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Review article

Solar particle event storm shelter requirements for missions beyond low Earth orbit

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ABSTRACT

Protecting spacecraft crews from energetic space radiations that pose both chronic and acute health risks is a critical issue for future missions beyond low Earth orbit (LEO). Chronic health risks are possible from both galactic cosmic ray and solar energetic particle event (SPE) exposures. However, SPE exposures also can pose significant short term risks including, if dose levels are high enough, acute radiation syndrome effects that can be mission- or life-threatening. In order to address the reduction of short term risks to spaceflight crews from SPEs, we have developed recommendations to NASA for a design-standard SPE to be used as the basis for evaluating the adequacy of proposed radiation shelters for cislunar missions beyond LEO. Four SPE protection requirements for habitats are proposed: (1) a blood-forming-organ limit of 250 mGy-equivalent for the design SPE; (2) a design reference SPE environment equivalent to the sum of the proton spectra during the October 1989 event series; (3) any necessary assembly of the protection system must be completed within 30 min of event onset; and (4) space protection systems must be designed to ensure that astronaut radiation exposures follow the ALARA (As Low As Reasonably Achievable) principle.

1. Introduction

Designing radiation protection for crews in spacecraft and surface habitats on future missions beyond low Earth orbit (LEO) requires that standards be established to guide the designers in their quest to provide adequate crew protection measures. The main sources of radiation exposure for crewed missions beyond low Earth orbit will be chronic exposures from energetic galactic cosmic radiation (GCR) and short term, possibly acute, exposures from energetic protons and heavier ions in solar particle events (SPEs). GCR particle fluxes, composed of $\sim$90% protons, $\sim$9% helium isotopes, and $\sim$1% heavier ions, are fairly constant – only varying by about a factor of two, primarily at the lower energy part of their spectra, over the approximate 11 year solar cycle. SPE particle fluxes, which also contain protons, helium isotopes and some heavier ions, are episodic, typically last only hours to days, but the intensity and spectral characteristics can vary dramatically from event to event. Ions heavier than helium that may be present in an SPE are generally not a health risk for shielded crews, since their energy spectra are softer than they are in the GCR spectrum (here softer is used to indicate that the particle spectrum is decreasing fairly rapidly with increasing particle energy) and do not significantly penetrate through shielding in human rated vehicles. Hence the main risk concern is incident SPE protons, since they may be energetic enough to penetrate thin spacecraft shielding and in sufficient numbers to present an acute hazard. Occasionally, helium isotope fluences in an SPE may be sufficient to contribute to the crew exposures as well.

GCR particles are much more difficult to shield against, but their lower fluences make them a chronic exposure hazard, rather than an acute hazard. The energy spectra of SPEs can vary both in intensity and in spectral hardness. During the 11 year solar cycle a few SPEs may

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have large incident proton fluences with hard energy spectra. These events are of particular concern since they can pose significant health risks to crews and may be mission-threatening or life-threatening for crews in thinly shielded environments. To mitigate the effects of these large SPEs, spaces with increased crew protective shielding, sometimes referred to as storm shelters, should be included in the spacecraft design.

2. Current NASA guidelines

NASA receives guidance on standards, policy, best practices and risk modeling related to space radiation protection from both the National Research Council (NRC) and the National Council on Radiation Protection and Measurements (NCRP). Recent NRC reports on these topics include Space Radiation Hazards and the Vision for Space Exploration: Report of a Workshop (National Research Council, 2006), Radiation and the International Space Station: Recommendations to Reduce Risk (National Research Council, 2000), Technical Evaluation of the NASA Model for Cancer Risk to Astronauts Due to Space Radiation (National Research Council, 2012), and Managing Space Radiation Risk in the New Era of Space Exploration (National Research Council, 2008). Guidelines from the NCRP include Guidance on Radiation Received in Space Activities (Report No. 98) (NCRP, 1989), Radiation Protection Guidance for Activities in Low Earth Orbit (Report No. 132) (NCRP, 2000), Operational Radiation Safety Program for Astronauts in Low Earth Orbit: A Basic Framework (Report No. 142) (NCRP, 2002), and Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low Earth Orbit (Report No. 153) (NCRP, 2006).

NASA implements standards and design requirements taking into account guidance from advisory groups within NASA Standards. NASA Permissible Exposure Limits (PELs) are implemented in NASA Space Flight Human-System Standard Volume 1, Revision A: Crew Health (NASA 2007). The NASA standard is an excess Risk of Exposure Induced Death (REID) from cancer of no more than 3% at the 95% confidence limit. Short term limits in the PELs, displayed in Table 1, are used to prevent clinically significant non-cancer effects, such as acute radiation syndrome response, and degradations in crew performance. Non-cancer limits are also spelled out in the PELs for purposes of limiting cataracts, central nervous system and circulatory disease effects from space radiation exposures. The units of mGy-Eq (milligray equivalent) are obtained by taking the product of the actual tissue dose in mGy from a particular radiation type (e.g. protons) impinging on the body and multiplying that dose by an RBE (Relative Biological Effectiveness) factor (1.5 for protons) (NCRP 2000).

In LEO, mission operations may be controlled to ensure that exposures are below thresholds and therefore early deterministic effects should not occur. However, during missions beyond Earth's magnetosphere, large SPEs might expose crew members to cumulative exposures that could exceed a dose threshold. For the Orion Multi-Purpose Crew Vehicle (MPCV), NASA previously adopted the August 1972 event proton spectrum, as parameterized by King (King, 1974), as the standard for assessing the ability of shielding to reduce astronaut radiation exposure to acceptable levels during an SPE (NASA, 2015).

Table 1
NASA PELs for short-term or career non-cancer effects (NASA, 2007). (BFO = Blood Forming Organs, CNS = Central Nervous System).

Organ	30 days (mGy-Eq)	1 year (mGy-Eq)	Career (mGy-Eq)
Lens	1000	2000	4000
Skin	1500	3000	6000
BFO	250	500	NA
Heart	250	500	1000
CNS	500 mGy	1000 mGy	1500 mGy
CNS ($Z \geq 10$)	–	100 mGy	250 mGy

However, in its report, Managing Space Radiation Risk in the New Era of Space Exploration, the NRC indicated that the King spectrum for the 1972 SPE was not representative of a worst case event (National Research Council, 2008) that could be encountered in deep space. Specifically, in its findings and recommendations the report stated:

a. *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.
b. *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.
c. *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.
d. *Recommendation 2–3:* Uncertainties in spectra data fitting. NASA should make use of existing data to reevaluate 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.

2.1. Habitat considerations

Habitats for future human missions beyond LEO are being considered under the NextSTEP (Next Space Technologies for Exploration Partnerships) effort, which is a public-private partnership to foster development of deep space exploration capabilities in cislunar space. (https://www.nasa.gov/nextstep). It is part of NASA's Advanced Exploration Systems Program. The habitation part of NextSTEP focuses on the development of a deep space habitat capable of supporting a crew of 4 for 30 to 60 day missions, which can later be augmented for longer missions. The NextSTEP partners currently include industry members Bigelow Aerospace LLC, Boeing, Lockheed Martin, Orbital ATK, and NanoRacks. During Phase 1, Bigelow, Boeing, Lockheed Martin, and Orbital ATK developed initial habitat concepts. Phase 2 will incorporate a more advanced habitat design. In order to accomplish this, an SPE requirement must be specified for purposes of evaluating the proposed storm shelter adequacy for radiation protection.

The current effective dose design requirement for the Orion Multi-Purpose Crew Vehicle (MPCV), as established in the Human-System Integration Requirements (HSIR) (NASA, 2016), states that the system shall provide protection from radiation exposure consistent with ALARA principles to ensure that effective dose (tissue averaged) to any crew member does not exceed 150 mSv for the design SPE specified in the Design Specification for Natural Environments (DSNE) (NASA, 2015). As stated in the HSIR, “The radiation design requirement is imposed to prevent clinically significant deterministic health effects, including performance degradation, sickness, or death in flight and to ensure that crew career exposure limits are not exceeded with 95% confidence.”

2.2. SPE considerations

Acute health effects. For SPEs, a major concern is acute exposures.