Robust Simulation of Radiation Shielding Effectiveness of a Layered Composite – 23738

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ABSTRACT

Unlike other environmental factors that affect material properties, ionizing radiation is one of the more difficult factors to analyze for material response. Most difficult to experimentally simulate is the space radiation environment, where ionizing radiation is composed of multiple types including electromagnetic radiation, and particle radiation of the full elemental spectrum. While experimental exposure of materials to certain single radiation sources may be possible, other radiation types require complex facilities and great expense. Computational simulation of radiation transport through materials offers an alternative to experimental methods, though such simulations are commonly based in Monte Carlo methodology and include an uncertainty associated with the statistical convergence towards a solution. This uncertainty may be decreased with an increase in the number of particles simulated and tracked through the transport code, though simulation time increases proportionally.

This investigation proposes a process for analyzing the radiation shielding response of a layered composite for dose after shielding in a silicon detector. From this analysis a dose attenuation curve may be developed, following a standard power law trend. A Worst-Case Robust optimization is then utilized to determine the minimum areal density necessary to provide radiation shielding in consideration of the inherent Monte Carlo uncertainty. Here, areal density is minimized while guaranteeing a desired dose after shielding value will not be exceeded. With this process, a layered material may be engineered for radiation shielding purposes with computational simulation.

In this investigation, the Fluid-Filled Cellular Composite is modeled with the MULASSIS tool from SPENVIS, in order to determine its radiation shielding characteristics. The Fluid-Filled Cellular Composite is a layered, foam core composite, where the interstitial space of the core is water filled. The low Z, hydrogen dense material components of the FFCC offer good radiation shielding, so FFCC shielding response is expected to be commensurate.

INTRODUCTION

A primary challenge for space exploration is the inherent risk of extreme levels of ionizing radiation for humans as well as sensitive electronics. For humans, acute radiation sickness and risk of carcinogenesis increase with radiation exposure [1]. For electronics, risks associated with ionizing radiation come in the form of displacement damage, single event effects, and total ionizing dose effects, all interrupting the ability of the equipment to function. The harsh radiation environment of space comes in multiple forms dependent on mission type and duration. Short duration, low Earth orbit missions are primarily subject to trapped electron and trapped proton radiation associated with the Van Allen Belts. Long duration, interplanetary missions are at risk from solar energetic particles (SEPs) and galactic cosmic rays (GCRs) where highly accelerated particles and high-energy EM waves make shielding difficult. Earth's magnetic field effectively shields Earth orbits from GCR and SEP, though outside Earth's sphere of influence, spacecraft are subject to the full bombardment of the GCR and SEP spectrum. The different space missions and various types of radiation environments necessitate the use of different materials for radiation attenuation [2]. Low Z materials, especially high-density hydrogen rich materials, have been shown to provide considerable shielding in this respect [3].

To address modern needs for deep space missions, light weight, multifunctional materials are commonly utilized [4]. These materials may not be a primary radiation shielding material, but may provide passive shielding in addition to other functions in structure [2]. Layered composites are of particular use in this realm, with great strength to weight ratio, low Z components, and multifunctionality. The composite investigated in this study is the Fluid-Filled Cellular Composite (FFCC, **Fig. 1**), a foam core composite with fiber reinforced skin layers, and a fluid filled core. This material is inspired by the mammalian skull structure, where: the fiber-reinforced polymer (FRP) layers mimic the skull bone. And, the open cell foam mimics the skull meninges, the cancellous internal structure that contains the cerebrospinal fluid. This structure has multiple properties determined from past investigations including impact resistance [5] and acoustic damping [6] in addition to mechanical structure [5, 6].

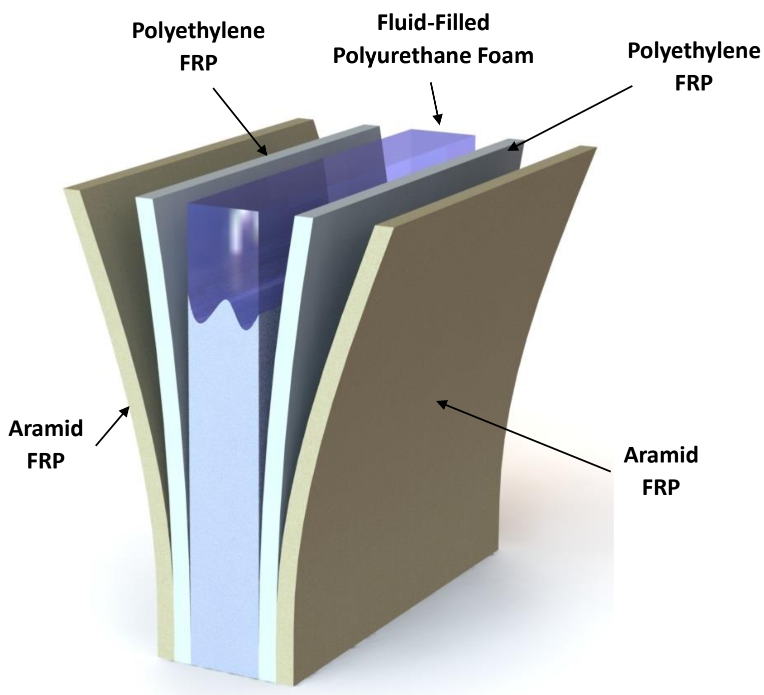

Fig. 1. Layer-wise composition of the FFCC.

TABLE 1. The Fluid-Filled Cellular Composite

FFCC Components:	Density (g/cm^3)	Areal Density Fraction
Aramid FRP	1.44	1/6
Polyethylene FRP	0.97	1/6
Fluid Filled Polyurethane Core	0.474	1/3
Polyethylene FRP	0.97	1/6
Aramid FRP	1.44	1/6

Simulation tools for particle transport through matter are useful to predict the radiation shielding effectiveness of materials in these passive shielding roles. Though many such simulations are based in Monte Carlo methodology which has an inherent uncertainty associated with statistical mechanics convergence on a solution [7]. This convergence is dependent on the number of particles simulated, whose interactions with matter are then tracked and tallied to predict dose-depth characteristics. Dependent on the simulation settings and the number of particles utilized, this uncertainty is commonly between 3% and 25% of the magnitude of the absorbed dose [8]. For a layered composite's composition to be engineered for passive radiation shielding by simulation primarily, this uncertainty is undesirable.

METHODS

The FFCC has been simulated in two space environments for total ionizing dose (TID) after shielding in a silicon detector, utilizing the method outlined by Santin et al. [9]. For simulation, the Multi-Layered Shielding Simulation (MULASSIS) tool is used within the Space Environment Information System (SPENVIS) [10]. MULASSIS is a tool for analyzing dose and fluence of layered shielding materials that utilizes and simplifies the application of GEometry ANd Tracking (GEANT4) code which was originally developed in C++.

The first environment investigated is a medium Earth orbit (MEO) of the LAPLACE mission [9] defined with: 23528 km Circular Orbit, 56.07 degree Inclination, 1 year duration starting at 01/01/2010. In this first mission, trapped electrons are dominant and the radiation environment can be seen in **Fig. 2** as Differential Flux v. Energy for the particles. Where the differential flux is the number of particles, *N*, on an incident surface over the particle energy, *E*, the time period, *t*, and normalized to the area of the surface, *A*.

$$Diff\ Flux = \frac{N}{A*E*t} \qquad \text{(Eq. 1)}$$

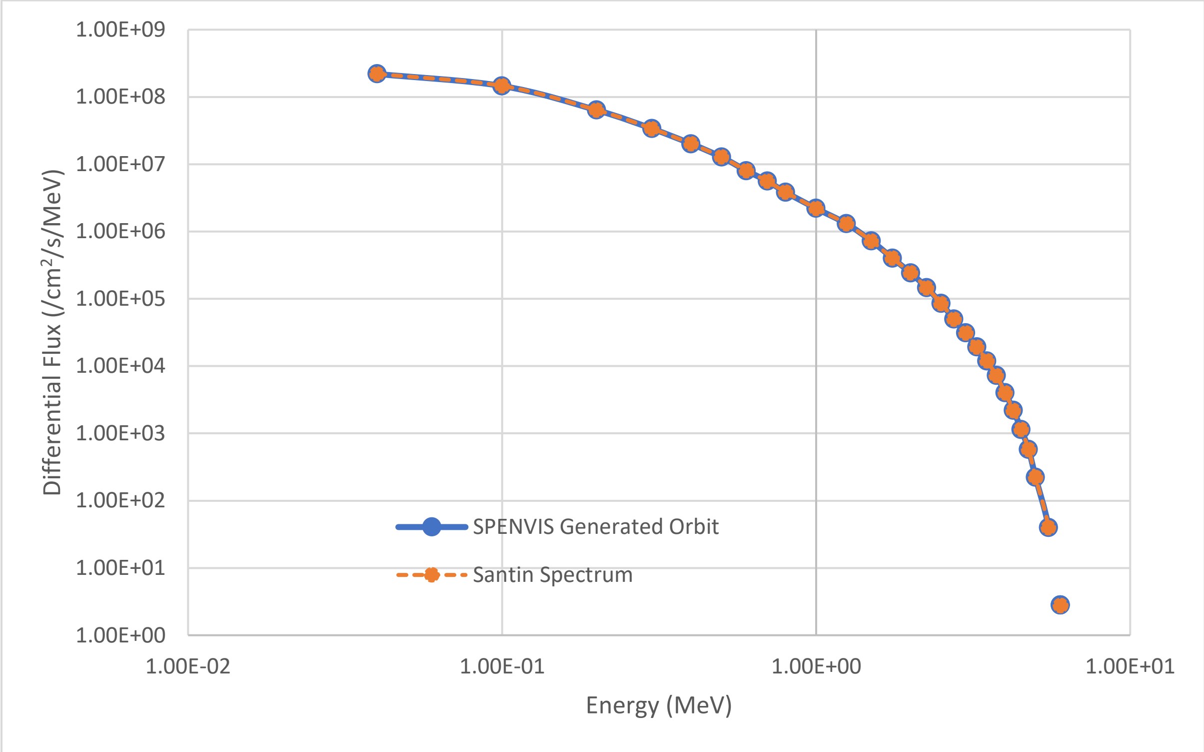

Fig. 2. Trapped Electron Spectrum AE8 Model [11], MEO. Comparison of Generated Radiation Environment with Santin Reference Values.

The second environment is an interplanetary mission inspired by the Mars Science Laboratory Mission [12]. The mission modeled in SPENVIS is in interplanetary space, at 1AU, with a duration of 254 days, beginning on 11/26/2011. This is expected to be a conservative estimate of dose for a Hohmann transfer as it excludes the greater heliocentric distances in the mission (compare to [13]). The radiation types investigated in this mission are protons (hydrogen nuclei) from SEP and GCR, as well as Helium-4 nuclei from SEP. The related radiation models utilized are the Rosenquist et al. (2005, 2007) model for SEP protons (Hydrogen-1), the ESP-PSYCHIC (total fluence) model for SEP Helium-4, and the CREME96 model for GCR protons (1-H).

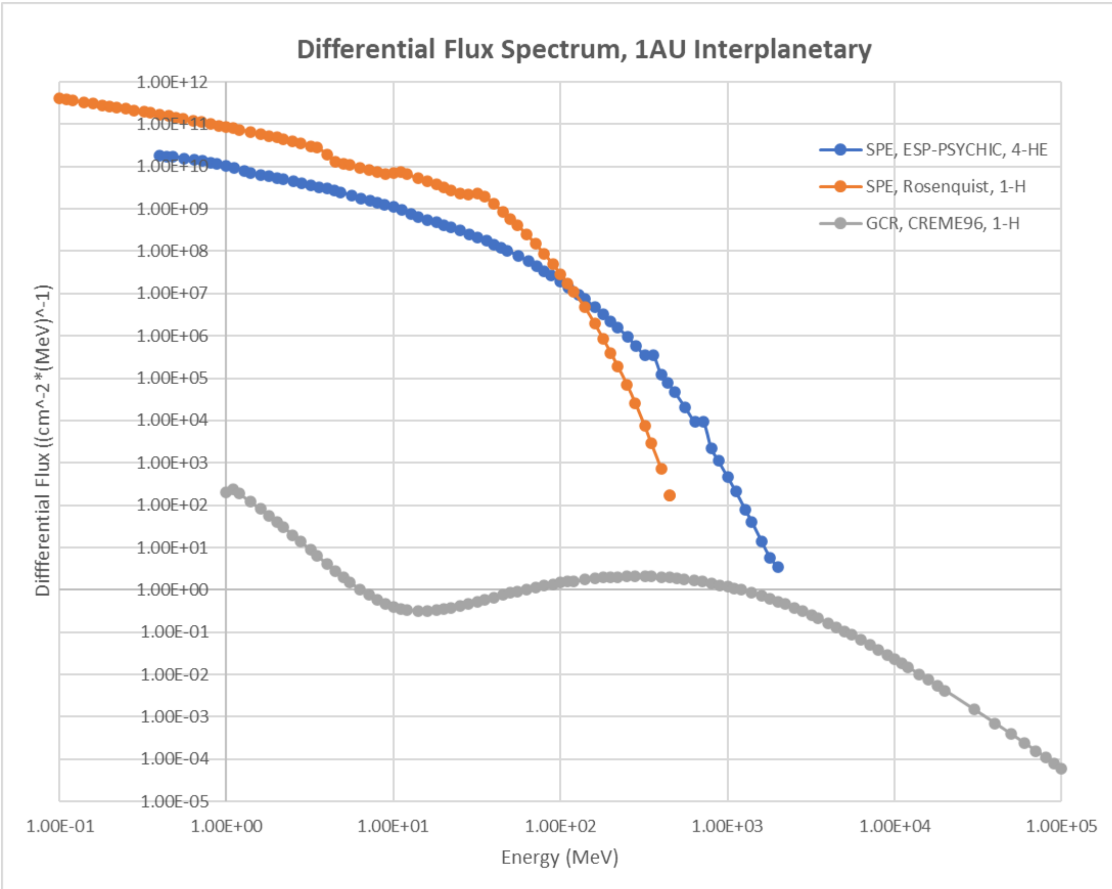

Fig. 3. GCR and SPE Radiation Spectrum Generated in SPENVIS for the interplanetary mission.

Multiple areal density values were modeled to develop a dose after shielding versus areal density curve for each shielding material. The radiation attenuation trend for each material will be considered a measure of radiation shielding effectiveness, where greater shielding is provided by materials that require lower areal densities for a desired dose after shielding. An example of this trend for can be seen for pure aluminum subject to trapped electrons in MEO in **Fig. 4**. Additionally, **Fig. 4** displays the same Aluminum material simulated with increasing number of particles in the Monte Carlo code, from 100,000, to 1,000,000, to 10,000,000 and the associated uncertainty as error bars.

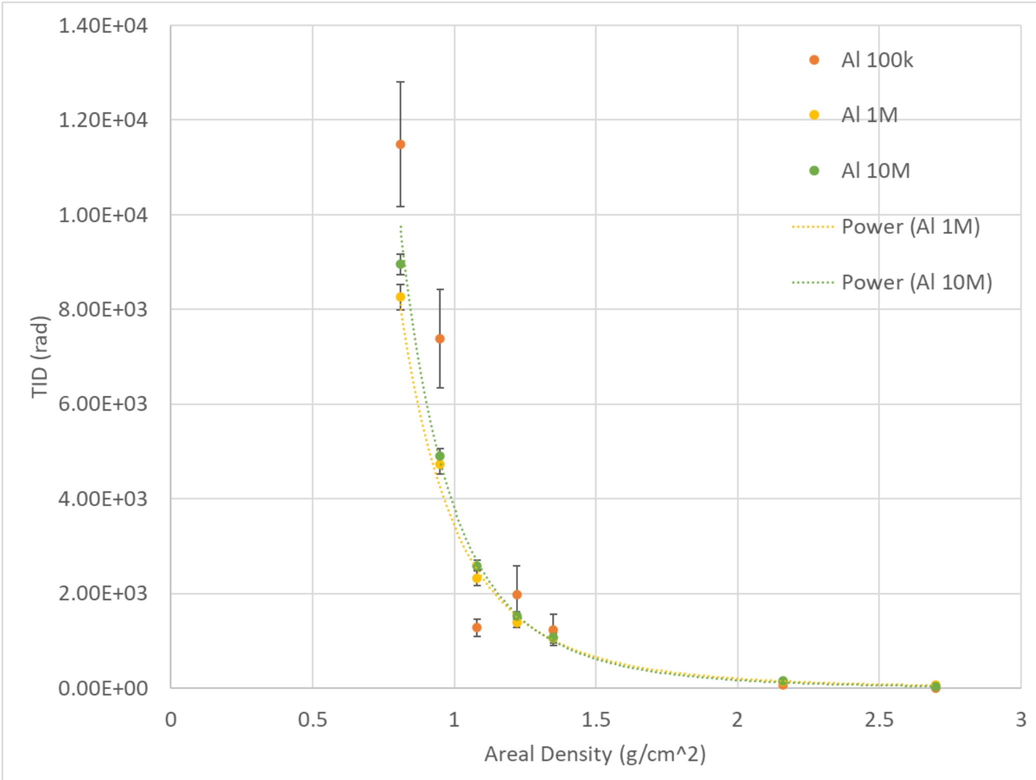

Fig. 4. Comparison of TID vs. Areal Density for Al, with 100k, 1M, and 10M particles used in simulation.

As shown in **Fig. 4**, power law trend can be fit to the TID data as a function of areal density. To account for the uncertainty from the Monte Carlo simulation, the uncertainty will be translated to upper and lower bounds on the curve fitting parameters. The power law form for the dose as a function of areal density, *x*, is given below.

$$TID(x) = \{a * x^{-b}; \alpha_L \leq a \leq \alpha_U \; and \; \beta_L \leq b \leq \beta_U\} \qquad \text{(Eq. 2)}$$

In order to find a radiation attenuation trend that guarantees a given areal density of material will shield the incident radiation to a desired level, a worst-case, robust optimization method is proposed in the standard form [14]:

$$\min(\sup(\{a * x^{-b}; \alpha_L \leq a \leq \alpha_U \; and \; \beta_L \leq b \leq \beta_U\})) \qquad \text{(Eq. 3)}$$

For engineering purposes, we add the desired constraints on the final TID value to determine an appropriate shielding thickness (as this trend asymptotes, a TID of zero is not reasonable). For example:

$$\begin{aligned} &\mathrm{TID} \leq 100 \; rad \\ &\mathrm{x} \geq 0 \; g/cm^2 \end{aligned} \qquad \text{(Eq. 4)}$$

This worst-case robust (WCR) optimization has been implemented in CVX [15] as a minimization of areal density subject to the maximum of the curve fit (with associated confidence intervals determined from uncertainty data) and the above constraints enforced.

RESULTS AND DISCUSSION

The three radiation types investigated in this analysis offer an example of the shielding response of the FFCC in two common missions representing a satellite orbit, and a mission to Mars. Similar methodology can be utilized for attenuation of any other radiation source by any planar material.

The areal density of the FFCC was scaled across layers to sum to the total areal density as shown in **TABLE 1**. This is a simplistic scaling method, though the methodology of the dose attenuation trend and following analysis are the focus of this investigation.

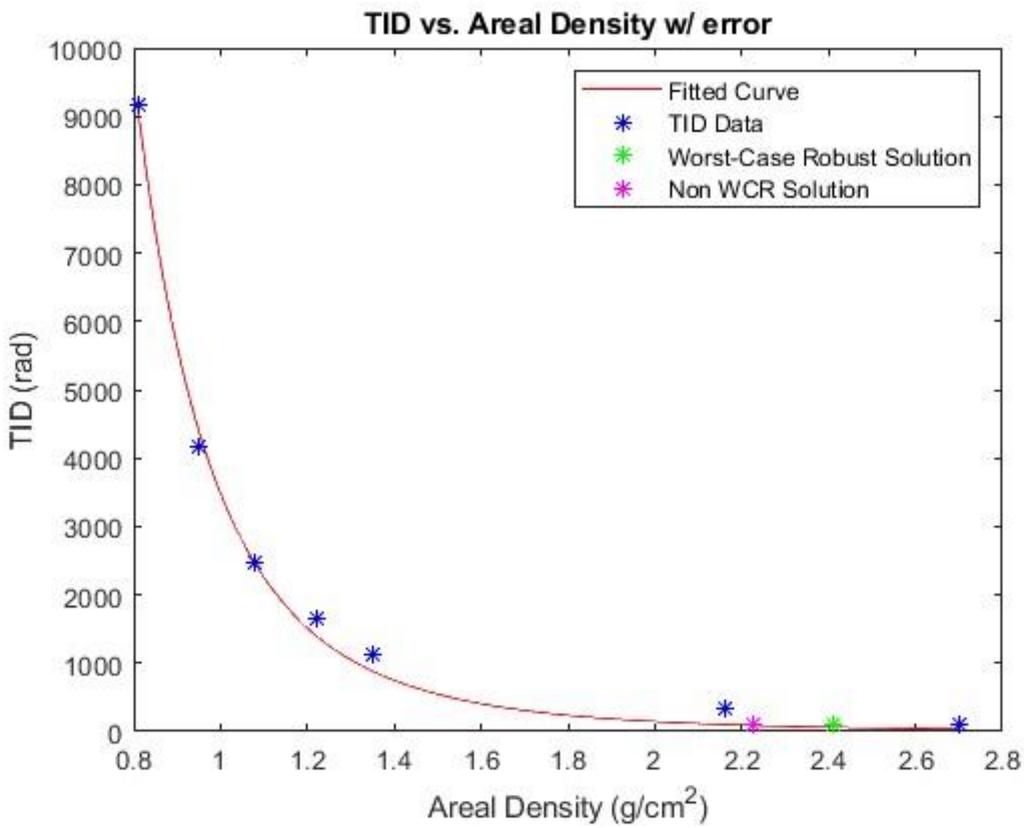

Fig. 5. Dose Attenuation Trend: MEO, AE8, Trapped Electrons

The dose attenuation of trapped electrons in MEO can be clearly displayed in the power law curve that has been fitted to the MULASSIS output data points in **Fig 5**. The green and magenta points represent the areal density value necessary to provide shielding with a maximum of 100 rad after shielding in the detector. Where, the green point includes the proposed WCR methodology and the magenta point does not. Meaning a FFCC with areal density of 2.41 g/cm^2 will shield all incident radiation to 100 rad after shielding while an areal density of 2.22 g/cm^2 may permit excess radiation by virtue of inherent Monte Carlo uncertainty.

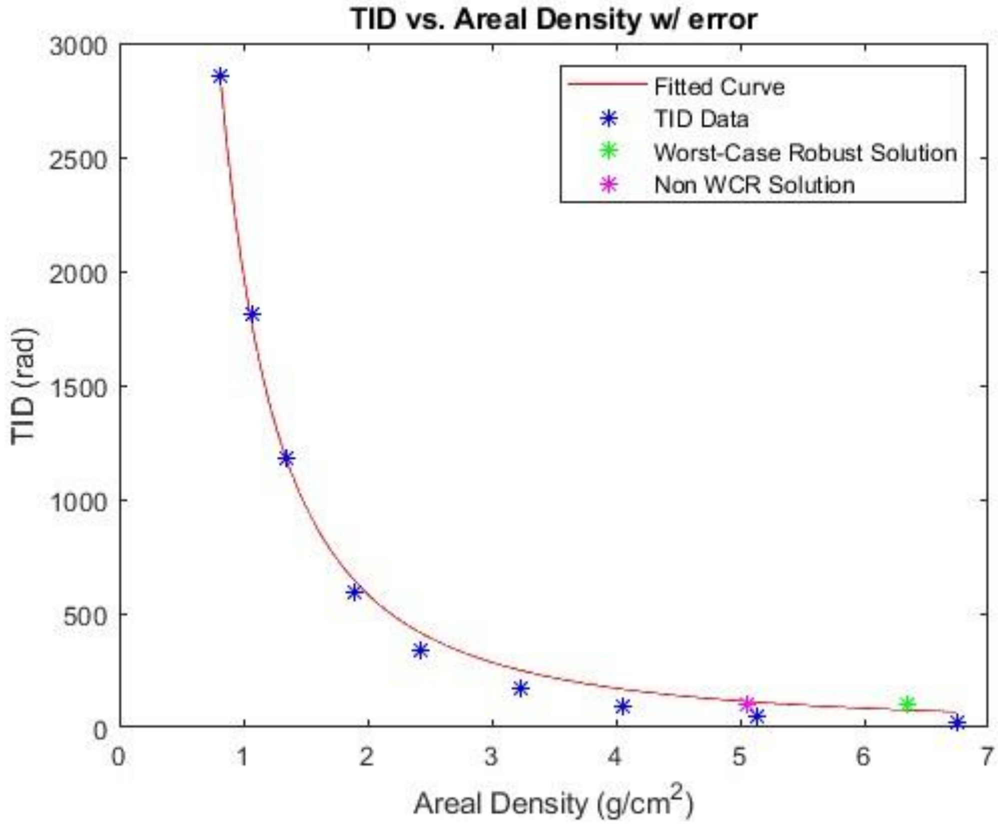

Fig. 6. Dose Attenuation Trend: Interplanetary, SEP, Rosenquist et al. (2005, 2007), H-1

Due to the harsher radiation environment of interplanetary space, increased material thicknesses are necessary to provide shielding. The solar protons modeled in this analysis (**Fig. 6**) are the most common solar particle with the highest fluence as shown in **Fig 3**. Where the WCR methodology predicts an areal density for shielding of 6.532 g/cm^2 over the trivial minimization solution of 5.063 g/cm^2.

The helium-4 particles simulated in **Fig. 7** are the next most common solar particle with the second highest fluence as shown in **Fig. 3**. In **Fig. 7**, the WCR methodology does not provide an areal density that is plainly higher in magnitude due to the position in the dose attenuation trend, though such difference does occur as a small difference in magnitude where non WCR method outputs 1.1207 g/cm^2 versus the WCR output of 1.1355 g/cm^2.

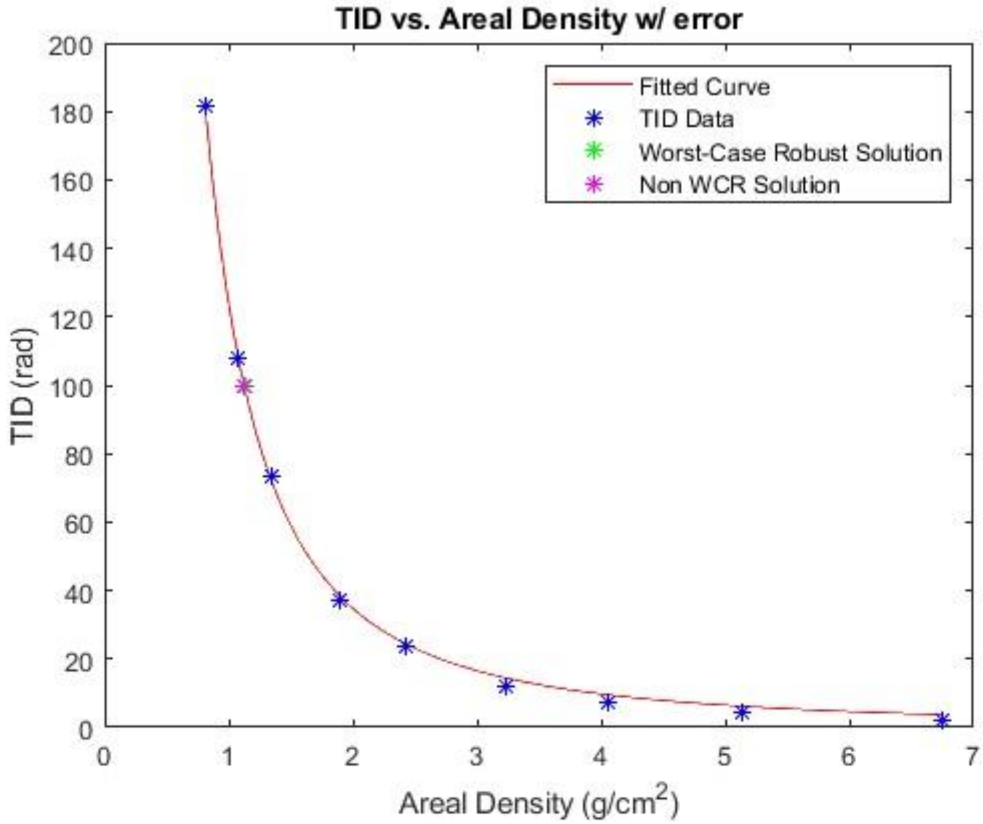

Fig. 7. Dose Attenuation Trend: Interplanetary, SEP, ESP-PSYCHIC, He-4

In comparison to pure aluminum in the same environments, the FFCC offers improved shielding in the interplanetary environment. These high energy particles commonly form secondary radiation in metals, decreasing shielding effectiveness, so the benefits of low Z shielding materials is realized to greater extent [16]. See **TABLE 2**. In comparison to polyethylene, the standard for all shielding materials [3], the FFCC provides a slightly depreciated radiation shielding.

TABLE 2. Total Ionizing Dose after Shielding, Comparison to Aluminum and Polyethylene.

TID After Shielding - Interplanetary 1AU, Rosenquist 97.7%, SEP, Proton (1-H)										
Materials	**Areal Density (g/cm^2)**									**# Particles**
	0.81	**1.08**	**1.35**	**1.89**	**2.43**	**3.24**	**4.05**	**5.13**	**6.75**	
FFCC	2855.5	1811.4	1179.0	593.8	340.7	170.6	96.5	52.3	24.5	10,000,000
Al	4160.6	2959.1	2056.5	1078.5	637.1	340.2	198.9	106.8	50.4	10,000,000
Polyethylene	2614.9	1596.7	1030.0	516.2	295.2	149.0	83.9	43.2	19.4	10,000,000
TID After Shielding - Interplanetary 1AU, ESP-PSYCHIC (total fluence) 97.7%, SEP, 4-He										
Materials	**Areal Density (g/cm^2)**									**# Particles**
	0.81	**1.08**	**1.35**	**1.89**	**2.43**	**3.24**	**4.05**	**5.13**	**6.75**	
FFCC	181.8	108.1	73.2	37.2	23.4	12.0	7.4	4.3	1.8	10,000,000
Al	303.7	186.4	127.3	67.3	39.9	22.6	13.5	8.2	4.4	10,000,000
Polyethylene	163.7	95.6	63.2	32.6	19.0	10.8	6.7	3.6	1.4	10,000,000

CONCLUSION

The methodology presented in this investigation offers a means of determining the dose attenuation trend of a layered composite material, here the FFCC, through simulation of incident energetic particles in SPENVIS/MULASSIS/GEANT4. This trend can then be utilized for engineering purposes by use of a Worst-Case Robust optimization of the shielding thickness necessary to shield radiation to a desired level. This WCR optimization method guarantees that the areal density output will provide the desired shielding in consideration of uncertainty associated with Monte Carlo based transport codes. The proposed methodology may find use when physical testing is difficult but when it is still necessary to determine the shielding effectiveness of materials that will be exposed to environmental radiation.

The FFCC offers radiation shielding that is improved in comparison to aluminum, the most common structural material utilized in space. The low Z and high hydrogen density components provide shielding that more closely resembles that of pure polyethylene.

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