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A Simple Engineering Analysis of Solar Particle Event High Energy Tails and Their Impact on Vehicle Design

*Robert C. Singleterry, Jr.
Langley Research Center, Hampton, Virginia*

*Steven A. Walker
Old Dominion University, Norfolk, Virginia*

*Martha S. Cloudsley
Langley Research Center, Hampton, Virginia*

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Abstract

The mathematical models for Solar Particle Event (SPE) high energy tails are constructed with several different algorithms. Since limited measured data exist above energies around 400 MeV, this paper arbitrarily defines the high energy tail as any proton with an energy above 400 MeV. In order to better understand the importance of accurately modeling the high energy tail for SPE spectra, the contribution to astronaut whole body effective dose equivalent of the high energy portions of three different SPE models has been evaluated. To ensure completeness of this analysis, simple and complex geometries were used. This analysis showed that the high energy tail of certain SPEs can be relevant to astronaut exposure and hence safety. Therefore, models of high energy tails for SPEs should be well analyzed and based on data if possible.

1 Introduction

Regulatory requirements^[1] are a key consideration in the radiation shielding design of a vehicle. These requirements can affect the total mass of a vehicle design and may place constraints on the mission as a whole. One element in these requirements may be a Solar Particle Event (SPE). These events may be used in determining the compliance of the vehicle to the requirements (referred to in this paper as the design basis SPE). The energy spectrum of the design basis SPE can directly influence the total vehicle mass and hence cost and capability. This paper investigates the high energy tail of three SPE models and determines their relevance to the astronaut exposure.

SPEs are bursts of protons emanating from the sun. These bursts can be caused by numerous physical processes on the sun's surface and in the corona. Usually, they are associated with a coronal mass ejection (CME) which is a large plasma cloud accelerated by the sun's corona. As the CME travels through space, the protons can be accelerated further because of the magnetic fields in the CME. SPEs can be intense and cause acute radiation risks to unprotected or under-protected astronauts. However, SPE's energy spectra vary widely and can have vastly different intensities at different energies. The combination of energy and intensity of the SPEs and the shielding of the spacecraft determines the energy available to be deposited in an astronaut. The energy deposited can be correlated to damage to an astronaut's cells and tissues which can then be correlated to risk. That risk correlation is defined in the regulatory requirements. Vehicles must be designed and operated to protect astronauts from SPEs as per the requirements. If an SPE has a large high energy component, that can mean a different vehicle design is needed than a vehicle designed to protect against a small high energy component.

Instruments on satellites are used to construct the energy spectrum of an SPE. Each deep space (outside the Earth's magnetic field) instrument's last (or highest) energy bin is unique, but the lower energy bound for this bin generally ranges from 100 to 700 MeV^[2] and includes all higher energy particles with varying detector efficiencies. However, SPEs can have proton energy tails that reach several GeV and higher, based on diffusive shock acceleration theory and through observation.^[3] Due to a lack of spectral data above 700 MeV, the data fits or models that researchers construct to represent the SPEs must then estimate the high energy tail.

On-going work to better estimate the high energy tail and augment the satellite data is using earth orbit based measurements to obtain a spectral model for the high energy SPE tails. Usually, this entails using neutron monitors on the ground to infer the intensity of high energy protons from an SPE.^[4-8] Satellite and ground level measurements are still generating large modeling uncertainties in the energy and intensity of the SPE's high energy tail. Therefore, these types of models for the high energy SPE tails are not included in this engineering analysis.

There are many methods to construct the high energy tail. This paper will look at three SPE models based on historical data. These SPEs will be used in a vehicle analysis, and then the high energy tail will be cut off to determine if the tail contributes to the whole body effective dose equivalent (H_T) as implemented in OLTARIS (On-Line Tool for the Assessment of Radiation In Space).^[9] The three SPE models are

1. August 1972 event as reported and modeled by King^[10] (generally considered a soft SPE spectrum),
2. September 1989 event as reported by Sauer^[11] and modeled by Badavi^[12] (generally considered a hard SPE spectrum), and

3. A historical data statistical event by Xapsos^[13] and modified by Slaba^[14] (generally considered a hard SPE spectrum).

Figure 1 shows the three SPE models in graphical form. The *soft spectrum* is generally considered to be less intensive at high energy while the *hard spectrum* is more intensive at high energy. The terms are qualitative and not quantitative.

The integrated proton flux, J , for the King spectrum has a mathematical model of

$$J(> E \text{ [MeV]}) = 7.9 \times 10^9 \left[\frac{1}{\text{cm}^2} \right] \times e^{\frac{30[\text{MeV}] - E}{26.5[\text{MeV}]}} ,$$

where E is in MeV. This gives a differential fluence, ψ , form of

$$\psi(E \text{ [MeV]}) = 2.98 \times 10^8 \left[\frac{1}{\text{cm}^2 - \text{MeV}} \right] \times e^{\frac{30[\text{MeV}] - E}{26.5[\text{MeV}]}} ,$$

According to King, this model gives an integrated high energy value of $J(> 100 \text{ MeV}) = 5.5 \times 10^8 \text{ cm}^{-2}$ which is taken directly from Bostrom's IMP (Interplanetary Monitoring Platforms) satellite data from John Hopkins University, Applied Physics Laboratory.^[15,16]

The Sauer data of the September 29 to October 14, 1989 event were modeled by Badavi in two distinct energy ranges: $\leq 10 \text{ MeV}$ and $\geq 30 \text{ MeV}$. A unitless quadratic function in the independent variable E (MeV) is used to smooth the values between 10 and 30 MeV. This gives a model of

$$\psi(E \text{ [MeV]}) = \begin{cases} 1.446 \times 10^8 \left[\frac{1}{\text{cm}^2 - \text{MeV}} \right] \frac{E+m}{\sqrt{E(E+2m)}} e^{\left[\frac{-\sqrt{E(E+2m)}}{102.118[\text{MeV}]} \right]} & E \leq 10 \\ (-0.0015E^2 + 0.07184E + 0.4304) \psi(10 \text{ [MeV]}) \left[\frac{1}{\text{cm}^2 - \text{MeV}} \right] & 10 < E < 30 \\ \frac{2.034 \times 10^7 \left[\frac{1}{\text{cm}^2 - \text{MeV}} \right]}{\sqrt{1 - \left(\frac{m}{E+m} \right)^2}} \left[\sqrt{\frac{E(E+2m)}{30[\text{MeV}](30[\text{MeV}]+2m)}} \right]^{-4.5} & E \geq 30, \end{cases} \quad (1)$$

where E is in MeV and m is the rest mass of the proton or 938 MeV.

Sauer reported the GOES (Geostationary Operational Environmental Satellite) data for a number of events between August and December 1989.^[11] The GOES data stopped at around 700 MeV^[17] and contain no error quantification. The model for $E > 30 \text{ MeV}$ in Equation 1 is extrapolated to high energy.

The Xapsos "event" is not a single event but a statistical event based on many individual historical events; therefore, no closed-form mathematical model exists. Since Xapsos only models satellite data to 300 MeV, Slaba^[14] used a linear extrapolation in \log_{10} space for the integral fluence out to a value of 10^{-20} cm^{-2} at 2500 MeV^a.

This paper will consider two versions of each SPE: the nominal SPE spectra, as discussed above, and a high energy cut off SPE, for which the tail of the spectra above 400 MeV has been removed. The high energy cut off version of the SPE is exactly the same as the nominal SPE below 400 MeV. A depth analysis is also included to isolate the tail from the full spectrum and determine its relevance. To assess H_T , the OLTARIS^[18] tool is used to analyze the nominal events and a command line version called TARIS, based on HZETRN, is used for the modified events. TARIS points to the same executables OLTARIS uses and is only available to the developers. The version of HZETRN currently available to the public isn't the latest version of the transport algorithms, physics, and response functions and is not used in the analysis.

Section 2 investigates the relevance of the SPE tails through astronaut exposure versus depth and isolating the tail from the rest of the SPE in determining astronaut exposure. Section 3 uses a specific vehicle to determine if the SPE tail has relevance in a full vehicle analysis. Section 4 summarizes the output of these analyses and makes recommendations about creating the design basis SPE in the future.

2 Depth Analyses

The astronaut response function used in this analysis is the OLTARIS H_T .^[9] H_T is a weighted sum of organ mass averaged dose equivalents.

^aOnce the integral fluence is generated, it is numerically differentiated to obtain the spectral fluence, and interpolated to the OLTARIS energy grid. This method preserves the integral fluence $J(> 1 \text{ MeV})$.

2.1 H_T versus Depth

The King and Sauer SPEs are analyzed versus aluminum depth for the nominal and high energy cut off^b. Figures 2 and 3 show the results for the King and Sauer SPE, respectively. As shown for the King SPE, the values of the fluence above 400 MeV are not relevant to the H_T . However, for the Sauer SPE, the fluence values above 400 MeV are relevant. These results are obvious as the King SPE is a soft spectrum, and the Sauer SPE is a hard spectrum.

2.2 H_T versus Low Cut Off Energy versus Depth

Another method for investigating the relevance of the SPE tail is to isolate the tail from the entire SPE and determine its direct relevance to H_T . Therefore, a “low cut off energy” is defined where the SPE is cut off (set to zero) below a cut off energy. Then, H_T is calculated for that new, low cut off energy distribution at numerous aluminum thicknesses (0 to 100 g/cm²). Figure 4 shows these results for the King and Sauer SPEs. The H_T at each aluminum thickness is shown at the low cut off energy values. At each low cut off energy value, the identity or value of the thickness is irrelevant as the general behavior of H_T through the thickness is what is relevant. However, H_T monotonically decreases through the thickness as shown in Figures 2 and 3.

For the King SPE, the H_T at a low cut off energy of 400 MeV for all thicknesses is three to four orders of magnitude below the nominal SPE (a low cut off energy of 0 MeV) and has a large negative slope. This large negative slope at 400 MeV and above shows that a small increase in the low cut off energy results in a large reduction of H_T leading to the tail not being relevant (as the low energy particles dominate the determination of the H_T). The results at 400 MeV and above confirm that for the King SPE, the high energy tail is not relevant. This is not the case for the Sauer SPE at 400 MeV and above. At a low cut off energy of 400 MeV, the values are less than two orders of magnitude below the nominal and have small negative slopes. Therefore, the high energy tail is relevant for this SPE.

In a real vehicle, the thickness of the vehicle varies greatly in all directions from the point of interest (or the astronaut phantom). As shown above, the SPE tail can be relevant, and an analysis in a real vehicle is performed in the next section.

3 Vehicle Analysis

The vehicle model used for this analysis is a version of the Habitat Demonstration Unit (HDU) which was originally developed and analyzed to represent a lunar habitat.^[19] This original model represented the “as-built” HDU and not a deployable space habitat. This means that a few of the necessary sub-systems were included in the main section (lower level), but the habitat was largely empty. The analyzed vehicle was outfitted for a one year, four person, free space mission; therefore, legs and stairs were removed and equipment, cargo, and consumables appropriate for a one year mission were placed on-board. From that research, the best vehicle configuration was chosen for this analysis and is shown in Figure 5. Here, “best” means the least mass for 70% reduction in H_T for the Xapsos event with Slaba’s tail for the nominal female astronaut.^[19] The astronauts are in their crew quarters during the SPE. The vehicle was arranged so that cargo was placed between the crew quarters and the pressure vessel. In addition, the crew quarters were outfitted with water walls 10 cm thick.

The vehicle being analyzed originated as a CAD (Computer Aided Design) model. A ray trace plugin exists and is used to extract material thicknesses from a point within the vehicle because the transport engine within OLTARIS is one dimensional.^[18] Five vehicle points, representing the approximate locations of the astronaut’s head, chest, pelvis, thighs, and calves, are used, and each of the human body ray traces for approximately 1000 body points are combined with the vehicle ray trace for the closest of the five vehicle points. A dose equivalent versus thickness database is generated for three materials: aluminum, polyethylene, and tissue, in that order. The approximately 1000 body point plus vehicle point thickness files are interpolated over the dose equivalent database, and organ averaged dose equivalents are determined. These average values are then summed with appropriate weights to determine H_T .

While the TARIS analysis is not complex, the results were confirmed against OLTARIS. For this confirmation, the five vehicle thicknesses were uploaded into OLTARIS and an analysis was performed with the

^bThe Xapsos model isn’t available on OLTARIS, so it was not included in the analysis.

King and Sauer SPEs. The OLTARIS and TARIS values are shown in Table 1 and they indicate that the TARIS analysis is complete and verified.

Using the verified TARIS analysis, the King, Sauer, and Xapsos nominal and high energy cut off tail SPEs are analyzed. Table 2 shows the H_T results of the analyses along with the nominal integrated fluence above 400 MeV for each SPE.

The King SPE's tail is not relevant as the differences between the 400 MeV high energy cut off and the nominal H_T value is less than one percent as shown in Table 2. The non-relevance is also shown in Figures 2 and 4. The King tail simply isn't intense enough at high energy to be relevant to the H_T response function in the vehicle modeled.

The Sauer SPE's tail is relevant as approximately 41% of the H_T comes from the protons above 400 MeV as shown in Table 2 between the nominal and 400 MeV high energy cut off. However, the tail is just an extrapolation of the model that reflects the measured data to about 500 MeV with no error analysis provided.

The Xapsos SPE's tail is also relevant as approximately 23% of the H_T comes from the protons above 400 MeV as shown in Table 2 between the nominal and 400 MeV high energy cut off. The $J(> 1 \text{ MeV})$ value is preserved with the choice of the extrapolation point 10^{-20} cm^{-2} at 2500 MeV; however, the accuracy of the $J(> 1 \text{ MeV})$ value in comparison to the measuring devices used is in question as no error analysis is provided.

For these three SPEs, there does not appear to be any indicator within the model spectrum itself to show that the high energy tail is relevant to the particular response function used in this paper, H_T . As is shown in the last column of Table 2, the integrated fluence values above 400 MeV ($J(> 400 \text{ MeV})$) are not a direct indicator of the relevance of the SPE's high energy tail. The 400 MeV high energy cut off to nominal H_T values for the King, Sauer, and Xapsos SPEs are 0.7%, 41%, and 23%, respectively. The Xapsos $J(> 400 \text{ MeV})$ value is approximately 1.5 times the Sauer value yet the Sauer tail is 18% greater than the Xapsos tail. The value of the model SPE at 400 MeV also isn't an indicator as it has the same problem as the $J(> 400 \text{ MeV})$ value.

4 Recommendations

From Table 1, the TARIS analysis methods are sound and reproduce the OLTARIS results which have been verified through an independent analysis.^[18] The TARIS analysis generated results for the King SPE in Figures 2 and 4 and for the Sauer SPE in Figures 3 and 4.

The King SPE high energy tail ($E > 400 \text{ MeV}$) has little relevance to the H_T response function as shown in Figure 2. Even in a detailed vehicle, Table 2 shows that the King SPE's tail is of little relevance because it has a less than 1% relative error between the nominal and high energy cut off SPE. For the Sauer SPE, the high energy tail contributes to the H_T response as shown in Figure 3, and therefore, at least based on the algorithm used, the tail is relevant. With a detailed vehicle, the Sauer SPE's tail is also relevant as shown in Table 2 with a 41% relative error difference between the nominal and high energy cut off SPE. The Xapsos tail has the same characteristics as the Sauer tail with a 23% relative error difference between the nominal and high energy cut off SPE.

The nominal models used in this analysis may or may not represent the actual SPE's high energy tail. However, the models are all that are available for characterization of the SPEs within shielding models as used in this analysis. For the King SPE, the tail is not relevant; however, for the other two SPEs, the tails are relevant. As seen from Table 2, if the model's tail is not accurate to the actual event's tail and the high energy tail effects H_T , then the difference between the actual and model tail can ultimately drive a vehicle's design (items like mass, cost, mission objectives, etc.). Therefore, the results of this analysis indicate that the design basis SPE high energy tail used for vehicle design should be well analyzed, understood, and tied to data, if it exists, and not just created to fit the low energy data. While this paper does not recommend any SPE for the design basis or method to investigate the SPE high energy tail, this paper does acknowledge that the high energy tail is an item that needs analysis for the characterization of a design basis event.

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Table 1: The OLTARIS and TARIS H_T results of the King and Sauer SPEs used for verification of the TARIS algorithm in cSv.

King		Sauer	
OLTARIS	TARIS	OLTARIS	TARIS
3.674798	3.674799	3.955958	3.955958

Table 2: Nominal and 400 MeV high energy cut off TARIS H_T results with relative errors and the integrated fluence above 400 MeV for nominal King, Sauer, and Xapsos SPEs.

SPE	Nominal cSv	400 MeV High Energy Cut Off		$J(> 400\text{MeV})$ cm^{-2}
		cSv	Rel Err %	
King	3.674799	3.698713	-0.650757	6.81911×10^3
Sauer	3.955958	2.344842	40.726317	1.09503×10^7
Xapsos	12.40322	9.587092	22.704814	1.52727×10^7

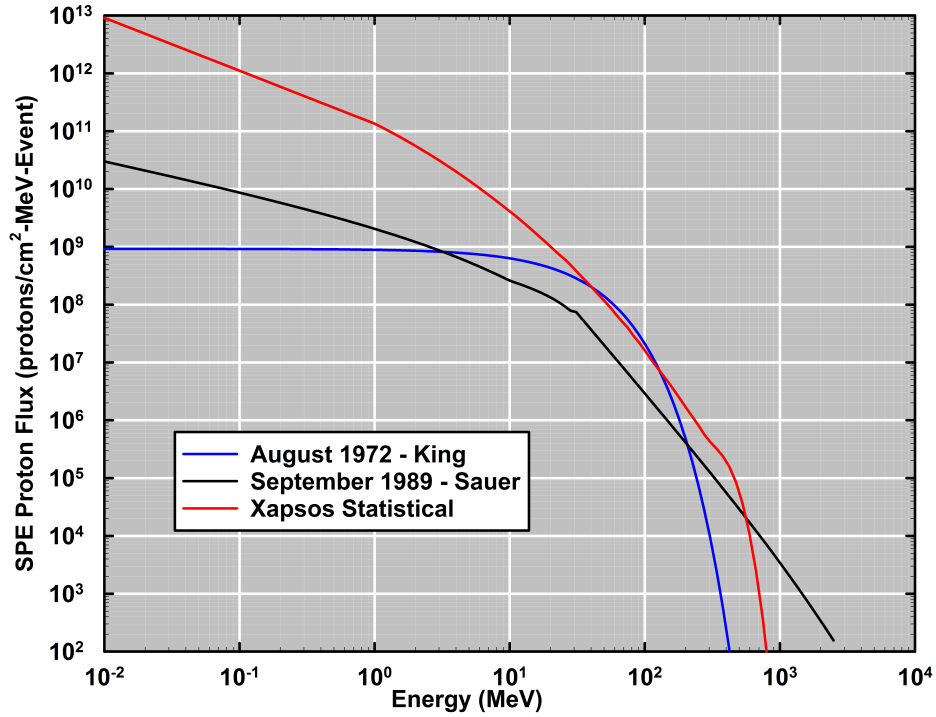


Figure 1: SPE proton flux versus energy for the King, Sauer, and the statistical Xapsos nominal models.

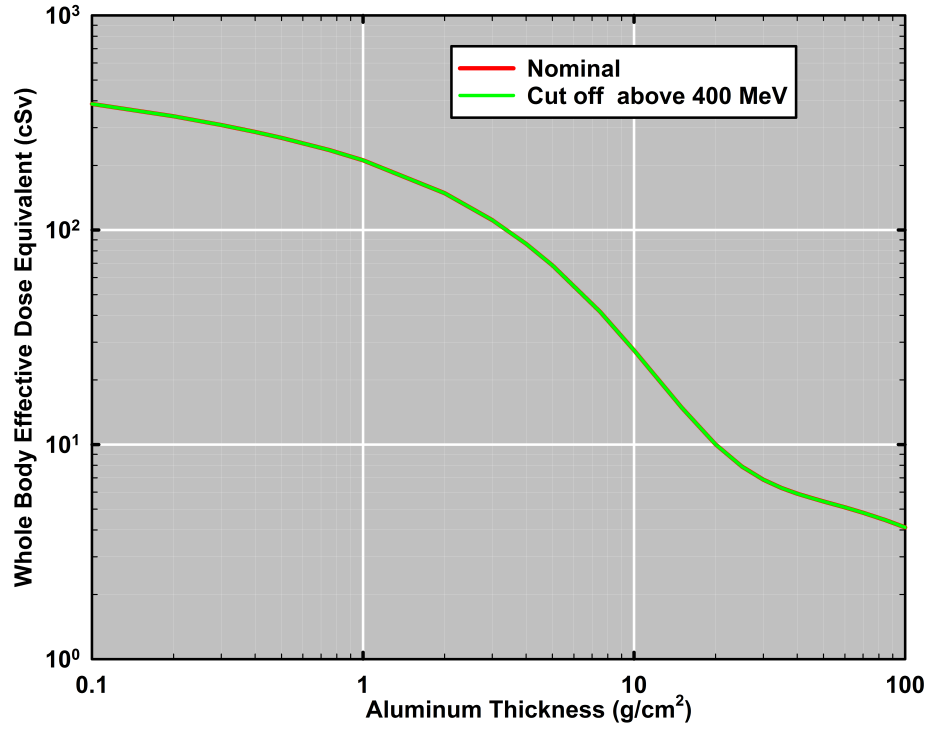


Figure 2: H_T versus depth for the nominal King SPE and the high energy cut off SPE.

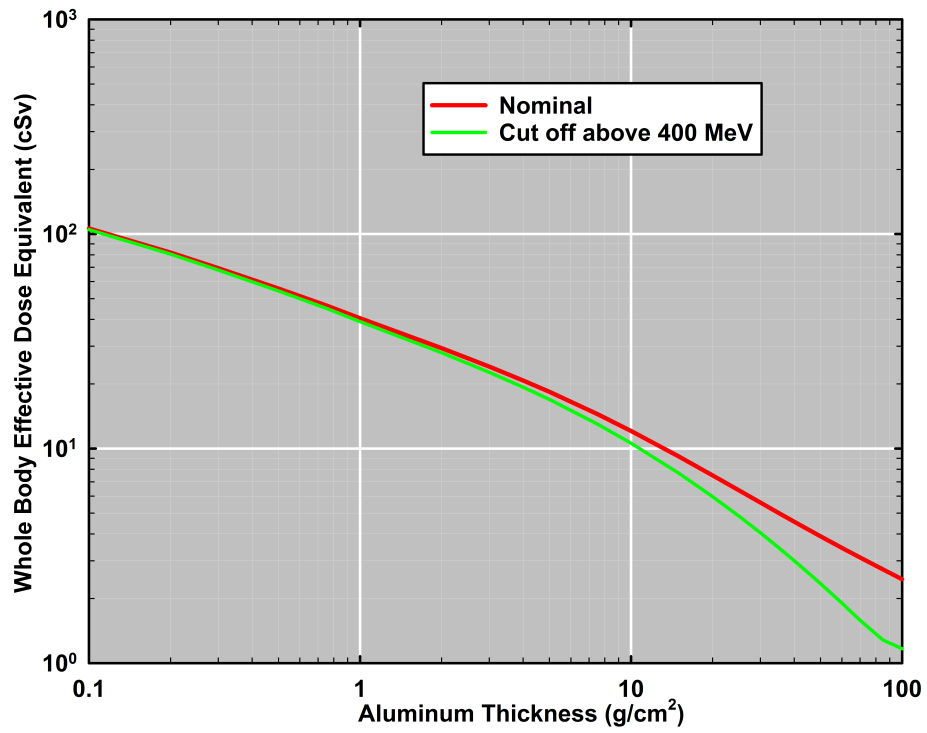


Figure 3: H_T versus depth for the nominal Sauer SPE and the high energy cut off SPE.

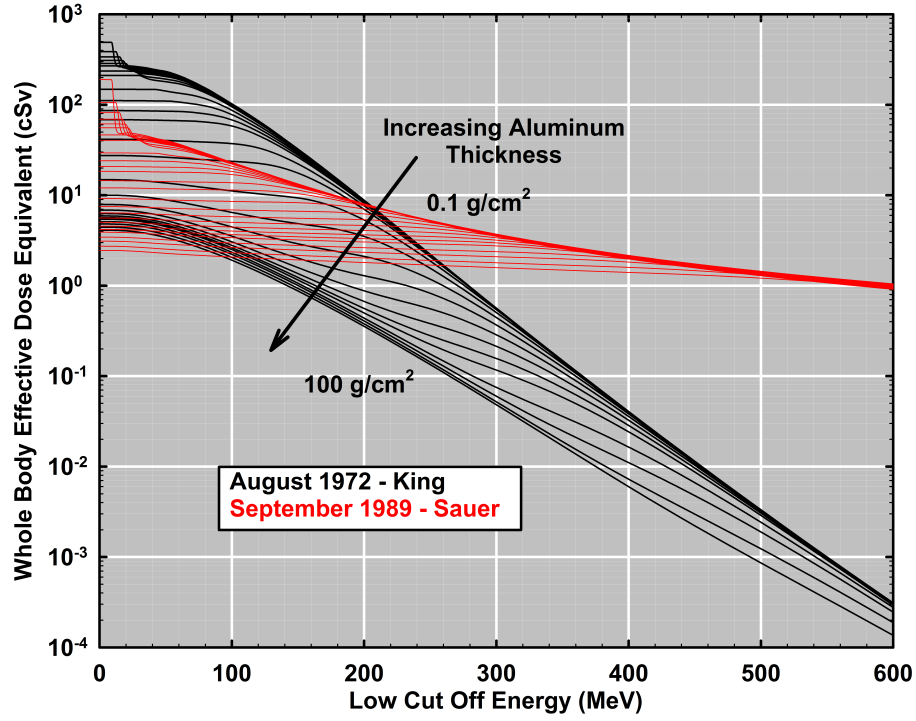


Figure 4: H_T as a function of the low cut off energy for the King and Sauer SPEs over all Aluminum thicknesses.

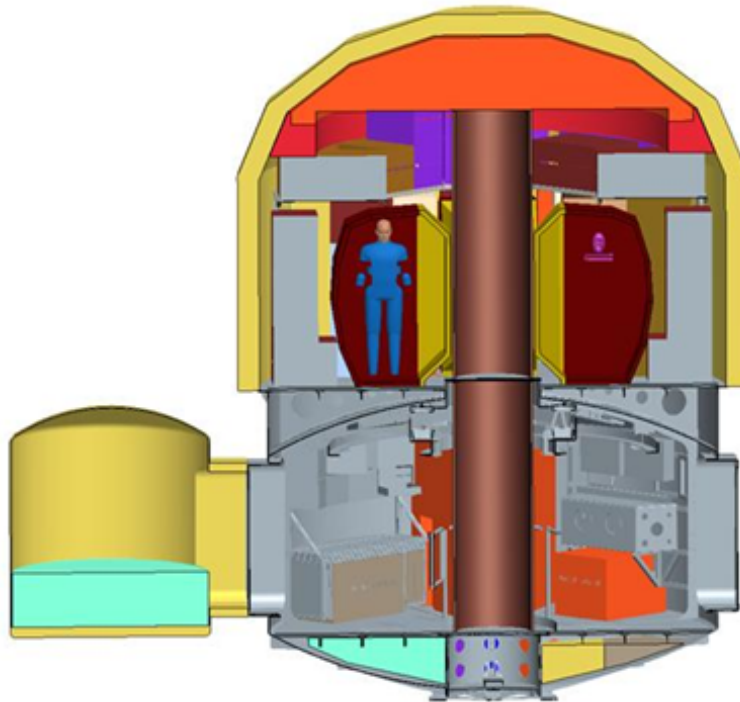


Figure 5: The vehicle configuration used in the initial analysis that gave the best mass and reduced the astronaut exposure by 70% for the Xapsos SPE.^[19] The pink, female phantom head and shoulders is the target phantom and the phantom in blue is a fellow astronaut.

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14. ABSTRACT The mathematical models for Solar Particle Event (SPE) high energy tails are constructed with several different algorithms. Since limited measured data exists above energies around 400 MeV, this paper arbitrarily defines the high energy tail as any proton with an energy above 400 MeV. In order to better understand the importance of accurately modeling the high energy tail for SPE spectra, the contribution to astronaut whole body effective dose equivalent of the high energy portions of three different SPE models has been evaluated. To ensure completeness of this analysis, simple and complex geometries were used. This analysis showed that the high energy tail of certain SPEs can be relevant to astronaut exposure and hence safety. Therefore, models of high energy tails for SPEs should be well analyzed and based on data if possible.					
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