Radiation Protection Research Recommendations for Missions Beyond LEO

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Abstract—At the request of the National Aeronautics and Space Administration, the National Council on Radiation Protection and Measurements prepared NCRP Report 153, *Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit.* This lengthy report, over 400 pages in length, published in November 2006, was drafted by NCRP Scientific Committee 1-7, and is a continuation of NCRP Report 132, *Radiation Protection Guidance for Activities in Low-Earth Orbit,* which provided guidance on limiting radiation exposures on missions in low-Earth orbit. The new report provides research recommendations in the broad areas of the space radiation environment, radiation physics and transport, radiation dosimetry, radiation biology, and radiation risk assessment. In this work, an overview of the committee membership, and the report contents and research recommendations will be presented and discussed.[1][2]

TABLE OF CONTENTS

1. INTRODUCTION

Astronauts on missions of long duration beyond low-Earth orbit (LEO) will be exposed to radiation levels that will significantly exceed those faced by crews in near-earth spacecraft, such as the Space Shuttle (STS) and International Space Station (ISS). Radiation fields encountered include the full intensity of the galactic cosmic ray (GCR) background, sporadic solar energetic particle events (SPEs), energetic protons and electrons during outbound and inbound transits of the Van Allen radiation belts, and exposure to any on-board sources. Although crews on missions in low-earth orbit (LEO) are exposed to some extent to all of these radiation fields, they are not exposed to the full intensities of the GCR and SPE spectra because of the protection provided by the Earth's geomagnetic field, which tends to deflect protons and heavier ions at lower energies back into deep space thereby preventing them from reaching spacecraft in LEO. The level of protection is a function of spacecraft orbital inclination and altitude. In addition, significant shielding, nearly 2π in solid angle, is provided by shadow shielding from the Earth itself. Hence, particle fluxes from GCR and SPE sources, especially at lower energies, are much lower in LEO than will be encountered in missions beyond LEO, where no protection from the magnetosphere or planetary bulk exists. Typically, astronauts on ISS receive ~ 1 mSv d^{-1}, with approximately 75 percent coming from GCR ions and 25 percent coming from protons encountered in passages through the South Atlantic Anomaly (SAA) region of the Van Allen belts.

In deep space, organ doses and dose equivalents are expected to be higher (about a factor of two or more) than those measured in LEO, since spacecraft in deep space will be externally exposed to the full intensities of these GCR and SPE sources. Properly describing how these radiation fields are altered by passage through the spacecraft structure is carried out using radiation transport codes, which model the atomic and nuclear interactions of these particles and describe the resulting composition and energy spectra of the transmitted radiation field. Additional shielding is also provided by the body tissues overlying critical internal organs and must be accounted for as well. The biological effects of these unique radiation fields are not well known. The associated radiation risks for stochastic effects, such as cancer induction and mortality, are also unknown for these radiations.. Unlike terrestrial exposures, which can be lowered by increasing shield thickness and mass, the high costs of launching materials into space precludes the purely engineering solution of providing as much additional shielding as is needed to reduce radiation exposures to some desired level. In addition, there are some model predictions which indicate that some types of shielding materials may give rise to secondary particle radiation fields that are more biologically-damaging than the unattenuated primary fields

1

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which produced them. Finally, in order to be effective in minimizing radiation exposure, the space radiation protection program must include dosimetry instrumentation and data processing tools, which can evaluate any realistic change in the exposure characteristics, and make this evaluation in a fairly short time period. This evaluation must include sufficient characterization of the radiation fields to allow determination of the dose and equivalent dose, and to estimate the reduction in equivalent dose that might be achieved by moving to areas of the spacecraft that provide added shielding.

At the request of the National Aeronautics and Space Administration (NASA), the National Council on Radiation Protection and Measurements (NCRP) prepared NCRP Report 153, *Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit* [1]. This lengthy report, over 400 pages in length, published in November 2006, was drafted by NCRP Scientific Committee 1-7, and is a continuation of NCRP Report 132, *Radiation Protection Guidance for Activities in Low-Earth Orbit* [2], which provided guidance on limiting radiation exposures on missions in low-Earth orbit. Hence, the purpose of NCRP Report 153 is to provide recommendations concerning the information needed to provide radiation protection for crewed space missions beyond low-earth orbit. It does not provide guidance as to what deep space radiation limits should be. Current space radiation guidelines pertain only to missions in low-earth orbit and are not considered relevant for future deep space missions.

In the following sections, the charter and committee membership of Scientific Committee 1-7 is presented. After a brief description of the NCRP report drafting process, and an outline of the report contents, the major research recommendations from the report are discussed.

2. NCRP SCIENTIFIC COMMITTEE 1-7

Committee Charter

(1) Assess the status of scientific understanding related to the transport and interaction of solar particles and galactic cosmic rays in spacecraft structures and human tissues and provide recommendations of research needed to improve the foundation on which to base radiation exposure guidance for deep space missions

(2) Evaluate the risks to humans for various components of the space radiation environment including cancer and deterministic effects such as cataracts and make recommendations of needed research on the biological effects of deep space radiation in order that appropriate radiation exposure guidance may be provided at a later time

Committee Membership

(1) Lawrence W. Townsend (Chair) - University of Tennessee

(2) Gautam D. Badhwar (deceased) - NASA Johnson Space Center

(3) Eleanor A. Blakely - Lawrence Berkeley National Laboratory

(4) Leslie A. Braby - Texas A & M University

(5) Francis A. Cucinotta - NASA Johnson Space Center

(6) Stanley B. Curtis - Fred Hutchison Cancer Research Center

(7) Charles E. Land - National Institutes of Health

(8) Don F. Smart - Air Force Geophysics Laboratory (retired)

(9) R. J. Michael Fry - Oak Ridge National Laboratory (retired)

3. NCRP REPORT DRAFTING PROCESS

The process begins with the decision by the NCRP Board of Directors to establish a scientific committee for the purpose of drafting a report in response to a request by a governmental, public or private agency/organization for guidance on a specific radiation protection topic relevant to the NCRP charter. In the case of NCRP Report 153, this request was made, and funded, by NASA. The Chair of the committee is selected by the Board of Directors. The members of the committee are then recommended by the Chair of the committee and approved by the Board. The next step is for the committee to draft the report. Usually several different meetings over a time frame ranging from months to several years are required. The initial meeting focuses on the report outline, expected content areas, and writing assignments. Subsequent meetings are used to fill out and refine the report content and come to a consensus regarding recommendations. The final draft report, once completed and approved by the committee, is submitted for critical review. This step involves reviews by outside experts within the fields addressed by the report. Once the report has been revised to address concerns made during the critical review, it is submitted to the full Council (100 members) for their review and approval. Comments and concerns offered by the Council must be addressed, either in the form of revisions, or accommodations. In order to be issued as an NCRP report, no more than two negative votes by Council members are permitted. Report 153, after approval by Council, was printed and issued in November 2006.

4. NCRP REPORT 153 OUTLINE

The research areas considered by the committee included: (1) the deep space radiation environment (both GCR and Solar Particle Events); (2) space radiation physics and transport; (3) space dosimetry; (4) space radiation biology; and (5) space radiation risk assessment methodology.

The report consists of 8 sections and one appendix:

(1) 1 – Executive Summary

(2) 2 – Introduction

(3) 3 – Space Radiation Environment

(4) 4 – Space Radiation Physics and Transport

(5) 5 – Space Dosimetry

(6) 6 – Space Radiation Biology

(7) 7 – Space Radiation Risk Assessment Methodology

(8) 8 – Summary of Information Needed

(9) App. A – Summary Tables of Literature by Radiation Type

Each research topical area presents a detailed overview of the status of research in that area, and makes recommendations as to future research needed to enable radiation limits to be established for deep space missions.

5. REPORT RECOMMENDATIONS

Space Radiation Environment

As mentioned earlier, for exploratory missions beyond LEO, the main radiation related concerns are chronic exposure to the GCR background, and acute exposure to sporadic SPEs. Both sources vary with the ~11 y solar cycle. The maximum intensity of the GCR spectrum occurs during the period of minimum solar activity. SPEs can occur at any time during the ~11 y long solar cycle, but are much more prevalent during periods of maximum solar activity, when the GCR intensity is reduced. The main concerns with GCR exposures to the human body are thought to be from late effects, such as the risk of cancer induction and mortality. For SPEs, especially very large ones, the primary concern is the risk of acute effects. However, SPEs also contribute to late effects, such as cancer induction and mortality. Most SPEs are relatively low in intensity and have spectra that are soft (*i.e.*, particle fluence rates decrease rapidly with increasing energy). Hence, they are of minor importance with regard to radiation protection since spacecraft structures can usually provide adequate shielding. Extremely large SPEs, however, may occur several times during the solar cycle. In these events the fluence rates can be high and the spectra hard (*i.e.*, particle fluence rates decrease slowly with increasing energy). Increased shielding in the form of a storm shelter may be necessary to reduce radiation doses received by astronauts to acceptable levels from these events.

Galactic Cosmic Radiation

Assessing radiation risk requires knowledge of the composition and energy spectra of cosmic rays in interplanetary and their spatial and temporal variation. Current models of the GCR environment are based on the standard diffusion-convection theory of solar modulation [3]. Typical uncertainties in the particle fluence rates predicted by the models are ~15 %. Measurements of GCR fluence rates are ongoing using satellites beyond the influence of Earth's magnetosphere. Hence, refinements to the models are indicated as additional data become available. Therefore, the NCRP recommended:

- Improve the accuracy and extend the range of energies and elemental species included in GCR models

Solar-Particle Events

For manned interplanetary missions there is great concern that a large SPE could, in a short time period (hours or a day), subject the spacecraft and crew to large numbers of protons with energies above tens of MeV. Hence, doses from exposures to large SPEs could be mission threatening for crews and equipment that are not adequately protected. Large SPEs (~5×10^9 protons cm^{-2} at energies >30 MeV) occurred in 1960, 1972, and 1989. Using the JPL model of Feynman et al [4], the probability of an event of this magnitude during a 2 y interplanetary mission near the solar activity maximum is ~0.1. Even larger events have occurred during the past 500 y [5]. Recent estimates of absorbed doses from the largest of these historic events, the Carrington event of September 1859, exceed 1 Gy for bone marrow and 10 Gy for skin and ocular lens, for thinly-shielded spacecraft in deep space [6].

However, the current ability to forecast large SPEs is poor. It is not presently possible to project the probability of SPEs 1 to 3 d in advance. When SPE predictions are issued and a significant event occurs, the observed fluence rate is generally, but not always, within an order of magnitude of the predicted peak particle fluence rate. Predictions of the spectral characteristics of an SPE are unreliable for large events. However, development of event-triggered methods of forecasting SPE doses over time using dosimeter measurements obtained early in the evolution of an event, coupled with Bayesian inference and artificial neural

network methods, have met with some success [7] and [8]. Therefore, the NCRP recommended:

- Develop SPE forecasting and prediction capabilities that are able to observe or account for interplanetary shocks and Coronal Mass Ejections. These capabilities should include the ability to reliably predict the fluence spectra and time evolution of an SPE
- Develop realistic models of the largest expected SPE fluence rates, which may be encountered on exploratory missions. Assessments of their biological effects and shielding requirements need to be carried out

Space Radiation Physics and Transport

When high-energy nuclei (protons, light ions, and heavier ions) pass through materials, such as spacecraft shielding or body tissues, they interact with the atoms and the atomic nuclei of the target materials. At the atomic level, interactions occur very frequently ($\sim 10^8$ cm^{-1}). Although particle identities are not changed by atomic collisions, they do result in nearly continuous energy losses by the incident radiation fields as the atoms of the target materials are excited and ionized. However, the identities of the particles in the incident radiation fields can be altered by nuclear collisions, which are much less frequent, occurring only once every few centimeters of travel. These collisions often result in the breakup of the incident and target nuclei. Hence, both the energy spectra and the actual composition of the transmitted radiation fields are altered in passing through materials. In addition, energetic neutrons are produced in large numbers by the nuclear collisions. The propagation of these radiation fields and their alterations by atomic and nuclear collisions are modeled using radiation transport codes. Currently, space radiation transport codes introduce uncertainties in assessing risk at an ~ 25-50% level. The codes also do not adequately treat all component particle types (e.g., mesons and electromagnetic cascades). Thus, the NCRP recommended:

- Develop and validate space radiation transport codes and nuclear cross-section models that treat all components of the primary and secondary spectra of the space radiation environment including protons, neutrons, light ions, heavy ions, mesons, and electromagnetic cascades

- Improve existing nuclear interaction databases for properly assessing risk and concomitant shielding requirements, especially for neutrons and light ions

Space Dosimetry

Radiation exposure sources include GCR, SPEs, protons and electrons in the trapped belts, and radiation from any man-made sources onboard the space vehicle. Each has its own characteristics and variability. The onboard dosimetry system must be able to simultaneously and adequately characterize the exposure from all types of radiation and sources that are present. Both active and passive systems will be needed. Instrumentation and techniques for some of these measurements exist, but improvements are necessary to provide reliable dosimetry in these complex space radiation fields. Therefore, the NCRP recommended:

- Develop radiation spectrometers, which can accurately measure the fluence of indirectly ionizing particles in the presence of a fluence of directly ionizing particles

Space Radiation Biology

Health effects of radiation exposures on humans during and after exploration missions are not completely known. Significant future research is needed. The goal is to provide radiation dose limits that will limit the risk of radiation effects from occupational radiation exposure in space to an acceptable level. Historically, it has been assumed that major early effects of radiation exposure could be avoided simply by the augmenting radiation shielding within the spacecraft. The focus, therefore, has been on estimating the risk of late radiation effects such as cancer and cataracts. However, the problem is broader and potentially includes both early and late radiation effects. With what is known today, there are concerns about early effects on the brain and peripheral nervous system. There are also indications of increasing risk of cardiovascular disease resulting from radiation exposure. Further study of defects in immunological function from exposure to low doses of high dose-rate radiation that contribute to life-shortening or diminished quality of life is also needed. Using biomarkers to identify individuals at increased risk due to genomic predisposition, as well as radiation biodosimetry to estimate cumulative radiation doses may provide guidance for future individual mission worthiness. However, links between the appearance and abatement of some of the early biodosimetric markers and the risk of later medical consequences are uncertain. Finally, combined effects of radiation exposure with other stressors, such as microgravity, have not been studied adequately. Therefore, the NCRP recommended:

- Determine the carcinogenic effect of protracted exposures of relevant energies of protons, neutrons and heavy ions

- Determine the carcinogenic effects of heavy ions to provide data for determining quality factor values

- Conduct experiments to underpin the risk estimates such as cell and molecular biology experiments using realistic cell and tissue models

- Determine whether or not there is a significant risk of effects on the function of the central nervous system (CNS) from space radiations

- Determine the effect of protracted exposures of relevant energies of protons, neutrons and heavy ions on other tissues, such as the ocular lens, bone marrow, cardiovascular, and immune system

- Develop methods of using experimental data for estimating risks of late and early effects in humans

- Conduct studies of the effects of SPE dose rates on early radiation responses (*e.g.*, prodromal effects, such as nausea and vomiting) in order to determine the appropriate biological effectiveness factors to use in establishing gray equivalent limits to apply to organs and tissues for early effects

- Evaluate biomarkers for their ability to detect adverse effects

- Evaluate biomarkers to estimate cumulative doses

- Assess countermeasures for their efficacy in preventing adverse effects

Space Radiation Risk Assessment Methodology

On long-term missions outside Earth's magnetic field, three areas of radiation health risks are of concern: (1) late effects (*e.g.*, cancer); (2) early effects due to acute, or short-term, exposures from large SPEs; and (3) possible effects to the CNS from the high-energy, high atomic number (HZE) component of GCR. There is not enough information currently available to estimate the risk of other potential late noncancer radiation health risks, such as cataracts or cardiovascular disease.

The three factors that are most important in their influence on the probability of noncancer effects occurring are total dose, dose rate, and radiation quality. The importance of dose rate and radiation quality is different between GCR and radiation from the SPEs. The radiation from GCR is continuous and varies in dose rate by about a factor of two to three depending on the phase of the solar cycle. Also, it never reaches what is considered to be a high dose rate. The highest dose rates in space occur during large SPEs, where absorbed-dose rates as high as 1.4 Gy h^{-1} have been estimated for missions beyond LEO for an event similar to the large event of August 1972 [9]. Regarding radiation quality, the spectrum of energies and linear energy transfers (LETs) of the HZE particles must be taken into account in the estimation of the risk of noncancer effects in deep space. Unfortunately, most of the data for noncancer effects have been obtained after exposure to acute high dose irradiation and there is no information about effects in humans of whole-body absorbed doses <1 Gy protracted over 1 to 2 y, such as would occur in space. The evidence, however, suggests that in most tissues, repair and recovery are efficient in reducing or eliminating the damage caused by radiation at the dose rates experienced in space. Within this context, the NCRP recommended:

- Several future considerations for improving noncancer risk assessments are warranted. These include expanding the database for RBEs as a function of radiation quality and dose rate, and developing models that include possible synergistic effects of microgravity and stress on early responses

- To be fully utilized in risk assessment, mathematical models of molecular interactions and genetics are needed to support the interpretation of results, and the extrapolation of data across radiation quality, dose, and dose rates. The modeling of surrogate endpoints for cancer or other risks will be of particular value in improving the accuracy of risk assessments

6. CONCLUSIONS

The charter, composition and activities of NCRP SC 1-7 in drafting NCRP Report 153 have been reviewed presented. A brief description of the content of each research area and the major research recommendations from the report, for each research topical area, have been presented The report is available from NCRP in paper or electronic form.

REFERENCES

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BIOGRAPHY

Lawrence W. Townsend *is a Professor in the Nuclear Engineering Department at The University of Tennessee. He has over 20 years experience in space radiation protection research. He is a former U.S. Navy nuclear submarine engineer officer and NASA Senior Research Scientist. He took an early retirement from NASA Langley Research Center in 1995 and entered academia. He is a Fellow of the American Nuclear Society, a Fellow of the Health Physics Society, and a Senior Member of the IEEE. He is also an NCRP Council Member. He has a BS in physics from the U.S. Naval Academy, an MS in physics from the U.S. Naval Postgraduate School, and a PhD in physics from the University of Idaho.*