Shielding Considerations for CubeSat Structures During Solar Maximum

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ABSTRACT

The purpose of this lessons learned paper is to communicate the utility of shielding in small spacecraft planning for the support of mission assurance and reliability. Numerous SmallSats have been flying in polar low Earth orbit for science, communications, technology demonstrations, and imaging with academic, commercial, and government interests. Shielding has been part of mission assurance and reliability from the advent of long duration spacecraft missions. The Shields-1 CubeSat has been operating in polar low Earth orbit since 16 December 2018 with atomic number (Z)-grade radiation shielding and demonstrates shielding effectiveness. Shields-1 has collected a representative example of solar minimum data in 2019 with 8 Teledyne μDosimeters over varying shielding effectivenesses. It serves as current experimental data and has been compared with NOVICE Shielding estimates using the AP8 – AE8 trapped radiation model with the Shields-1 CAD and generic CubeSat 3 unit (U) models. Using NOVICE model radiation analysis coding, the shielding effectivenesses, based on a generic CubeSat 3U structure with 4 electronic boards, were estimated for aluminum wall thicknesses ranging from 0.204-cm to 4.44-cm (0.550-g/cm^2 – 12.0-g/cm^2) thick aluminum. For modeled polar orbiting spacecraft, solar maximum total ionizing dose (TID) increases by nearly a magnitude for thin-walled aluminum 0.550-g/cm^2 - 0.686-g/cm^2 (0.204-cm – 0.254-cm) typical CubeSat structures. The shielding effectiveness by NOVICE Sigma estimates, which is a shielding sphere approximation around a detector, showed a linear relationship with wall thickness, which increased over the wall thickness by a ratio of 1.43 determined by linear regression analysis. Using NOVICE Adjoint Monte-Carlo Modeling of solar minimum and solar maximum with the inclusion of a worst-case solar particle event over a 1-year mission without geomagnetic shielding, the TID for minimum and maximum conditions for a generic 3U with a wall thickness of 0.254 cm is 158 RAD and 1540 RAD, respectively. The modeled total solar maximum TID is over estimated, because at low orbital latitudes a spacecraft will have shielding from the Earth's magnetic field. However, TID will still be significant at high latitudes over the poles, where a spacecraft is exposed in a solar particle event. In contrast, to a thin-walled generic 3U CubeSat, the Shields-1 electronics enclosure has a shielding effectiveness of 21.3 g/cm^2 from NOVICE Sigma modeling and is expected to show reduced total ionizing dose increases during the present active Solar Cycle 25 period. Because solar particle events during solar maximum increase TID on electronic parts with thin-walled shielding in short periods of time, it is a mission assurance and reliability consideration on the spacecraft's mission value versus adding shielding for risk reduction of premature spacecraft or instrument payload loss. Since the volumes of many instruments and system electronics have reduced with small spacecraft, shielding material costs and weight penalties have diminished. A small spacecraft project budget and schedule may limit traditional radiation-hardened part use and radiation testing requirements, where shielding can contribute to mission assurance and reliability with reduced costs.

INTRODUCTION

Shielding has been part of mission assurance and reliability practices for long duration spacecraft missions for decades, such as Voyager 1 and 2 and Galileo with the use of a shielded electronics enclosure or vault. NASA's reliability guidelines include system level radiation design margin, total ionizing dose levels for commercial electronic parts, charge mitigation, and mission assurance and reliability practices.[1-3] Radiation design margin has been used to increase reliability by reducing the system level uncertainty of individual electronic parts working together in a radiation environment. The Voyager series used a radiation design margin of 2.[3] Galileo used a radiation design of 2 and 3 for parts requiring spot shielding.[4] Total ionizing dose for commercial parts have been recommended at levels from 2 to 10 kRADs with lower values for complementary metal oxide semiconductor (CMOS) parts which are important in various aerospace applications.[2] Shielding reduces the effects of internal charging from the electron environment.[5] Mission assurance and reliability practices describe for all mission types from flagship missions to high risk experiments, such as CubeSat technology demonstrations, the importance of adding radiation design margin into the system in addition to other reliability tests and strategies.[1]

The shielding of CubeSats has been challenging due to the volume constraints of the standard unit (U). A 1U CubeSat has a 10-cm x 10-cm x 10-cm volume. Typical aluminum wall thicknesses have been limited to thicknesses from 0.204-cm – 0.254-cm thick with corresponding areal densities of 0.550-g/cm^2 - 0.686-g/cm^2 or a skeletal design. The earliest CubeSat design described using 0.318 cm.[6] The various CubeSat design specifications document the structural exterior interface requirements for deployers provide the outer volume dimensions.[7]

Shields-1[8] (figure 1) was launched on 16 December 2018 with a shielded electronics enclosure (vault), part of the NASA CubeSat Launch Initiative (CSLI) ELaNaXIX Mission into a 500-km altitude circular orbit at an 85° inclination.[9] The Shields-1 electronics enclosure (vault) includes a 3-g/cm^2 atomic number (Z)-grade wall thickness.[10]

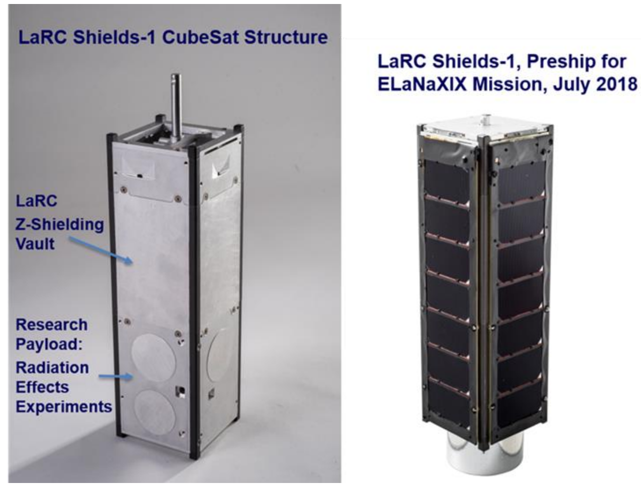

Figure 1. Shields-1 electronics enclosure (vault) with a 3 g/cm^2 Z-grade wall thickness with and without solar panels over the structure. (Image Credits: NASA)

The Shields-1 Z-grade electronics enclosure (vault) was designed with aluminum, titanium, and tantalum to reduce the overall thickness compared with aluminum of the same areal density at 1.1 cm, which enabled incorporation of the electronics. The challenge of putting mass into CubeSat shielding is the volume, because aluminum has a low density of 2.7 g/cm^3 compared with other metals with higher Z values. Figure 2 shows a thin Z-Shields, a NASA Langley Research Center (LaRC) innovation with shielding thicknesses from 0.204 cm to 0.254 cm (1.15 to 3.00 g/cm^2), on top of a plastic CubeSat 1 unit (U) skeletal structure. In figure 2, an aluminum plate is on the right, which is 1.1-cm (3.0-g/cm^2) thick and compared with the thin Z-Shield, which has a typical CubeSat structure thickness. Because the shielding structure must comply with the CubeSat standard volume constraints, the use of aluminum beyond the typical 0.204-cm to 0.254-cm thickness reduces the volume available for system bus electronics or instrument payloads. The thin Z-Shields adds mass needed for shielding at a reduced volume.

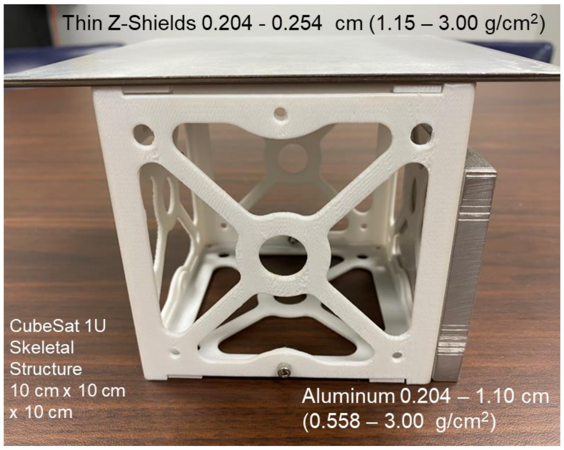

Figure 2. A comparison of thin Z-Shields and aluminum thicknesses for adding structural shielding mass to a CubeSat 1 unit (U). Thin Z-Shields enables increased mass thickness. (Image Credit: NASA)

For polar low Earth orbit, there are shielding considerations for both total ionizing dose and proton single event effects from the South Atlantic Anomaly (SAA) during solar minimum. During solar maximum, there are shielding considerations for solar particle event (SPE) proton total ionizing dose, SPE proton single event effects (SEEs), and increase trapped belt electron total ionizing dose. The solar activity has been increasing over the past 2 years due to the current solar cycle proceeding towards an estimated solar maximum in 2025.[11] According to the NOAA Space Weather Prediction Center (SWPC), a typical solar cycle has a severity (S) scale event probability from S1-S5 with 50 minor (S1), 25 moderate (S2), 10 strong (S3), 3 severe (S4), and less than 1 extreme (S5) solar particle event (SPE). SEEs have increased probability of occurrence from moderate to extreme severity because of the increased likelihood of proton energies greater than the minimum proton thresholds of the spacecraft shielding. The SWPC evaluates the severity from magnitude flux levels above 10-MeV proton energies with the S scale with severities corresponding to historical occurrence rates for a 11-year solar cycle. Many SPEs last several days and longer with increased flux over a short amount of time. The additional proton flux from solar particle events increases radiation effects on electronics behind thin-walled shielding.

Spacecraft radiation shielding around electronics has been described in terms of shielding effectiveness. When shielding is estimated for a space environment application, it is typically estimated by a slab approximation using a point source approximation with the shielding perpendicular to incident radiation for one-dimensional stopping power or range calculations[12-13] or as a spherical shell for isotropic radiation.[14-15] Other shielding arrangements include solid sphere, dual slab, and slab backslab.[14, 16] The slab and spherical approximations provide preliminary estimates of the radiation environment. However, most spacecraft are built with internal electronic components and shapes other than spheres. For instance, the CubeSat Standard has Us of various shapes from cubic to rectangular with planar exterior walls. The Shields-1 electronics enclosure (vault), figure 1, shows the Z-shielding planar slabs being used as the exterior structural wall. More specific shielding estimates are achieved with computer-aided design (CAD) ray trace designs of the spacecraft structure to determine the shielding effectiveness, which incorporates all materials of the spacecraft for the combined shielding contributions around a location inside the structure. By using the ray tracing function in NOVICE SIGMA for specific locations inside a CAD spacecraft design, the shielding effectiveness is approximated to a sphere with the shielding contribution of all materials in the spacecraft. The shielding effectiveness enables a way of comparing different spacecraft and structural radiation shielding with a spherical shielding approximation in an aluminum equivalent value. The shielding effectiveness is determined from SIGMA effective mass thickness estimates.[14] The linear energy transfer (LET) cross-section for each material in the sector analysis around a spherical detector is used for each particle transport. The calculated effective material shielding is reported as an aluminum equivalent for the shielding effectiveness. In addition to the shielding effectiveness measurements, a related measurement determined from the space environment proton radiation fluence and the shielded fluence is the proton minimum threshold, which can be determined by slowing down approximation. The minimum proton particle threshold for a detector is the minimum proton particle energy that transmits through spacecraft shielding to the detector. Minimum proton energy threshold for a detector is determined from the space environment proton integral fluence and the integral proton fluence at each modeled detector. By knowing the integral fluence of the modeled environment and the shielded fluence, the percent particles remaining can be calculated. This work describes the relationship between generic CubeSat shielding structures with 4 electronic boards and the Shields-1 electronics enclosure (vault) in the polar low Earth orbiting radiation environment for modeled solar minimum and solar maximum environments.

EXPERIMENTAL

NOVICE Shielding Modeling

The polar low Earth orbit radiation environment was modeled for a circular 85º- inclination and 500-km altitude, using The Aerospace Corporation (A) proton (P) 8 and The Aerospace Corporation (A) electron (E) 8 model for solar minimum and maximum over a 1-year mission period. Solar Particle Event (SPE) environment was modeled using the SOLPRO (King) Model, 95% confidence, over a 1-year period. The SOLPRO model is at 1 astronomical unit (AU) and geomagnetically unshielded. Using NOVICE SIGMA model radiation analysis coding, the shielding effectivenesses, based on a generic CubeSat 3U structure with 4 electronic boards, were estimated for aluminum wall thicknesses ranging from 0.204-cm to 4.44-cm (0.550-g/cm^2– 12.0-g/cm^2) thick aluminum for the AP8 minimum environment. The generic CubeSat 3U structure was compared with the Shields-1 electronic enclosure CAD with a wall thickness of 3.02 g/cm^2, containing the spacecraft electronics and the research payload shielding. NOVICE ADJOINT Monte Carlo modeling was done for modeling the shielded fluence and total ionizing dose.[14, 17]

Shields-1 Electronics Enclosure (Vault) Dosimetry Measurement

Using a Teledyne μDosimeter in the Shields-1 electronics enclosure (vault), measurements were taken using the high-count channel, which is 0.94 +/- 0.04 Rad/step. A step is a voltage increase for each channel count. The measurements were taken over a 2-month period from July 2019 to September 2019.

RESULTS AND DISCUSSION

Shielding Effectiveness

The shielding effectiveness 3U generic CubeSat structures wall thicknesses from 0.204-cm to 4.44-cm (0.550-g/cm^2 - 12.0-g/cm^2) thick aluminum were plotted as a function of SIGMA shielding effectiveness, figure 3.

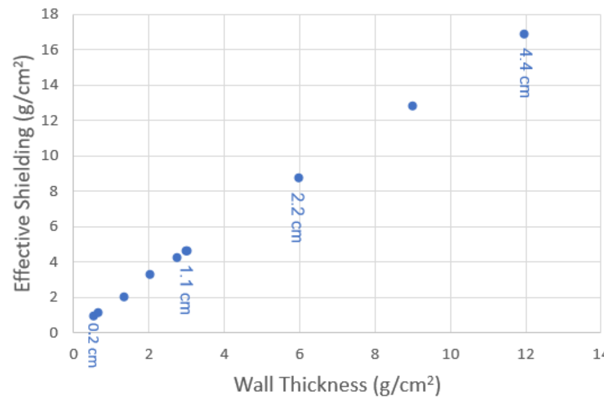

Figure 3. Generic 3U CubeSat with 4 electronic boards effective shielding as a function of wall thickness, showing a linear relationship.

The shielding effectiveness showed a linear relationship with wall thickness, which increased over the wall thickness by a ratio of 1.43, which is the slope determined by linear regression analysis. The effective shielding was greater than the wall thickness in all cases, for example a 0.550-g/cm^2 (0.204-cm) thick wall has an effective shielding of 0.788 g/cm^2. In comparison, the Shields-1 electronics enclosure (vault), figure 1, effective shielding was determined to be 21.3 g/cm^2. The Shields-1 electronic enclosure (vault) contains wall thicknesses of 6 g/cm^2 in the research payload in addition to shielding slabs from 1.28 g/cm^2 to 3.02 g/cm^2, which contributed to the high effective shielding value.[8]

Total Ionizing Dose and Radiation Design Margin

Using NOVICE Adjoint Monte-Carlo Modeling of solar minimum and solar maximum with the inclusion of a worst-case solar particle event over a 1-year mission without geomagnetic shielding, the total ionizing dose (TID) for minimum and maximum conditions for a generic 3U CubeSat with a wall thickness of 0.254 cm is 158 RAD and 1540 RAD, respectively. (Figure 4)

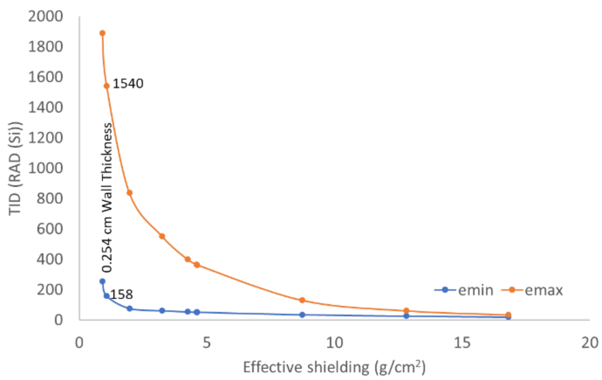

Figure 4. Generic 3U CubeSat Thin-Walled Aluminum Structure with a 10-times increase in TID from solar minimum (emin) to maximum (emax).

The modeled total solar maximum TID is over estimated, because at low orbital latitudes a spacecraft will have shielding from Earth's magnetic field. However, TID will still be significant at high latitudes over the poles, where a spacecraft is exposed in a solar particle event. There is very little contribution to TID from solar maximum as the shielding increases above 4 g/cm^2 with the total ionizing dose approximately 400 RAD and decreases to below 200 Rad at 7 g/cm^2 and negligible change at higher shielding levels. The implication of solar maximum for thin-walled CubeSat shielding is that by adding radiation design margin of 2 or 3 into space environment mission planning, it shows that there is a system risk for radiation effects on sensitive commercial electronic parts, where the typical range is 2 to 10 kRAD, which does not include margin, because 1.5 kRAD from figure 4 with a radiation design margin of 2 is 3 kRAD and 4.5 kRAD for 3. If a spacecraft design is to last multiple years during increased solar activity, then a thin-walled spacecraft structure is at system risk for commercial parts with low TID hardness.

In contrast to the generic 3U CubeSat of 0.254-cm aluminum wall thickness, the Shields-1 total ionizing dose at solar minimum is experimentally determined over a 2-month period to have 75.6 +/- 3.2 RAD/yr, figure 5.

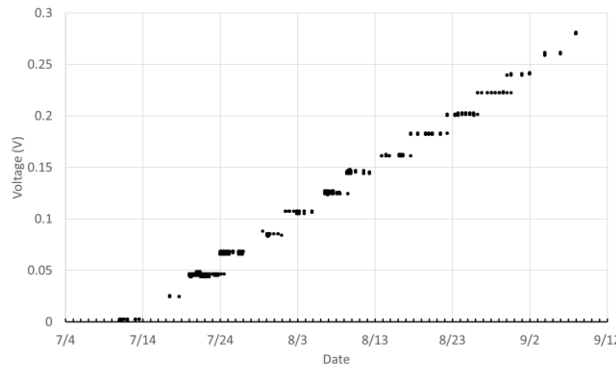

Figure 5. The Shields-1 electronics enclosure (vault) Teledyne μDosimeter high-count channel, where the step increases correspond to 0.94 +/- 0.04 RAD/step. The dose occurred over a 2-month period.[10]

Minimum Proton Threshold and Percent Proton Particles Remaining

The minimum proton threshold was measured for the 0.55-g/cm^2 (0.204-cm) generic 3U CubeSat wall thickness and the Shields-1 electronics enclosure (vault) with 3.02-g/cm^2 Z-shielding wall thickness. Table 1 shows a summary of values determined from the AP8 solar proton minimum fluence and the shielded fluences for the generic 3U CubeSat and Shields-1 electronic enclosure (vault).

Table 1. Thin-walled generic 3U CubeSat shielding and Shields-1 electronics enclosure values for minimum proton threshold and percent particles remaining. Solar minimum total proton integral fluence is 2.20E+09.

Name	Shields-1 Electronic Enclosure	Generic CubeSat (3U)
Material	AlTiTa	Al
Wall Areal Density (g/cm^2)	3.02	0.55
Total Proton Integral Fluence ($protons/cm^2$)	1.52E+08	5.68E+08
Proton Minimum Threshold Energy (MeV)	151	36.2
Effective Shielding (g/cm^2)	21.3	0.788
% Particles Remaining	6.90	25.8

The table values of the total proton integral fluence ($protons/cm^2$) were determined from the definition of an integral proton spectrum, where the total number of integrated protons is the summed value of protons for each energy binned value from highest proton energy to lowest proton energy, figure 6. The extrapolated proton minimum threshold energy assumes spherical shielding from ADJOINT Model.

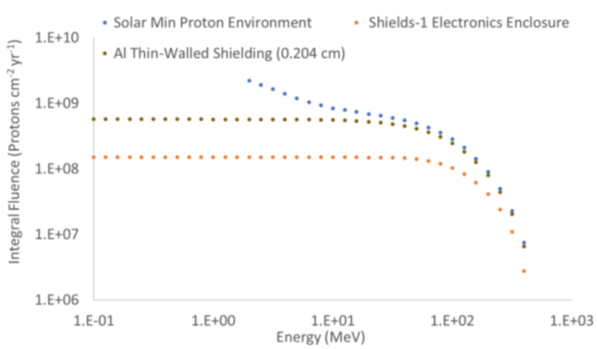

Figure 6. Proton fluences of the AP8 solar minimum environment, the Shields-1 electronics enclosure (vault), and the Al thin-walled shielding (0.204 cm). The total number of $protons/cm^2$ in the AP8 minimum or shielded environment for each plot is the highest Y-axis value.

Figure 6 proton fluences show that the total proton integral fluence is the highest Y-axis value for each plot. Table 1 shows the number of $protons/cm^2$ and percent remaining, which shows the Al thin-walled generic 3U CubeSat has 1.52 x 10^8 $protons/cm^2$, 25.8%, particles remaining in comparison with 5.68 x 10^8 $protons/cm^2$, 6.90%, particles remaining for the Shields-1 electronics enclosure. By plotting the total shielded integral fluence ($protons/cm^2$) onto the Y-axis of the AP8 min curve and extrapolating to the proton energy X-axis in figure 6, the minimum proton threshold energy is determined for each shielded fluence. Table 1 shows that the minimum proton threshold for the thin-walled generic 3U CubeSat is 36 MeV and for the Shields-1 electronics enclosure is 151 MeV. The significance of the minimum proton thresholds can be described in terms of shielding for not just the SAA energetic protons that contribute to dose, but also to single event effects for various semiconductor device hardnesses. Figure 7 shows the differential AP8 solar minimum fluence and shielded fluences. For the shielded differential fluences the reduction in overall proton numbers for each energy shows more attenuation at lower incident energies. At higher energies, above 100 MeV, table 2 shows less attenuation.

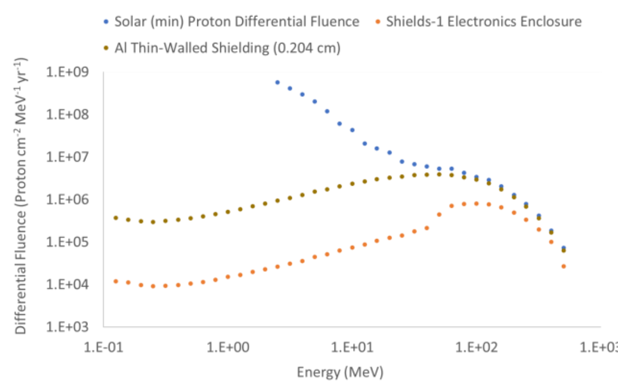

Figure 7. Differential AP8 solar minimum fluence versus shielded fluences, showing attenuation at low energies for both Al thin-walled shielding and Shields-1 electronics enclosure. At energies above 100 MeV, the Shields-1 electronics enclosure shows over 60% attenuation.

Table 2. The proton attenuation at high proton energies for Shields-1 Electronics Enclosure is greater than the thin-walled Al (0.204-cm) generic 3U CubeSat. (Percent attenuation determined by the ratio of the differential shielded fluence value at a specific energy and the AP8 minimum differential fluence at the same specific energy and multiplied by 100.)

Name	Proton Attenuation (%)		
	100 MeV	200 MeV	500 MeV
Shields-1 Electronic Enclosure	76.5	61.7	63.0
Generic CubeSat (3U)	13.7	12.4	12.6

The Shields-1 electronic enclosure attenuates protons at 76.5% for 100 MeV, 61.7% for 200 MeV, and 63% for 500 MeV, which are in the SAA and contribute to proton single event effects for a range of semiconductor hardnesses. In contrast, the thin-walled Al generic 3U CubeSat structure attenuates less at 13.7% for 100 MeV, 12.4% for 200 MeV, and 12.6% for 500 MeV, which show that there are some protons that contribute to single event effects in the SAA for thin-walled structures. For reliability and mission assurance considerations, shielding provides a mitigating approach for single event effects not just from SAA protons, but also from SPE protons.

Worst-Case SPE Estimates and Implications during Increased Solar Activity

During solar active periods, SPEs increase the proton flux over a period of days in many instances or longer. The proton single event environment increases when the energies are greater than the minimum proton thresholds for the shielding as determined in table 1. Because the SOLPRO (King) model calculations were determined for a geomagnetically unshielded environment, the total spacecraft exposure in the SPE is reduced to the times over the poles for Shields-1 and a generic 3U CubeSat operating in polar low Earth orbit. The period over the poles exposes the spacecraft to geomagnetically unshielded conditions, without Van Allen Belt attenuation. For a worst-case solar particle event, the Shields-1 electronics enclosure attenuates over a magnitude the number of protons than a thin-walled aluminum structure across the worst-case SPE spectrum, figure 8.

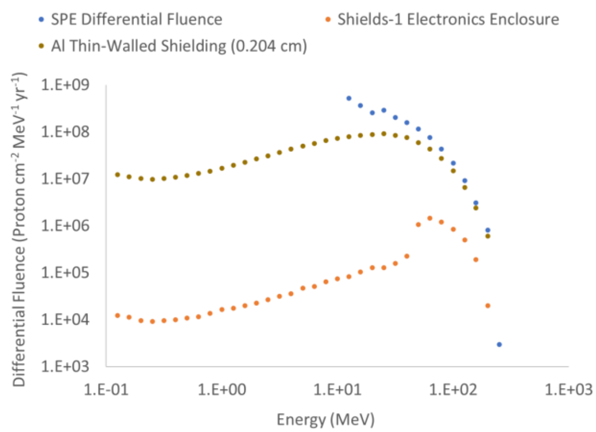

Figure 8. Differential SPE worst-case spectrum, showing magnitude level or more attenuation over all energy levels.

In figure 9, the integral proton fluence for the worst-case SPE environment shows that Al thin-walled generic CubeSat structure attenuates the total number of protons/cm^2 less than the Shields-1 electronics enclosure.

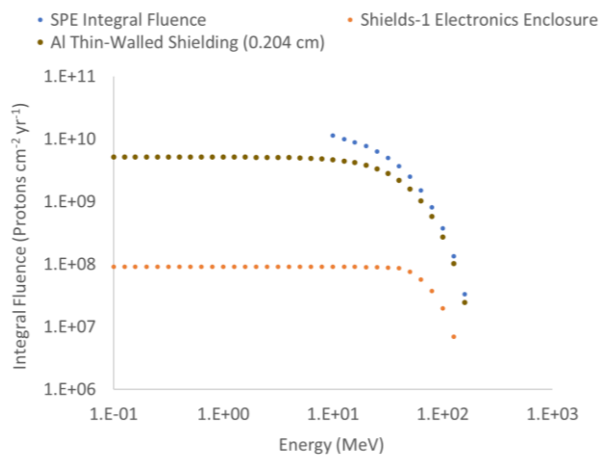

Figure 9, Worst-case SPE Integral fluence compared with shielded integral fluences of Shields-1 electronics enclosure and Al thin-walled generic 3U CubeSat shielding.

Shields-1 electronics enclosure has a 2-order reduction in SPE protons compared with less than a magnitude for the thin-walled structure, when comparing the total integral fluences in figure 9. For safety and mission assurance mitigation approaches from single event upset phenomena, the number of bit error corrections or reset frequency due to SPE protons would be significantly reduced or eliminated for most solar particle events due to the high minimum proton threshold for the Shields-1 electronics enclosure of 151

MeV, table 1. Table 3 shows that virtually all protons are attenuated with the shielding with less than 1% protons remaining for the Shields-1 electronics enclosure.

Table 3. Total SPE proton integral fluence compared with shielded fluence with Shields-1 electronic enclosure having less than 1% particles remaining and 46% for Al thin-walled generic 3U CubeSat. SPE total proton integral fluence is 1.13E+10.

Name	Total Proton Integral Fluence (protons/cm^2)	% Particles Remaining
Shields-1 Electronic Enclosure	9.14E+07	0.809
Generic CubeSat (3U)	5.15E+09	45.6

The reduction of solar particle event fluence for a shielded structure during solar maximum increases mission assurance and reliability by reducing or eliminating the probability of a proton single event upset over a short period of time of the flux increase for a SPE. NOAA describes the occurrence of varying levels from low to extreme intensity solar particle events with its reporting scales of 10 MeV flux. NOAA also tracks 50 MeV and 100 MeV channels on the GOES-16 spacecraft.[18] Based on an 11-year solar cycle and solar cycle 25 estimated solar maximum in July 2025, the number of minor intensity SPE events will be shielded completely with an Al thin-walled generic 3U CubeSat, which is estimated at approximately 50 (S1) events, because the minor intensity events have a magnitude increase in the 10 MeV flux, and the 50 MeV and 100 MeV proton channels flux counts are less or not changed. The other SPE NOAA severity (S) scale estimates for 25 moderate (S2), 10 strong (S3), 3 severe (S4), and less than 1 extreme (S5) events during a solar cycle put thin-walled aluminum generic CubeSat at risk of single event effects with increased flux in a short amount of time. The 10 MeV GOES 16 channel flux increases by magnitude for each severity from minor to extreme, and an SPE has a broad proton spectrum as shown in figure 8. The lower energy SPE protons have the higher fluence and decrease at the higher energies. The NOAA SPE number predictions for the increasing severities suggest that proton single event effects would increase in probability for increasing SPE severity, since more proton flux energies will be higher than the 36 MeV minimum proton threshold for a thin-walled aluminum structure, table 1. The challenge with CubeSat shielding is adding the mass within the volume constraints of the CubeSat standard as described with the thin-walled Generic 3U CubeSat. The Z-shielding enables increased shielding effectiveness within the constraints of thin-walled structures for not only total ionizing dose reduction, but also for proton single event mitigation, as described in table 3 by the less than 1% protons remaining for a worst-case solar particle event for the Shields-1 electronics enclosure

CONCLUSION

Shielding provides a system level mitigation for total ionizing dose and proton SEE. CubeSats have limited volume and wall thickness constraints using aluminum. The Shields-1 electronics enclosure and thin Z-Shields offer increased mass and therefore shielding for thin-walled structures, such as CubeSats. Mission assurance and reliability describes the importance of adding radiation design margin and space environment considerations during spacecraft development for all mission types including typical research technology demonstrations that use CubeSat platforms. Minimum proton thresholds increase with shielding areal density, which reduces the number of energetic protons available for total ionizing dose and SEE from the SAA or solar activity. Energetic proton attenuation reduces TID and SEE for commercial, radiation-tolerant, and radiation-hardened parts and adds mission assurance and reliability not just during solar maximum, but also for solar minimum periods.

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