shielding has been estimated by NASA researchers to be in the range of $10 billion to $30 billion.[9] In comparison, the cost of a ground-based, dedicated HZE particle research accelerator is estimated (in 1996) to be $18.7 million, with an annual operating cost of about $4 million for 2000 operating hours per year.[10],[11] The disparity between the excess cost of additional shielding and the annual NASA budget for biology and space radiation physics indicates the need for a significant increase in the research budget for these areas.

12. Major radiation facilities-including both specialized radiation sources and animal colonies-have been shut down in recent years. At present, there are severe limits on the availability of radiation particle types and particle energies for HZE particle research. NASA can no longer rely on the Department of Energy and the Department of Defense for expertise, research, and facilities. If the necessary facilities, expertise, and funding were available now, it would take approximately 10 years to provide data that NASA needs to assess the best way to provide appropriate safeguards for its spaceflight crews.

13. Unless NASA obtains access to a reliable source of HZE particles with an appropriate support staff for a significant fraction of each year, it will take well over 10 years, perhaps over 20 years, depending on the level of effort, to reduce the present large uncertainties in particle transport behavior and in the biological response functions for cancer induction. Such a delay will postpone the design of necessary shielding or may result in the use of excess shielding (at a higher cost) and possibly delay any planned Mars mission beyond the next quarter century.

14. In Chapter 4, the task group outlines its recommendations for research priorities that NASA should follow to obtain the information needed to evaluate the biological risks faced by humans exposed to radiation in space and to mitigate such risks. The research priorities recommended by the task group include extensive physical and biological experiments, including animal studies using light and heavy nuclei up to 1 GeV/ nucleon. Such experiments could take more than 20 years at NASA's present utilization rate of approximately 100 hr/yr of accelerator time at Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS), the only source for HZE particles supported by NASA.

15. To carry out needed research expeditiously, NASA should explore a number of possibilities, including international collaborations, so as to increase the research time available for experiments with HZE particles and protons at energies over 250 MeV. Such possibilities include a combination of more running time at the AGS and at lower-energy accelerators, expansion of existing facilities (see Appendix C), the commissioning of new beam lines at existing facilities, and the construction of a new facility. A 1992 National Research Council letter report (Appendix D) emphasized the need for a dedicated HZE particle facility.

The fact that the present report reaches conclusions similar to those in the 1989 report of the National Council of Radiation Protection[12] underscores the need for additional resources and facilities in order to understand quantitatively the radiation biology associated with interplanetary flights.

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To discuss quantitatively the biological effects of ionizing radiation, we need a radiation dose unit that is directly related to those effects. All effects of radiation are assumed to be directly proportional to the amount of ionization produced in the biological organism. The amount of ionization is in turn proportional to the amount of deposited energy. Therefore, we define a radiation dose unit called the rad, as 1/100 of a joule of ionizing energy deposited per kilogram of tissue, which is. 1 rad = 0.01 J/kg. For example, if a 50.0-kg person is exposed to ionizing radiation over her entir Ionizing radiation in very high levels is known to increase the incidence of cancer, birth anomalies, erythema, and other problems. In low levels, these effects are either very, very small compared to natural incidences or non-existent depending on the biological model used for estimating the potential risk. Regulatory agencies assume that radiation effects observed in people exposed to very high doses can be linearly extrapolated to background levels. Space radiation environments include fast neutrons with a wide energy range beyond several tens of MeV.Â These instruments can perform chronic irradiation for a few years and have been supplying important information on the biological effects of chronic low dose rate irradiation to mice [46]. The instruments at the Research Institute for Radiation Biology and Medicine (RIRBM), Hiroshima University, Central Research Institute of Electric Power Industry (CRIEPI), University of Occupational and Environmental Health (UOEH), and National Institute of Radiological Sciences, National Institutes for Quantum and Radiological Science and Technology (QST-NIRS), can also perform chronic irradiation with dose Ionizing radiation can cause biological effects which are passed on to offspring through the epigenome. The effects of radiation on cells has been found to be dependent on the dosage of the radiation, the location of the cell in regards to tissue, and whether the cell is a somatic or germ line cell. Generally, ionizing radiation appears to reduce methylation of DNA in cells.