Meeting Radiation Protection Requirements and Reducing Spacecraft Mass – A Multifunctional Materials Approach

Steve's draft

William Atwell[1]
The Boeing Company, Boeing Research & Technology, Space Exploration, Houston, TX 77059

Steve Koontz[2] and Brandon Reddell[3]
NASA Johnson Space Center, Houston, TX 77058

Kristina Rojdev[4]
NASA Johnson Space Center, Houston, TX 77058
PhD Student, University of Southern California, Los Angeles, CA 90089

and

Jennifer Franklin[5]
Student Intern, Universities Space Research Association, Houston, TX 77058
Undergraduate Student, University of Houston, Houston, TX 77002

Both crew and radio-sensitive systems, especially electronics must be protected from the effects of the space radiation environment. One method of mitigating this radiation exposure is to use passive-shielding materials. In previous vehicle designs such as the International Space Station (ISS), materials such as aluminum and polyethylene have been used as parasitic shielding to protect crew and electronics from exposure, but these designs add mass and decrease the amount of usable volume inside the vehicle. Thus, it is of interest to understand whether structural materials can also be designed to provide the radiation shielding capability needed for crew and electronics, while still providing weight savings and increased useable volume when compared against previous vehicle shielding designs. In this paper, we present calculations and analysis using the HZETRN (deterministic) and FLUKA (Monte Carlo) codes to investigate the radiation mitigation properties of these structural shielding materials, which includes graded-Z and composite materials. This work is also a follow-on to an earlier paper, that compared computational results for three radiation transport codes, HZETRN, HETC, and FLUKA, using the Feb. 1956 solar particle event (SPE) spectrum. In the following analysis, we consider the October 1989 Ground Level Enhanced (GLE) SPE as the input source term based on the Band function fitting method. Using HZETRN and FLUKA, parametric absorbed doses at the center of a hemispherical structure on the lunar surface are calculated for various thicknesses of graded-Z layups and an all-aluminum structure. HZETRN and FLUKA calculations are compared and are in reasonable (18% to 27%) agreement. Both codes are in agreement with respect to the predicted shielding material performance trends. The results from both HZETRN and FLUKA are analyzed and the radiation protection properties and potential weight savings of various materials and materials lay-ups are compared.

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[1] Boeing Technical Fellow, Boeing R&T, 13100 Space Center Blvd./MS HB 2-30, AIAA Associate Fellow.
[2] International Space Station System Manager for Space Environments, 2101 NASA Parkway, MS: ES4.
[3] Radiation Effects and Environments Engineer, 2101 NASA Parkway, MS: EV5.
[4] Aerospace Engineer, 2101 NASA Parkway, MS: EA341, AIAA Student Member.
[5] Student Intern, 2101 NASA Parkway, MS: EA34.

Nomenclature

cGy = centi Gray (1 rad)
ESP = Energetic Solar Particle event
FLUKA = FLUktuierende KAskade; a 3-D Monte Carlo high energy particle transport code
GeV = a unit of particle energy; giga electron volts (1 GeV = 1000 MeV)
GLE = Ground Level Event (Enhancement)
HETC = High Energy Transport Code
HZETRN = A Hi Z and Energy TRaNsport code developed by NASA Langley Research Center
MeV = a unit of particle energy; million electron volts
SPE = Solar Proton Event

I. Introduction

The space radiation environment is monitored via dosimeters and other space radiation detection systems to assure that deleterious effects to humans and radio-sensitive systems, especially electronics, are minimized. In order to estimate the pre-mission exposures, various computational tools and computer codes have been developed to make these exposure assessments and pre-mission estimates have been compared with the actual flight measurements. Solar particle events present an especially high level radiation threat to spacecraft crew and electronic systems( ). Under shielding mass areal thicknesses as high a 30 g/cm^2,solar particle event dose rates can be 2 to 3 orders of magnitude higher that background galactic cosmic ray dose rates( ) . In earlier publications[1-3] we have presented and discussed a new method for completely describing solar proton events (SPEs) using the Band method and analyzed the shielding properties of various materials. In this paper we investigate and compare the results of the shielding properties of several Z-graded (multi-layered) materials using the high energy particle transport/dose codes, NASA Langley Research Center's HZETRN code (Dr. Martha S. Clowdsley, NASA Langley, private communication, 2008) and the FLUKA[4] code for the series of SPEs that occurred during October 1989. The calculated dose results using two transport codes are discussed in detail along with the radiation protection properties of the materials and the potential weight savings offered by specific material lay-ups in comparison with an all aluminum baseline case.

II. The October 1989 SPEs

A series of extremely large SPEs occurred during the 19-24 October 1989 timeframe. These events produced Ground Level Enhancements (GLEs) that were measured at several high latitude neutron monitor stations, which indicated that extremely energetic solar protons were associated with these events. Figures 1-4 show the particle fluence profiles (integral and differential spectra) for the events occurring on the 19th, 22nd, and 24th of October 1989. In addition, a bow shock enhancement, called an Energetic Solar Particle (ESP) event, followed the GLE of 19 October 1989. The ESP integral and differential spectra are shown in Figure 2.

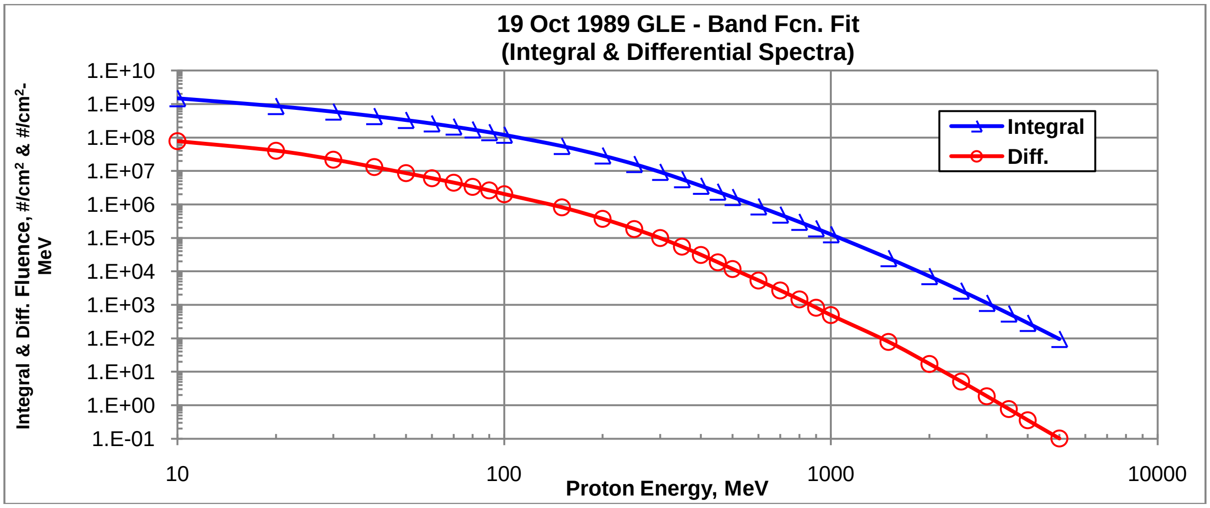

Fig. 1. Integral and differential spectra (Band fit) for the 19 Oct. 1989 GLE.

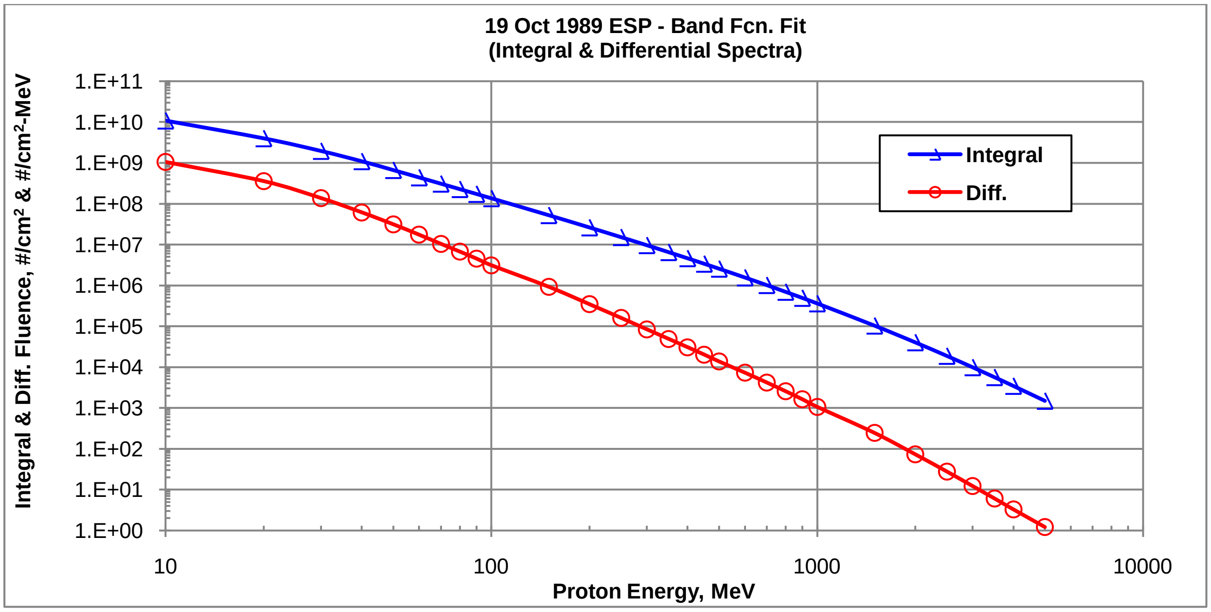

Fig. 2. Integral and differential spectra (Band fit) for the 19 Oct. 1989 ESP.

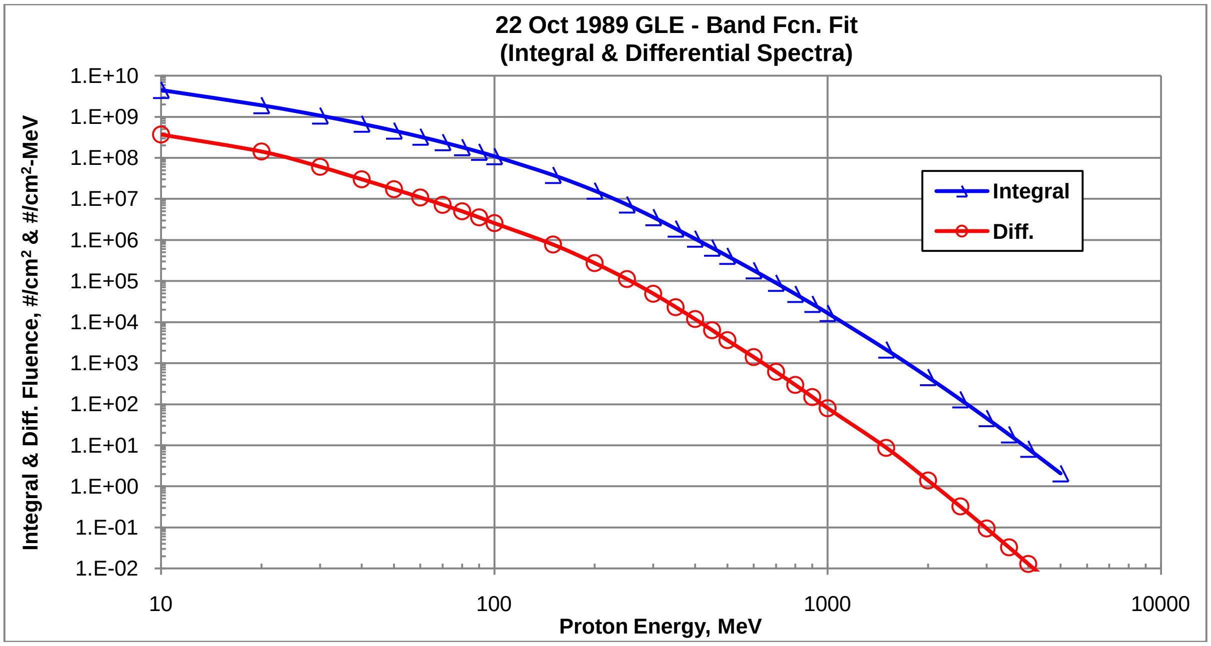

Fig. 3. Integral and differential spectra (Band fit) for the 22 Oct. 1989 GLE.

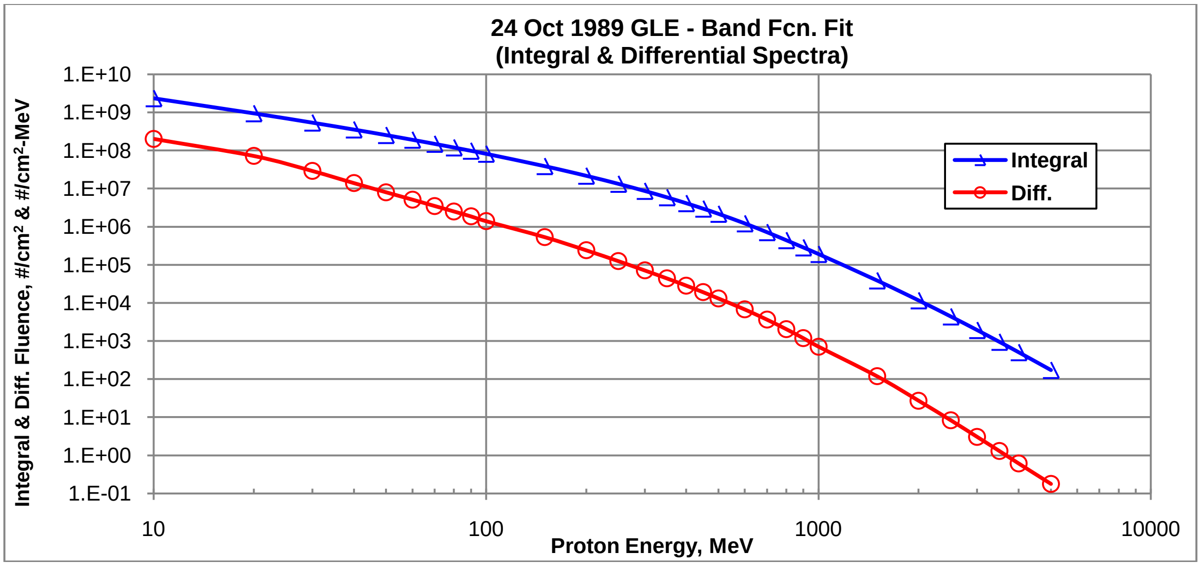

Fig. 4. Integral and differential spectra (Band fit) for the 24 Oct. 1989 GLE.

Figure 5 shows the integral and differential spectra when we combined the four events.

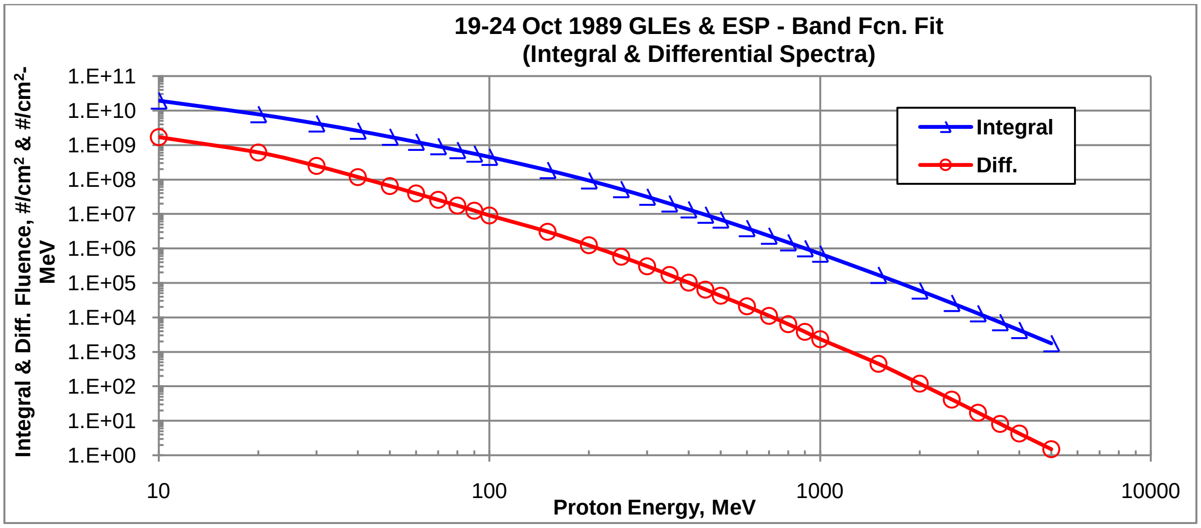

Fig. 5. Integral and differential spectra (Band fit) for the combined 19-24 Oct. 1989 events.

The combined differential spectrum (Fig. 5. – **red** font) was used as the radiation environment source term for the absorbed dose calculations shown later in the paper.

III. Shielding Materials

We have considered four (4) shielding materials cases, which are described below. The total areal shielding mass is on the order of 10 to 30 g/cm^2 in all cases. These materials lay-ups do not represent specific components like pressure shells or MM/OD shielding but rather represent overall shielding mass distributions expected in manned spacecraft and our intent is to show how both average atomic number and relative position in the lay-up affect ionizing dose.

A. Case 1 – 3-layered aluminum, HDPE and aluminum

Case 1 consists of three (3) layered materials: aluminum (density = 2.7 g/cc), high density polyethylene (HDPE) (density = 0.95 g/cc), and aluminum (density = 2.7 g/cc) with thicknesses ranging from 0 g/cm^2 to 10 g/cm^2.

B. Case 2 – 3-layered carbon fiber, HDPE, and carbon fiber

Case 2 consists of three (3) layered materials: carbon fiber (density = 1.648 g/cc), HDPE (density = 0.95 g/cc), and carbon fiber (density = 1.648 g/cc) with thicknesses ranging from 0 g/cm^2 to 10 g/cm^2 for the carbon fiber and 0 g/cm^2 to 10 g/cm^2 for the HDPE.

C. Case 3 – 3-layered boron carbon fiber, 30% boron-doped polyethylene, and boron carbon fiber

Case 3 consists of three (3) layered materials: borated carbon fiber (density = 1.97 g/cc), 30% boron-doped polyethylene (density = 1.19 g/cc), and borated carbon fiber (density = 1.97 g/cc) with thicknesses ranging from 0 g/cm^2 to 10 g/cm^2 for the borated carbon fiber and 0 g/cm^2 to 10 g/cm^2 for the 30% boron-doped polyethylene.

D. Case 4 – aluminum and HDPE

Case 4 consists of two (2) layered materials: aluminum (density = 2.7 g/cc) and HDPE (density = 0.95 g/cc) with thicknesses ranging from 0 g/cm^2 to 10 g/cm^2.

IV. High Energy Particle Transport/Dose Codes

Routinely, we use the HZETRN (1-dimensional / deterministic) code to perform radiation analyses for a broad number of investigations due to its quick-running and accurate computations. The FLUKA code is a 3-D Monte Carlo code that requires much long runtimes and more computational resources. For each shielding mass configuration, dose calculations made with HZETRN are compared with dose calculations made with the FLUKA code. Comparisons of the results are discussed later in the paper.

A. NASA Langley Research Center HZETRN 2005 Code

The NASA Langley Research Center (LaRC) HZETRN 2005 computer code is a 1-dimensional, deterministic high energy particle transport/dose code. It has built-in algorithms for the calculation of historical SPEs and galactic cosmic radiation (GCR) both solar minimum and solar maximum. It can handle 3 layered materials, and can compute absorbed dose and dose equivalent for water, tissue, and silicon detectors. As stated above, it is a very quick-running code.

B. The FLUKA Code

The FLUKA[4,5] code (FLUktuierende KAskade) is a fully integrated, 3-dimensional, Monte Carlo simulation package for the interaction and transport of particles and nuclei in matter. FLUKA has many applications in particle physics, high energy experimental physics and engineering, shielding, detector and telescope design, cosmic ray studies, dosimetry, medical physics and radiobiology. Since it is a Monte Carlo code, runtimes are quite long when compared with HZETRN and more computational resources are required. Current versions of HZETRN can accommodate only 3 different materials layers while FLUKA can accommodate many more and in more complex geometries if desired[4,5].

VI. Results

We present the results of this study for surface habitats on the Moon and assume the surface structures are hemispherical in shape, with the dose calculated at the center of the hemisphere. We also assume 2π shielding, since for a lunar surface scenario the moon “cuts out” half of the radiation exposure. In the following Tables we show the 10 minimum absorbed doses for each case. Within each case, the variation in dose between the minimum and maximum was between 15% and 17% of the minimum dose.

As expected, minimum radiation dose corresponded to maximum total areal density in all 4 cases. For materials cases 1-3 (Tables 1-3), all corresponding to 10 g/cm^2 for each of the three layers considered the order of shielding effectiveness from best to worst is: 1) carbon fiber – HDPE – carbon fiber (3.65 cGy), 2) borated carbon fiber – HDPE - borated carbon fiber (4.04 cGy), and 3) Al – HDPE – Al (4.45 cGy), with the best shielding mass lay-up showing an 18% reduction in lunar surface and absorbed dose compared to the worst.

Results for case 4 are shown in Tables 4 and 5 where the solar minimum daily GCR dose rate is compared with the total for the combined October 1989 SEP event set. Note that changes in shielding mass lay-up and total areal thickness produce significant changes (37% of the minimum value) in the predicted dose rate for the total October 1989 event but little or no change in the solar minimum daily GCR dose rate, which is 2 to 3 orders of magnitude smaller that the particle event dose. GCR has a much lower particle flux than the October 1989 combined event, however the GCR spectrum is much "harder" in that the percentage of particles at very higher energies is much larger. Finally it is interesting to note the relationship between the aluminum and polyethylene layers in Tables 1 and 4. For the same total thickness, placing the polyethylene external to the aluminum always produces a significantly lower dose than placing the aluminum external to the polyethylene as should be expected given the well known atomic number dependence of secondary particle production in energetic particle collisions with atomic nuclei.

Table 1. Case 1. – Minimum Radiation Exposures for the Band Oct. 1989 SPEs

Outer Layer Al g/cm^2	Middle HDPE g/cm^2	Inner Al g/cm^2	Free Space Absorbed Dose cGy	Areal Thickness g/cm^2	Physical Thickness cm	Lunar Surface Dose cGy
10	10	10	8.9	30.0	17.93	4.45
9	10	10	9.4	29.0	17.56	4.70
10	10	9	9.4	29.0	17.56	4.70
10	9	10	9.6	29.0	16.88	4.80
10	10	8	9.9	28.0	17.19	4.95
8	10	10	10.0	28.0	17.19	5.00
9	10	9	10.0	28.0	17.19	5.00
9	9	10	10.2	28.0	16.51	5.10
10	9	9	10.2	28.0	16.51	5.10
10	8	10	10.4	28.0	15.83	5.20

Table 2. Case 2. – Minimum Radiation Exposures for the Oct. 1989 SPEs

Outer Layer C-fiber g/cm^2	Middle Layer HDPE g/cm^2	Inner Layer C-fiber g/cm^2	Free Space Absorbed Dose cGy	Areal Thickness g/cm^2	Physical Thickness cm	Lunar Surface Dose cGy
10	10	10	7.3	30	22.66	3.65
9	10	10	7.7	29	22.06	3.85
10	10	9	7.7	29	22.06	3.85
10	9	10	7.8	29	21.61	3.90
8	10	10	8.2	28	21.45	4.10
9	10	9	8.2	28	21.45	4.10
10	10	8	8.2	28	21.45	4.10
9	9	10	8.3	28	21.00	4.15
10	9	9	8.3	28	21.00	4.15
10	8	10	8.4	28	20.56	4.20

Table 3. Case 3. – Minimum Radiation Exposures for the Oct. 1989 SPEs

Outer Layer B C-fiber g/cm^2	Middle Layer 30% B-doped PE g/cm^2	Inner Layer B C-fiber g/cm^2	Absorbed Dose cGy	Areal Thickness g/cm^2	Physical Thickness cm	Surface Dose cGy
10	10	10	8.08	30.0	10.68	4.04
9	10	10	8.59	29.0	10.17	4.30
10	10	9	8.59	29.0	10.17	4.30
10	9	10	8.64	29.0	10.63	4.32
8	10	10	9.15	28.0	9.66	4.58
9	10	9	9.15	28.0	9.66	4.58
10	10	8	9.15	28.0	9.66	4.58
9	9	10	9.20	28.0	10.12	4.60
10	9	9	9.20	28.0	10.12	4.60
10	8	10	9.25	28.0	10.57	4.63

Table 4. Case 4. – Minimum Radiation Exposures for the Oct. 1989 SPEs

Outer Layer Al g/cm^2	Inner Layer HDPE g/cm^2	Free Space Absorbed Dose cGy	Areal Thickness g/cm^2	Physical Thickness cm	Lunar Surface Dose cGy
10	10	16.66	20.0	14.23	8.33
9	10	17.96	19.0	13.86	8.98
10	9	18.46	19.0	13.18	9.23
8	10	19.41	18.0	13.49	9.71
9	9	19.98	18.0	12.81	9.99
10	8	20.57	18.0	12.12	10.29
7	10	21.04	17.0	13.12	10.52
8	9	21.68	17.0	12.44	10.84
9	8	22.35	17.0	11.75	11.18
6	10	22.90	16.0	12.75	11.45

Table 5. Case 4. – Minimum Radiation Exposures for GCR Solar Minimum

Outer Al g/cm^2	Inner HDPE g/cm^2	Free Space Absorbed Dose cGy	Areal Thickness g/cm^2	Physical Thickness cm	Lunar Surface Dose/day cGy
10	10	0.0400	20	14.23	0.0200
9	10	0.0400	19	13.86	0.0200
8	10	0.0401	18	13.49	0.0201
6	10	0.0402	16	12.75	0.0201
7	10	0.0402	17	13.12	0.0201
5	10	0.0403	15	12.38	0.0202
9	9	0.0403	18	12.81	0.0202
10	9	0.0403	19	13.18	0.0202
4	10	0.0404	14	12.01	0.0202
8	9	0.0404	17	12.44	0.0202

V. Conclusions

In this paper we have provided the integral and differential Band function fits for the series of SPEs that occurred during October 1989 and used the combined differential spectra to investigate the shielding properties of several Z-graded (layered) materials by computing the absorbed dose for a number of thicknesses. The absorbed dose values were then sorted to arrive at a range of minimum doses at a physical thickness of 30 g/cm^2. These values were compared with each other and with aluminum. We find a considerable dose reduction for all three material lay-ups when compared with the "standard" material, aluminum. Carbon fiber-HDPE-carbon fiber lay-ups provided the best shielding performance and showed a 18% improvement over Al-HDPE-Al. Table 6 shows the results. In addition, the exponential in rigidity fit to the Oct 1989 SPE spectra, as we have shown in several earlier publications[1-3], considerably underestimates the radiation exposure when compared with the Band function fit. The Band function fit is based on actual solar proton emission and is a true representation of the total proton energy spectrum from 10 MeV to ~20 GeV[1].

The total dose accumulated over a few days from the October 1989 solar particle events was 2 to 3 orders of magnitude greater that the solar minimum GCR dose over a r4enag of shielding mass thicknesses ranging from 14 to 20 g/cm^2.

For a specified solar particle event dose requirement and using the October 1989 combined event as the design environment, a ___% reduction in spacecraft mass is anticipated by using the carbon-HDPE-carbon materials instead of aluminum as spacecraft structure when shielding masses are on the order of 10 to 30 g/cm^2.

Table 6. Comparison of Relative Absorbed Doses and Thicknesses Ranges for the Four Material Cases

Case 1	Al / HDPE / Al	Lunar Surface Dose cGy	Minimum Dose Wall Thk. cm	Areal Thickness g/cm^2
BAND Fit		4.45	17.93	30.00
Exponential Fit		0.80	17.93	30.00

Case 2	C fiber / HDPE / C fiber	Lunar Surface Dose cGy	Minimum Dose Wall Thk. cm	Areal Thickness g/cm^2
BAND Fit		3.65	22.66	30.00
Exponential Fit		0.61	22.66	30.00

Case 3	B C-fiber / 30% B-doped PE / B C-fiber	Lunar Surface Dose cGy	Minimum Dose Wall Thk. cm	Areal Thickness g/cm^2
BAND Fit		4.04	10.68	30.00
Exponential Fit		0.72	18.56	30.00

Case 4	Al	Lunar Surface Dose cGy	Minimum Dose Wall Thk. cm	Areal Thickness g/cm^2
BAND Fit				30.00 20.00
Exponential Fit				30.00 20.00

1. The data shown in Table 13 indicate that Cases 1-3 provide better shielding that the “standard” shielding lay-up of aluminum and polyethylene, although Cases 1 and 2 require thicker physical thicknesses than Case 3.
2. Of the three cases considered, the composite Case 3 (Boron Carbon-fiber / 30% Boron-doped polyethylene / Boron Carbon-fiber) significantly out-performs the “standard” Case 4 configuration.
3. The GCR exposures per day ranged from 0.02 cGy/day for solar minimum to 0.006 cGy/day for solar maximum for all four cases, which was expected, since GCR particles are practically impervious to shielding.
4. When we compared the FLUKA results with the HZETRN results, we found that the FLUKA results were within 18-27% of the HZETRN corresponding to excellent agreement between the tow very different codes and providing a high degree of confidence in the results.

Additional follow-on work will include:

1. Investigate other composite lay-up materials and compare them with the “standard” Al/HDPE lay-up
2. Investigate the durability of the Case 3 material lay-up in a harsh radiation environment and utilization as a lunar surface habitat material

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