

Radiation Exposure Analyses Supporting the Development of Solar Particle Event Shielding Technologies

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NASA has plans for long duration missions beyond low Earth orbit (LEO). Outside of LEO, large solar particle events (SPEs), which occur sporadically, can deliver a very large dose in a short amount of time. The relatively low proton energies make SPE shielding practical, and the possibility of the occurrence of a large event drives the need for SPE shielding for all deep space missions. The Advanced Exploration Systems (AES) RadWorks Storm Shelter Team was charged with developing minimal mass SPE storm shelter concepts for missions beyond LEO. The concepts developed included “wearable” shields, shelters that could be deployed at the onset of an event, and augmentations to the crew quarters. The radiation transport codes, human body models, and vehicle geometry tools contained in the On-Line Tool for the Assessment of Radiation In Space (OLTARIS) were used to evaluate the protection provided by each concept within a realistic space habitat and provide the concept designers with shield thickness requirements. Several different SPE models were utilized to examine the dependence of the shield requirements on the event spectrum. This paper describes the radiation analysis methods and the results of these analyses for several of the shielding concepts.

I. Introduction

THE space radiation environment beyond LEO results from the combination of galactic cosmic rays (GCR), solar particle events (SPEs), and secondary particles resulting from interactions of the charged ions of these environments with the materials surrounding the astronauts. Galactic cosmic rays are a low intensity, ever present background radiation consisting of nuclei covering the entire periodic chart. Due to their high energies, GCR penetrate materials easily, and therefore, even large quantities of shielding material may not provide enough protection for astronauts for long duration missions. In contrast, large solar particle events are rare and their durations are measured in hours to days. Shielding materials are effective at reducing astronaut exposure to these events because SPEs are made up primarily of low and medium energy protons. Therefore, if adequate shielding is provided, the SPE risk can be managed through appropriate design and operational considerations.

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Because of the nature of an astronaut's exposure that results from a SPE, adequate shielding *could* be provided by simply surrounding a vehicle with a large enough quantity of shielding materials. However, it is cost prohibitive to launch the necessary mass to shield an entire space habitat or vehicle when that mass is dedicated only to radiation shielding (purely parasitic) and serves no other function. For this reason, the objective of any SPE protection plan should be to reuse and, where necessary, reconfigure available onboard mass to shield a smaller area within the vehicle or habitat to provide a temporary refuge: a SPE storm shelter. In this way, the need for parasitic shield mass can be minimized or perhaps eliminated.

NASA's Advanced Exploration Systems (AES) projects were created to advance the readiness levels of existing technologies to the level needed for exploration missions. The AES RadWorks project is focused on reducing astronaut risk to space radiation through the development of improved dosimetry and shelter concepts. The RadWorks Storm Shelter team was charged with designing minimal mass shield concepts for SPE protection. Four concepts of protection were developed: a "wearable" shield, an individual protection concept, a group protection concept, and a shielding augmentation to the crew quarters. All of these protection schemes were designed to leverage onboard structure, logistics, food, or other consumables.

The protection provided by each of the shielding concepts was analyzed with the radiation transport codes, human body models, and vehicle geometry tools contained in OLTARIS¹ (On-Line Tool for the Assessment of Radiation in Space - <http://oltaris.nasa.gov>) developed at the NASA Langley Research Center. OLTARIS enables the evaluation of structures from a simple one dimensional single material slab to materially and structurally complex spacecraft. OLTARIS also contains detailed human geometry, allowing evaluation of radiation exposure to humans in addition to spacecraft. The transport algorithm used by OLTARIS is based on the High charge (Z) and Energy TRaNsport (HZETRN)^{2,3} deterministic code, which was also developed at NASA Langley Research Center. HZETRN can be used to rapidly perform transport calculations, allowing (through OLTARIS) the inclusion of radiation analysis in the design cycle of a spacecraft. OLTARIS also enables rapid trade studies where a small number of vehicle parameters may be varied to see the impact design choices can have on radiation protection.

The remainder of the paper is organized as follows. Section II provides a description of the shelter concepts analyzed in this study. Section III describes the habitat assumed for the analysis of the concepts and the necessary geometry handling. Section IV describes the analysis process used. Section V describes the baseline analyses. Section VI presents the results of the analyses for each shelter concept. Section VII presents conclusions. It is important to note that the goal of this paper is not to champion a particular concept, but to provide information to designers so they can decide what would work for them.

II. Description of Shielding Concepts

Four categories of shielding ideas were investigated: wearable protection, deployable shelters for individuals, deployable group shelters, and augmentations to the crew quarters. For each of these four concepts, a Computer Aided Design (CAD) model of the concept was generated and placed into the habitat shielding model. A detailed description of each of the shielding concepts follows.

A. Wearable Shielding Concept

In order to minimize the material necessary for protecting individual crewmembers, a wearable protection strategy of augmenting crew sleeping bags with water bladders or logistics was proposed. By protecting crew members directly, the mass of the protection medium is minimized. By using the sleeping bags, work and sleep can be accommodated in a space proven to be habitable. Additionally, sleeping bags are portable, so protection could be maintained while moving within the habitat.

Two variations in wearable concepts were evaluated. The first was a sleeping bag with an integrated water bladder, as shown in Fig. 1a. The bladders were pre-integrated into the sleeping bags and could be either pre-filled or filled as needed for a SPE. A detachable, water-filled hood was added to the sleeping bag to provide protection to the head and neck. Baffles were provided to maintain the desired shape when the bladders are filled. Upper and lower body sections were designed as separate pieces which would be overlapped to aid mobility while maintaining complete protection of blood-forming organs.

The second variant was to use a sleep restraint as a base, and add on top of it a 'dragon scale'-like grid of overlapping pockets filled with food pouches and/or trash formed into 'green bricks' (also known as heat melt compact bricks, or HMC bricks), as shown in Fig. 1b. This logistics-based wearable variant could be used in combination with or in lieu of a water-based system. In this concept, pockets of food pouches and green bricks could be pre-filled in rows that would fold up accordion-like for storage, or the entire grid could be one integrated object (see Fig. 1b) and stored folded up. Each row of pouches would have straps and/or Velcro for fast deployment onto a

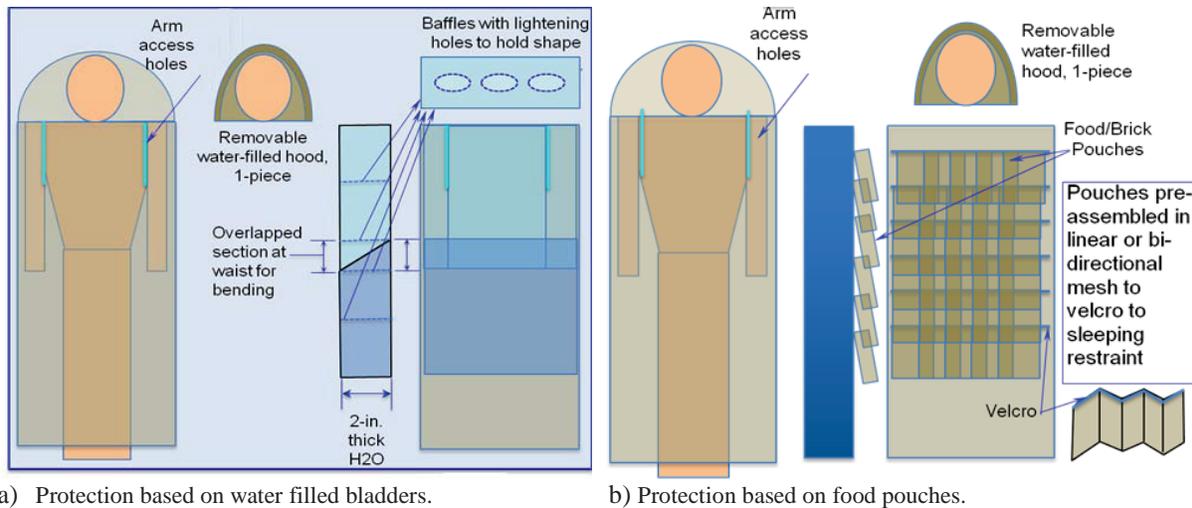


Figure 1. Wearable shielding concepts.

sleep restraint system. This system would be deployed at the onset of a SPE. A detachable, water-filled hood would also be added to this system to provide protection to the head and neck.

B. Deployable Shielding, Individual Protection Concept

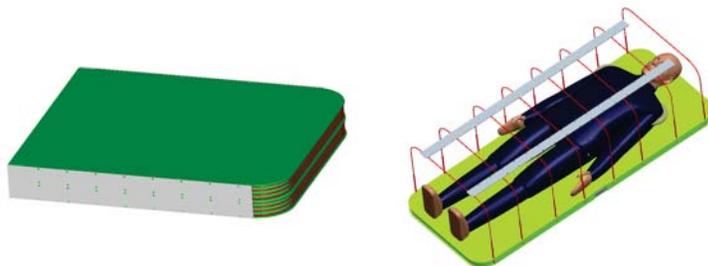


Figure 2. Individual protection deployable shielding concepts.

The individual shelter concept had as a base (backing) a two-part hinged water containment system. This backing would contain some of the contingency life support water. Each half of the backing held shelter frame supports, thin squared U-shaped rods (the red in Fig. 2). These rods were placed into pre-existing holes to create the spacing between the astronaut and the protection medium, and would have thin metal strips as a stiffener. Figure 2a shows the deployable shelter in its stowed configuration, and Fig. 2b shows the internal structure of the shelter after it

had been deployed. HMC bricks, cargo transfer bags (CTBs), food storage, etc. could serve as the protection medium and could be pre-integrated into sheets, similar to those used for the sleep restraint variant of the wearable concept, which could be attached to the deployed shelter framing.

C. Deployable Shielding, Group Protection Concept

A group shelter concept would ideally be positioned in an already protected area and built out of moveable structural components, possibly augmented by repositioning logistics to provide added shielding. The concept, as implemented in this study, used floor/ceiling structural panels, augmented by the ability to add water to a hollow core within the panels, to create a shelter in the central core of the habitat that ran from the main section floor to the lower loft. In Fig. 3a, the brown column rising through the middle of the core section of the habitat roughly defines the volume this concept would protect. Additional panels provided a cap at the top of the lower loft. These water filled panels could also serve as attachment points for pre-bundled logistics to enhance the shelter's protection, as shown in Fig. 3b.

D. Augmentation to Crew Quarters Concept

This concept utilized crew quarters similar to those in the International Space Station (ISS), but with integrated hollow structural walls that would be filled with water to provide radiation protection. Figure 4 shows a single ISS-

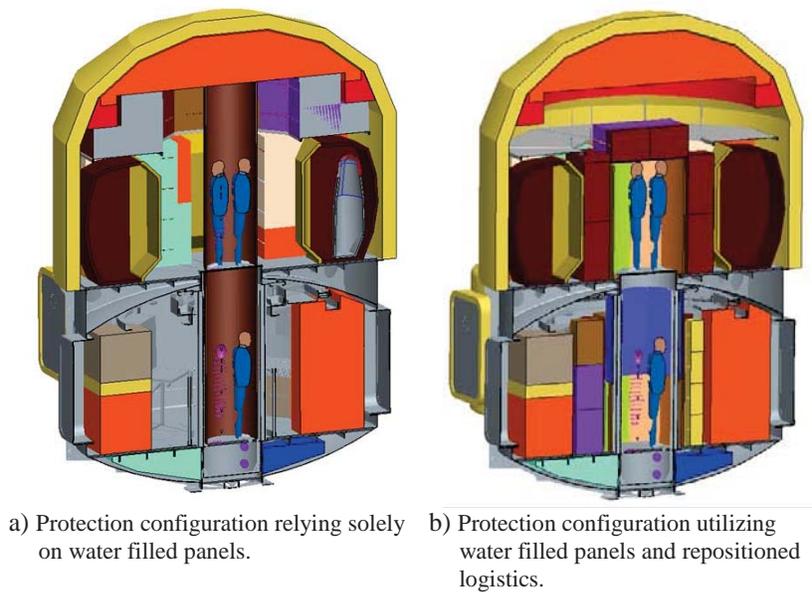


Figure 3. Deployable group protection shielding concept.

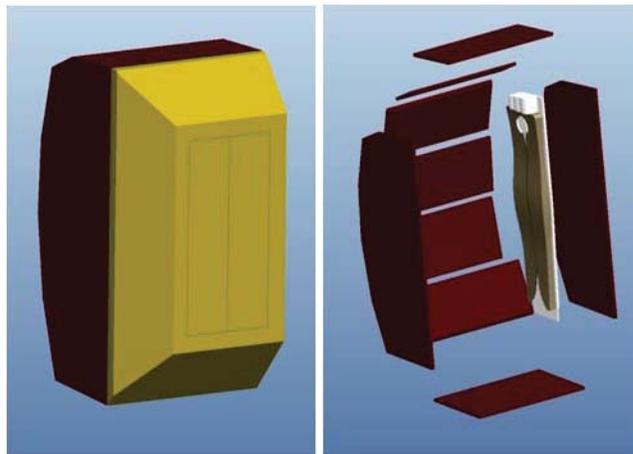


Figure 4. CAD model of the crew quarters. The white and grey object is the sleep restraint.

type crew quarter which had been redesigned with thick structural panels which provide containment for contingency life support system water. Figure 4a shows an exterior view of the crew quarters, with the yellow portion being the door bump out. Fig. 4b removes the door and displays an exploded view of the panels. The white and grey item is the sleep restraint. In Fig. 4b, the left-most and right-most panels are the side panels, the top-most and bottom-most panels are the top and bottom panels, and the remaining panels are the back panels. To preserve the inner mold line of the original design, the additional wall thicknesses were applied outward. Individual wall panels could be permanently filled or

filled and drained on an as-needed basis. From a radiation protection perspective, placing the crew quarters as close to the center of the habitat as possible is useful, because this could provide space between the outer wall of the habitat pressure shell and the outward wall of the crew quarters that could be filled with logistical materials to provide additional protection. The major advantage of crew quarters-based shelters was that the space within the crew quarters had been designed and proven for durations of occupation much longer than the length of an SPE. Additionally, crew members were accustomed to spending prolonged periods within their crew quarters and would have the ability to perform some of their daily tasks from this location. Another advantage was that if the walls were permanently filled with water, they would provide some degree of continuous protection from galactic cosmic rays for the crew.

III. CAD Models and Ray Tracing

Radiation analysis of a vehicle or habitat has two major parts: geometry preparation/handling and the transport calculations with analysis. The first part involves creating the radiation shield model to represent the vehicle/habitat, insuring all the parts are solid elements, every part has a material definition and density, all the needed subsystems are in place, all the logistics and cargo have been placed, there are no holes or overlaps anywhere, etc. Once the vehicle is ready to be used, human phantoms must be placed in the appropriate positions with the correct orientations. The second part is taking this starting point and performing the calculation transporting the external environment through the shielding materials and human tissue, and then calculating whole body effective dose equivalent (effective dose).⁴ This section will focus on the first step, the creation of shield models and the coupling of the shield model to the transport calculation.

A. Free Space Habitat Shield Model

The habitat model used for this project was a free space adaptation of the Habitat Demonstration Unit (HDU), shown in the first panel of Fig. 5. The HDU was originally developed to represent a lunar habitat for Human-In-The-Loop (HITL) operational testing. The HDU model, which was delivered in Standard for the Exchange of Product model data (STEP) format, was originally created in Computer Aided Three-dimensional Interactive Application (CATIA) developed by Dassault Systèmes. This model represented the “as built” HDU; not a deployable space habitat. While a few of the necessary sub-systems were included in the main section (lower level), the habitat was largely empty, as shown in the second panel of Fig. 5.

The conversion process began by importing the provided STEP files into Parametric Technology Corporation’s Pro/ENGINEER®. While maintaining the size and lay-out of the surface habitat, the HDU was converted to a free space habitat by removing external legs, staircases, etc. Numerous duplicate parts and interferences (overlapping parts) were identified and corrected, and appropriate densities were assigned for all structural and sub-structure elements. Because the number of parts requiring material assignment was large, parts were converted to be either: equivalent aluminum, equivalent polyethylene or equivalent tissue masses. Figure 5c shows the first major parts to be placed: the crew quarters. Finally, the habitat was populated with consumables and equipment appropriate for a 365 day mission as shown in the last three panels of Fig. 5, d-f. Estimating appropriate quantities of food, water, and other cargo for a one year mission and finding space for these items in the habitat was one of the major challenges of this effort. Figure 6 shows the major areas of the habitat model.

Once the HDU shield model was ready, human models were placed into the CAD model. Two types of human models were used. The first was a male ‘mannequin’, representing a 50th percentile male. This was a low fidelity model, in which all of the internal structure was smeared into an average tissue. The second model was a female ‘phantom’, which served as a place holder for a 50th percentile female, modeled here by the Female Adult voXel model (FAX).⁵ The FAX model is a high fidelity female model, based on CT (X-ray Computed Tomography) scans, in which organs and tissues are explicitly identified voxel by voxel or segmented. The FAX model was designed to comply with the International Commission on Radiological Protection (ICRP) reference female.⁶ For a more detailed treatment of FAX as used on OLTARIS, see Slaba et al.⁷

B. Ray Tracing

The coupling between the CAD geometry and HZETRN transport code is done through ray tracing. Ray tracing is done by choosing one or more dosimetry points and at each location projecting a large number of rays (in this case 1002 rays) to cover the full 4π steradians. Along each ray, the intersection of the ray with each model part is recorded. Figure 7 shows an example of ray tracing performed on an International Space Station (ISS) model, where the red lines are the intersections between model elements and individual rays.

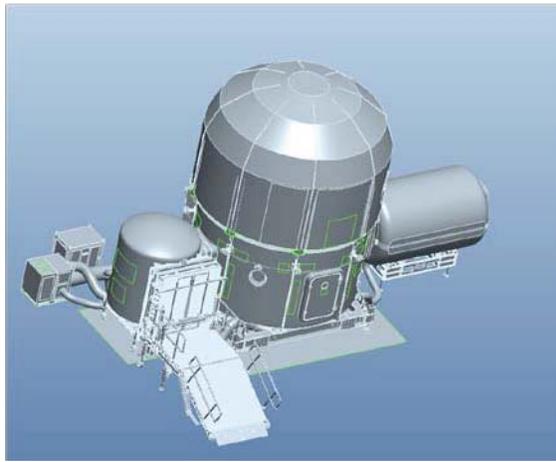
Figure 8 shows a proxy used to position the human phantom, FAX for this analysis, in the CAD habitat model for ray tracing. In Fig. 8, the three points labeled A, B, and C in the proxy form an orthogonal triad that defines the reference rays to correctly orientate the CAD model with the pre-computed FAX ray traces. The HDU shield model was ray traced at each of the five points in the proxy, and the pre-computed FAX ray traces were then added to the appropriate point ray trace. For a more complete explanation of using the proxies see Singleterry et al.,¹ or the OLTARIS website (http://oltaris.nasa.gov/help_documentation/OLTARIS_phantom_process_v2.pdf).

IV. Radiation Analysis Description

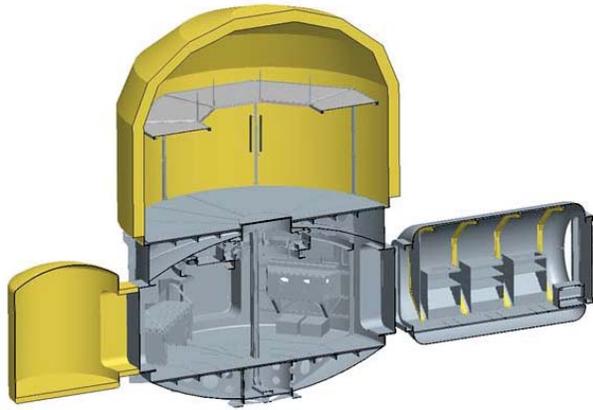
The shielding effectiveness of each concept was evaluated in terms of the reduction in astronaut exposure provided. Two protection levels were used, a threshold of 50% reduction and a goal of 70% reduction. Radiation shield models were developed for both the habitat and the shielding concepts as previously described. The reduction in exposure was evaluated by using as a basis the effective dose for a 50th percentile female astronaut in the habitat’s normal configuration and then repeating the calculation for the same astronaut within the habitat reconfigured to include the shielding concept. The habitat and shielding concepts were ray traced with scripts utilizing Sigmaxim’s SmartAssembly™ tool set (www.sigmaxim.com). The radiation analysis tools (geometry algorithms, HZETRN transport code, effective dose scripts) developed for OLTARIS were used to calculate effective dose. The FAX phantom was used to model the female astronaut, utilizing the recommended anatomical point distribution of Slaba, et al.⁷ CAD models for three 50th percentile male astronauts were also included in the habitat.

A. SPE Model Chosen

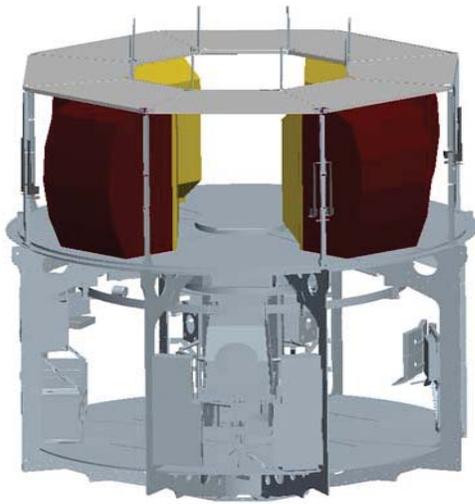
SPEs vary in magnitude and spectral shape. Previous architecture studies had used fits for individual historic events or models for probabilistic events as a design basis. The requirements for the CEV Orion⁸ module utilized



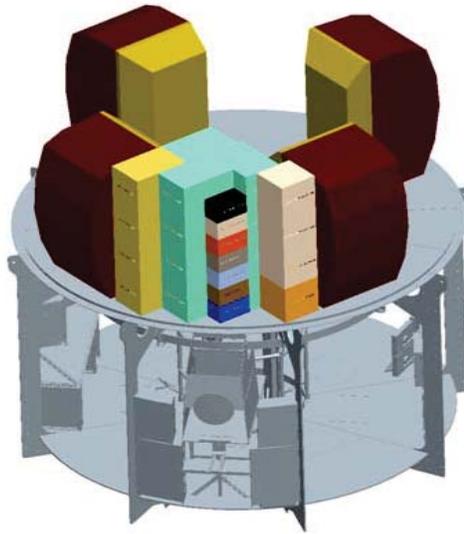
a) Original, ground based structure.



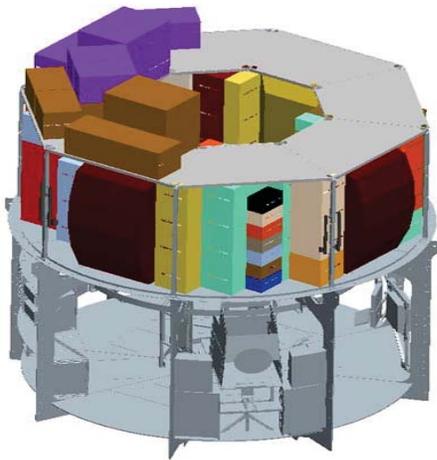
b) Cut away internal view of the HDU with all the external structure removed.



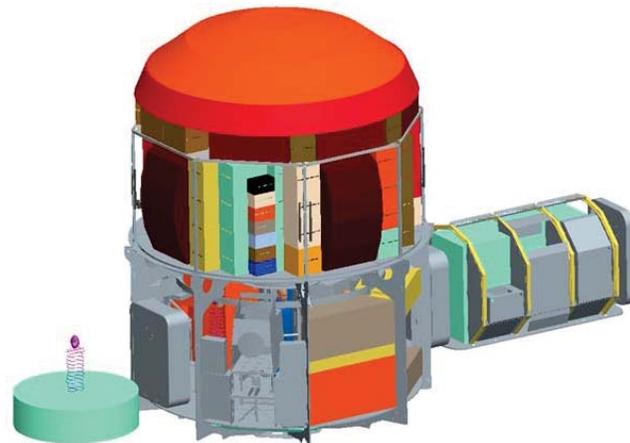
c) HDU core section with crew quarters.



d) Beginning step of placing logistics in the HDU.



e) Intermediate step of placing logistics in the HDU.



f) HDU with all the logistics and internal sub-systems placed.

Figure 5. CAD model development of the HDU.

the King fit for the August 1972⁹ event. However a design basis SPE for other exploration mission architectures has not yet been identified.

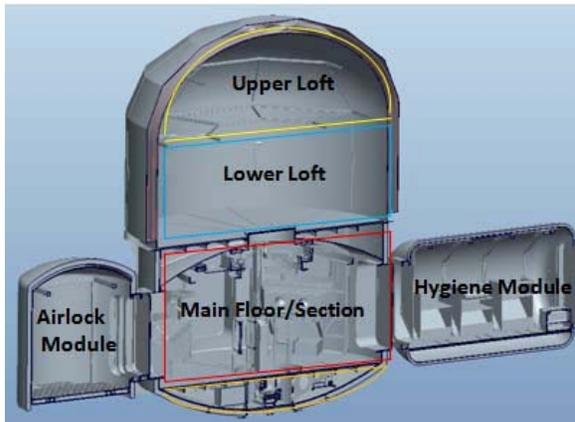


Figure 6. The major zones of the HDU. The loft and main section combined will be referred to as the core section or just the core of the HDU.

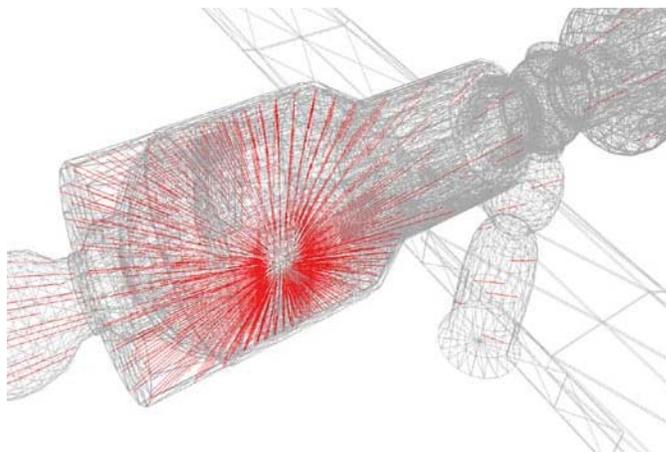


Figure 7. Example ray trace using the International Space Station. The red lines are the intersections of the rays with model elements. Figure courtesy of Garry Qualls, NASA Langley Research Center.

will vary depending on the SPE spectrum. The four other spectra used were the King fit for the August 1972⁹ event, a Band fit for the August 1972* event, developed by Allen Tylka of the Naval Research Laboratory, a Band fit for the September 1989* event developed by Tylka, and a second fit for the September 1989¹¹ event which had been used in previous studies and is labeled “Sept 89 OLTARIS.”¹ Figure 9 displays the differential proton spectra for all the SPEs used for the analyses.

B. Effective Dose Computation

Effective dose represents a whole body exposure. At each point ray traced, the total thickness of aluminum, polyethylene, and tissue along each ray were computed. For each SPE considered, a dose equivalent verses depth in aluminum, polyethylene, and tissue table was pre-computed using the ICRP 60 quality factors.¹² The

For this effort, a SPE spectrum calculated using a tool developed by Xapsos¹⁰ to produce maximum proton environments due to solar particle events for missions with durations of one year or more was used. The user of this tool chooses a mission duration and a confidence level, and the tool outputs integral proton fluences for energies ranging from 1 MeV to 300 MeV for both the total SPE exposure that would occur during the mission and a “worst case” SPE. This “worst case” SPE is the single largest event that the model predicts to occur during the mission time frame. For this analysis, the total proton fluence for a one year mission with a 95% confidence was used. The integral proton fluence spectra was extrapolated to cover the energy range from 0.01 MeV to 2,500 MeV and then the differential proton spectrum shown in Fig. 9 was calculated. The slight kink in the Xapsos spectrum is due to numerical effects.

While the Xapsos was used as the design basis, analyses were also performed for four other SPE spectra to facilitate comparisons with previous studies and provide some insight into how much results

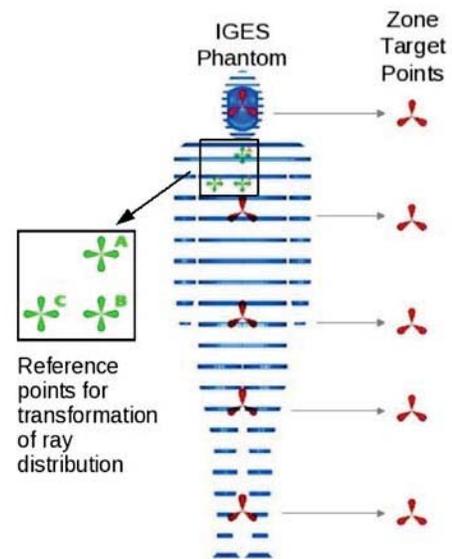


Figure 8. An example of the Initial Graphics Exchange Specification, IGES, phantom, a proxy used to position a human in CAD geometry. The left part of the figure has extracted the reference points which define the orientation of the proxy in the CAD model for clarity. The right part of the figure has the five points used for the vehicle ray traces. Figure courtesy of Garry Qualls, NASA Langley Research Center.

* Private communication with William (Bill) Atwell, Boeing Company, for the coefficients used for both band fits.

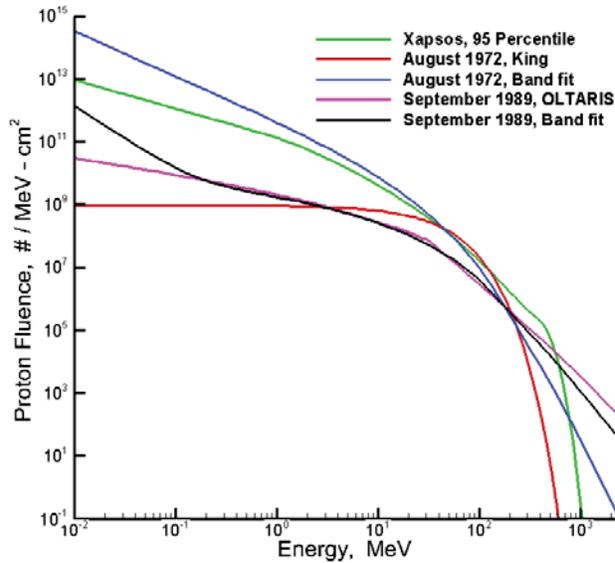


Figure 9. Proton fluence as a function of energy for the SPEs considered here.

dose equivalent verses depth table was interpolated for the three thicknesses to compute the dose equivalent along a ray. The dose equivalent along each ray was integrated to find the dose equivalent at a point in an organ. After the dose equivalent at all the points in the organ had been found, the mass averaged dose equivalent for the organ was computed. Once all the organ dose equivalents were found, the effective dose was then computed using the National Council on Radiation Protection and Measurements (NCRP) 132 tissue weighting factors.⁴

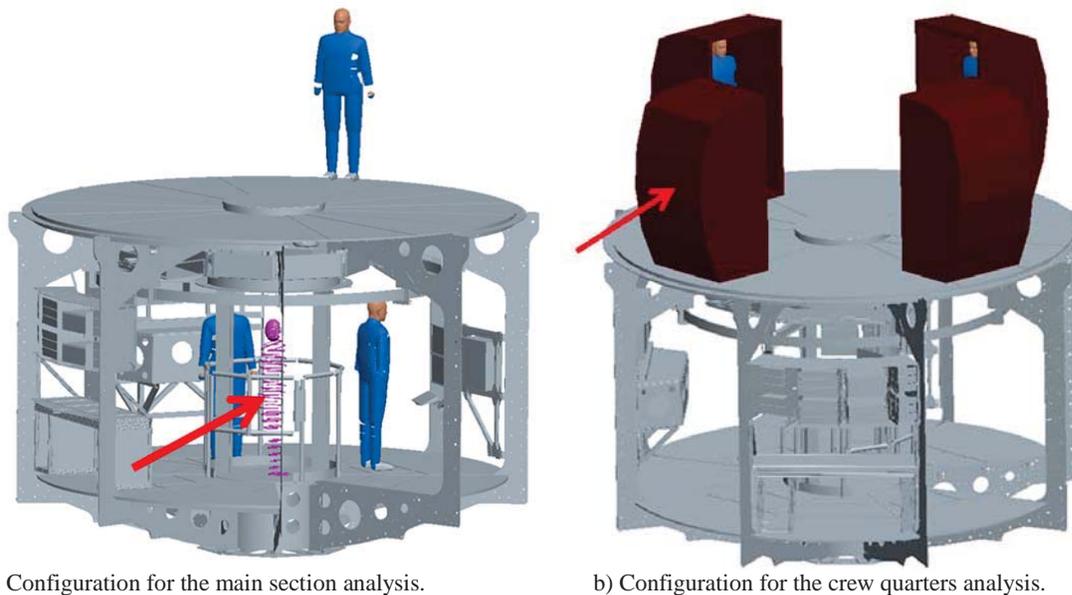
C. Concept Analysis Description

For each concept, the quantity of water, food, or other materials providing shielding was varied, an effective dose for each thickness was generated, and the percent reduction was computed. In addition to the target effective dose values, the total mass for each concept was estimated. The estimated mass was used to provide a figure of merit for each

concept; the lower the mass, the more viable the concept. Some of the materials used would already be on board, so it might be more appropriate to evaluate the concept based only on the extra materials needed, the parasitic mass. However, estimates for the exact quantities of water, food, and other logistics that will be available for use in the shield concepts vary widely. For this reason, the total shielding masses are presented in this work.

V. Baseline Radiation Analysis

Before evaluating the effectiveness of any of the shielding concepts, the astronaut exposure was calculated in the habitat in its normal configuration without deploying any shielding concepts. This calculation was performed for two different astronaut locations, one in the crew quarters and one in the main section central area. Figure 10 shows the positions of all of the astronauts for these calculations. The location of the astronaut for which the calculation was performed is identified with a red arrow in each part of Fig. 10. Table 1 shows the results for all five SPEs considered. As shown in the table, there was a large variation in the effective dose values depending on which SPE



a) Configuration for the main section analysis.

b) Configuration for the crew quarters analysis.

Figure 10. Position of the female phantom (red arrow) and male mannequins for the baseline radiation analyses. The major structures and subsystems have been removed for clarity.

was chosen. Shielding concepts will meet the required exposure reduction, if the effective dose for the astronaut inside the concept is less than 50% of the Xapsos 95% event for the habitat in its normal configuration (the first column of effective doses in Table 1). However, the goal was a reduction of 70%. Therefore, effective dose values for shielding concepts in the crew quarters are compared to the baseline value of 450 mSv, and effective dose values for shielding concepts in the main section were compared to the baseline value of 361 mSv.

Table 1. Effective dose values for each SPE considered for the basic HDU configuration. The values of the first column, Xapsos 95%, are taken as the baseline values.

	Effective Dose, mSv				
	Xapsos 95%	Aug. 1972 (King)	Aug. 1972 (Band)	Sept. 1989 (OLTARIS)	Sept. 1989 (Band)
Crew Quarters	450	311	190	106	102
Main Section, Center	361	225	139	89	82

VI. Radiation Analysis Results

This section presents the results of the radiation analysis, including the total mass of the concept, for each of the concepts.

A. Wearable Shielding Concept



Figure 11. Simplified CAD model of the wearable protection concept.

Unlike the other concepts, a CAD model was not required for the fabrication of the wearable concept; so a simplified CAD model was created for radiation analysis purposes, as shown in Fig. 11. As with the baseline analysis, protection provided by the wearable concept was analyzed for two scenarios: the astronaut using the wearable shielding in the crew quarters and the astronaut in the wearable shield in the central area in the main section. The shielding material was assumed to be water. A separate analysis showed that the contents and packaging of the food packets could be approximately modeled as water, as long as the thicknesses and masses were scaled to account for the lower densities of the food packets. The thickness of the wearable concept was uniformly varied and the effective dose calculated for each thickness and plotted in Fig. 12.

Figure 12a shows the effective dose plotted against the thickness of the wearable concept in inches for the case in which the wearable concept is utilized in the crew quarters, and Fig. 12b shows the reduction in effective dose provided by the wearable concept plotted against the thickness in inches. As seen in the baseline analysis, there is a large variation in results depending on the SPE chosen. For example, 2.1 inches (5.3 g/cm^2) of water are required for a 50% reduction for the Xapsos SPE, but only 0.9 inch (2.3 g/cm^2) would be needed for the King SPE. Similarly, 5.0 in. (12.7 g/cm^2) of water would be needed for a 70% reduction for the Xapsos SPE, but only 1.9 in. (4.8 g/cm^2) would be needed for the King event. The Xapsos 95th percentile event effective dose is clearly much larger than the rest. Also, as seen in Fig. 12b, the

percent reduction for the Xapsos SPE and the Band fit to the Sept. 1989 are very similar, while their values are very different, as seen in Fig. 12a. Similar trends were seen for all the concepts investigated; only the results for the Xapsos SPE will be presented for the remainder of this paper.

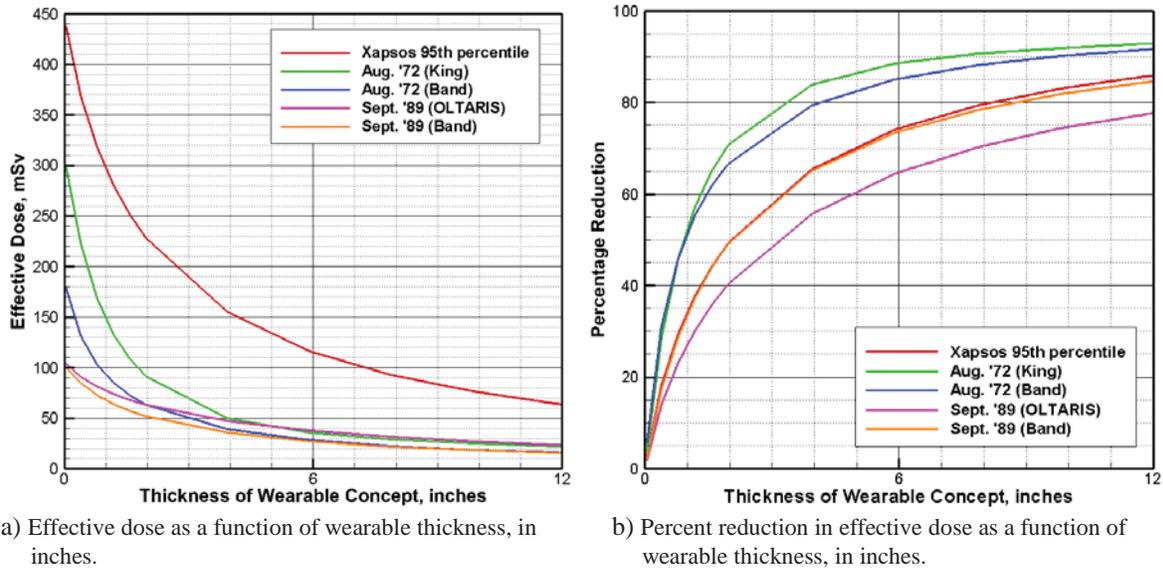


Figure 12. Results for the wearable concept used in the crew quarters.

The results for the scenario in which the wearable concept was used in the main section are not plotted here, but the trends were similar. The required water bladder thicknesses and corresponding water mass values are given in Table 2 for both scenarios and both protection levels. Based on these results, it appeared possible to create a wearable concept, 2-3 inches thick, that would meet the 50% exposure reduction requirement, but a wearable concept that would meet the 70% protection level would probably be too thick to allow mobility.

Table 2. Results for the wearable concept. The first two columns are the thicknesses needed for the indicated percent reduction and the last two columns are the masses needed for the indicated percent reduction.

	Water Wall Thickness, in		Total Mass for 4 Astronauts, lbm	
	50%	70%	50%	70%
Wearable Shield in Crew Quarters	2.1	5.0	1527	3636
Wearable Shield in Main Section	2.8	6.1	2036	4436

B. Deployable Shielding, Individual Protection Concept

The radiation analysis for the deployable concept was performed by uniformly varying the thickness of the layer of food packets and/or HMC bricks utilized in this concept and calculating the effective dose for each thickness. The thickness of the water reservoir was held constant at 2 inches. These calculations were performed for two different materials. First, the food packet/HMC brick layer was modeled as water. This was a good approximation, if this shielding layer is primarily made up of food packets. The calculations were repeated, modeling the food packet/HMC brick layer as pure aluminum. This represented a worst case for the protection provided by the HMC bricks. Results for this concept are presented in units of g/cm^2 rather than inches, because the absolute thicknesses will vary depending on the densities of the food packets and/or bricks making up the shielding layer.

Calculations were first performed for only one deployable unit at a variety of locations in the main section to examine the variation in results and identify preferential locations. The locations examined were standing in the center of the main section, lying down in the center of the main section, lying against the ceiling of the main section, standing against a wall sheltered by large mass subsystems, and lying on the floor sheltered by the same subsystems. Figure 13 shows the percent reduction versus the thickness of water used for those five locations. Results varied significantly depending on the location of the shield. For example, the shield thickness required for the 50% protection level varied from $2.7 \text{ g}/\text{cm}^2$ to $10.4 \text{ g}/\text{cm}^2$ using the water approximation and from $4.0 \text{ g}/\text{cm}^2$ to $15.5 \text{ g}/\text{cm}^2$ using the aluminum approximation. This analysis showed that the locations abutting the floor were better locations.

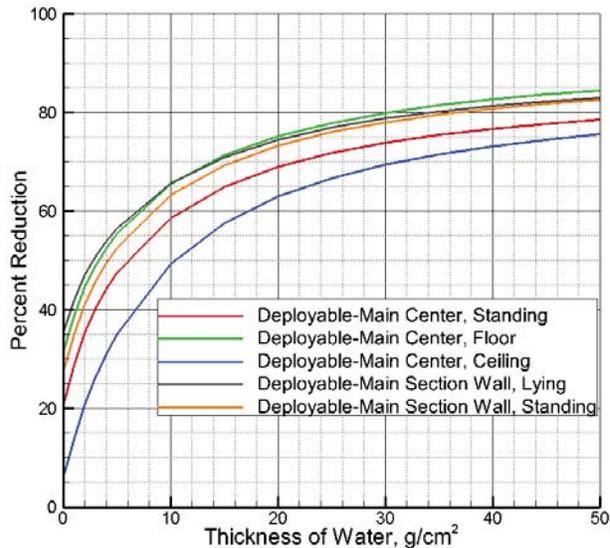


Figure 13. Percent reduction versus thickness of water for five possible locations in the main section of the HDU to find preferable places to position the astronauts for the individual protection concept.

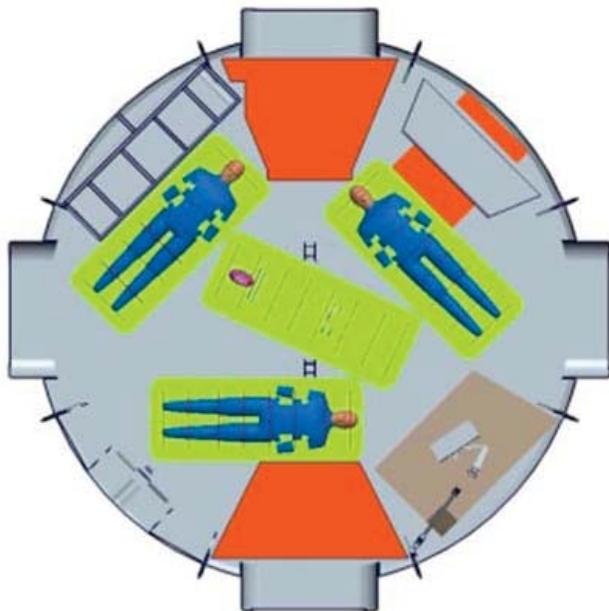


Figure 14. Configuration for the radiation analysis for the four individual deployable protection units.

Table 3. Results for the deployable shield, individual protection concept. The first two columns are the thicknesses needed for the indicated percent reduction and the last two columns are the masses needed for the indicated percent reduction.

	Food/Brick Layer Thickness, g/cm ²		Total Mass for 4 Astronauts, lbm	
	50%	70%	50%	70%
Modeled as Water	1.33-2.35	8.70-11.23	627	3693
Modeled as Aluminum	1.86-3.43	14.69-20.65	905	6520

The effective doses for each of four astronauts in four separate deployable shielding units all in locations abutting the floor, as shown in Fig. 14, were then calculated. The results for these calculations are presented in Table 3, with the astronaut in the center location and the top right location getting slightly better protection than the other two. The results in Table 3 were similar to those for the floor cases of the initial five places examined. The masses in Table 3 are the total of the masses required for all four of the deployable shields. Based on these results, it appears to be possible to design a deployable concept of this type that will meet either the 50% or the 70% protection level, but the 70% protection level may require more food and/or HMC bricks than are present on the habitat at some points during the mission duration.

C. Deployable Shielding, Group Protection Concept

Two scenarios were evaluated for the group deployable shield concept. In the first scenario, the panels used to create the storm shelter and the water within them provided the shelter. In the second scenario, the reconfigurable panels which may or may not contain water provide support for logistics and cargo which was moved to surround the storm shelter created in the central area.

In both cases, the thickness of the water wall was varied uniformly and the effective dose was calculated for each of the four astronaut locations for each thickness. The thicknesses and the corresponding masses needed to reach the two protection levels were then identified. The results are shown in Table 4. A thickness of 1.04-1.65 inches corresponds to a mass of 1321-2109 lbm, a thickness of 4.04-5.00 inches corresponds to a mass of 5146-6372 lbm, and a thickness of 1.67-2.85 corresponds to a mass of 2129-3630 lbm. The range in results represents the variation depending on which astronaut location was used as a basis. The loft locations produced thinner shield requirements than the locations in the main section. For each set of astronauts in either the loft or main section, one person required more protection than the other. The larger thickness value needed in each section was used to determine the thickness for the 50% and 70% reduction. Thus, the masses in Table 4 are the sums of the masses of the augmentation needed to provide a 50% or a 70% reduction for both astronauts on each level. Based on these results, it appears possible to create a storm shelter using the floor panels that will meet either the 50%

Table 4. Results for the group protection deployable shielding concept. The first two columns are the thicknesses needed for the indicated percent reduction and the last two columns are the masses needed for the indicated percent reduction.

	Water Wall Thickness, in		Total Mass of Water, lbm	
	50%	70%	50%	70%
Panels Only	1.04-1.65	4.04-5.00	1696	5785
Panels Plus Logistics	0	1.67-2.85	0	2677

or the 70% protection levels, but the large quantity of water needed to meet the 70% protection level (~5800 lbm) may be more than is available. For the scenario in which logistics surrounded the shelter, it may be possible to reach the 50% protection level without utilizing water and the quantity of water needed for the 70% protection level is smaller than without logistics. It should be noted, however, that this evaluation assumed a panel thickness of 1.59 g/cm² without water. If the actual panels are thinner, more water may be needed.

D. Augmentation to Crew Quarters Concept

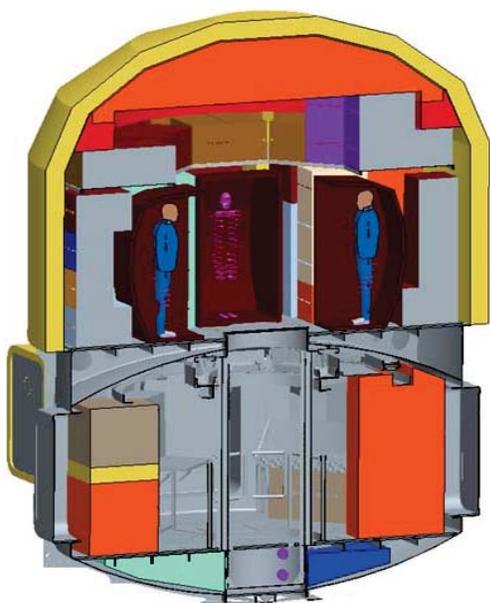


Figure 15. Augmented crew quarters concept after the crew quarters have been moved inward and logistics have been placed behind them.

Three scenarios were evaluated for the crew quarters concept. In the first, the four crew quarters were left in their original positions abutting the exterior walls, as previously shown in Fig. 5 and Fig. 10, and the thickness of water walls built into the crew quarters' walls were varied uniformly. In the second scenario, the four crew quarters were repositioned closer to the center of the habitat and surrounded by logistics and cargo, and then the thickness of water walls built into the crew quarters walls were varied. The repositioned crew quarters are shown in Fig. 15. In the third scenario, all four of the crew quarters were repositioned, but only two of the crew quarters were outfitted with water walls and two astronauts were placed in each of the augmented crew quarters for the duration of the SPE.

Several options were evaluated: water walls included in all of the walls of the crew quarters including the door; water walls in all walls except the door; water walls in the back and sides only; and water walls in the back only. After considering volume, mass, and functionality, having water walls in the back and sides only was deemed the best option for this habitat and only results for that option are presented here.

The water wall thicknesses required to have met each of the protection levels and the total masses of water

Table 5. Results for the crew quarter augmentation concept. The first two columns are the thicknesses needed for the indicated percent reduction and the last two columns are the masses needed for the indicated percent reduction.

	Water Wall Thickness, in		Total Mass of Water, lbm	
	50%	70%	50%	70%
Crew Quarters in Original Position	2.7	7.7	3119	8942
Crew Quarters Moved Inward	0.49-0.84	4.95-5.12	676	5827
Astronauts Doubling Up	0-0.82	3.50-4.93	379	2656

needed for all of the crew quarters augmented are given in Table 5. Only one of the four crew quarters was analyzed in the original position for each protection level. The masses in Table 5 are thus four times that result. For the other scenarios, one computation was performed for each of the four astronaut's positions and the masses summed. The crew quarters moved inward required between 0.49-0.84 inches of water for a 50% reduction and between 4.95-5.12 inches for a 70% reduction. For the astronauts doubling up, as was done for the group protection concept in Section C., the largest thickness needed for each

pair of astronauts was used for the 50% and 70% reduction. The mass reported is the total mass of the two

augmented crew quarters required to ensure that all four astronauts meet the 50% or 70% reduction level. Based on these results, it appears to be possible to create a water walls system for the crew quarters in their original position that would meet either the 50% or the 70% protection levels, but the large quantity of water needed for the 70% protection level (~5800 lbm) may be more than is available. Moving the crew quarters to a more central location and surrounding them with onboard materials significantly reduces the amount of water required to meet each of the protection levels. Providing water walls in only two of the crew quarters and having them “double up” also reduces the amount of water needed, especially for the 70% protection level.

VII. Conclusion

Four different shielding concepts were evaluated: a wearable concept; a deployable individual shield protection concept; a deployable group shield protection concept; and a crew quarters augmentation concept. Each of the four shielding concepts were able to meet the 50% reduction in exposure requirement and all of the shielding concepts, except possibly the wearable concept, were able to meet the 70% reduction in exposure goal, but several of them required large, ~2700 lbm minimum, quantities of water, food, or HMC bricks. These shielding requirements were driven, in large part, by the choice of the Xapsos 95th percentile SPE as a design basis. Astronaut effective dose values and storm shelter shield masses were shown to vary significantly depending on the energy spectrum of the SPE. For example, the baseline vehicle exposure for the crew quarters ranged from 102-450 mSv, and the baseline vehicle exposure for the center of the main section ranged from 82-361 mSv. The reconfiguration of cargo to surround either the crew quarters or the deployable group shield protection concept was also shown to have a significant impact on astronaut exposure.

Several important points can be drawn from the analysis process and its results. First, creating a radiation shield model for a space habitat in the early stages of the design process presents numerous challenges: unknown lay-out, missing systems, quantification and placement of consumables and equipment, identification of materials and densities, to name a few. Creating the shielding model was the most time consuming part of the exposure analysis performed for this project. Second, these results highlight the importance of ongoing efforts to develop probabilistic SPE exposure models. If a single SPE is used as a design basis and that SPE is too large, shield mass requirements may be exceptionally large. However, if a single SPE is used as a design basis and that SPE is too small, astronauts could receive an unacceptably large dose. Finally, these results show that it is possible to design minimal SPE storm shelters that provide astronauts with adequate protection and that the availability of water, food, HMC bricks, and cargo and logistics for use in SPE shields will play a significant role in the choice of shielding technologies for future habitats.

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