Space Radiation Risk Assessment for Future Lunar Missions

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Abstract

For lunar exploration mission design, radiation risk assessments require the understanding of future space radiation environments in support of resource management decisions, operational planning, and a go/no-go decision. The future GCR flux was estimated as a function of interplanetary deceleration potential, which was coupled with the estimated neutron monitor rate from the Climax monitor using a statistical model. A probability distribution function for solar particle event (SPE) occurrence was formed from proton fluence measurements of SPEs occurred during the past 5 solar cycles (19-23). Large proton SPEs identified from impulsive nitrate enhancements in polar ice for which the fluences are greater than $2 \times 10^9$ protons/cm$^2$ for energies greater than 30 MeV, were also combined to extend the probability calculation for high level of proton fluences. The probability with which any given proton fluence level of a SPE will be exceeded during a space mission of defined duration was then calculated. Analytic energy spectra of SPEs at different ranks of the integral fluences were constructed over broad energy ranges extending out to GeV, and representative exposure levels were analyzed at those fluences. For the development of an integrated strategy for radiation protection on lunar
exploration missions, effective doses at various points inside a spacecraft were calculated with detailed geometry models representing proposed transfer vehicle and habitat concepts. Preliminary radiation risk assessments from SPE and GCR were compared for various configuration concepts of radiation shelter in exploratory-class spacecrafts.
Problem

• The continuous galactic cosmic radiation (GCR) pose a serious health risk to humans and contribute to failure rates for electronics during space missions. The risks must be predicted accurately for future lunar missions.

→ A practical approach of expected GCR environment

• Solar particle events (SPEs) are a concern for space missions outside Earth’s geomagnetic field.
• The sporadic occurrence of SPEs and number of large SPEs in a short period are major operational problems for planning space missions and protecting humans during missions.

→ A probability of large SPE during the mission periods.

To develop an integrated strategy for radiation protection on lunar exploration missions
Climax Neutron Monitor Rate Measurements and Projection to Solar Cycles 23 and 24
## Database of Solar Particle Events

<table>
<thead>
<tr>
<th>Solar Cycle</th>
<th># of SPE</th>
<th># of Day</th>
<th>Period</th>
<th>Fluence, $\Phi_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle 23</td>
<td>92</td>
<td>3897</td>
<td>5/1/1996-12/31/2006</td>
<td>$\Phi_{10,30,50,60,100}$</td>
</tr>
<tr>
<td>Cycle 22</td>
<td>77</td>
<td>3742</td>
<td>2/1/1986-4/30/1996</td>
<td>$\Phi_{10,30,50,60,100}$</td>
</tr>
<tr>
<td>Cycle 21</td>
<td>70</td>
<td>3653</td>
<td>2/1/1976-1/31/1986</td>
<td>$\Phi_{10,30}$</td>
</tr>
<tr>
<td>Cycle 20</td>
<td>63</td>
<td>4140</td>
<td>10/1/1964-1/31/1976</td>
<td>$\Phi_{10,30}$ and $\Phi_{10,30,60}$</td>
</tr>
<tr>
<td>Cycle 19</td>
<td>68</td>
<td>3895</td>
<td>2/1/1954-9/30/1964</td>
<td>$\Phi_{10,30,100}$ and $\Phi_{10,30}$</td>
</tr>
<tr>
<td>Impulsive Nitrate Events</td>
<td>71</td>
<td>390 years</td>
<td>1561 - 1950</td>
<td>$\Phi_{30}$</td>
</tr>
</tbody>
</table>

(1) GOES SEM data: [http://goes.ngdc.noaa.gov/data/](http://goes.ngdc.noaa.gov/data/)
\[ \Phi(> E) = 5.644 \times 10^{10} e^{-\frac{\sqrt{E \times (E+1876)}}{92.469}} \]

\[ \Phi(> E) = 1.91 \times 10^{12} e^{-2.5677E^{0.256}} \]
Extended Cumulative Distributions of 5 Sample SPE Populations
SPE Probability in 2-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space

![Graph showing SPE Probability and BFO Exposure Level](image-url)
SPE Probability in 1-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space

![Graph showing SPE/Mission vs. Size of Event (≥Φ₃₀) with markers and trend lines representing different scenarios and limits.]

- **SPE/Mission**
  - Average Probability of Space Era
  - Extended Average Probability
  - Impulsive Nitrate Events
  - BFO Dose of Worst Case SPE Model
  - BFO Dose of SPE during Space Era

- **BFO Dose, cGy-Eq**
  - NCRP 30-day limit at BFO for LEO mission
Probability of SPE with $\Phi_{30} > 2 \times 10^9$ cm$^{-2}$ in 1-Week Mission

• Calculation using the sample SPE population distributions in space era:
  \[ P_{\Phi_{30} \geq 2 \times 10^9 \text{ cm}^{-2}} = 0.391\% \pm 0.40\% \]

• Calculation using the data in the interval 1561-1950 with the extended SPE population distributions and the correction of seasonal effect:
  \[ P_{\Phi_{30} \geq 2 \times 10^9 \text{ cm}^{-2}} = 0.489\% \pm 0.387\% \]

• Observed probability in the interval 1561-1950 with the correction of seasonal effect:
  \[ P_{\Phi_{30} \geq 2 \times 10^9 \text{ cm}^{-2}} = 0.466\% \]
Probability of SPE during a Given Mission Period
Event Threshold $\Phi_{30} > 10^7 \text{ cm}^{-2}$

Cumulative probability

- 90-d mission
- 120-d mission
- 180-d mission
- 270-d mission

At least 1 SPE, N(SPE) > 1, N(SPE) > 2, N(SPE) > 3, N(SPE) > 4, N(SPE) > 5, N(SPE) > 6, N(SPE) > 7
Shielding Distributions at 4 Locations of Spacecraft
## Organ Dose Quantities for Two Orientations

**August 1972 SPE**

<table>
<thead>
<tr>
<th></th>
<th>Random orientation</th>
<th></th>
<th></th>
<th></th>
<th>Aligned orientation</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DLOC1</td>
<td>DLOC2</td>
<td>DLOC3</td>
<td>DLOC4</td>
<td>DLOC1</td>
<td>DLOC2</td>
<td>DLOC3</td>
<td>DLOC4</td>
</tr>
<tr>
<td><strong>X-coordinate, cm</strong></td>
<td>43.18</td>
<td>-43.18</td>
<td>40.64</td>
<td>-40.64</td>
<td>43.18</td>
<td>-43.18</td>
<td>40.64</td>
<td>-40.64</td>
</tr>
<tr>
<td><strong>Y-coordinate, cm</strong></td>
<td>119.38</td>
<td>119.38</td>
<td>119.38</td>
<td>119.38</td>
<td>119.38</td>
<td>119.38</td>
<td>119.38</td>
<td>119.38</td>
</tr>
<tr>
<td><strong>Z-coordinate, cm</strong></td>
<td>52.71</td>
<td>52.71</td>
<td>-79.34</td>
<td>-79.34</td>
<td>52.71</td>
<td>52.71</td>
<td>-79.38</td>
<td>-79.38</td>
</tr>
<tr>
<td><strong>AI-Eq x_avg, g/cm²</strong></td>
<td>15.18</td>
<td>15.08</td>
<td>15.85</td>
<td>15.33</td>
<td>15.18</td>
<td>15.08</td>
<td>15.85</td>
<td>15.33</td>
</tr>
<tr>
<td><strong>xmin - xmax</strong></td>
<td>0 - 102.07</td>
<td>0 - 105.50</td>
<td>0 – 83.21</td>
<td>0 - 85.79</td>
<td>0 - 102.07</td>
<td>0 - 105.50</td>
<td>0 – 83.21</td>
<td>0 - 85.79</td>
</tr>
</tbody>
</table>

- **Avg skin**
  - Random orientation: 126.61, 121.07, 104.08, 108.59
  - Aligned orientation: 150.92, 135.41, 111.45, 114.45
- **Eye**
  - Random orientation: 86.76, 84.36, 73.58, 77.06
  - Aligned orientation: 89.71, 89.94, 81.62, 79.72
- **Avg BFO**
  - Random orientation: 16.91, 16.82, 15.2, 15.88
  - Aligned orientation: 18.14, 18.20, 16.05, 15.98
- **Stomach**
  - Random orientation: 7.38, 7.37, 6.77, 7.03
  - Aligned orientation: 6.94, 6.89, 6.59, 6.63
- **Colon**
  - Random orientation: 14.42, 14.36, 13.04, 13.6
  - Aligned orientation: 14.46, 14.36, 12.67, 12.79
- **Liver**
  - Random orientation: 10.37, 10.33, 9.41, 9.8
  - Aligned orientation: 9.43, 9.60, 8.92, 9.23

- **CAM organ dose, cSv**
  - Lung: 12.16, 12.12, 11.04, 11.5
  - Esophagus: 11.61, 11.57, 10.54, 10.98
  - Bladder: 7.54, 7.53, 6.9, 7.17
  - Thyroid: 18.39, 18.31, 16.55, 17.28
  - Chest: 72.23, 70.58, 61.85, 64.83
  - Gonads: 35.27, 34.74, 30.76, 32.24
  - Front brain: 29.54, 29.32, 26.31, 27.53
  - Mid brain: 16.2, 16.15, 14.68, 15.3
  - Rear brain: 28.93, 28.72, 25.79, 26.98
- **Effective dose eq, cSv**
  - Aligned orientation: 22.42, 21.09, 19.43, 18.64
- **Point dose eq, cSv**
  - Random orientation: 254.68, 242.74, 207.92, 216.83
  - Aligned orientation: 253.48, 241.76, 205.76, 211.88
SPE Shelter Concepts on Rover

Vertical Configuration

ID=70"

80" - 30" = 50" = 127 cm (thickness: 2, 4, 6, and 8 cm)

30" (76.288 cm) raised from the surface (thickness=1cm)

Horizontal Configuration

ID=70"

80"

Upper 180°: 2, 4, 6, and 8-cm thick wall

Bottom 180°: 1cm-thick PE

Front view
# EVA Exposure Inside Cylindrical Polyethylene Shelter on Lunar Surface from August 1972 SPE (One Crew Member)

<table>
<thead>
<tr>
<th>Polyethylene cylinder shelter thickness (ID=70”, H=80”)</th>
<th>E, cSv</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Horizontal Orientation</td>
<td></td>
<td>Vertical Orientation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass, kg</td>
<td>Astro</td>
<td>Suit</td>
<td>MARKIII</td>
<td>Mass, kg</td>
<td>Astro</td>
</tr>
<tr>
<td>2 cm (1.84 g/cm²)</td>
<td></td>
<td>229</td>
<td>51.90</td>
<td>52.03</td>
<td>52.21</td>
<td>242</td>
<td>53.49</td>
</tr>
<tr>
<td>4 cm (3.68 g/cm²)</td>
<td></td>
<td>389</td>
<td>24.76</td>
<td>24.88</td>
<td>25.16</td>
<td>429</td>
<td>25.06</td>
</tr>
<tr>
<td>6 cm (5.52 g/cm²)</td>
<td></td>
<td>556</td>
<td>13.37</td>
<td>12.96</td>
<td>12.80</td>
<td>624</td>
<td>12.39</td>
</tr>
<tr>
<td>8 cm (7.35 g/cm²)</td>
<td></td>
<td>729</td>
<td>8.22</td>
<td>8.36</td>
<td>8.74</td>
<td>825</td>
<td>7.74</td>
</tr>
<tr>
<td>5 g/cm² polyethylene sphere (ID=80”)</td>
<td></td>
<td>684</td>
<td>19.48</td>
<td></td>
<td></td>
<td>684</td>
<td>19.48</td>
</tr>
</tbody>
</table>
Summary

- A temporal forecast of GCR has been derived from the GCR deceleration potential ($\phi$) - Point dose equivalent in interplanetary space is influenced by solar modulation by a factor of 3.

- Relationship between large SPE occurrence and $\phi$ is clearly shown.

- Exposure levels of 34 big SPEs and worst-case SPE by Xapsos et al. (IEEE Trans. Nuc. Sci. 47(6), 2218-2223, 2000) are analyzed with differential energy spectra from Weibull distribution function.

- A probability of SPE at a given fluence level is obtained for various mission periods.

- Detailed distribution of directional risk assessment shows better protection for risk mitigation inside a habitable volume/shelter/spacecraft during future exploration missions.