OVERVIEW OF NASA'S SPACE RADIATION RESEARCH PROGRAM

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ABSTRACT

NASA is developing the knowledge required to accurately predict and to efficiently manage radiation risk in space. The strategy employed has three research components: (1) *ground-based* simulation of space radiation components to develop a science-based understanding of radiation risk; (2) *space-based* measurements of the radiation environment on planetary surfaces and interplanetary space, as well as use of space platforms to validate predictions; and, (3) implementation of countermeasures to mitigate risk. NASA intends to significantly expand its support of ground-based radiation research in line with completion of the Booster Applications Facility at Brookhaven National Laboratory, expected in summer of 2003. A joint research solicitation with the Department of Energy is under way and other interagency collaborations are being considered. In addition, a Space Radiation Initiative has been submitted by the Administration to Congress that would provide answers to most questions related to the International Space Station within the next 10 years.

INTRODUCTION

The radiation hazard outside the Earth's magnetic field is mainly due to protons and energetic, highly charged nuclei (HZE particles). Protons are produced as part of solar particle events (SPE) and are also the most abundant of galactic cosmic rays (GCR). HZE particles are principally found as part of Galactic Cosmic Rays (GCR). The range of GCR nuclei of biological significance extends from protons to iron. The relevant characteristics of the particles constituting space radiation are listed in Table I.

The main problem associated with SPEs is the development of realistic forecasting and warning strategies. This development hinges principally on advances in solar physics and on the development of suitable observational capabilities. Similarly, for trapped radiation, the main problems are physical in nature. The trapped radiation environment is dynamic, with short-term changes that are not fully understood and that are difficult to predict accurately. Shielding is effective against low energy protons in SPE and trapped radiation, and the hazards of trapped radiation for extravehicular activities can be effectively mitigated by appropriate scheduling. On the other hand, while the GCR background is fairly well characterized by existing models (Badhwar and O'Neill, 1992), the amount of shielding that can be used on spacecraft is only of limited effectiveness against the high energy HZE radiation. Moreover, the main problem is that the biological effects of HZE exposure are poorly understood, but are known to be the most significant hazard in space.

This range of particle energies and types is well covered by two accelerators at Brookhaven National Laboratory (BNL) in Long Island, New York: the Alternating Gradient Synchrotron (AGS) and the AGS Booster Synchrotron. These accelerators are currently operated by the high energy and nuclear physics programs of the U.S. Department of Energy (DOE), and NASA purchases beam time for several experimental campaigns per year. The main purpose of simulating space radiation at these facilities is to determine the biological factors of risk. However, they can also be used to obtain required data on the physical interactions of these beams with materials and space instruments (Miller, 2003).

RADIATION PROTECTION IN SPACE

The goal of radiation protection in space is to eventually enable long-term, or even permanent, human presence in space without incurring unacceptable health risks due to the unavoidable exposure to ionizing space radiation. Accomplishing this goal requires: (1) predicting health risks accruing due to exposure of humans to radiation in space; in particular, identifying risks not seen or not seen at comparable doses, with exposure to terrestrial sources of occupational exposure; (2) predicting these health risks with sufficient accuracy to enable space missions to proceed with substantial assurance that radiation limits will not be exceeded; and, (3) reducing radiation risk by operational measures, radiation shielding and discovery of biological countermeasures.

The length of time associated with different missions is listed in Table II. The current limits on risk (NCRP, 2000) are set for both short term exposure, limiting health risks below the threshold of effects that could become manifest during a mission or shortly thereafter, and career exposures. Career exposures are currently the limiting factor. Career exposure limits are based on not increasing the actuarial probability of cancer fatality by more than

Table I. Characteristics of space radiation

Characteristic	SPE	GCR	Trapped
proton energy range (MeV)	up to several 100	up to several 1000	up to several 100
HZE energy range (MeV/nucleon)	no significant contribution	up to several 1000	no significant contribution
LET range (keV/µm)	0.25 – 10	0.25 – 1000	0.25 – 10

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Table II. Length of Different Types of Exploration Missions

Destination	Days
Low Earth Orbit	180
Earth's Moon, libration points	100
Accessible Planetary Surfaces: Mars, Asteroids, other Moons	500 – 1000
Outer Planets	> 2000

3% above current probabilities for unexposed populations. Operational radiation limits are required to use adequate safety margins, a principle of good practice known in radiation protection under the acronym ALARA – As Low As Reasonably Achievable (NCRP, 1998). Since risk is not measured directly by radiation detection instruments, limits are set by reference to radiation levels (e.g., in Sievert), that can be converted into a probability of cancer fatality using established methods (ICRP, 1990; NCRP, 2000).

Predictions about the nature and magnitude of these risks are subject to very large uncertainties (Cucinotta *et al.*, 2001), and the potential for adverse health effects of radiation on astronauts threatens NASA's ability to develop long-duration space missions for humans. The magnitudes of these uncertainties are due to lack of scientific knowledge. They are difficult to estimate and depend on the type of risk and the models used for risk prediction. These large uncertainties lead to unacceptable constraints on shielding mass for spacecraft or habitats, tours of duty of crews on the International Space Station (ISS), and on the radius and duration of sorties on planetary surfaces. For example, using a 95% confidence level to define the safety margin, the career limit for a 45-year old male astronaut starting his career on ISS could be as little as 250 days (during solar minimum, when the intensity of GCR is highest). As a consequence, a third of the current astronaut corps would not qualify to fly more than one or two 180-day missions without exceeding career risk limits when the uncertainties in risk projections are used as a safety margin.

Countermeasures are approaches to mitigate risk. There are five possible approaches, but only the first two of these are currently practical and cost-effective. The five approaches are:

1. ***Operational***: limit the time of exposure and the duration of exposure by various strategies, such as selecting older crew members, avoiding extravehicular activity during passage through high-intensity portions of the trapped radiation belts, using spacecraft transfer trajectories that minimize the duration of interplanetary travel, etc.
2. ***Shielding***: reduce the number of particles penetrating to the interior of a spacecraft or space habitat by interposing a thick material between the external radiation environment and the crew; clever multifunctional arrangements of structural materials and equipment layout can add significant shielding to any space habitat.
3. ***Screening***: it is well known that some individuals have genetic predispositions resulting in a higher cancer risk than normal. Procedures to screen for radiation susceptibility (or, if it can be demonstrated, abnormal radiation resistance) are currently of limited usefulness. Complicating the issue are questions related to the proper course of action to follow if testing reveals higher cancer susceptibility and whether aggressive surveillance of such individuals, if they elect to continue working in a space radiation environment, is warranted or even beneficial.
4. ***Prevention***: current knowledge of substances useful for radiation protection is limited. Pharmaceuticals can be used as radioprotectants for planned radiation exposures, but they have serious side effects and may not be useful for protection against HZE particles. Genetic methods to enhance the organism's ability to repair radiation damage may be conceptually possible but are beyond the horizon.
5. ***Intervention***: may be required to deal with prompt radiation effects arising, for example, from high radiation levels caused by solar disturbances. Biomolecular intervention after radiation exposure may be possible in the future, perhaps using gene therapy or related methods to induce improved processing of radiation damage in cells.

RADIATION RESEARCH PROGRAM

A Strategic Plan and Critical Path Roadmap have been developed at NASA for identifying radiation risks and setting goals using past external guidance from NAS/NRC and NCRP report recommendations and input from principal investigators and other interested scientists. [a](NASA, 1998). The plan sets forth a research program with three components: (1) *ground-based* simulation of space radiation; (2) *space-based* measurements of the radiation environment on planetary surfaces and interplanetary space, as well as use of space platforms to validate predictions; and, (3) implementation of countermeasures to mitigate risk.

The major scientific component is the use of ground-based accelerator facilities to develop a science-based understanding of radiation risk. While epidemiological studies of bomb survivors constitute the current basis for evaluation of radiation risk, studies on life shortening and other late effects in small mammals are used to convert epidemiological studies on high dose and dose rate exposures to estimates of radiation risk at the much lower doses and dose rates prevalent in space. Similarly, extrapolation of data from cellular biology, in conjunction with *in vivo* studies, are used to derive conversion of risk estimates for different types of radiation and for the relative weight to be assigned to different organs at risk.

[a] National Aeronautics and Space Administration (NASA). 1998. Space Radiation Health Research Strategic Program Plan. Available on the Internet at: http://spaceresearch.nasa.gov/common/docs/radiation_strat_plan_1998.pdf

Finally, models of the interaction of radiation with matter and the subsequent fate of the chemical species produced can be used to integrate the entire chain of reasoning into the ultimate risk predictions in space. Thus, ground-based studies offer the only means of acquiring a statistically significant knowledge base for developing mechanistic, rather than phenomenological, predictions of radiation risk and for significantly reducing the uncertainties involved in such predictions.

A new ground-based irradiation facility, the Booster Applications Facility (BAF), is being built by NASA at BNL.[b)] The BAF will provide a cost-effective way to simulate space radiation for radiobiologists and materials scientists in the program. It is expected to be commissioned in July, 2003. Together with the AGS, BAF will be able to simulate all components of space radiation, and it will become the main asset of the NASA Space Radiation Health Program. The BAF will be used to complete the radiation shielding database, and to perform the radiobiological research and data collection for risk prediction, uncertainty reduction, and countermeasure discovery. Table III shows the beams and energies to be used. A filled circle shows where data are not available; the X-marks show where partial data are available. As may be seen from the table, the existing knowledge base is very sparse.

Not all studies can be performed on the ground. The requirements for space-based research have been discussed elsewhere (Schimmerling, 1995). Predictions using ground laboratory data need to be validated in space flight, to take into account the limitations of particle accelerators in simulating space radiation, and to take into account aspects associated with living in space. Some important problems can only be resolved in space. One important example is the characterization of the shielding properties of planetary surfaces. Defining the radiation dose and radiation quality on the surface of Mars, which depends on the shielding properties of the Martian atmosphere, and demonstrating the accuracy of model calculations, requires an on-site measurement. Other requirements for space-based research involve validation of predictions and eventual countermeasures in space. Such validation involves carefully selected experiments that are able to provide statistically significant results on questions hinging on interaction of radiation with weightlessness and other factors present in space, but not on the ground.

At the present time, the implementation of countermeasures has to be limited to the development of improved operational methods and improved use of materials to provide radiation shielding. A substantial literature exists on radioprotectants and significant work is being performed exploring various pharmaceutical intervention techniques. However, given the limitations of our biological knowledge, it would be premature to invest substantial resources in the mitigation of radiation risk before a better understanding is achieved of the biological mechanisms on which these risks are based.

The program has both basic science and applied science aspects. It is likely, and even desirable, that most research will have both basic and applied components, and the illustrations offered here are not intended to be exclusive. Basic science investigations are concerned with acute and early effects of radiation, the risks of carcinogenesis, central nervous system damage and other end points, and will consider the interaction of spaceflight factors with radiation. Applied science investigations are concerned with the definition and measurement of the space radiation environment, including dosimetry and the development of biological markers of radiation exposure, physics of the interaction of radiation with matter, leading to radiation shielding and spacecraft design, and with crew risk mitigation.

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b) [Note added in proof] This facility has since been renamed the NASA Space Radiation Laboratory (NSRL).

Table III. Points for Data Base. *($\varepsilon_{P,}$ the energy per nucleon of a particle p, a quantity related to particle velocity rather than energy, is conventionally denoted by the Greek lower case epsilon. Values of ε_P to be addressed are marked by filled circles. Cases in which some experimental data exist are marked by Xs.)*

ε_P (GeV/ u)	**Particle Species**										
	H	He	C	N	O	Ne	Si	Ar	Ca	Mn	Fe
0.1		●	●		●		●				●
0.2	●	●	●X	X	●X		●X	X			●X
0.4			●		●		●	●			●
0.6		●			●	X	●X				●X
0.8							●	●			●
1.0	●										●X
1.5		●	●		●		●	●	●	●?	●
2.0	●				●						●
5.0	●				●		●				●

Based on external reviews as well as internal assessments, NASA management are determined to significantly increase the rate of progress of this program. Accordingly, the Office of Biological and Physical Research (OBPR) has included Space Radiation, a new interdisciplinary initiative involving basic and applied life and physical sciences, within its Research and Technology Program budget request for FY2003. This Space Radiation initiative was prompted by the need for increased understanding of the biological effects of the radiation environment in Low Earth Orbit, and by new radiation epidemiological data that lead to higher levels of concern, including the establishment of more restrictive guidelines for astronaut exposure levels.

The Radiation Initiative is intended to accomplish advances in the understanding of the basic physical, biological, and biochemical mechanisms of the action of radiation on cells, tissues and organs, and to leverage relevant advances in other areas of biological and biomedical research.. The accurate prediction of risk is based on data obtained by multiple disciplines. Biological as well as physical implications must be taken into account in the optimization of spacecraft shielding designs. This interdependence of objectives served by all participants in the initiative requires an integrated approach to assign priorities, coordinate research support, and consolidate data for the purpose of risk management. The objective achieved by the expected increase in knowledge, improved accuracy in risk prediction, and new countermeasures is intended to enable NASA to assure, at a 95% confidence level, three 180-day missions on ISS and, eventually, a permanent presence in space without exceeding risk limits.

With the substantially accelerated pace enabled by the radiation initiative, the scope of the radiation program becomes:

- **Generate knowledge** required to assure that humans can live and work in space without exceeding established working limits for radiation risk at required statistical confidence levels
  - Train a generation of radiobiologists to participate in generating breakthroughs in science and leveraging them for NASA
  - Assure three 180-day missions in LEO with 95% confidence (or similar requirement)
  - Assure one 1000-day Mars mission with 95% confidence (or similar requirement)
  - Eventually: assure permanent presence in space -- anytime, anywhere
- **Predict risk** (using the Critical Path Roadmap):
  - Mechanistically based predictions of cancer in humans
  - Behavorial/ neurological functional impact
  - Germ cell impact
  - Interaction of radiation sensitivity with other spaceflight factors
- **Reduce uncertainty**
  - Biomarkers to predict individual risk
  - Biological and physical data base accessible at AGS, BAF
  - Critical experiments on ISS, Mars, and other platforms that may become available, to validate predictive models
- **Develop Rational Intervention**
  - Optimized shielding methodologies
  - Biology breakthroughs
  - Criteria for medical surveillance and treatment
  - Genetic screening and counseling

The radiation initiative is intended to accomplish several milestones, including improvements in the predictions of risk of cancer lethality and incidence with an accuracy of ±150% or better (a two-fold improvement over current estimates). In addition, predictions of risk to CNS and other radiation endpoints should become available, together with estimates of their accuracy. A substantial expansion of the available data is expected. These data include compilations of nuclear interactions with relevant materials, as well as molecular and cellular radiation effects. Radiation transport codes will have been validated in the laboratory and developed as an engineering tool for practical use of these data in the design of spacecraft. Comparison of cellular and animal studies is expected to contribute important methods for the extrapolation of radiation effects to humans. Finally, studies of the interaction of radiation effects with effects of weightlessness and procedures for the discovery of biology-based countermeasures will have been put in place.

The emphasis of the research program will be on investigator-initiated research relevant to the NASA mission. As a matter of policy, all research supported by the radiation initiative shall be peer-reviewed according to the highest standards. All research results will be publicly available; evaluation of scientific and technical progress will be based on the investigators' prompt publication in the peer-reviewed open literature. The first of what will become annual research solicitations was issued on August 30, 2002.[c)]

EXTERNAL LINKS

The National Space Biomedical Research Institute (NSBRI) has a Radiation Team that works closely as part of the US radiation research community. NSBRI scientists participate in all program activities and have been productive users of the BNL facilities. NSBRI will continue to play an important role as one of the major users of these facilities.

A modern, state-of-the-art Space Radiobiology Laboratory has been established at the Loma Linda

[c)] The NASA Research Announcement on Ground-Based Research in Space Radiation Biology and Space Radiation Shielding Materials is available on the Internet at: http://research.hq.nasa.gov/code_u/open.cfm

University Proton Therapy Synchrotron of Loma Linda University at Congressional direction. This facility will be used for a maximum of 400 beam hours per year (depending on user demand), mainly for studies related to SPE protons, especially long-term, low-dose rate exposures to simulate space irradiations.

NASA has signed current Memoranda of Understanding with the National Institutes of Health and with the Department of Energy (DOE). A joint research program with the National Cancer Institute, in support of studies on Genomic Instability, was conducted in the period 1997–2001. This program was productive, with almost 50 articles published in scientific journals. In addition, this research has stimulated wide interest in the problems of genomic stability as evidenced in continuing research by other investigators, not supported by this program. New interagency efforts with NIH institutes continue to be explored and will be implemented as they develop.

NASA and DOE have agreed to a joint solicitation whereby NASA provides supplementary funding for radiobiology research in the DOE Low Dose Radiation Research Program that also has application to the low fluence aspects of GCR particles. The first solicitation was issued in February, 2002, and led to six investigators selected for joint support. The second solicitation was issued in November, 2002. Within budget constraints, NASA funding is intended in subsequent years, as appropriate.

There is active participation of international partners in all aspects of research. This is particularly effective in radiation research, where scientists from the international radiation research community have participated in the annual Space Radiation Health Investigators' Workshop for the past 13 years and have hosted two international versions of this workshop (in Arona, Italy, in 2000; and in Nara, Japan, in 2002). Together with the international partners, NASA also has an active ongoing effort in space radiation measurements. Workshops in Radiation Measurements on the International Space Station (WRMISS) have been held in different countries for the past seven years. Research solicitations have been coordinated with international partners and continued coordination along these lines is planned for Initiative research solicitations.

The HIMAC facility at the National Institute of Radiological Sciences in Chiba, Japan, has a moderate amount of beam time available and an active collaboration between the NASA Space Radiation Health Program and this laboratory has been under way since 1995. The heavy ion accelerator SIS at the GSI research institute in Darmstadt, Germany, is in high demand by the German nuclear physics community. In addition, use of the facility for cancer therapy started in December, 1997. While the facility is not available for space radiation research, the GSI scientists continue to make significant contributions to HZE radiobiology and have participated in many workshops and other activities initiated by the NASA program.

CONCLUSIONS

The NASA Space Radiation Research Program is developing the capabilities required to enable human space exploration. The Radiation Initiative is a first, major step that will lead to the level of accuracy in risk prediction that is required for adequate protection of ISS crews. It will also contribute the basis for significant advances toward the long-term goal of enabling human exploration without exceeding radiation risk limits.

ABBREVIATIONS

AGS = Alternating Gradient Synchrotron

ALARA = As Low As Reasonably Achievable (guidelines for radiation safety margins)

ASGSB = American Society for Gravitational and Space Biology

BAF = Booster Applications Facility (renamed NASA Space Radiation Laboratory)

BNL = Brookhaven National Laboratory

CNS = central nervous system

DOE = United States Department of Energy

GCR = Galactic Cosmic Rays

GSI = Gesellschaft für Schwerionenforschung Institut

HIMAC = Heavy Ion Medical Accelerator at Chiba

HZE = High atomic number (Z) and kinetic energy (E) nuclei in space radiation

ISS = International Space Station

LEO = low Earth orbit

NASA = National Aeronautics and Space Administration (United States of America)

NAS-NRC = National Academy of Sciences - National Research Council of the United States of America

NCRP = National Commission of Radiation Protection and Measurements

NSBRI = National Space Biomedical Research Institute

SIS = Schwerionen Synchrotron at the Gesellschaft für Schwerionenforschung Institut laboratory

SPE = solar particle events resulting from solar disturbances

USA = United States of America

WRMISS = Workshop(s) on Radiation Measurements on the International Space Station

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