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**Key Points:**
- Heavily shielded spacecraft can limit acute biological responses to worst-case SEP events
- Integral proton fluence is a good proxy for vehicle dose during SEP events
- Vehicle storm shelters can reduce SEP dose by 38% on average and factor two for soft events

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**Characterization of Solar Energetic Particle Radiation Dose to Astronaut Crew on Deep-Space Exploration Missions**

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**Abstract**
Human radiation exposure from solar energetic particle (SEP) events during deep-space exploration missions has a greater impact on mission planning and operations compared to spaceflight missions to low Earth orbit. Deep-space SEP radiation exposure may require in-flight preventative actions in order to reduce the radiation risks to as low as reasonably achievable, to limit the onset and severity of acute biological responses, and to ensure that astronaut permissible exposure limits are not exceeded. In this paper, radiation dose to the blood forming organs (BFO) of astronaut crew is calculated from a set of historical SEP events, using the design of the Orion Multipurpose Crew Vehicle (MPCV). The BFO doses from the historical events are analyzed in several ways. The results show the range and upper limit of BFO doses expected in heavily shielded space vehicles such as the Orion MPCV, based on calculations from the major SEP events encountered in the space age. The dose reduction properties of the MPCV storm shelter are characterized over the broad range of SEP events included in the historical database. Correlations are derived between the integral proton fluence and BFO dose in the vehicle, showing that integral fluence is a good proxy for predicting or forecasting vehicle BFO dose. The best correlation with MPCV BFO dose is from the >100 MeV integral fluence. These results will assist in the design of future space weather architectures by identifying models and measurements needed to expand and extend NASA’s existing SEP radiation risk tools in the support and management of human space exploration missions.

1. **Introduction**

Ionizing radiation exposure from galactic cosmic rays and solar energetic particle (SEP) events present an increased health risk to astronauts on deep-space exploration missions (Cucinotta, 2014; Cucinotta et al., 2013, 2010). Late biological effects are the primary health concerns from the ubiquitous galactic cosmic ray source of radiation. The National Aeronautics and Space Administration’s (NASA) radiation protection approach against late biological effects is to limit the number of days in space by defining permissible exposure limits, such that the risk of exposure-induced (cancer) death does not exceed 3% at the 95% confidence level over the astronaut’s career (Cucinotta, 2014). In addition, an implementation of the ALARA principle (National Council on Radiation Protection, 2000, 2003) ensures that mission design and operations achieve a best effort to keep the radiation risks as low as reasonably achievable.

The primary in-flight radiation health risk to astronaut crew on deep-space missions is from exposure to the rare and unpredictable SEP events (Reames, 2017). The onset and severity of acute radiation syndromes are the major health concerns from SEP exposure, which can significantly impact mission planning and operations (Cucinotta, 2014; Cucinotta et al., 2013, 2010). NASA has established a limit of 250 milli-gray-equivalent (mGy-Eq) in the blood forming organs (BFOs) as a means of minimizing SEP radiation exposure and limiting acute biological responses to worst-case SEP events. As a result, NASA’s radiation protection approaches against SEP exposure will require effective in-flight shielding strategies combined with real-time, operational radiation environment monitoring and risk analysis tools (Cucinotta et al., 2010; Hu et al., 2009). In a previous paper, the methodology and initial assessment of a new operational acute radiation risk tool was presented (Mertens et al., 2018), which is based on the Orion Multipurpose Crew Vehicle (MPCV) design and utilizes the MPCV’s onboard dosimeter measurements.

This paper presents calculations of BFO doses at the crew locations of the Orion MPCV from a set of historical SEP events. The objective is to provide results that will help guide the development of future space exploration risk tools.
weather architectures needed to support SEP radiation risk mitigation strategies by enhancing and extending the current nowcast capability of the acute radiation risk tool (Mertens et al., 2018). The range of possible BFO doses in the heavily shielded Orion MPCV are quantified by analyzing the set of historical SEP events. The effectiveness of the MPCV storm shelter is also quantified over the broad range of spectral and intensity characteristics of the historical SEP events. Moreover, statistical relationships are derived between free-space SEP proton integral fluences and the MPCV BFO dose. These results will aid in identifying models, measurements, and tools required for operational support of human space exploration missions.

2. Vehicle BFO Dose Calculations

This section provides a summary of the transport and dose calculation procedures employed to produce the results given in section 3. The calculation details were previously published by Mertens et al. (2018).

Total dose to the BFO sites is calculated from 65 historical SEP events using the design of the Orion MPCV (Mertens et al., 2018). The free-space SEP proton spectra of the historical events are parameterized by double power law fits in kinetic energy to event-accumulated integral fluence measured by the Geostationary Operational Environmental Satellites and ground-based neutron monitor data (Raukunen et al., 2018). This set of events includes ground-level enhancements (GLEs) and associated SEPs extending from the 23 February 1956 event (GLE 5) through the 17 May 2012 (GLE 71) event. The proton spectra of these events are shown in Figure 1.

The free-space SEP spectra in Figure 1 provide the boundary conditions for radiation transport calculations through the Orion MPCV spacecraft. There are four crew locations within the Orion MPCV, and the BFO doses are calculated at each crew location from numerical solutions of the Boltzmann transport equation using the HZETRN2015 code (Slaba et al., 2016; Wilson et al., 2016). The material shielding thicknesses required for performing the transport calculations are determined by ray tracing the computer-aided design model of the MPCV along 10,000 raypaths surrounding each BFO site, covering 4π steradians in direction.

The shielding materials of the spacecraft important for transport and dose calculations are aluminum and high-density polyethylene. The distributions of shielding thicknesses surrounding the crew locations are shown in Figures 2 and 3 in terms of aluminum equivalent (Al-Eq) areal depths. The thickness distributions in Figure 2 correspond to the Orion MPCV crew locations in the nominal, seated configuration. The range of median shielding thicknesses at the seated crew locations is 32–39 g/cm² Al-Eq. The Orion MPCV has provision for the crew to erect a storm shelter within the spacecraft during SEP events. Figure 3 shows the thickness distributions for the sheltered configuration. The range of median thicknesses of the crew located within the vehicle storm shelter is 36–43 g/cm² Al-Eq. The storm shelter is configured by redistributing mass within the spacecraft. Note that although the median shielding thickness has decreased at Crew Location 3 for the sheltered configuration compared to the seated configuration, the slope of the sheltered thickness distribution is much steeper than the seated distribution; thus, there are less lightly shielded directions surrounding Crew Location 3 with the storm shelter erected. To calculate BFO dose, the MPCV computer-aided design model of materials and thicknesses are combined in the transport and dosimetric calculations with the tissue and organ thicknesses of the Male Adult voXel and Female Adult voXel models of the human body (Slaba et al., 2010).
The BFO doses presented in the next section are averages of the doses calculated at each of the crew locations for both male and female human body models (Male Adult voXel and Female Adult voXel). Moreover, BFO doses are shown for both the (nominal) seated and sheltered crew configurations, providing insight into the shielding effectiveness of the vehicle storm shelter over a broad range of historical SEP events. The BFO doses are reported in units of gray equivalent (Gy-Eq), which is the dosimetric quantity relevant to assessing acute radiation risk (National Council on Radiation Protection, 2000). The gray equivalent dose is approximated by multiplying the calculated BFO dose (Gy) by the average relative biological effectiveness of protons, which is a factor of 1.5 (Hu et al., 2009).

3. Results

This section presents the results of the transport and dose calculations described in the previous section. BFO doses in the Orion MPCV are calculated for the seated and sheltered crew configurations for the set of 65 historical SEP events.

3.1. Energy Contributions to Dose

Figures 4 and 5 show the contributions to the total BFO dose from various spectral segments of the free-space proton energy spectrum for the set of historical SEP events. The abscissa points are minimum energies, which are defined in this context as the lowest energies of the free-space SEP spectrum, shown in Figure 1, used in the transport and dose calculations. Thus, the ordinate point at each minimum energy is the contribution to the total BFO dose that arises from the energies of the free-space proton spectrum that are greater than the minimum energy. For the seated configuration, more than 99% of the total BFO dose comes from proton energies greater than 10 MeV for all of the historical SEP events. The average and median contributions for proton energies greater than 100 MeV, for example, are 80% and 87%, respectively. The range of contributions to total BFO dose from this set of historical SEP events for energies greater than 100 MeV extends from 54% to 95%. Note for comparison, an aluminum slab with a thickness in the range of the median shielding thicknesses at the Orion MPCV crew locations would stop all protons with energies less than about 200 MeV. The average and median contributions to BFO dose from proton energies greater than 500 MeV is between 3% and 4%, but the spread in dose contributions is quite large. At the upper end of the dose contributions,
Figure 5. Fractional contribution to total BFO dose calculated in the Orion MPCV for the storm shelter crew configuration as a function of the minimum energy of the free-space SEP proton spectrum used in the transport and dose calculations. The shaded regions contain the fractional BFO dose contributions versus the minimum energies for the set of 65 historical SEP events. Nearly 25% of the total BFO dose is coming from energies greater than 500 MeV, which corresponds to the spectrally hard February 1956 event.

The shielding effectiveness of the storm shelter can be inferred by comparing the results in Figures 4 and 5 for the seated and sheltered crew configurations, respectively. The storm shelter reduces the absolute dose (see section 3.3 and Tables 2–5) and shifts the relative energy contributions to the total dose by shielding more of the lower energy protons. The relative contributions from energies below 100 MeV have been reduced for the sheltered configuration. The exception to this feature is the energetic storm particle component of the 24 August 1998 SEP event, which represents the lower border of the shaded region in Figures 4.

Figure 6. (diamond symbols) BFO dose calculated in the Orion MPCV for the seated crew configuration versus the integral fluence (cm$^{-2}$) for the set of 65 historical SEP events. (solid lines) Linear fit of BFO dose to integral fluence. The fit coefficients are given in Table 1, and the adjusted R-square of the fits are shown in the legends.
and 5 for incident protons energies below 100 MeV. This event produced the lowest BFO dose of the set of 65 historical SEP events (∼0.1 and ∼0.2 mGy-Eq for the sheltered and seated configurations, respectively). For hard proton spectra, the peak in the spectral BFO dose is around ∼100 MeV for both seated and sheltered configurations, which is the mean energy for a proton with a range in aluminum near to the median thicknesses of the vehicle shielding distributions at the crew locations shown in Figures 2 and 3. For soft proton spectra with relatively large spectral fluence below 100 MeV, a secondary peak forms in the spectral BFO dose distribution near ∼1 MeV due to a combination of a number of lightly shielded directions in the thickness distributions, the rapidly increasing stopping power below 100 MeV, and a relatively large incident proton fluence at low-to-medium energies. For the energetic storm particle component of the August 1998 SEP event, in particular, the secondary peak in the spectral dose is quite high since this event has the largest spectral power law index (5.29) of all the 65 historical SEP events (Raukunen et al., 2018). For the sheltered configuration, the spectral BFO dose is reduced in the 10–100 MeV range such that both peaks in the spectral dose are of comparable size. As a result, the contribution to the total dose for proton energies below 100 MeV is larger than for the seated configuration. This result is accidental in the sense that it cannot be reproduced for a slab geometry and is sensitive to the specific details of the vehicle shielding environment.

Table 1

| $\Phi^a$ (MeV) | Seated | Sheltered |
|----------------|--------|-----------|
|                | a      | b         | a        | b         |
| >30            | −13.94 | 0.83      | −13.71   | 0.79      |
| >60            | −14.48 | 0.91      | −14.38   | 0.88      |
| >100           | −14.52 | 0.97      | −14.55   | 0.94      |
| >500           | −9.16  | 0.89      | −9.77    | 0.90      |

Note. Fit equations: ln(BFO Dose) = a + b·ln($\Phi^a$).

*aIntegral proton fluence (cm$^{-2}$).
Table 2
Top 5% SEP Episodes With Largest Calculated Orion MPCV BFO Dose for Seated Crew Configuration

| Episode rank | GLE number | Date       | BFO dose (mGy-Eq) | Shelter factor | Φ(> 30) x10^8 | Φ(> 60) x10^8 | Φ(> 100) x10^8 | Φ(> 500) x10^8 |
|--------------|------------|------------|-------------------|----------------|----------------|----------------|----------------|----------------|
| 1            | 10         | 11/12/60   | 150               | 1.5            | 49             | 14             | 4.8            | 0.06           |
|              | 11         | 11/15/60   |                   |                |                |                |                |                |
|              | 12         | 11/20/60   |                   |                |                |                |                |                |
| 2            | 43         | 10/19/89   | 141               | 1.5            | 42             | 12             | 4.5            | 0.07           |
|              | 44         | 10/22/89   |                   |                |                |                |                |                |
|              | 45         | 10/24/89   |                   |                |                |                |                |                |
| 3            | 5          | 02/23/56   | 139               | 1.3            | 14             | 6.4            | 3.3            | 0.22           |

For the sheltered configuration in Figure 5, the average and median contributions to the total BFO dose are ∼92% and 96%, respectively, from proton energies greater than 100 MeV. The spread in the contributions to total dose for energies greater than 100 MeV has narrowed for the sheltered configuration, with a range of 67–98% for this set of historical events. The average and median contributions to BFO dose from energies greater than 500 MeV have doubled for the sheltered configuration compared to the seated configuration. Furthermore, nearly 30% of the February 1956 event BFO dose originates from proton energies greater than 500 MeV for the sheltered configuration.

3.2. Dose-Fluence Relationship

Figure 6 shows the event-accumulated BFO dose for the seated crew configuration versus the free-space event-accumulated integral fluence (cm⁻²) for the historical SEP events. The dose-fluence relationships are shown for proton energies greater than 30, 60, 100, and 500 MeV. All four integral fluence quantities provide a good indicator of the BFO dose in the Orion MPCV, with the magnitudes of dose and integral fluence well correlated even for energies greater than 500 MeV.

The highest correlation between the BFO dose and integral fluence quantities is for the >100 MeV integral fluence. This result is not surprising given the approximate step-function relationship between the average and median fractional BFO dose and the spectral cutoff energy shown in Figure 4, which makes a sharp transition between zero dose and total (100%) dose at a spectrum cutoff energy between 100 and 200 MeV. A nowcast (measurement or model) or a forecast of the integral fluence quantities could, for example, predict the BFO dose in the Orion MPCV with a simple linear relationship.

The dose-fluence relationships for the sheltered configuration of the Orion MPCV are shown in Figure 7. The good correlations between BFO dose and the integral fluence quantities are similar to the results for the seated configuration shown in Figure 6. The linear fit coefficients between BFO dose and integral fluence are listed in Table 1 for both seated and sheltered crew configurations.
Table 4

Top 5% SEP Events With Largest Calculated Orion MPCV BFO Dose for Seated Crew Configuration

| Event rank | GLE number | Date       | BFO dose (mGy-Eq) | Shelter reduction factor | \(\Phi(>30)\) \(\times10^8\) | \(\Phi(>60)\) \(\times10^8\) | \(\Phi(>100)\) \(\times10^8\) | \(\Phi(>500)\) \(\times10^8\) |
|------------|------------|------------|-------------------|--------------------------|----------------------------|-------------------|-------------------|-------------------|
| 1          | 5          | 02/23/56   | 139               | 1.3                      | 14                         | 6.4               | 3.3               | 0.200             |
| 2          | 10         | 11/12/60   | 99                | 1.5                      | 32                         | 8.9               | 3.2               | 0.040             |
| 3          | 24         | 08/04/72   | 66                | 2.3                      | 78                         | 14                | 2.6               | 0.002             |
| 4          | 42         | 09/29/89   | 50                | 1.6                      | 14                         | 4.9               | 1.7               | 0.030             |

3.3. Accumulated Dose

The total BFO dose and integral proton fluence for the three largest SEP episodes calculated for the Orion MPCV are given in Tables 2 and 3 for the seated and sheltered configurations, respectively. The integral proton fluences reported in the tables are fluences outside the spacecraft. The shelter reduction factor column in the tables is the amount of dose reduction that the vehicle storm shelter provides for the event. In this context, an episode defines events originating from the same active region on the Sun, which may include a single event or multiple events. The three episodes in Tables 2 and 3 represent the top 5% of the historical SEP episodes with respect to calculated BFO dose in the Orion MPCV. The largest SEP episode is the November 1960 events. The free-space proton spectra from this episode produce an average BFO dose in the Orion MPCV seated configuration of 150 mGy-Eq. The second and third largest episodes are the October 1989 (141 mGy-Eq) and February 1956 (139 mGy-Eq) events, respectively. Note that these three episodes are, in reality, indistinguishable in their calculated radiation risk characteristics since the separation in computed BFO doses among these episodes is smaller than the uncertainties in the calculations (Mertens et al., 2018).

Considering all 65 SEP events in the historical database, the Orion MPCV storm shelter reduced the BFO dose by 38% on average compared to the nominal, seated crew configuration. For the softest events, the storm shelter reduced the BFO dose by more than a factor of 2. From Tables 2 and 3, the storm shelter reduces the BFO dose for the November 1960 and October 1989 events by 33%. The storm shelter was least effective for the spectrally hard February 1956 event, with a 23% reduction of BFO dose, since a larger fraction of the dose originates from relativistic protons (e.g., >500 MeV).

The impacts of the spectral shapes of the SEP events on the BFO doses are also observed by comparing the ranking of the SEP episodes for the seated and sheltered configurations in Tables 2 and 3. For the seated configuration, the ranking of the episodes with respect to BFO dose is aligned with the ranking of the magnitude of the integral proton fluence for energies greater than 30, 60, and 100 MeV. The February 1956 event has the smallest integral fluence at these energies; on the other hand, it has the largest >500 MeV integral fluence. The storm shelter is not as effective at shielding large, spectrally hard events; thus, the February 1956 event ranks as the largest event for producing BFO dose in the sheltered configuration.

Tables 4 and 5 list the individual SEP events from the historical database that represent the top 5% in BFO dose for the seated and sheltered configurations, respectively. When considering individual SEP events, the February 1956 event produces the largest BFO dose for both the seated and sheltered crew configurations. The most interesting event in this list is the spectrally soft 4 August 1972 event. From Table 4, the integral proton fluences at energies greater than 30 and 60 MeV are larger for the August 1972 event than for the...
February 1956 and the 12 November 196 events, which produced higher BFO doses in the seated configuration. On the other hand, the integral fluences at energies greater than 100 and 500 MeV are smaller for the August 1972 compared to the two events that ranked higher in terms of BFO dose. Thus, most of the BFO dose from the August 1972 event comes from lower energy protons (<100 MeV). The storm shelter is very effective at shielding soft events; for example, the storm shelter reduced the BFO dose for the August 1972 event by a factor of 2.3. The impact of this significant reduction in dose, shown in Table 5, is that the August 1972 event no longer ranks among the top 5% in BFO dose for crew located within the storm shelter.

4. Conclusions

The shielding design of the Orion MPCV is sufficient to protect in-flight astronauts against acute radiation syndromes for all SEP events encountered during the space age. The calculated BFO doses for the set of historical SEP events are well below the threshold for deterministic biological effects (~500 mGy-Eq) and NASA’s 250 mGy-Eq 30-day BFO dose limit (International Commission on Radiological Protection [ICRP], 2012; Cucinotta et al., 2013). However, acute biological responses to SEP exposures are possible for astronauts in less shielded environments, if no further mitigation strategies are implemented. In addition, large SEP events can significantly increase the risk of cancer death and contribute significantly toward reaching NASA’s permissible exposure limits.

The challenge in protecting against SEP exposure is the current inability to distinguish a large event from a small event in real time. Consequently, SEP events impact mission planning, pose a potential for mission disruption, and can interfere with extravehicular activities (Cucinotta et al., 2010). This reality, combined with the radiation protection practice of making the best effort to keep risks as low as reasonably achievable (i.e., the ALARA principle: National Council on Radiation Protection, 2000; National Council on Radiation Protection, 2003), requires real-time measurements and nowcast/forecast models of the space radiation environment to inform operational radiation risk analysis tools.

The results of this paper elucidate important factors that should be considered in the design and development of future space weather architectures. Heavily shielded spacecraft such as the Orion MPCV significantly limit the possibility and severity of acute radiation syndromes. Most of the BFO dose (>80% on average) at the MPCV crew locations originates from free-space SEP proton energies greater than 100 MeV. A significant contribution (~25–30%) to the BFO dose is produced by protons with energies greater than 500 MeV for spectrally hard SEP events.

From the set of historical SEP events, the BFO dose calculations quantified the range of dose reduction factors that the MPCV storm shelter can provide, as well as determine the radiation environment conditions where the storm shelter would be the most effective. On average, the Orion MPCV storm shelter reduces the BFO dose by 38%. The storm shelter is most effective for spectrally soft events, with possible dose reduction factors on the order of a factor of 2.

The results presented in this paper help identify key quantities that must be measured and predicted for effective operational management of radiation risks on human space exploration missions during SEP events. For example, a forecast of integral proton fluence, and especially >100 MeV integral fluence, can potentially yield a reliable forecast of vehicle BFO dose, a quantity that can be evaluated and adjusted or improved in real time using the existing operational acute radiation risk tool (Mertens et al., 2018).

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