1. Executive Summary

The purpose of this Report is to identify and describe information needed to make radiation protection recommendations for space missions beyond low-Earth orbit (LEO). Current space radiation guidelines pertain only to missions in LEO and are not considered relevant for missions beyond LEO. Radiation protection in deep space is complicated because of the unique nature of the space radiation environment, which is unlike any radiation environment present on Earth or in LEO. The Executive Summary lists the major information that is needed. A summary of all needed information is included in Section 8.

1.1 Background

Astronauts on exploration missions of long duration beyond LEO face exposures to radiation levels that may easily exceed those routinely received by terrestrial radiation workers, or even those faced by crews in near-Earth spacecraft, such as the Space Transport Shuttle (STS) and International Space Station (ISS). Radiation fields encountered include the galactic cosmic radiation (GCR) background, sporadic solar-particle events (SPEs), energetic protons and electrons during traversals of the Van Allen radiation belts, and exposure to possible onboard radioactive sources used for power generation, propulsion, medical testing, and instrument calibration. Although it is true that crews on missions in LEO may be 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 afforded by Earth's atmosphere and geomagnetic field, which tend to deflect protons and heavier ions at lower energies back into deep space thereby preventing them from reaching spacecraft in LEO. The degree of protection is a function of spacecraft orbital inclination and altitude. Orbits at higher inclinations, such as the 51.6 degree orbit of ISS are exposed to greater numbers of GCR particles because transmission through the magnetosphere is increased due to the reduced intensity and less favorable orientation of the magnetic field at these higher inclinations. However, significant shielding is provided by Earth's magnetic field and by shadow shielding from Earth itself. Hence, particle fluence rates from GCR and SPE sources are much lower in LEO than will be

encountered in missions beyond LEO, about a factor of three from ISS to deep space, where no protection from the magnetosphere or planetary bulk exists. Typically, astronauts and cosmonauts on ISS receive from 0.5 to 1.2 mSv d^{-1}, with ~75 % coming from GCR ions and 25 % coming from protons encountered in passages through the South Atlantic Anomaly region of the Van Allen belts. In deep space, radiation doses received by astronauts are expected to be higher (about a factor of two) than those measured in LEO. The main radiation sources of concern for missions beyond LEO are GCR and SPEs. Since spacecraft will be externally exposed to the full intensities of these sources, the radiation fields within the interior of the spacecraft are mitigated only by the shielding provided by the spacecraft structure. 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 radiation field constituents. 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, nor are the associated radiation risks for late effects such as cancer induction. Unlike the situation for terrestrial exposures, the high costs of launching materials into space place limitations on spacecraft size and mass and preclude the purely engineering solution of providing as much additional shielding mass 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 damaging than the unattenuated primary fields which produced them. Finally, in order to be effective in minimizing radiation exposure, the radiation protection program must include dosimetry instrumentation and data processing tools which can rapidly evaluate any realistic change in the exposure characteristics. This evaluation must include sufficient characterization of the radiation fields to allow determination of the radiation doses that would be received by astronauts, and to estimate the reduction in these doses that could be achieved by moving to areas of the spacecraft that provide different shielding.

The acceptable levels of risk for space exploration beyond LEO have not been defined at this time and need to be dealt with before sending manned missions to colonize the moon or to deep space such as a mission to Mars.

Other radiation health risks besides cancer are of concern for long-duration missions beyond LEO. Important questions related

to the addition of these risks and their possible impact on mortality and morbidity need to be addressed.

1.2 Space Radiation Environment

For exploratory missions beyond LEO, the main radiation-related concerns are chronic exposure to the ever-present 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. In the case of SPEs, especially very large SPEs, the primary concern is the risk of acute effects. 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 provide adequate shielding. Extremely-large SPEs, however, may occur several times (generally one to four 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.

1.2.1 *Galactic Cosmic Radiation*

The assessment of radiation risk requires detailed knowledge of the composition and energy spectra of cosmic rays in interplanetary space, and their spatial and temporal variation. Current models are based on the standard diffusion-convection theory of solar modulation (Badhwar and O'Neill, 1992; Chen *et al.*, 1994a; Nymmik, 1996; 1997; Tylka *et al.*, 1997a); they are briefly discussed in Section 3. Typical uncertainties in the particle fluence rates predicted by the models are 15 %. Measurements of GCR fluence rates are ongoing using instrumented satellites outside of Earth's magnetosphere. Hence, refinements to the models are indicated as additional data become available.

1.2.2 *Solar-Particle Events*

For manned interplanetary missions there is concern that a large SPE could, in a short time period (hour or day), subject the spacecraft to substantially large numbers of protons with energies

above tens of megaelectron volts. Hence, doses from exposures to large SPEs could be large for crews and equipment that are not adequately protected. Large SPEs (~5×10^9 protons cm^{-2} at energies >30 MeV) occurred in November 1960, August 1972, and October 1989. Even larger events have occurred during the past 500 y (McCracken *et al*., 2001a). Estimates of absorbed doses from the largest of these 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 (Townsend *et al*., 2006). If it is assumed that the satellite energetic particle measurements acquired during the space era (1965 to the present) are representative of the SPE distributions to be encountered during missions beyond LEO, and utilize the Jet Propulsion Laboratory proton fluence model (Feynman *et al*., 1993) is used to estimate the probability of occurrence of a large event, then the probability of an event containing a >30 MeV fluence of ~5×10^9 protons cm^{-2} during a 2 y interplanetary mission near the solar cycle activity maximum is ~0.1. However, the ability to forecast large SPEs is poor. It is not currently possible to project the probability of SPEs 1 to 3 d in advance. The lack of a method to observe or account for interplanetary shocks and coronal mass ejections (CMEs) directed toward Earth is one of the major deficiencies of quantitative SPE predictions. 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 (Section 3). Prediction of an SPE's spectral characteristics has not proven to be reliable for large events. Similarly, the intensity-time fluence-rate profile predictions have not been adequate for large shock-dominated SPEs. 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 (Hoff *et al*., 2003; Neal and Townsend, 2001; Townsend *et al*., 1999).

1.3 Space Radiation Physics and Transport

Whenever high-energy nuclei (protons, light ions, and heavier ions) pass through bulk materials, such as 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 (~10^8 cm^{-1} of travel) and result in 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 are not altered by these atomic interactions. Nuclear

collisions on the other hand are much less frequent, occurring only once every few centimeters of travel. These collisions, however, can be violent and 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 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. Clearly, an accurate description of these transported radiation fields requires accurate modeling methods for particle interactions and transport.

1.4 Space Dosimetry

Radiation exposures originate with different types of sources, each with distinct properties and variability. These sources include GCR, radiation from the sun including SPEs, protons and electrons in the trapped belts, and radiation from man-made sources intentionally included in the space vehicle. The onboard dosimetry system must be able to adequately characterize the exposure from all types of radiation and sources that are present. Both active and passive dosimetry systems will be needed. Instrumentation and techniques for some of these measurements exist, but several improvements are necessary to provide reliable dosimetry in these complex radiation fields.

1.5 Space Radiation Biology

Health effects of radiation exposures on humans during and after exploration missions beyond LEO are not completely known. Significant future research is needed to complete the estimation of these effects (Cucinotta, 2005; NCRP, 2000). The goal is to provide a consensus of radiation dose limits that will limit the risk of serious and persistent 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 radiation shielding of 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. The eminent problem of unpredictable large SPEs, and the potential of a rapid and progressive exposure to charged particles representing a wide array of atomic numbers, energies and dose rates (and any resulting secondary radiation cascades) is a daunting issue that requires extensive further study.

With what is known today, there are concerns about early effects on the brain and peripheral nervous system. There is concern about potential radiation damage to neural function, particularly in older individuals following exposure to low doses of high dose-rate radiation. Convincing evidence also is emerging for concern regarding the risk of cardiovascular disease. Defects in immunological function from exposure to low doses of high dose-rate radiation that contribute to life-shortening or diminished quality of life need further study. Biomarkers for identification of 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. The combined effects of radiation exposure with other biophysical stressors, such as microgravity, exposure to ultraviolet (UV) light, or to microwaves have not been studied adequately.

1.6 Space Radiation Risk Assessment Methodology

On long-term missions outside Earth's magnetic field, three specific areas of radiation health risks can be identified as being of primary concern: (1) late effects (*e.g.*, cancer); (2) early effects due to acute, or at least short-term, exposures from large SPEs; and (3) possible effects (still to be identified) to the central nervous system (CNS) from the high-energy, high atomic number (Z) component of GCR. There is not enough information available to estimate the risk of other unknown potential late noncancer[1] radiation health risks. There are three factors that are important in their influence on the probability of noncancer effects occurring as a result of exposure to radiation in deep space: total dose, dose rate, and radiation quality. The importance of dose rate and radiation quality is different between ambient GCR and radiation from the SPEs. The radiation from GCR is continuous and varies in dose rate by perhaps a factor of two to three depending on the phase of the solar cycle, but does not reach what is considered to be a high dose rate. The highest dose rates in space occur during large SPEs. The dose rate and total dose depend on a number of factors that include the intensity of the disturbance on the sun, the longitude of the disturbance on the sun's disk relative to the position of the spacecraft, the condition of the interplanetary magnetic field between the sun

[1]The term noncancer refers to health effects other than cancer (*e.g.*, cataracts, cardovascular disease) that occur in the exposed individual.

and the spacecraft, and the amount of shielding provided by the spacecraft. 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 (Parsons and Townsend, 2000). Regarding radiation quality, the spectrum of energies and linear energy transfers (LETs) of the heavy ions must be taken into account in the estimation of the risk of noncancer effects in deep space. The relative biological effectiveness (RBE) of neutrons, protons, carbon, neon and argon ions for the induction of noncancer effects was examined by ICRP (1989). 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. 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. The equivalent dose[2] (in sievert) obtained using radiation weighting factors (w_R) derived from RBE information for late stochastic effects (*i.e.*, cancer and genetic effects), is not appropriate for use in describing the risk of early or late noncancer effects. The quantity gray equivalent[2] has been suggested as the analogy to equivalent dose when considering deterministic (see Glossary) noncancer effects (NCRP, 2000). As discussed in NCRP Reports No. 132, No. 137, and No. 142 (NCRP, 2000; 2001a; 2002) the organ dose equivalent[3] (in sievert), may be used as a surrogate for the equivalent dose when dealing with the space radiation environment. The effective dose[2] (in sievert) can be calculated by summing the products of the equivalent dose for each organ and the appropriate tissue weighting factor (w_T) from column three of Table 3.1 of NCRP Report No. 137 (NCRP, 2001a).

1.7 Major Information Needed

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

[2]The terms equivalent dose (H_T), effective dose (E), and gray equivalent (G_T) refer to quantities formulated for radiation protection purposes. The first two quantities apply to stochastic effects (*i.e.*, cancer and genetic effects), and the third applies to deterministic effects (see equivalent dose, effective dose, and gray equivalent in Glossary).

[3]The term organ dose equivalent ($\bar{H}_T$) refers to a quantity obtained by averaging or integrating over the quantity dose equivalent (H_T) that is measured or calculated at a number of points in an organ or tissue. For space radiations, $\bar{H}_T$ is used as the surrogate for equivalent dose (see organ dose equivalent and dose equivalent in Glossary).

- Develop SPE forecasting and prediction capabilities that are able to observe or account for interplanetary shocks and CMEs. These capabilities should include the ability to reliably predict the fluence spectra and time evolution of 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.
- 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.
- 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 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.
- Develop radiation spectrometers which can accurately measure the fluence of indirectly ionizing particles in the presence of a fluence of directly ionizing particles.