Design for Ionizing Radiation Protection

V1: 4.2.10.1
V2: 6095-6101

Overview

Executive Summary

During any mission, crewmembers face threats of ionizing radiation from a variety of sources. Standards outlined in NASA-STD-3001 state that crews are not to be exposed to radiation that increases their risk of radiation-related mortality by 3%. Design choices and shielding strategies can be implemented to reduce the threat posed by radiation and ensure crew safety and health.

Summary of Standards

Volume 1

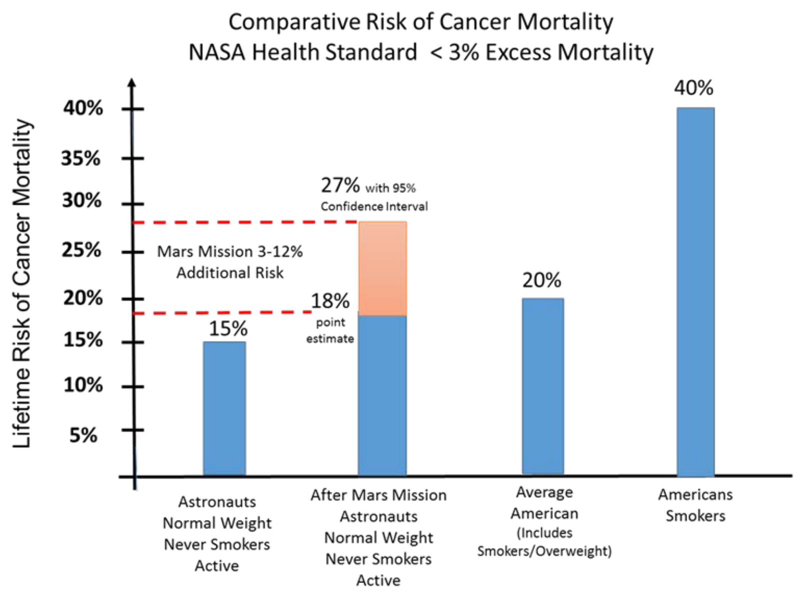
- [4.2.10.1] Planned career exposure to ionizing radiation shall not exceed 3 percent Risk of Exposure-Induced Death (REID) for cancer mortality at a 95 percent confidence level to limit the cumulative effective dose (in units of Sievert) received by an astronaut throughout his or her career.

Volume 2

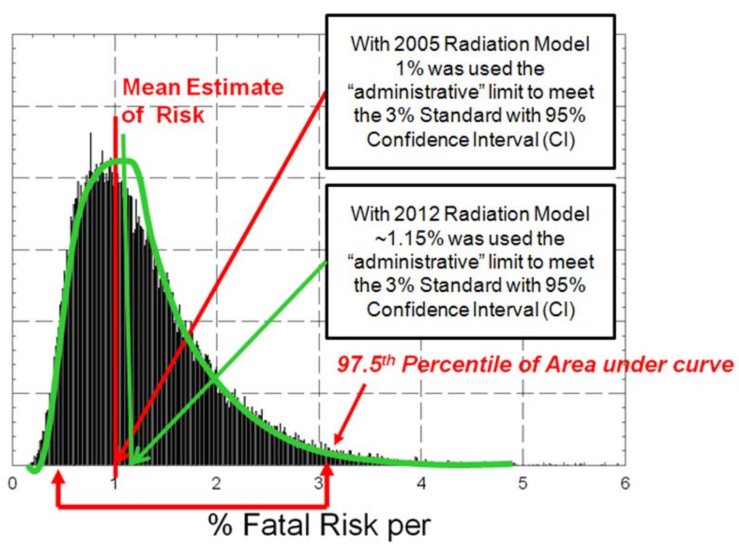
- [V2 6095] The program shall set system design requirements to prevent potential crewmembers from exceeding PELs as set forth in NASA-STD-3001, Volume 1.
- [V2 6096] The program shall set an age- and gender-dependent baseline of crew makeup when setting radiation design requirements.
- [V2 6097] The program shall design systems using the ALARA principle to limit crew radiation exposure.
- [V2 6098] The program shall specify the radiation environments to be used in verifying the radiation design requirements.
- [V2 6099] The program shall set requirements specifying appropriate capabilities to be provided for real-time monitoring of space weather for characterization of the radiation environment and operational response by ground personnel and the crew.
- [V2 6100] The system shall include a method to alert all crewmembers when radiation levels are expected to exceed acceptable levels.
- [V2 6101] To characterize and manage radiation exposures, the program shall provide methods for monitoring personal dose and dose equivalent exposure, ambient monitoring of particle fluence as a function of direction, energy, and elemental charge and monitoring of ambient dose and ambient dose equivalent.

Standard Overview

[V1 4.2.10.1] Planned career exposure to ionizing radiation shall not exceed 3 percent Risk of Exposure-Induced Death (REID) for cancer mortality at a 95 percent confidence level to limit the cumulative effective dose (in units of Sievert) received by an astronaut throughout his or her career.



NASA Standard is 95% Confidence level for Risk of Exposure Induced Death (REID) less than 3%–less than 1 in 33 excess chance of cancer death. The limit of 3% fatal cancer risk is based on 1989 comparison of risks in "less-safe" industries.



95% confidence is intended to account for uncertainties inherent in risk projection model – vary from 50% - 330%. Additionally, the long-term effects of low-dose radiation have not been entirely characterized. As such, radiation exposure is actually limited to a REID of less than 1%.

Updates to the prediction models have varied over the years. In order to maintain the confidence interval the actual limit is ~1% with a factor of ~3 to stay below the standard of 3%.

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Background

Space Radiation Environment Overview

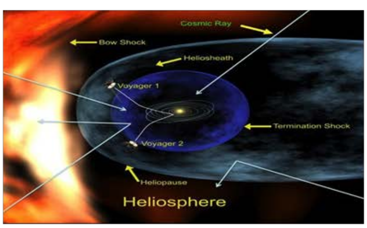
Galactic cosmic rays (GCR) - penetrating protons and heavy nuclei

Occurs continuously, omni-directional, varying in flux with solar cycle - lower GCR levels occur during solar maximum

GCR dose & SPE probability are anti-correlated over 11-year solar cycle.

Shielding is **NOT** effective due to secondary radiation produced in shielding and tissue

Countermeasure: Biological uncertainties cloud understanding of effectiveness of possible mitigations



Omni-directional GCR

Trapped particles are a third type of radiation that is a risk in certain circumstances (ISS: SAA; Lunar: Van Allen belts). These medium-to-low energy protons and electrons are a secondary source of exposure that contribute to long-term health effects (not acute). However due to short passes through the SAA and Van Allen belts, and the fact that typical SPE shielding is effective against trapped particles, additional radiation shielding is not required.

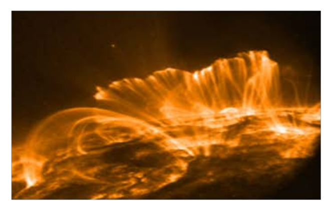
Solar Particle Events (SPE) - low to medium energy protons

Infrequent events occurring most often during solar cycle maximum (~11-year cycles) – peak activity during solar maximum

Lunar Surface provides significant protection vs. free space

Shielding (5-20 g/cm^2 Al and polyethylene) **IS** effective, optimization to reduce weight

Countermeasures: Shielding, monitoring, accurate event determination, dosimetry and timely reporting to alert crew to seek shelter are essential for crew safety



Solar Flares - SPEs

Risks of Radiation Exposure

Long Term Health Impact – Post Mission

Carcinogenesis

Radiation exposure may cause increased cancer morbidity or mortality risk for astronauts. There is also a risk of changes in cognition, motor function, and behavior or neurological disorders.

In Mission Risk

Acute Radiation Syndromes from Solar Particle Events

Acute radiation syndromes, such as nausea, vomiting, and fatigue, may occur due to in mission radiation exposure, as well as skin injuries and depletion of blood-forming organs. Effective shielding and environmental monitoring minimizes this risk. See shielding guidelines.

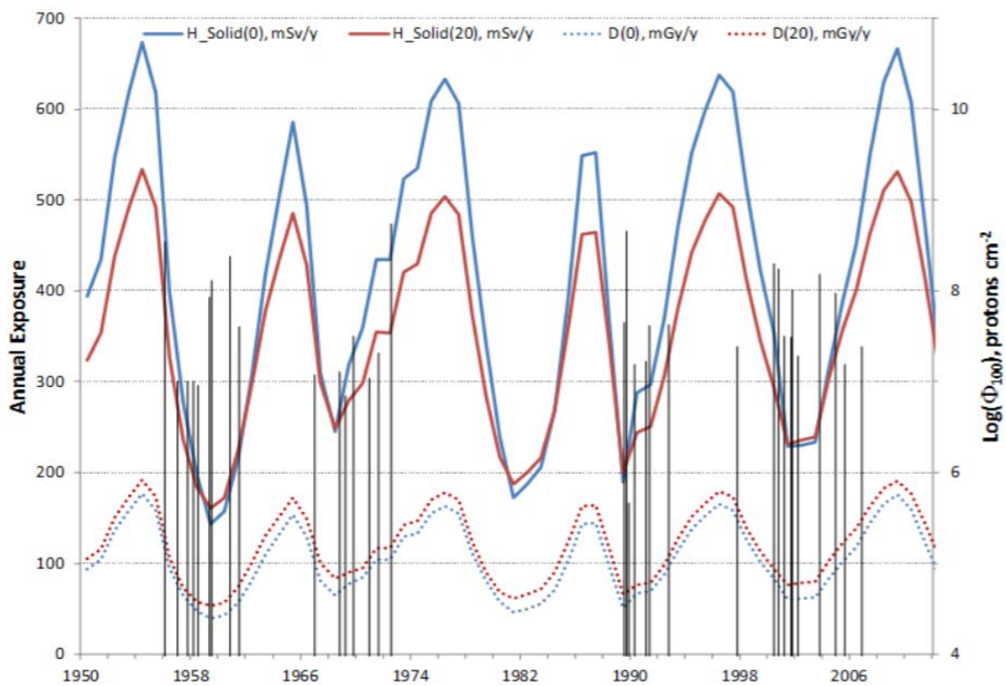
Background

Space Radiation Environment Overview

Probability of Space Radiation Events

- GCR dose & SPE probability are anti-correlated over 11-year solar cycle.
- Near or long-term prediction of SPE occurrence is not accurate, however the dose-rates for the large majority of past SPE's show real-time responses and should be adequate to reduce exposures to well below NASA dose limits.
- In an effort of prudence and preparation, current plans are in place for 1 in 100 (centennial) and 1 in 1000 (millennium) SPE events.

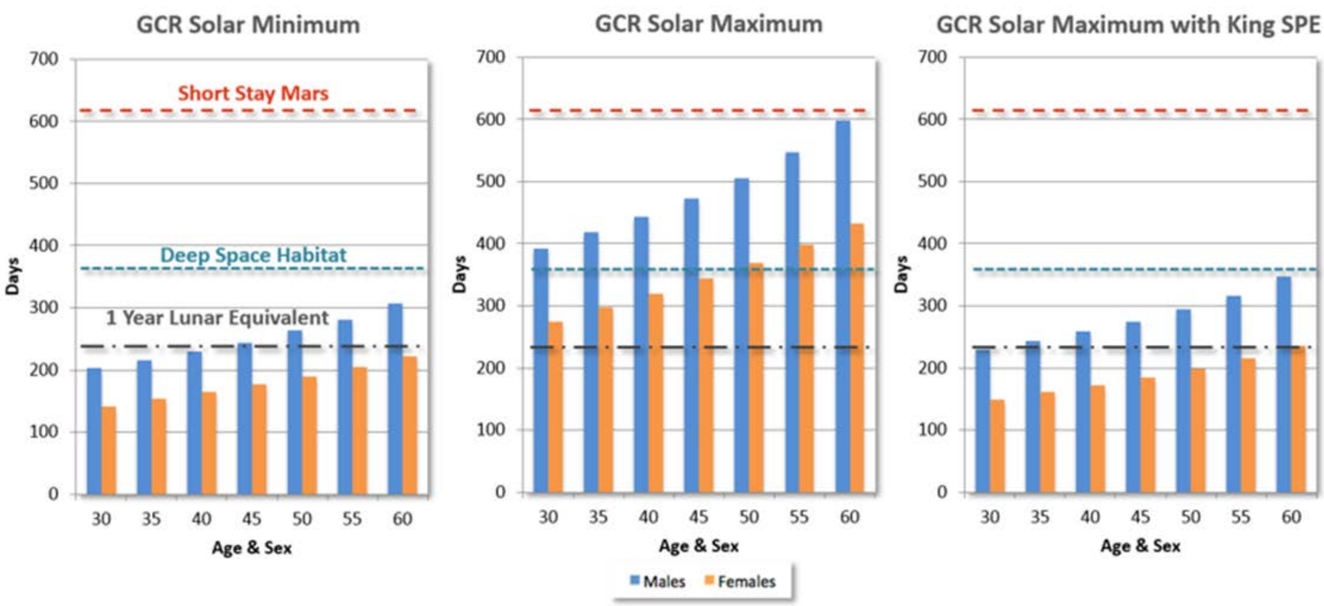
GCR Dose-Rates and SPE Occurrence

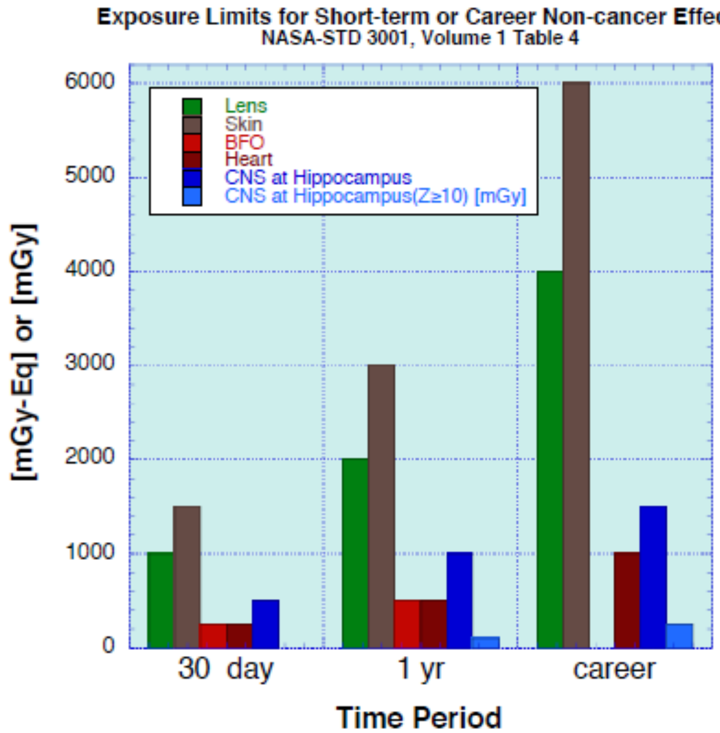


- To better understand risk of GCR exposure, dose rates are calculated utilizing simulators which retrospectively estimate secondary particle fluence as well as ambient dose equivalent rates and effective dose rates at any point in the atmosphere. Further information can be found in the reference article: *Numerical calculation of the radiation exposure from galactic cosmic rays at aviation altitudes with the PANDOCA core model* (Matthia, Meier, & Reitz, 2014).

Reference Data

Permissible mission duration; broken down by age and sex.





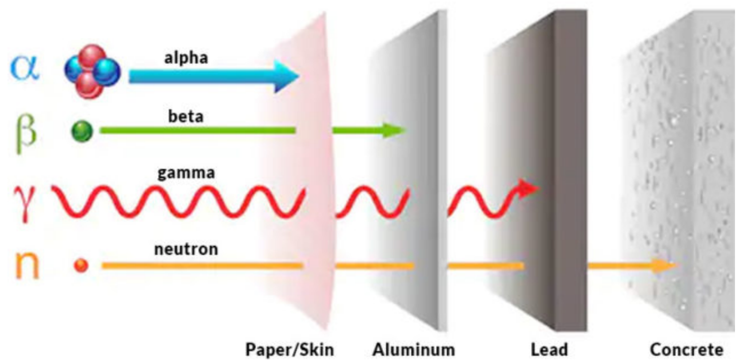
Reference Data

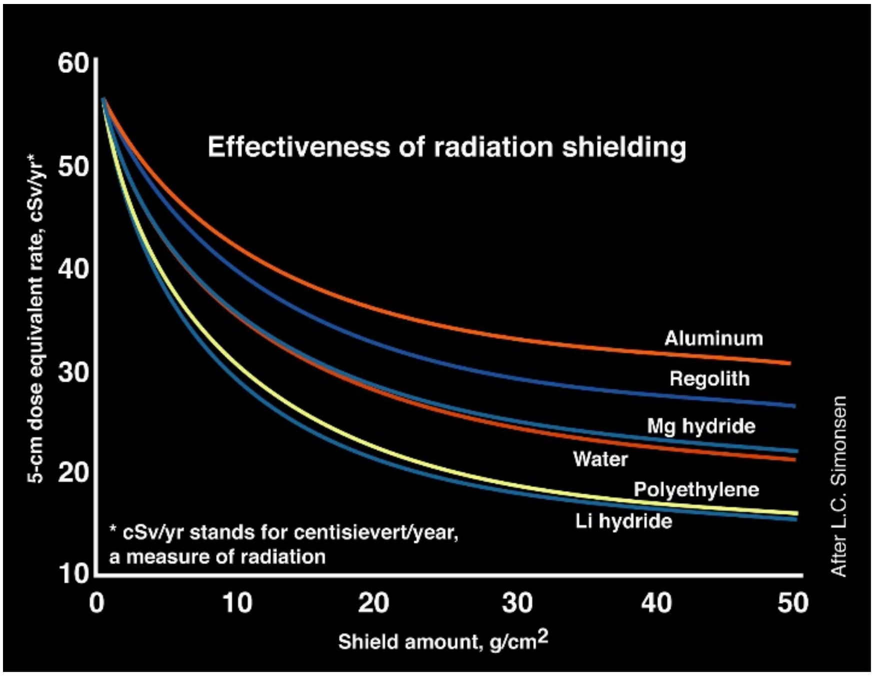
Engineering Countermeasures

- The best way to shield from ionizing radiation is to provide as much physical material between a person and the source of radiation as possible. Dense and thick materials that essentially absorb the high energy particles from incoming radiation are ideal but prove difficult in space travel due to their significant amounts of mass.

Shielding Materials

- Aluminum and polyethylene are the most commonly used shielding materials. They provide an average 50% reduction in dosage levels from SPE radiation. GCR radiation does not respond to shielding, with only an average 7% reduction in dosage levels. Additionally, secondary radiation is produced within tissues, further reducing any benefits of GCR shielding.

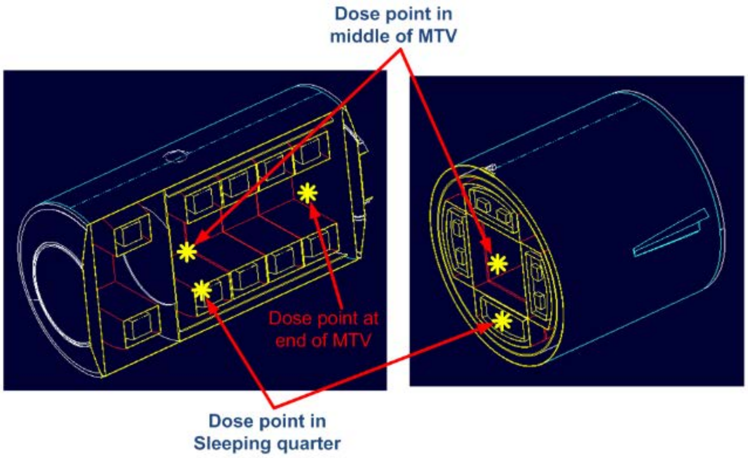




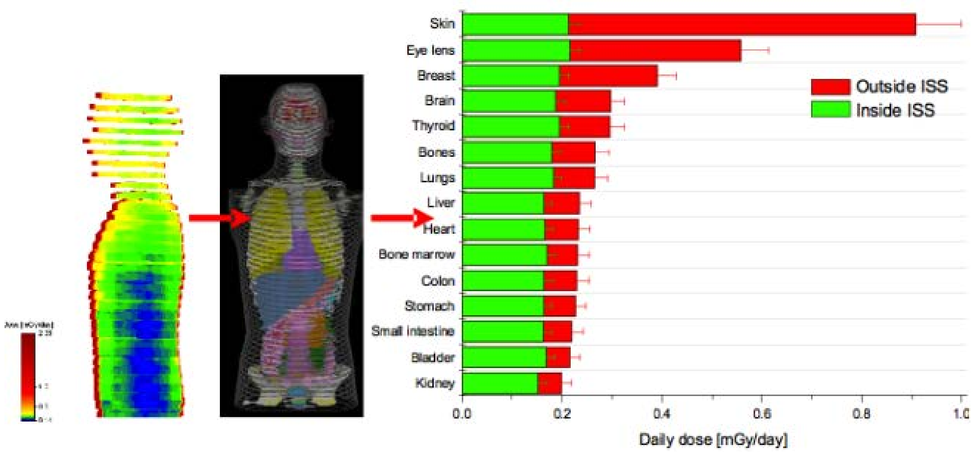
Reference Data

Ray Tracing tools and Effectiveness of Shielding

Ray Tracing technology examines the effectiveness of shielding tools in blocking radiation. Evenly distributed rays are created to start from dose point and end outside the vehicle. Each ray records distance and respective density of the parts it passes. Areal mass density is calculated and used in transport code that evaluates particle flux at dose point.



Effect of ISS Shielding on crew daily dose



Effect of using water bags/stowage as a shelter during an SPE event beyond low earth orbit in a Capsule

Effective Dose (mSv) by crew location within capsule*	Crew #1	Crew #2	Crew #3	Crew #4
Effective Dose E	214	210	259	231
Effective Dose (Optimized Pre-Launch Stowage)	68	65	66	66
Effective Dose (Optimized Return Stowage)	83	75	73	83

*Note the different doses based on location within a vehicle

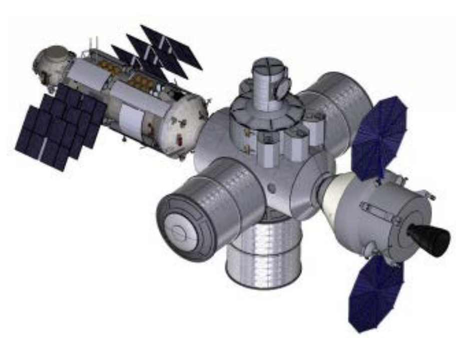
Application Notes

Design Considerations

- Shielding design must implement ALARA for mission duration < 6 months with respect to SPE protection.
- For missions > 6 months, it is recommended that vehicle shielding be at least 20g/cm^2 to protect the crew from SPEs.
- Storm shelter: Additional Storm Shelter with an added 10 cm water equivalent in crew quarters to protect against centennial solar particle event.
    - This can be achieved by rearranging items such as water containers and/or high hydrogen content materials.
    - Timelines of SPE's allow sufficient time for re-configuration.
    - Protection for a 1000-year SPE event would require ~20 cm water equivalent for shielding.
- Due to the nature of GCRs, shielding is less effective. GCR particles scatter into multiple particles when they strike shielding.
- Radiation alerting provides an additional layer of protection to limit exposure to SPEs (early warning allows for crew to safe vehicle and configure shelter).
    - Real-time alert dosimetry also provides a very high level of protection for EVAs if termination occurs within 2 hrs and there is access to shielding.
- Radiation dose monitoring provides critical occupational health information to understand the effects of radiation exposure.
- Designs can be evaluated and maximized for shielding effectiveness utilizing existing Shield Geometry Model and Shielding Analysis by CAD tools, as well as conducting Ray Tracing.

Vehicle Design Considerations

- Current engineering and design teams are researching the possibility of utilizing a 'surrounded' vs. 'in-line' architecture approach for crew habitat in hopes that there is a reduction in overall exposure to GCR radiation. A surrounded architecture approach utilizes the hub and spoke ideology, with a centralized node module acting as the core/hub at the center of the layout where crew activity takes place most of the time. The structure surrounding the core/hub would be comprised of major structural elements that contain logistics, equipment, trash, props, etc.



Source: Bailey (2012) – Deep Space Habitat Project

Application Notes

Guidelines for Space Radiation Shielding Requirements for Exploration Missions

- HMTA has developed Shielding Requirement Guidelines for exploration missions that were reviewed by Space Radiation Research Clinical Advisory Panel (RCAP). These Guidelines are intended to provide closure for vehicle design requirements.
  - Analysis shows decennially large solar particle events (SPE's) lead to doses for average spacecraft shielding below NASA Dose limits requiring only ALARA.
  - However centennial and millennial events require a well designed "storm shelter".
- Large majority (~95%) of SPE's require only ALARA considerations and do not approach dose limits.
  - A Centennial Event (1 per 100 years) can be shielded below NASA dose limits with additional <u>10 cm water</u> equivalent storm-shelter shielding.
  - Millennial Event (1 per 1000 year) with additional <u>20 cm water</u> equivalent storm-shelter shielding.
- Assuming a vehicle with 20 g/cm2 aluminum – Additional Storm Shelter with additional 10 cm water equivalent in crew quarters to protect against centennial solar particle event.
  - Combination of inherent and reconfigurable shielding.
  - Timelines of SPE's allow sufficient time for re-configuration.
- Mission disruption is a major risk from SPEs, especially for EVAs.
  - Spacecraft shielding requirements could be impacted by additional doses incurred by crew during EVA, especially on lunar surface.
  - Real-time alert dosimetry provides a very high level of protection if EVA termination occurs within 2 hrs.
  - The probability of EVA organs doses >100 mSv is less than one in a million based on SPE statistics of event frequency, size and energy spectra.
- Shielding Guidelines could be modified by new knowledge of GCR CNS, cancer and other risks.

Major Changes Between Revisions

Rev B → Rev C

- Added information regarding shielding materials and vehicle/spacecraft design considerations.
- Added information regarding frequency of radiation events.
- Added additional information about ray tracing
- Added new HMTA proposed guidelines for space radiation shielding requirements
- Overall formatting/template updates

References

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- *Space Faring: The Radiation Challenge. An Interdisciplinary Guide on Radiation and Human Space Flight*. https://www.nasa.gov/sites/default/files/atoms/files/space_radiation_ebook.pdf
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- CR-HSRB-16-005: *Risk of Adverse Health Outcomes and Performance Decrements Resulting from Space Radiation Exposure*.
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- Matthia, D., Meier, M.M., and Reitz, G. Numerical calculation of the radiation exposure from galactic cosmic rays at aviation altitudes with the PANDOCA core model. *Space Weather*, 12(3): 161-171.
- *Artemis, meet ARTEMIS: Pursuing Sun Science at the Moon*. (Oct 7 2019). https://www.nasa.gov/feature/goddard/2019/artemis-meet-artemis-pursuing-sun-science-at-the-moon