RadWorks Storm Shelter Design for Solar Particle Event Shielding

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In order to enable long-duration human exploration beyond low-Earth orbit, the risks associated with exposure of astronaut crews to space radiation must be mitigated with practical and affordable solutions. The space radiation environment beyond the magnetosphere is primarily a combination of two types of radiation: galactic cosmic rays (GCR) and solar particle events (SPE). While mitigating GCR exposure remains an open issue, reducing astronaut exposure to SPEs is achievable through material shielding because they are made up primarily of medium-energy protons. In order to ensure astronaut safety for long durations beyond low-Earth orbit, SPE radiation exposure must be mitigated. However, the increasingly demanding spacecraft propulsive performance for these ambitious missions requires minimal mass and volume radiation shielding solutions which leverage available multi-functional habitat structures and logistics as much as possible. This paper describes the efforts of NASA's RadWorks Advanced Exploration Systems (AES) Project to design minimal mass SPE radiation shelter concepts leveraging available resources. Discussion items include a description of the shelter trade space, the prioritization process used to identify the four primary shelter concepts chosen for maturation, a summary of each concept's design features, a description of the radiation analysis process, and an assessment of the parasitic mass of each concept.

Nomenclature

<u>Acronyms</u>

AES	=	Advanced Exploration Systems
BEO	=	Beyond Earth Orbit
BNNT	=	Boron Nitride Nanotubes
CAD	=	Computer-Aided Design
CQ	=	Crew Quarter
CTB	=	Cargo Transfer Bag
DSH	=	Deep Space Habitat
FAX	=	Female Adult voXel
GCR	=	Galactic Cosmic Ray
HAT	=	Human Spaceflight Architecture Team
HDU	=	Habitat Demonstration Unit
HMC	=	Heat Melt Compactor
HZETRN	=	High charge (Z) and Energy TRaNsport code
ISS	=	International Space Station
KPP	=	Key Performance Parameter
LEO	=	Low Earth Orbit
OLTARIS	=	On-Line Tool for the Assessment of Radiation in Space
SPE	=	Solar Particle Event

I. Introduction

The ability to affordably and sustainably mitigate the risks associated with exposure of human crews to space radiation is a major challenge in designing for human exploration of the Solar System beyond Earth orbit (BEO). Exposure of astronaut crews to the deep space radiation environments increase the risk of deleterious physiological effects such as radiation sickness and late-term effects, central nervous system damage, and increased incidence of debilitating or fatal cancers. Current design and operational strategies for mitigating radiation-related risks include: 1) the deployment of radiation monitoring instrumentation to enable a measured, balanced, real-time response to radiation events during human missions, and 2) the addition of "shielding" to spacecraft designs to protect the crew directly. Legacy approaches of each strategy, while valid in concept, do suffer from shortcomings in their current and past engineering implementations. NASA's RadWorks Advanced Exploration Systems (AES) Project builds upon past lessons and advances real-world solutions to radiation risk mitigation through analysis, design, demonstrations and operational implementation on future missions.

The RadWorks Project consists of two top-level elements. The first of these is the maturation of advanced, miniaturized radiation measurement technologies, or dosimeters. The second is the development of a radiation storm shelter which leverages the design of multi-functional habitat structures and logistics to minimize radiation shielding mass at launch. This paper focuses on the second of these, the Storm Shelter.

The deep space radiation environment beyond the Earth's magnetosphere results from the combination of galactic cosmic rays (GCR), solar particle events (SPEs), and secondary particles which are created during interactions between the charged ions in these environments and the materials surrounding the astronauts. GCR radiation consists of charged particles which exist pervasively throughout the galaxy. Some GCR particles are difficult to shield with practical amounts of shielding because of their high energies and the secondary particles which can be formed by their collision with shielding materials. The rates of exposure associated with GCR are relatively low, but also extremely difficult to mitigate without large amounts of shielding (on the order of a few meters). This limits acceptable mission durations until innovative solutions to the GCR problem are developed. In contrast to GCR, large SPEs are rare, short-lived (durations are measured in hours), high-exposure rate events. Fortunately, shielding materials (particularly those with high concentrations of hydrogen such as polyethylene and water) 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 and astronauts receive sufficient warning to enter the sheltered area, the SPE risk can be managed through appropriate vehicle design.

Adequate shielding *could* be provided by simply surrounding a vehicle with a large enough mass. However, it is cost prohibitive to launch the mass necessary to shield an entire space habitat. It is also undesirable to carry single-purpose shielding mass dedicated only to provide radiation shielding (i.e. *parasitic mass*) when logistics and subsystems necessary to support humans can provide sufficient shielding. To address this design problem, the objective of the Radworks Storm Shelter is to design low parasitic mass, temporary SPE shelter concepts which reconfigure, redeploy, and/or reuse available logistics and subsystems to shield smaller areas within a habitat when an SPE occurs. The production of integrated shielding concepts with minimized system impact will feed into the specification of a Concept of Operations for managing the crew SPE exposures for exploration missions. The design effort will also provide valuable insight into how truly integrated vehicle designs can contribute to the mitigation of the GCR issue.

This paper describes the process used by the Storm Shelter team to identify, analyze, and evaluate leading candidates for these SPE shelters and improve them through the creation of subscale and full-scale demonstration articles. Section II describes the identification of shelter options and the preliminary down selection process to the four primary concepts evaluated in FY'12, and Section III describes the pros/cons and operations associated with each of these concepts. Section IV outlines the radiation analysis used to determine the parasitic mass in Section V. Section VI describes the operational performance of each concept including deployment time. Section VII covers the decision analysis which led to a reduction of concepts being matured to two. Finally Sections VIII and IX outline the conclusions from the study and the future work planned for FY'13.

II. Design Space Exploration

The RadWorks Storm Shelter team was charged with creating storm shelter designs applicable for a one year mission with four crew in the deep space radiation environment. Each of these shelters was designed to be deployable by two crew in less than an hour and capable of housing astronauts for up to 36 hours. A brainstorming session was held December 2011 to generate a set of storm shelter alternative concepts which utilize or modify existing logistics items for protecting astronauts from the harmful effects of SPE radiation. In particular, the objective was to propose innovative ideas compatible with space habitat design which could potentially achieve "zero" mass solutions while maintaining reasonable assumptions about use of available shielding materials. The session resulted in the identification of four major parameters which characterized the design space: the sheltered area's location/size, a basic shelter strategy, the choice of shielding materials, and a strategy of shelter deployment. Options from these categories (shown below) can be combined to form multiple SPE shelter alternatives.

After formalizing this design space into a trade tree, the ten likely alternatives shown in Table 1were generated for a preliminary qualitative evaluation to reduce the number of concepts. These alternatives fell into the following protection scheme categories: 1) pre-integrated waterwalls, 2) built-up waterwalls, 3) wearable shelters, 4) deployable shelters, and 5) built-up structures. It was recognized that the optimal solution used in practice would likely utilize some hybrid combination of these methods (e.g., a wearable shelter in combination with a pre-integrated crew-quarters derived waterwall), but since these final decision would be based upon the availability of protection materials and the scale of the shelter, only non-hybrid concepts were evaluated during FY'12.

- **Various Shelter Configuration/Location Options**
  - Surrounding habitat
  - Surrounding each crew quarters
  - Surrounding all crew quarters
  - Surrounding galley/group meeting area
  - Airlock shelter
  - Wearable shelter
  - Combination approaches
- **Shelter Strategies**
  - Panels
  - Bricks
  - Soft goods storage
  - Cargo Transfer Bags (CTBs) (redesigned or coated)
  - Blankets
  - Water bags
  - Baffled tank walls
  - Blinds / louvers
  - Pre-integrated structure
- **Materials Choices**
  - High density polyethylene
  - Carbon nanomaterials
  - Metal hydrides (e.g. LiH)
  - Other advanced materials
  - Potable Water
  - Grey/waste water
  - Water-ice
  - Repurposed CTBs
  - Trash
- **Deployment Methods**
  - Pre-integrated / pre-deployed
  - Construction from panels/bricks
  - Moving of materials
  - Moving water bags
  - Water shift
  - Inflatables

Table 1: Ten initially proposed shelter concepts

Protection Scheme Category	Shelter Concept
Pre-Integrated Waterwall	1) Pre-integrated waterwall for two person crew quarters
	2) Pre-integrated waterwall plus logistics stacking, multiple walls of main section
Built-up Waterwall	3) Built up waterwall for two person crew quarters
	4) Built up waterwall plus logistics, in main section
	5) Water bladder for two person crew quarters
Water Bladder-based Wearable	6) Water bladder based wearable
Built-up Structures	7) Build up of panels and logistics in the main section, (floorboards, CTBs, panels...)
Deployable	8) Deployable via release and pull into place, roller blinds, with pre-integrated ceiling/floor protection in the center core of the habitat
	9) Deployable via inflation, fabric with pre-integrated ceiling/floor protection in the center core of the habitat
	10) Deployable via elastic forces (panel/fabric tent) in main section

A decision analysis-based prioritization of the concepts was implemented to reduce the number of concepts developed to four concepts which would be further developed during the FY'12 design cycle. Assuming similar levels of radiation dose reduction for all concepts, the decision analysis process utilized three figures of merit to make the selections: 1) the anticipated mass of the concept, 2) the anticipated shelter assembly time, and 3) the level of crew functionality within the habitat. These figures of merit were weighted with a heavy emphasis on reduced mass and summed to determine the overall preference between the 10 alternative shelter concepts. Finally, the results were discussed and similar concepts were combined to arrive at the four FY'12 SPE shelter concepts. These four concepts will be analyzed for integration into the Habitat Demonstration Unit (HDU)[1], which is a NASA owned analog used for testing proposed technologies and operations for future deep space missions.

III. Concept Definition

The decision analysis process resulted in the following concepts being selected for FY'12 demonstration based upon the rationale described:

1) Water bladder Based Wearable: Highly rated and captures a personal protection concept.
2) Deployable Blind Concept: Not as highly rated as the other three but was the top rated concept in the "Deployable" category. This concept evolved to an approach which was not only deployable within the habitat, but has potential of being deployed from the habitat to other exploration elements.
3) Pre-Integrated Water Wall for Two Person Crew Quarters: The top rated concept amongst the team which captures active water wall technology.
4) Build-up of Panels and Logistics in the Main Section: Moderately rated but captures a non-water wall solution.

Each of these concepts was further developed with a concept design, radiation analysis, deployment scenarios, and parasitic mass estimate to inform future decisions to futher reduce the number of concepts which would be developed using full scale mockups. This section of the paper will describe the basic premise of the concept design including a descriptions of potential advantages and challenges to implementation.

A. **Wearable Individual Shelter**

In order to minimize the material necessary for protecting individual crewmembers in the existing crew quarters, a wearable protection strategy to augment crew sleeping bags with water bladders or logistics was proposed. By protecting crew members directly, the surface area required for protection is minimized which also minimizes the mass of the protection medium. By using sleeping bags in existing crew quarters, work and sleep can be accommodated in a space proven to be habitable and productive within the spacecraft for the duration of an SPE. Additionally, sleeping bags are portable, so protection could be maintained during limited crew translation within the habitat.

Two approaches to wearable concepts are included in the storm shelter protection options: 1) a sleeping bag with an integrated water bladder and 2) a sleep restraint with a mesh of food pouches and/or Heat Melt Compacted (HMC) bricks[2,3], which are created from compacted trash. The water bladder sleeping bag concept shown in Figure 1 seeks to leverage the existing sleeping bag/restraint system available to the crew and also the available contingency life support water to reduce the delivery of additional mass. The bladders would be pre-integrated into the sleeping bags and could be either pre-filled or filled as needed for an SPE. A detachable, water-filled hood would be added to this sleeping bag to provide protection to the head and neck (thyroid). Baffles within the bladder are provided to maintain desired shape when filled. The bladder within the sleeping bag covers the body from the head to the knees maintaining complete protection of blood-forming organs.

Since the sleeping bag/bladder concept would already be located and used in the crew quarters, the deployment operation would consist of filling the bladder with water. The bladder can be either pre-filled or filled-on-need. Pre-filling the bag would significant reduce time to deploy the bag for SPE protection as all would be required is for the crew member to translate to the quarters and don the filled sleeping bag. If the bag is not filled until an SPE event has been identified, then the crew member would have to take the bag to a faucet location and fill the bag prior to donning it.

Key challenges to the water bladder-based protection strategy include mobility/comfort of a crew member and how fill times would impact the deployment time. Thermal and mobility issues associated with these bladders will have to be investigated. Water provides a heat sink drawing heat out of the body unless heated, insulated, or designed such that it doesn't have significant surface area contact with a crewmember. Conversely, the thickness and close confinement around the body may generate heat requiring additional cooling, such as ventilation. The comfort/mobility of the crew will be affected if the amount of water required for protection requires a thickness that tends to immobilize crew body movements (the "Michelin Man" effect). The other issue with the water-filled concept is the fill rate. ISS faucets have a water flow rate of 500 mL/min (about 1/10 the speed of Earth faucets) which is intended for filling drinks/food and washing. If this flow rate is imposed upon the wearable concepts, each sleeping bag could take more than 5 hours to fill as opposed to 31 min for a typical Earth faucet.

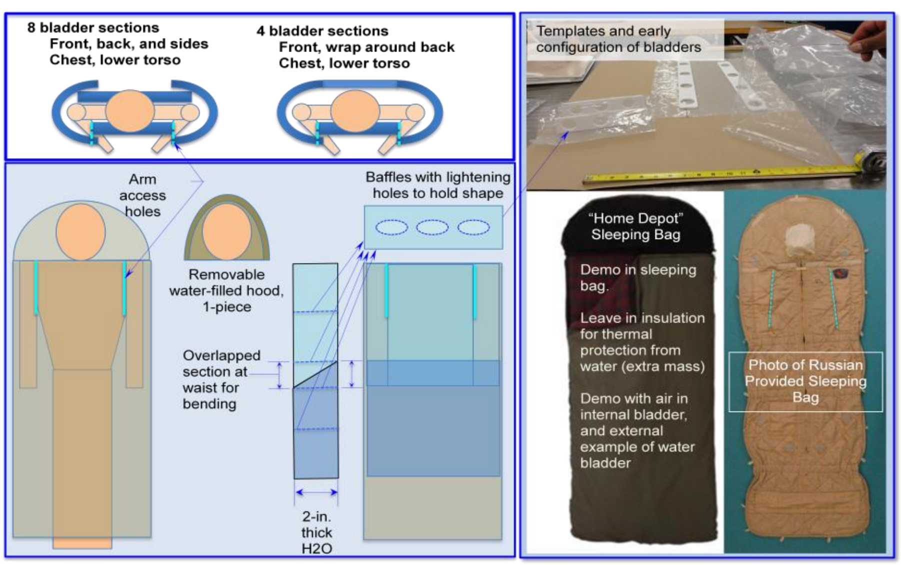

Figure 1 - Wearable Option 1 - Water bladder in sleeping bag

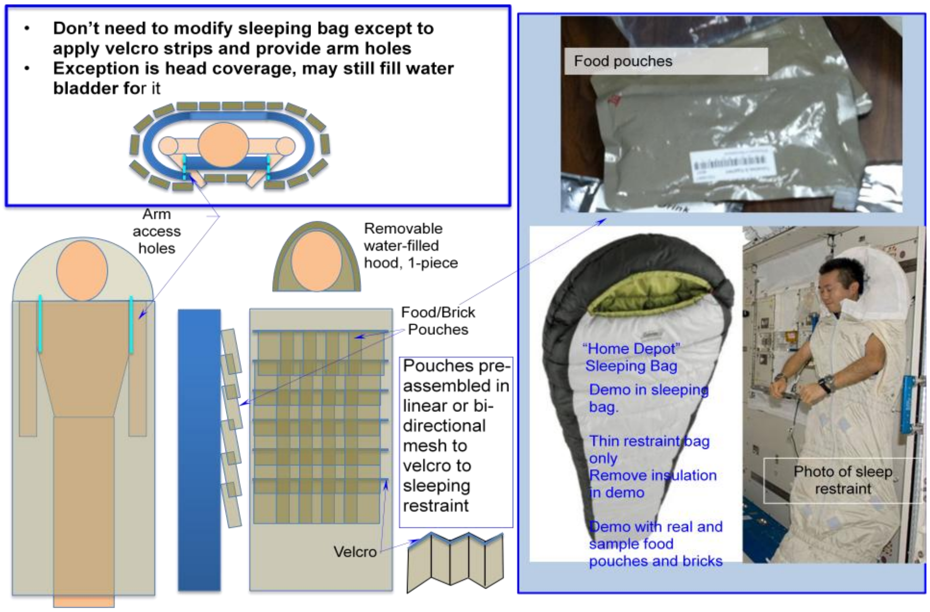

Figure 2 - Wearable Option 2 - Sleep restraint with food pouches/compacted trash bricks

Figure 2 shows a sleeping system dependent upon food pouches and/or compacted trash bricks for protection. This could be used in combination with or in lieu of a water-based system. In this concept, pouches of food and compacted trash bricks can be pre-assembled into a netting of rows or sheets using straps and Velcro for fast deployment onto a sleep restraint system. This system would be deployed when alerted of an SPE. A detachable, water-filled hood would be added to this sleeping bag to provide protection to the head and neck (thyroid). As with the sleeping bag/bladder concept the protection covers the body from the head to the knees.

The food pouches would be preassembled and packaged such that the system could easily be pulled from storage and quickly attached to the sleeping bag/restraint. The assumption is that the food used would be predominantly contingency food, but the packaging would be arranged so that food pouches could be exchanged, used or replaced with the green bricks as needed.

Key challenges to a logistics/trash-based protection system are similar to the water bladder system: thermal control (overheating only) and potentially large thicknesses of the protection material causing mobility reduction. The decreased protection efficacy of food and trash bricks may result in thick, bulky layers of protection material, which can cause productivity and mobility issues. While this concept does not require filling a bladder with water (except for the hood), the full complement of food pouches/bricks must be in place for adequate protection. Using contingency food can reduce the need for maintenance of the food pouches. Otherwise operations would require a strict maintenance of food and trash to ensure protection is at hand throughout the duration of the mission.

B. Deployable Shelter Concepts (Individual and Group Shelters)

Deployable concepts feature a quick structural deployment utilizing available materials (e.g., logistics, water, trash, etc.) to protect a region(s) of a habitat interior. Initial concepts investigated include "blinds" of protection material which fold out of ceiling and wall locations, "cargo netting concepts" which use netting to arrange logistics carried in Crew Transfer Bags (CTBs), and concepts utilizing unfolded CTB and Heat Melt Compacted (HMC) bricks[2,3] and/or food provisions to provide a quickly deployable SPE protection shelter. Kinematic structures such as pop-up ribbing to support a radiation protection cover material were also discussed.

During FY'12, two deployable concepts were pursued for further analysis: 1) a deployable individual shelter leveraging contingency water and logistics and 2) a deployable group shelter focused on utilizing only logistics and minimizing parasitic mass. Figure 3 shows the features of the individual deployment shelter concept. A two-part hinged assembly water containment system is proposed for storage of the contingency life support water. Each half holds shelter frame supports which assemble onto the unfolded assembly to support positioning of logistics elements. HMC bricks, CTB's, food storage etc. could serve as the protection medium and could be pre-integrated into sheets which could be attached to the deployed shelter framing.

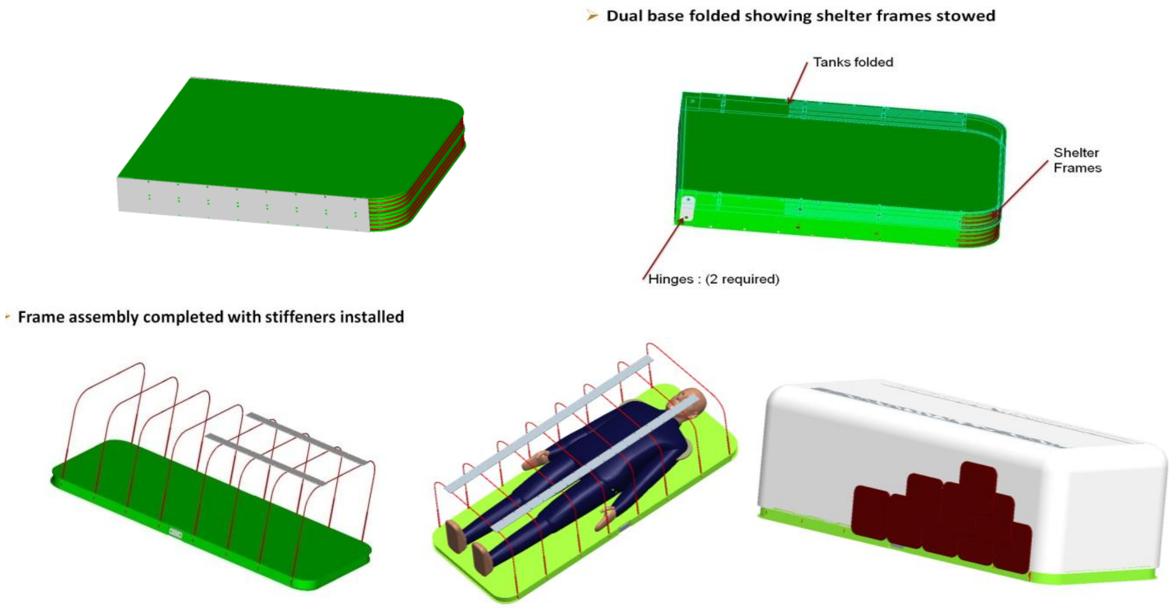

Figure 3 - Deployed water containment system for individual astronaut protection

Key challenges to this concept are the logistics management issues and space management challenges of deploying four shelters. Maintaining the sheets of logistics with appropriate levels of protection as logistics are consumed requires logistics management software and strict logistics maintenance practices. The other issue is that four deployed shelters take up the majority of the open space within the habitat. Shape and deployment location will be traded in future iterations.

The group deployment shelter concept investigated features a frame of aluminum which is used to create an attachment structure for large panels of CTBs as shown in Figure 4. The advantages of this concept are that it is relatively easy to deploy and may have a smaller surface area than individual protection strategies. With the use of lightweight structural materials, the parasitic mass of this solution can be attractively low. The greatest challenges to this concept are maneuvering the large amounts of logistics and maintaining the logistics in the sheets to provide adequate levels of uniform protection. Another potential challenge for this concept is ensuring that the logistics alone can provide sufficient protection for the worst case SPEs.

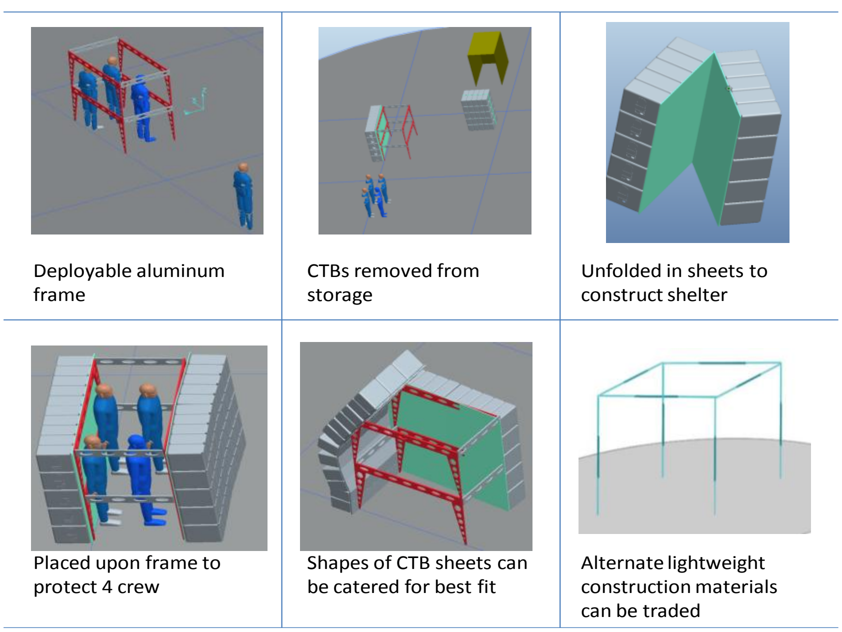

Figure 4 - Deployed logistics containment system for group protection

C. **Crew Quarters – Derived Waterwall Shelter Concept**

Crew quarters-derived concepts seek to leverage a proven habitable volume occupiable by crew for the duration of a SPE by augmenting crew quarters structure with an integrated waterwall functionality. Figure 5 shows a single ISS-type crew quarter which has been redesigned to be constructed from 2-inch thick structural panels which also provide containment for contingency life support system water. To preserve the inner mold line of the original design, wall thickness increases are applied outward. These walls and/or individual wall panels can then be filled and/or drained on an as needed basis for radiation protection. Potentially making the waterwalls thicker to accommodate more system water could also be an efficient solution for habitat designers to consider.

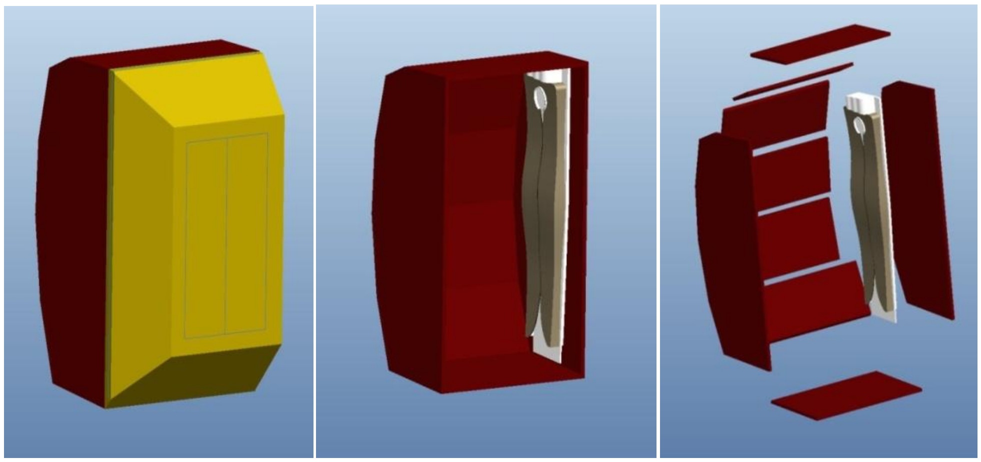

Figure 5 - Buildup of crew quarters, including bump out and sleeping restraint

Figure 6 shows two crew quarters positioned in a loft concept which includes additional recently proposed loft system hardware. Either vertical or horizontal integration of the crew quarters could be demonstrated. An additional savings could be provided if the crew quarters can be grouped together, sidewall to sidewall. The adjacent sidewall would not have to be a radiation shield and the mass of it would not count in the radiation protection mass penalty calculation.

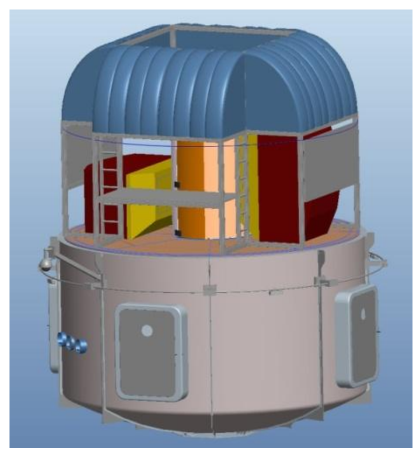

Figure 6 - Centralized crew quarters

From a radiation protection perspective, placing the crew quarters as close to the center of the habitat as possible is useful because it can provide space between the outer wall of the habitat and the outward wall of the crew quarters. The arrangement in Figure 7 shows a smaller crew quarters (no bump out) but is likely not feasible based on presumed loft hardware that may exist in the HDU at the time of concept demonstration.

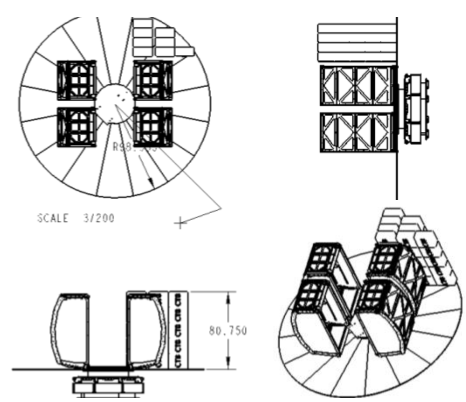

Figure 7 - Centralization of reduced size crew quarters

The major advantage of crew quarters-based shelters is that the space within the crew quarters has been designed and proven for durations of occupation similar to the length of an SPE. Crewmembers are accustomed to working for prolonged periods within their crew quarters. Another advantage is that walls could be permanently filled to provide some degree of continuous protection for crew.

Another potential advantage of the integrated water wall concept is the increased synergy with the work of related projects into the development and demonstration of multi-functional panels for habitat structures[4]. The honeycomb "smart panels" being developed incorporate self healing features and could incorporate the radiation waterwall feature. For crew quarters waterwall concepts, the combined multi-layers of Surlyn, PVC, Kevlar, aluminum, and fiberglass epoxy would be adjusted to deal with potential issues associated with crew quarters waterwall design. These issues include corrosion, maintenance, and fill/drain requirements.

D. **Reconfigurable Structure Group Shelter**

The reconfigurable structure group shelter features the incorporation of dual use structure and the repositioning of logistics to reduce parasitic mass of the shelter. Within the HDU, this approach leverages multiple structural floor panels that can quickly be removed without tools and assembled together to construct a radiation shelter. These flooring panels are attached to sub-flooring structure using “no-tools” fasteners, ensuring that these panels can quickly be removed and repositioned around a centralized shelter location. There they can serve as shielding if filled with water and as a support structure/attachment location for logistics relocated and repurposed as shielding. Figure 8 shows the HDU Loft and Main regions with these “dual-use” floor panels highlighted in blue, and the completed shelter region in the Loft and Main sections of the HDU on the upper right, and the shelter after adding logistics on the lower right. Figure 9 shows a possible modification to an existing honeycomb structure from another NASA project which might be able to serve as the repurposed flooring system.

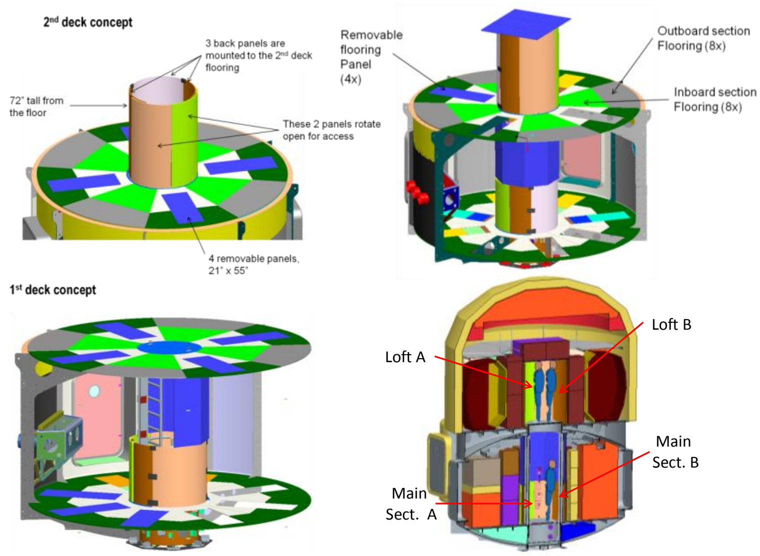

Figure 8 - Reconfigurable structure group shelter: Loft and Main region (left), completed configuration (upper right), with logistics added (lower right)

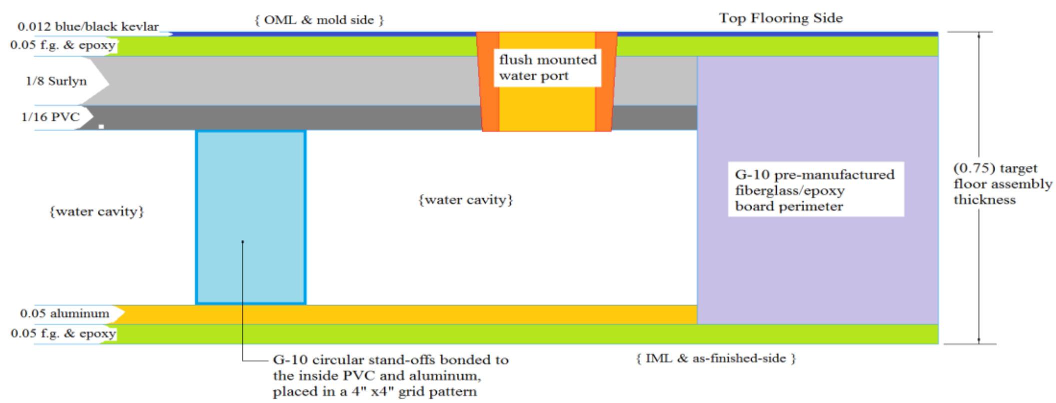

Figure 9 - Design features for a .4 inch waterwall panel, .75 inch overall height

The reconfigurable structure group shelter concept described here has good potential to be a low mass solution. Using existing logistics for shielding further enhances the natural radiation protection efficiency coming from being centrally located within the habitat. The challenges to implementing this concept are the deployment time, potential for leakage of the panels if using them as waterwalls, and the challenge of recovering the water after the event.

IV. Radiation Analysis

A. **Radiation Analysis Process**

A radiation analysis of each shelter concept described above was performed to determine the amount of protection material needed to reduce astronaut radiation exposure (described in detail in Ref. 5) . The first step of the radiation analysis is to develop a CAD model to represent the habitat structure, which is an in-space adaptation of an existing Habitat Demonstration Unit (HDU) Computer-Aided Design (CAD) model. This habitat model is then populated with consumables (food, water, cargo, etc.) and equipment (life support equipment, medical suite, exercise stations, etc.) required to support four crew for a year-long mission, as shown in Figure 10. CAD models of each of the shelter concepts are then analyzed within this outfitted habitat model to determine the thickness of the shielding material necessary to achieve two protection levels: a threshold of 50% reduction and a goal of 70% reduction. This percent reduction in exposure is evaluated by calculating the effective dose for a 50th percentile female astronaut in the habitat in its normal (unprotected) configuration to establish the baseline exposure and then performing the calculation for the female astronaut within the habitat reconfigured to include the shielding concept. The 50% female astronnaut is an industry standard in radiation analysis chosen to increase modeling conservativism because females are more radiologically sensitive than males.

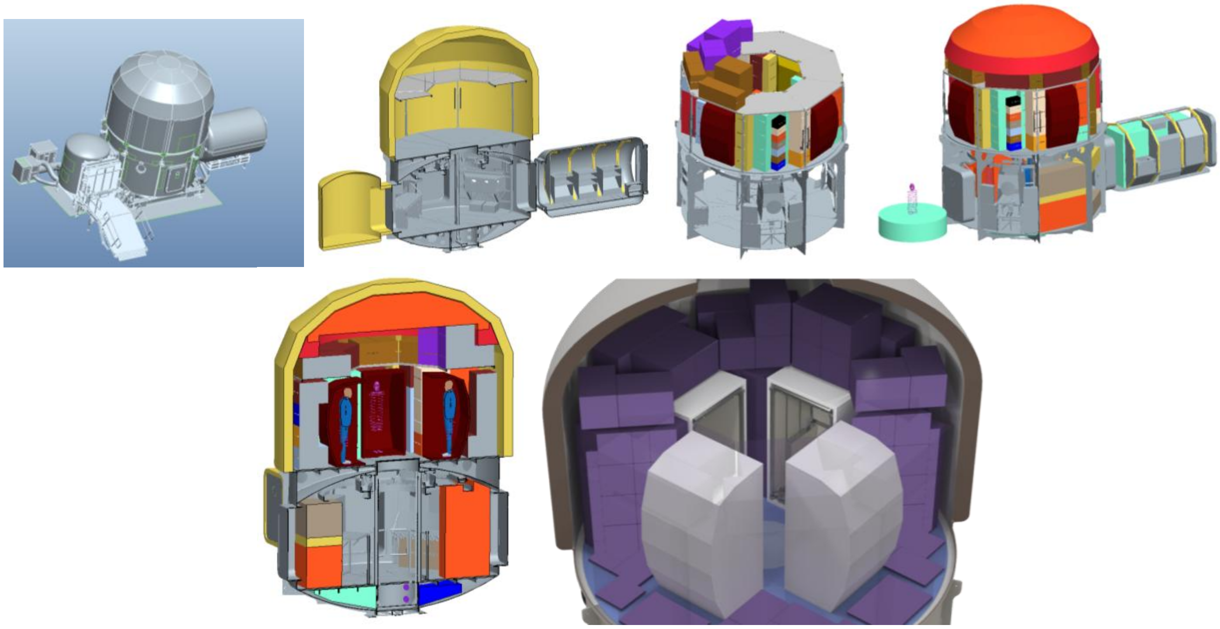

Figure 10: Construction of HDU radiation CAD model

Effective dose is a measure of whole body exposure. It is determined by calculating the dose equivalent at a large number of points in the body and taking a weighted average of these values utilizing tissue weighting factors to account for the varying sensitivity of the various organs and tissues. In order to determine the dose equivalents, points representing the body of the female astronaut placed within the CAD models of the habitat and shielding concepts are ray traced with scripts utilizing the Sigmaxim SmartAssembly™[6] tool set, an analysis add-on for the Pro/Engineer CAD Software. Based upon the total thicknesses of aluminum, polyethylene, and tissue observed along each ray, a dose equivalent along each ray is computed using the International Commission on Radiological Protection (ICRP) Publication #60 quality factors[7] and integrated to determine the dose equivalent at each point in an organ. After the dose equivalents at all the points in the organ have been found, the mass-averaged dose equivalent for the organ is computed. Then once all the organ dose equivalents are found, the effective dose is then computed using the National Council on Radiation Protection and Measurements (NCRP) Report #132 tissue weighting factors[8].

This process is carried out using several radiation analysis tools (geometry algorithms, High charge (Z) and Energy TRaNsport code (HZETRN)[9,10], effective dose scripts) developed for the On-Line Tool for the Assessment of Radiation in Space (OLTARIS)[11] to calculate the effective dose. The Female Adult voXel (FAX) phantom[12] was used to model the female astronaut. The CAD models for three 50th percentile male astronauts were also included in the habitat to account for the protection they would provide the female astronaut. For a more complete explanation of radiation analysis using OLTARIS with phantoms see Ref. 11 or the OLTARIS website (https://oltaris.larc.nasa.gov/help_documentation/OLTARIS_phantom_process_v2.pdf).

In addition to the habitat geometry, outfitting and shielding materials, the effective dose is also driven by the choice of the SPE. For this effort, the design basis SPE chosen is referred to as the Xapsos 95th percentile event. It was calculated using a tool developed by Dr. Michael Xapsos to produce probabilistic proton environments due to solar particle events for missions with durations of one year or more[13]. For an input mission duration and a confidence level, the tool outputs integral proton fluences for energies ranging from 1 MeV to 300 MeV for both the total SPE fluence that would occur during the mission and a “worst case” SPE spectra. The 95% confidence level chosen represents the confidence that the total SPE fluence would not be exceeded. The total 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 Figure 11 was calculated. More details on the selection of this SPE over the others shown in the figure can be found in Ref. 5.

As mentioned previously, the effectiveness of a shelter concept is measured by the percent reduction in effective dose over a baseline effective dose in the habitat with no additional radiation protection. The two baseline astronaut locations used to set this baseline effective dose are shown in Figure 12, one in the crew quarters and one central in the main section. The effective doses for each are shown for each of the investigated SPE spectra in Table 2. It is clear that the choice of SPE model has more impact than the location of the baseline astronaut. The 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 are compared to the baseline value of 361 mSv.

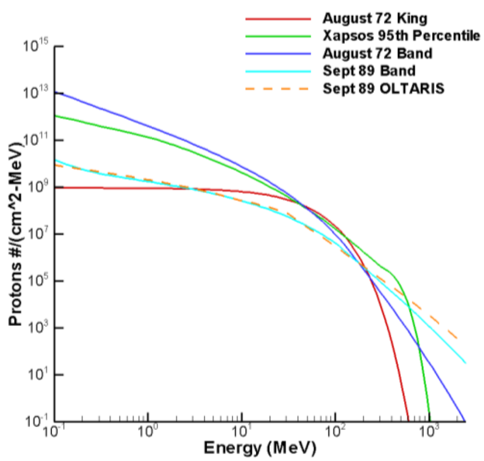

Figure 11: Solar particle event spectra

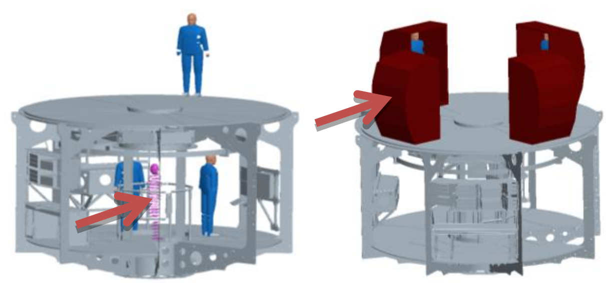

Figure 12: Placement of astronaut within HDU radiation CAD model for baseline exposure determination

Table 2: Baseline astronaut exposure in shelter locations for various SPEs

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

B. **Shelter Concept Radiation Analyses Results**

This radiation analysis procedure is used to assess trade variations of each of the shelter concepts. Table 3-6 show the shielding thicknesses and total shielding masses for each of the shelter concepts at various deployment locations in the habitat and for various analysis assumptions. Ranges in the thickness data indicate the ranges of thicknesses required for either multiple individual shelter units simultaneously deployed or multiple locations of crew within a group shelter. Based on Table 3, it appears possible to create a wearable concept, 2-3 inches thick that would meet the 50% exposure reduction requirement in either deployment location, but a wearable concept that would meet the 70% protection level would probably be too thick to meet mobility requirements. In the analysis of the deployable individual shelter concept, the shielding materials (food and HMC bricks) are modeled as water and aluminum to determine bounds on the thickness and mass required to achieve the dose reductions. The shelters are positioned as shown in Figure 13. Based on the results shown in Table 4, 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.

Table 3: Radiation analysis results for *wearable, sleeping bag derived shelters*

	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

Table 4: Radiation analysis results for *deployable individual shelter*

	Food/Brick Layer Thickness, in		Total Mass for 4 Astronauts, lbm	
	50%	**70%**	**50%**	**70%**
Modeled as Water	0.52-0.92	3.43-4.42	627	3693
Modeled as Aluminum	0.27-0.50	2.14-3.01	905	6520

Table 5: Radiation analysis results for *individual crew quarters based shelters*

	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

Table 6: Radiation analysis results for *reconfigurable structure group shelter* leveraging available structure

	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

Three scenarios are evaluated for the crew quarters concept. In the first, the four crew quarters were left in their original positions abutting the exterior walls and the thickness of water walls built into the crew quarters walls were varied uniformly. In the second, 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 Figure 14. 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. Based on the results in Table 5, it appears to be possible to create a water wall 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 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.

Based on the analysis of the reconfigurable structure group shelter (shown in Figure 15) , it appears to be possible to create a storm shelter using the floor panels that will meet either the 50% or the 70% protection levels, but the large quantity of water needed to meet the 70% protection level 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 walls and the quantity of water needed for the 70% protection level is smaller. It should be noted, however, that this evaluation assumed a floor panel thickness of 1.59 g/cm^2 without water. Further investigation is required to determine whether this is sufficient for structural concerns to validate this assumption.

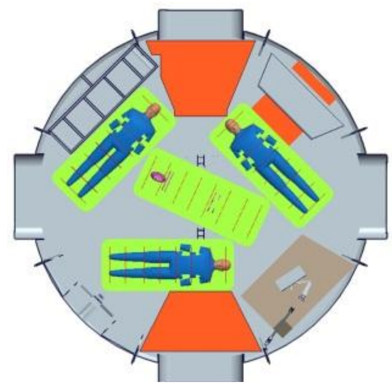

Figure 13: Location of individual deployable shelter concepts within HDU radiation CAD model

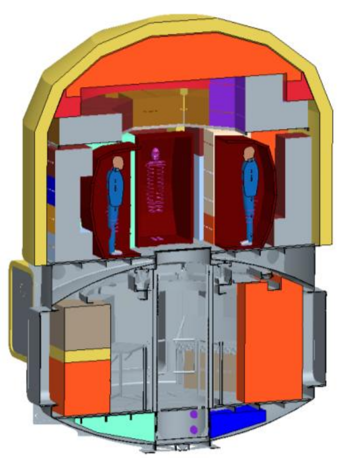

Figure 14: Location of crew quarters centric shelter concepts within HDU radiation CAD model

V. Parasitic Mass Estimation

The results in Table 3-6 highlight the total mass of the shielding material required, but the key figure of merit is the amount of "parasitic mass" or single-purpose shielding mass manifested only to provide radiation shielding. Parasitic mass primarily comes from two sources: 1) basic structure/hardware necessary to support or implement a protection strategy and 2) protection materials which serve no alternative purpose than radiation shielding. Any of these items which are also utilized for any non-radiation protection purpose are not counted as parasitic mass. For example, water mass is not considered parasitic unless is exceeds the 1300 lbm of contingency water which is assumed for the mission. Any additonal water which is included to increase radiation protection is counted as parasitic, even though it may be useful in an emergency if sufficient access to it is provided. Similarly, food packets/bricks are not considered parasitic unless they exceed the quantity available for the mission.

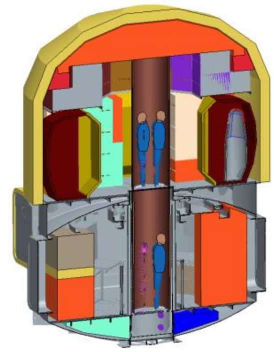

Figure 15: Location of crew in reconfigurable structure group shelter within HDU radiation CAD model

The parasitic mass is estimated for each concept to determine which concepts more effectively leverage the habitat layout or available logistics and consumables. Additionally, the "raw shielding" mass that would be required if polyethylene panels are used to construct a fully parasitic shelter around the central shaft (Figure 15) is also estimated for comparison (this location had the lowest parasitic mass of ones investigated). Table 7 summarizes the parasitic masses required to achieve the effective dose reductions in each of these cases. Detailed breakdowns of how these parasitic masses are estimated are included in Table 11 – 20 in Appendix A. The majority of the parasitic mass in the wearable concept comes from the water which exceeds the assumed contingency water quantity. Because the deployable individual concept is designed with a fixed size water wall which does not exceed the contingency water mass allotment, there will be no parasitic water mass. The remaining five sides of the deployed enclosure are assumed to be shielded with HMC bricks which also are not declared to be parasitic. The brick manufacturing equipment itself is non-parasitic as it is assumed to be required hardware for the purpose of garbage compaction regardless of the use of its created product. Because of these assumptions, the parasitic mass for the deployable individual concept is constant between conditons of 50 or 70% radiaiton reduction.

Table 7- Parasitic mass summary for four crew members

	50% Effective Dose Reduction	**70% Effective Dose Reduction**
Concept	**Parasitic Mass, lbm**	**Parasitic Mass, lbm**
All-Polyethylene (Baseline Mass)	1500	4000
Wearable	805	2577
Deployable Individual Shelter	784	784
Individual Crew Quarters (4 CQs)	246	4763
ReconfigurableStructure Group Shelter (Logistics)	209	2113
ReconfigurableStructure Group Shelter (No Logistics)	1619	5703

The crew quarters concept is similar to the wearable in that its parasitic mass is dominated by parasitic water, but moreso because of the larger surface area required for equivalent protection. Because of the uncertainty around the acceptability of a two person crew quarters derived shelter, the four person variant is used for the downselection process. It should be noted that if the acceptability of the two person crew quarters derived shelter is validated, the parasitic mass reductions are ~120kg for the 50% radiation reduction case and ~3300 kg for the 70% radiation reduction case. The reconfigurable structure group shelter which does not leverage logistics is also driven by the amount of parasitic water required. However, if the group structure concept is designed to leverage the available logistics, the parasitic water (and the resulting total parasitic mass) descreases substantially.

VI. Deployment Time Estimation

Another primary figure of merit used to compare the shelter concepts is the deployment time required to setup the shelter once a SPE is identified. This time is estimated through the development of an operational timeline, which outlines the required tasks to setup the shelter including identification of if tasks must be performed in series or parallel. These timelines are summarized here in Table 8.

Table 8: Concept deployment for 50% dose reduction shelter variants

Concept	Deployment time, minutes
Wearable Prefilled	15.0
Wearable Fill as Needed	36.0
Deployable Individual	26.0
Individual CQ Waterwall Prefilled	7.0
Reconfigurable Structure	27.0
Reconfigurable Structure & Logistics Adjustment	60.0

A. **Wearable:**

The sleeping bag wearable concept is assessed in two different operational scenarios. The first assumes the sleeping bags are prefilled with water prior to identification of a SPE, and the second assumes each sleeping bag must be filled with water from the habitat life support system upon identification of a SPE. For the prefilled scenario, the crew person in the loft proceeds directly to his crew quarters to don the sleeping bag and hood protection. Some timing cushion is provided to allow for translation of astronauts through the central corridor from the other locations to their respective crew quarters. The total time estimated to implement this solution is 15 minutes. This deployment strategy assumes the water used for protection is primarily contingency water and is not required for on-demand access by the habitat's life support system.

The non-prefilled wearable operational assessment assumes the water bladders used for protection would have to be filled from a water source prior to donning for the SPE. Adequate water is assumed to be available in the primary life support system and that four ports may be simultaneously utilized to fill each sleeping bag concurrently. The total time estimated to implement this solution is 36 minutes.

B. **Individual Deployable Shelter:**

The individual deployable shelter concept selected for assessment consists of removing an existing piece of wall or table that is constructed using the stowed deployable structure. The back side of this device is pre-filled with contingency water. The deployable shelter is unfolded and the skeleton structure erected. This structure can then be covered with a pre-filled flexible wall made of pockets of food or HMC bricks, where the mix is determined by how far into the mission duration an SPE occurs. It is assumed in this operational approach that all four deployable shelters are assembled simultaneously by each astronaut. The total time estimated to implement this solution is 26 minutes.

C. **Crew Quarters-Derived:**

The crew quarters waterwalls are also assumed to be pre-filled with contingency water. This is the simplest operational scenario as the crewmembers just have to find their way to their respective quarters to prepare for the SPE. A buffer of time to allow each crew member to make that move without interfering with another crew member is provided. The total time estimated to implement this solution is 7 minutes.

D. **Reconfigurable Structure Group Shelter:**

Utilizing repositioned structural panels to create a group shelter is a multistep process. To implement this concept, crew members are assigned simultaneous tasks including removal of structural/protection panels from a habitat floor or wall and positioning these panels around an existing central framework to create a protective enclosure. The panels are considered pre-filled with contingency water. There is considerable amount of assembly in this approach, but because the crew is working on parallel tasks the deployment time is only 27 minutes. If instead of utilizing pre-filled water based panels, normal structural panels are scarred as a structural framework for the attachment of logistics, the deployment time increases substantially to ~60 minutes.

VII. Concept Comparisons – Decision Analysis

A decision analysis process was implemented to down select between the concepts based upon the performance of several figures of merit which map directly to shelter design requirements (listed in Appendix C). These figures of merit include quantitative measures such as parasitic mass and deployment time in addition to several qualitative measures capturing less measurable factors such as habitability, functionality, and complexity. The proposed shelter concepts were compared through calculation or qualitative assessment of the relative performance within each figure of merit using the decision analysis software program, "Logical Decisions"[14]. This raw score data feeding the comparison is shown in Table 9 and Table 10 for the 50% and 70% dose reduction design cases. These raw scores are converted to the same units through the use of utility functions, which convert measured values to non-dimensional relative performance measures with values between 0 and 1 representing zero and full utility, respectively. Appendix B Table 22 shows how a raw score such as percent mass savings or deployment time is assigned a utility value thru a utility function.

Table 9 - FOM ratings for the 50% radiation reduction condition

	protects 4 astronauts	habitability	deploy in less than 60 minutes	added mass % of baseline protection	design for ops in 1g environment	integrates with FY13 HDU	facilitates egress during an SPE	deployable by 2 persons or less
Wearable Prefilled	4.0	0.4	15.0	54	Yes	Yes	0.8	1.0
Deployable	4.0	0.6	26.0	52	Yes	Yes	0.5	2.0
Reconfigurable Struct.	4.0	0.6	27.0	108	Yes	Yes	0.7	2.0
CQ Waterwall Prefilled	4.0	1.0	7.0	16	Yes	Yes	0.9	1.0
Wearable Fill as Needed	4.0	0.4	36.0	54	Yes	Yes	0.8	4
Reconfigurable Structures & Logistics Adjustment	4.0	0.6	60.0	14	Yes	Yes	0.6	2.0

Table 10 - FOM ratings for the 70% radiation reduction condition

	protects 4 astronauts	habitability	deploy in less than 60 minutes	added mass % of baseline protection	design for ops in 1g env.	integrates with FY14 HDU	facilitates egress during an SPE	deployable by 2 persons or less
Wearable Prefilled	4.0	0.0	15.0	64	Yes	Yes	0.0	1.0
Deployable	4.0	0.6	26.0	20	Yes	Yes	0.5	2.0
Reposition Panels	4.0	0.6	27.0	143	Yes	Yes	0.7	2.0
CQ Waterwall Prefilled	4.0	1.0	7.0	119	Yes	Yes	0.9	1.0
Wearable Fill as Needed	4.0	0.4	72.0	64	Yes	Yes	0.0	4
Reposition Panels and Logistics Adjustment	4.0	0.6	60.0	53	Yes	Yes	0.6	2.0

The weighted summation of all FOM utility values provides a concept's integrated utility rating, or composite score, which can be used to distinguish between concepts. The weightings are used to establish the relative importance of the FOMs reflecting designer preferences. Four likely preferences were used to create four possible weightings (Appendix B Table 21):

1) All FOM's rated of equal importance
2) Baseline FOM weighting
3) Mass Savings Emphasis (minimization of protection mass)
4) Deployment Time Emphasis (minimization of deployment time)

Using multiple weighting sets provides additional rigor with respect to concept selection. If the same concept(s) always appear at the top of a ranking despite the ratings set chosen, it is a more programmatically robust selection. For the Baseline FOM weighting, note that three requirements are given zero importance. This is not because they are not important in general, but because they are not important as a discriminator between concepts. The Mass Savings and Deployment Time weighting sets then provide more value to concepts which minimize mass or deployment time respectively.

Appendix B Figure 16 through Figure 23 show the shelter concept rankings resulting from each of the four weighting sets and each of the two radiation reduction conditions, 50% and 70%. For example, it can be seen in Appendix B Figure 16 that the crew quarters waterwall concept derives the most overall utility assuming an equal FOM weighting for the case of 50% radiation reduction.

Some trends that can be observed from the integrated final utility scoring are:

- In general, for all weighting sets and under multi criteria consideration, crew quarters protection appears as the top ranked concept
- For 50% radiation reduction, prefilled wearables are the second most favored concept in general.

- There is no change in concept ranking order for equal FOM weighting vs. Baseline FOM weighting for either the 50% or 70% radiation reduction cases. Though there is difference in going from the 50% to the 70% condition.
- Wearables drop to mid to low ranking for the 70% radiation conditions.
- For 70% radiation reduction, individual deployables are the second most favored concept. Note this is tempered by the fact that HMC bricks were not used for the crew quarters option and a large amount of water is parasitic for the case of 70% radiation reduction.
- For a mass savings only weighting set, in the case of 50% radiation reduction, the reconfigurable structures and logistics approach is best (Figure 20 red bar only)
- For a mass savings only judgment, in the case of 70% radiation reduction, the individual deployable approach is best (Figure 21 red bar only)
- Filling wearables on an as needed basis is not an attractive option.

The use of the decision analysis process is useful for group discussion and understanding of each protection mechanism's pros and cons from a system viewpoint. Based upon the results, the crew quarters-derived shelter concept has consistent merit and should be investigated in future work. The deployable concept, despite achieving fairly good ratings, is considered somewhat similar to a crew quarters approach without the inherent habitability advantages a crew quarters. However, the deployable concept also shows the advantage possible with incorporating HMC bricks and food for protection in crew quarters-derived concepts to reduce the amount of parasitic water required. The reconfigurable structures approach was somewhat poorly rated, but is unique in that it demonstrated the merit of a single protection region for the full crew. The wearable approach, which was well rated for the 50% radiation reduction condition, is seen as a useful means to provide augmentation to other concepts and short duration mission situations.

VIII. Conclusions

In summary, several viable concepts were identified and assessed to protect astronauts from SPEs. 50% and 70% reductions in effective dose over an unprotected habitat were achieved with practical amounts of shielding leveraging available logistics and consumables to provide reasonable parasitic masses. Several additional conclusions from this work include:

- The development of mass-efficient, multifunctional elements that facilitate the deployment, utilization, and disposition of a shelter with sufficient shielding properties is an enabling technology for long duration space exploration beyond Earth orbit.
- The decision analysis tool allows the decision maker to determine sensitivity of selection ranking to figure of merit importance, or changes in figure of merit ratings. A selection process has been demonstrated to quantify storm shelter performance from a system level viewpoint. Replications of this process may require resetting of FOMs, weightings, or alternatives to be used on additional habitat elements not considered here, but should hold as an effective assessment tool.
- Water shielding is non-parasitic only if the water can be used, at least in contingency if not in daily living. To be useable as non-parasitic the water must be extractable from the water wall such as by being plumbed into the existing water system, or by the water wall segment having a positive expulsion device.
  - For assumed conditions, 30 day supply – 1300 lbm contingency water, water wall solutions were advantageous if the radiation requirements were not severe, or if logistics also assist in shielding.
  - In conditions requiring moderate radiation protection requirement, the wearable option may be sufficient as it easily can hold the required contingency water.
  - If only contingency water is used for radiation shielding, the water container should simply be one that is of a bladder nature such that it can be manually drained.
- In comparison to water, HMC brick shielded designs were not considered parasitic. As a result, conditions which require large amounts of shielding water (e.g., 70% radiation reduction) are biased on a mass savings basis towards HMC bricks. However HMC bricks are not available early in the mission timeline. It was assumed food packets or other logistics packages would have to be available for pre-placement in a radiation shield which will over mission time transition to HMC brick coverage.
- Recommendations for Habitat Design and Use:
  - In general for deep space habitat design, keep crew surrounded by logistics and element systems, Ex: Crew quarters down the center of a cylinder with logistics surrounding in an annular manner.

- If using HMC brick type solutions, is it feasible to keep brick dimensions and food packet dimensions of similar nature (or perhaps of an even multiple) such that food can easily be used for radiation protection until utilized when it is then replaced by bricks.

- Future collaborations with other habitation subsystems are critical for implementing low mass solutions to deep space habitation challenges such as SPE radiation protection.

IX. Recommendations and Future Work

The following concepts are being carried forward into FY '13:

- Develop a full scale model of a crew quarters waterwall protection mechanism to be incorporated into the waypoint DSH design.
- Develop a full scale model of a centralized storm shelter constructed from dual use panels and reconfigured logistics to be incorporated into the waypoint DSH design.
- Maintain the wearable approach as a possible demonstration item for augmentation of the two primary concepts selected.

There is a need to increase each of these shelter concepts's definition with respect to deployment operations, subsystem needs, ventilation, comfort (heat, humidity), lighting, power, etc. Operational risks and system integrity issues associated with water based shielding concepts were not quantified in this phase of the project. Such work should be continued through the crew quarters selected approach.

Finally, knowledge of the amounts of logistics on hand through a mission timeline is important to know if sufficient radiation protection is available for reconfiguration during an SPE. It is suggested to perform Discrete Event Simulation (DES) to quantify logistics, food product, and waste product usage over time. DES scenarios can answer operational questions such as how much of a particular item is required at mission start, how much is available throughout the mission and where at any point in time are the items located. Manpower is not currently unidentified for such work, but it may prove crucial in future design efforts.

Finally lessons learned from the FY'12 Storm Shelter radiation assessment and design process should be leveraged to influence the design and layout of future habitation concepts. Tightly coupled integration of all subsystems will be necessary to enable future deep space habitation challenges.

Appendix A – Parasitic Mass Estimates

Table 11 – Parasitic mass estimate for *wearable* protection concept (50% dose reduction, 2.8 inches water)

item - for single crew coverage	Sub assy Unit Mass, lbm	Assy Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Basic Sleeping Bag		7	1	7	0	0	1	0
bladder and bladder cover		17	1	17	1	17	1.1	19
2.8 inches water		509	1	509	0	0	1.5	0
Totals				534		17		19
Water Mass for 4 crew				2036				
parasitic_water for 4 crew				728				
Four Crew Parasitic Mass				805				

Table 12 - Parasitic mass estimate for *wearable* protection concept (70% dose reduction, 6.1 inches water)

item - for single crew coverage	Sub assy Unit Mass, lbm	Assy Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Basic Sleeping Bag		8	1	8	0	0	1	0
bladder and bladder cover		19	1	19	1	19	1.1	21
6.1 inches water		509	1	950	0	0	1.5	0
Totals				977		19		21
Water Mass for 4 crew				3800				
parasitic_water for 4 crew				2492				
Four Crew Parasitic Mass				2577				

Table 13 - Parasitic mass estimate for *individual, deployable* protection concept (50% dose reduction)

item - for single crew coverage	Sub assy Unit Mass, lbm	Assy Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Water Tanks		58.0	2.0	116.0	1.0	116.0	1.3	150.8
plate stiffeners		1.5	4.0	5.8	1.0	5.8	1.3	7.5
frames		0.3	8.0	2.5	1.0	2.5	1.3	3.3
hinges		0.2	2.0	0.4	1.0	0.4	1.3	0.5
membrane for shield attachment		6.0	1.0	6.0	1.0	6.0	1.3	7.8
water tank protection - water per tank		57.6	2.0	115.2	0.0	0.0	1.0	0.0
membrane protection - HMC bricks		170.0	1.0	170.0	0.0	0.0	1.0	0.0
Brick mfg equipment		200.0	1.0	200.0	0.0	0.0	1.0	0.0
Positive Expulsion Device		10.0	2.0	20.0	1.0	20.0	1.3	26.0
Totals				635.9		130.7		195.9
Four Crew Parasitic Mass								783.744

Table 14 - Parasitic mass estimate for *individual, deployable* protection concept (70% dose reduction)

item - for single crew coverage	Sub assy Unit Mass, lbm	Assy Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Water Tanks		58.0	2.0	116.0	1.0	116.0	1.3	150.8
plate stiffeners		1.5	4.0	5.8	1.0	5.8	1.3	7.5
frames		0.3	8.0	2.5	1.0	2.5	1.3	3.3
hinges		0.2	2.0	0.4	1.0	0.4	1.3	0.5
membrane for shield attachment		6.0	1.0	6.0	1.0	6.0	1.3	7.8
water tank protection - water per tank		57.6	2.0	115.2	0.0	0.0	1.0	0.0
membrane protection - HMC bricks		1065.0	1.0	1065.0	0.0	0.0	1.0	0.0
Brick mfg equipment		200.0	1.0	200.0	0.0	0.0	1.0	0.0
Positive Expulsion Device		10.0	2.0	20.0	1.0	20.0	1.3	26.0
Totals				1530.9		130.7		195.9
Four Crew Parasitic Mass								783.744

Table 15 - Parasitic mass estimate for *crew quarters-derived* protection concept (50% dose reduction)

item - for single crew coverage	Sub assy Unit Mass, lbm	Assy Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Panels		110	1	110	0.1	11	1.5	17
2 Sides	36							0
top	10							
bottom	9							
door	33							
back	23							0
Support Str. And Bumpout		225	1	225	0	0	1.5	0
Fasteners		11	1	11	0	0	1	0
Positive Expulsion Devices		10	3	30	1	30	1.5	45
Water		169	1	169	0	0	1	0
2 Sides	103							0
back	66							0
Totals				545		41		62
Water Mass				676				
parasitic_water				0				
Four Crew Parasitic Mass				246.06				

Table 16 - Parasitic mass estimate for *crew quarters-derived* protection concept (70% dose reduction)

item - for single crew coverage	Sub assy Unit Mass, lbm	Assy Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Panels		110	1	110	0.1	11	1.5	17
2 Sides	36							0
top	10							
bottom	9							
door	33							
back	23							0
Support Str. And Bumpout		225	1	225	0	0	1.5	0
Fasteners		11	1	11	0	0	1	0
Positive Expulsion Devices		10	3	30	1	30	1.5	45
Water		1456	1	1456	0	0	1	0
2 Sides	885							0
back	571							0
Totals				1832		41		62
Water Mass				5825				
parasitic_water				4517				
Four Crew Parasitic Mass				4763.432				

<u>Two crew quarter shelters, two crew per crew quarters:</u>

A more mass efficient operational approach for use of the crew quarters during an SPE event would be to use only two crew quarters and place two crew in each. For that approach the following reductions in protection mass requirement are noted.

- 50% radiation reduction mass is 379 lbm for 2 crew quarters
- 70% radiation reduction mass is 2656 lbm for 2 crew quarters

Table 17 - Parasitic mass estimate for *reconfigurable structures group* protection concept, no logistics assistance (50% dose reduction)

item - for 4 crew coverage		Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Lower Loft								
endcap panels		32	3	96	0.1	10	1.5	14
cyl. shield panels		49	3	147	0.1	15	1.5	22
cyl gate panel		76	2	152	0.1	15	1.5	23
Lower Loft Water in endcap panels		0	3	0	0	0	1.5	0
Lower Loft Water in shield panels		166	3	498	0	0	1.5	0
Lower Loft Water in gate panels		162	2	323	0	0	1.5	0
mounting hardware		1	3	3	1	3	1.5	5
Lower Loft Positive Expulsion Devices		5	3	15	1	15	1.5	23
Main Floor								
repositioned floor panels		32	8	256	0.1	26	1.5	
Shield panels		29	3	87	0.1	9	1.5	
Gate panels		45	2	90	0.1	9	1.5	14
mounting hardware		1	8	8	1	8	1.5	12
water in floor panels		154	8	1231	0	0	1	0
water in shield panels		135	3	404	0	0	1	0
water in gate panels		131	2	261	0	0	1	0
Main Floor Positive Expulsion Devices		5	13	65	1	65	1.5	98
Totals				3636		174		209
Water Mass				2717				
parasitic_water				1410				
Four Crew Parasitic Mass				1619				

Table 18 - Parasitic mass estimate for *reconfigurable structures group* protection concept, no logistics assistance (70% dose reduction)

item - for 4 crew coverage		Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Lower Loft								
endcap panels		32	3	96	0.1	10	1.5	14
cyl. shield panels		49	3	147	0.1	15	1.5	22
cyl gate panel		76	2	152	0.1	15	1.5	23
Lower Loft Water in endcap panels		0	3	0	0	0	1.5	0
Lower Loft Water in shield panels		430	3	1290	0	0	1.5	0
Lower Loft Water in gate panels		419	2	837	0	0	1.5	0
mounting hardware		1	3	3	1	3	1.5	5
Lower Loft Positive Expulsion Devices		5	3	15	1	15	1.5	23
Main Floor								
repositioned floor panels		32	8	256	0.1	26	1.5	
Shield panels		29	3	87	0.1	9	1.5	
Gate panels		45	2	90	0.1	9	1.5	14
mounting hardware		1	8	8	1	8	1.5	12
water in floor panels		379	8	3035	0	0	1	0
water in shield panels		332	3	995	0	0	1	0
water in gate panels		322	2	644	0	0	1	0
Main Floor Positive Expulsion Devices		5	13	65	1	65	1.5	98
Totals				7720		174		209
Water Mass				6801				
parasitic_water				5493				
Four Crew Parasitic Mass				5703				

Table 19 - Parasitic mass estimate for *reconfigurable structures group* protection concept, with logistics assistance (50% dose reduction)

item - for 4 crew coverage		Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Lower Loft								
endcap panels		32	3	96	0.1	10	1.5	14
cyl. shield panels		49	3	147	0.1	15	1.5	22
cyl gate panel		76	2	152	0.1	15	1.5	23
Lower Loft Water in endcap panels		0	3	0	0	0	1.5	0
Lower Loft Water in shield panels		0	3	0	0	0	1.5	0
Lower Loft Water in gate panels		0	2	0	0	0	1.5	0
mounting hardware		1	3	3	1	3	1.5	5
Lower Loft Positive Expulsion Devices		5	3	15	1	15	1.5	23
Main Floor								
repositioned floor panels		32	8	256	0.1	26	1.5	
Shield panels		29	3	87	0.1	9	1.5	
Gate panels		45	2	90	0.1	9	1.5	14
mounting hardware		1	8	8	1	8	1.5	12
water in floor panels		0	8	0	0	0	1	0
water in shield panels		0	3	0	0	0	1	0
water in gate panels		0	2	0	0	0	1	0
Main Floor Positive Expulsion Devices		5	13	65	1	65	1.5	98
Totals				919		174		209
Water Mass				0				
parasitic_water				0				
Four Crew Parasitic Mass				209				

Table 20 - Parasitic mass estimate for *reconfigurable structures group* protection concept, with logistics assistance (50% dose reduction)

item - for 4 crew coverage		Unit Mass, lbm	No. Units	Basic Mass, lbm	parasitic factor	Basic parasitic Mass	MGA Factor	Predicted Parasitic Mass, lbm
Lower Loft								
endcap panels		32	3	96	0.1	10	1.5	14
cyl. shield panels		49	3	147	0.1	15	1.5	22
cyl gate panel		76	2	152	0.1	15	1.5	23
Lower Loft Water in endcap panels		0	3	0	0	0	1.5	0
Lower Loft Water in shield panels		170	3	510	0	0	1.5	0
Lower Loft Water in gate panels		165	2	331	0	0	1.5	0
mounting hardware		1	3	3	1	3	1.5	5
Lower Loft Positive Expulsion Devices		5	3	15	1	15	1.5	23
Main Floor								
repositioned floor panels		32	8	256	0.1	26	1.5	
Shield panels		29	3	87	0.1	9	1.5	
Gate panels		45	2	90	0.1	9	1.5	14
mounting hardware		1	8	8	1	8	1.5	12
water in floor panels		192	8	1539	0	0	1	0
water in shield panels		168	3	504	0	0	1	0
water in gate panels		163	2	327	0	0	1	0
Main Floor Positive Expulsion Devices		5	13	65	1	65	1.5	98
Totals				4130		174		209
Water Mass				3211				
parasitic_water				1904				
Four Crew Parasitic Mass				2113				

Appendix B – Decision Analysis Data

Table 21 - Weighting set definitions for decision ranking

	Preference Set Name			
	All Weights Equal	Baseline	Mass Savings Emphasis	Deployment Time Emphasis
protects 4 astronauts	1	0	0	0
provide 36 hour habitability	1	7	7	7
deploy in less than 60 minutes	1	10	10	15
added mass % of baseline protection	1	10	15	10
design for ops in 1g env.	1	0	0	0
integrates with FY14 HDU	1	0	0	0
facilitates egress during an SPE	1	5	5	5
deployable by 2 persons or less	1	5	5	5

Table 22 - Mapping of intrinsic measures to utility values

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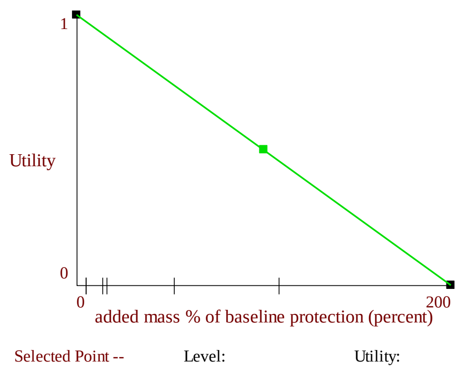
<td>added mass, % of baseline protection mass</td>
<td>
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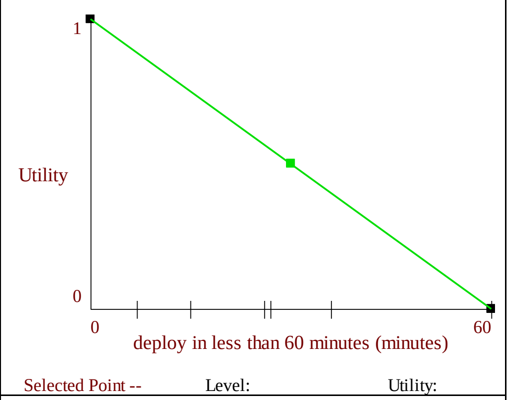
<td>deploy in less than 60 minute</td>
<td>
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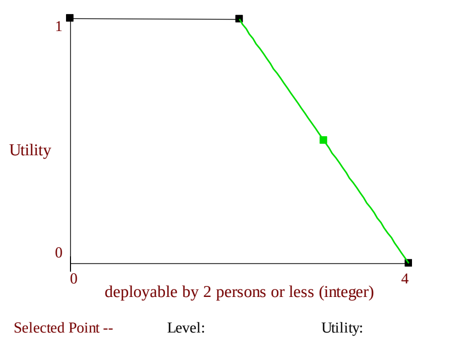
<tr>
<td>deployable by 2 persons or less</td>
<td>
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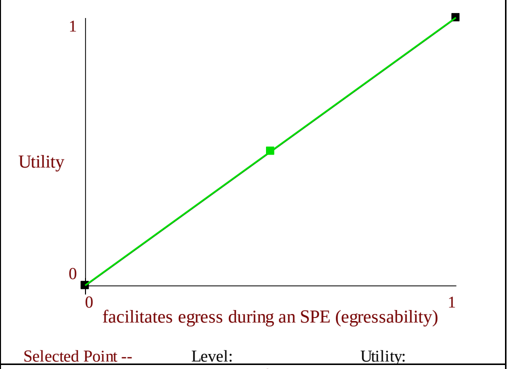
<td>facilitates egress during SPE event</td>
<td>
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</tr>
<tr>
<td>design for ops in 1g environment
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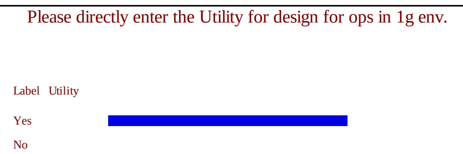
no = 0.0</td>
<td>
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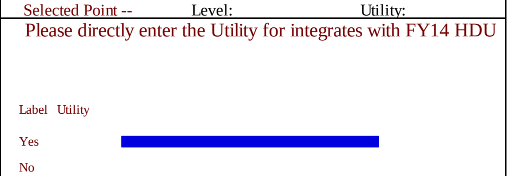
<td>integrates with FY14 HDU
yes= 1.0
no = 0.0</td>
<td>
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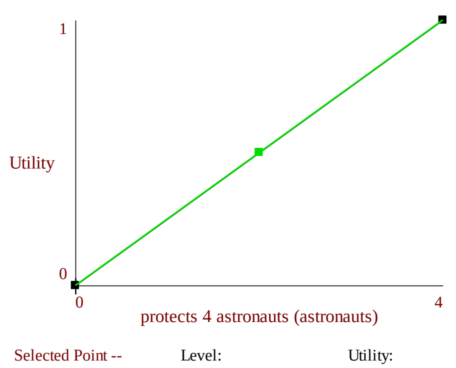
<td>protects 4 astronauts</td>
<td>
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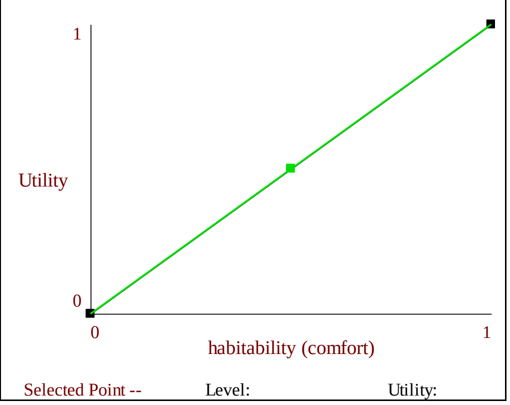
<td>
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	50% Radiation Reduction	70% Radiation Reduction
Equal FOM Weighting	Figure 16	Figure 17
Baseline FOM Weighting	Figure 18	Figure 19

Equal FOM Weighting — 50% Radiation Reduction

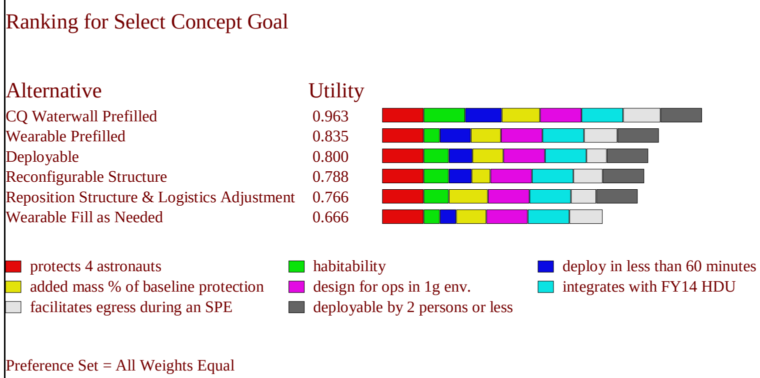

Figure 16

Equal FOM Weighting — 70% Radiation Reduction

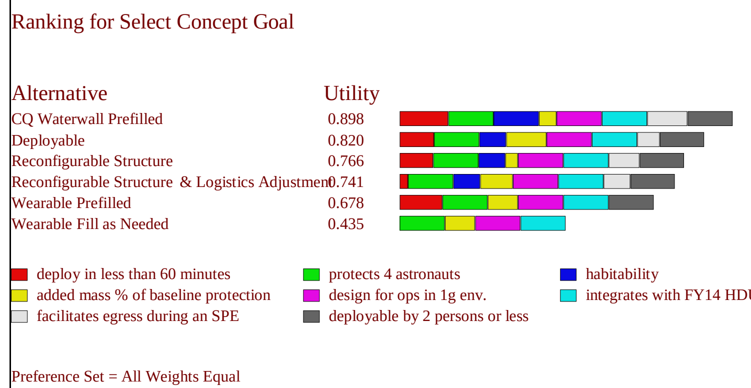

Figure 17

Baseline FOM Weighting — 50% Radiation Reduction

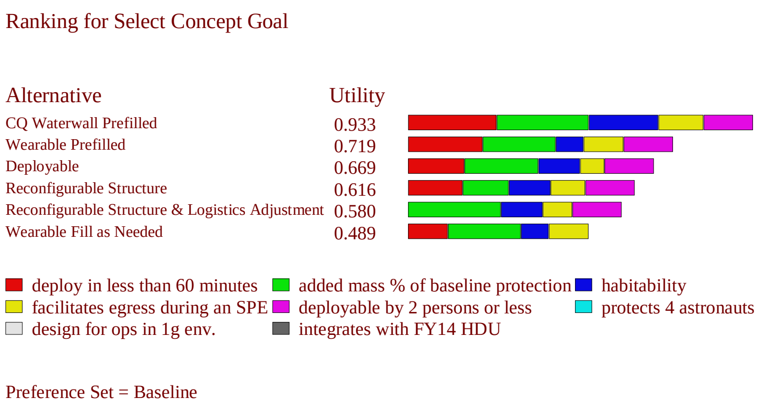

Figure 18

Baseline FOM Weighting — 70% Radiation Reduction

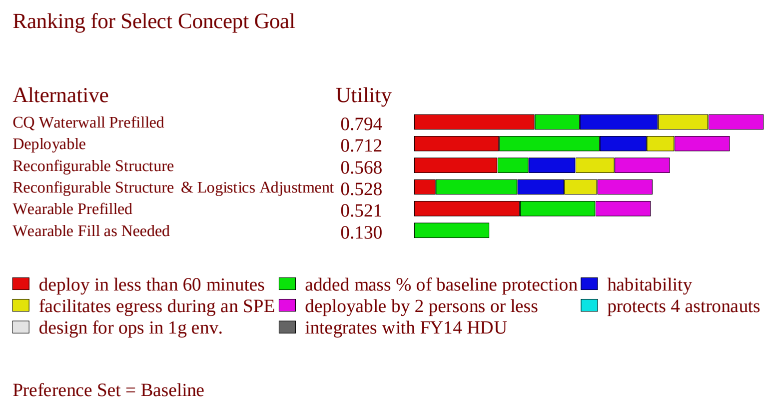

Figure 19

	50% Radiation Reduction	70% Radiation Reduction
Mass Savings Emphasis	Figure 20	Figure 21
Minimum Deploy Time Emphasis	Figure 22	Figure 23

Mass Savings Emphasis — 50% Radiation Reduction

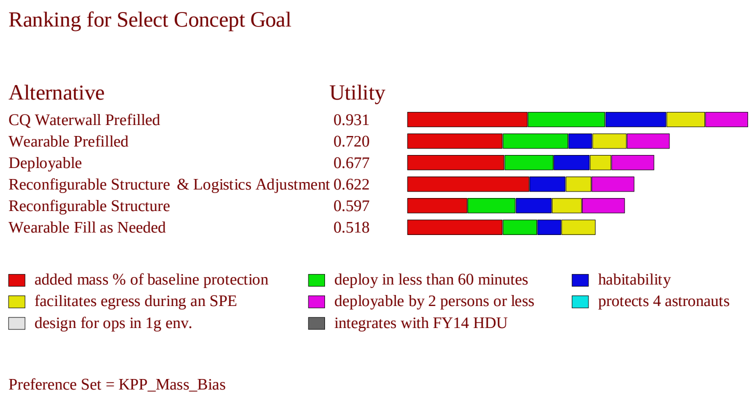

Figure 20

Mass Savings Emphasis — 70% Radiation Reduction

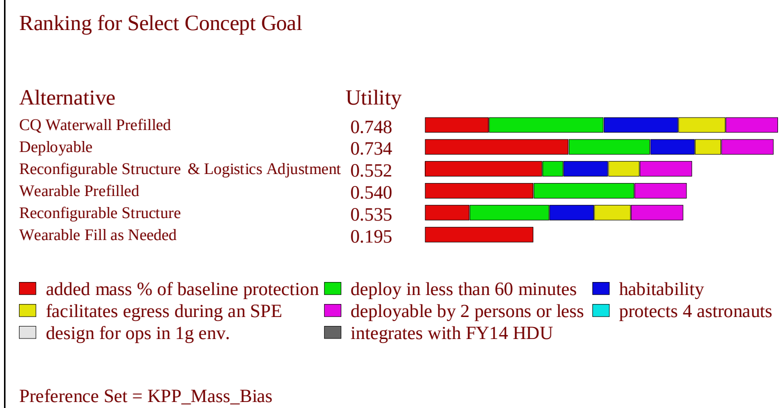

Figure 21

Minimum Deploy Time Emphasis — 50% Radiation Reduction

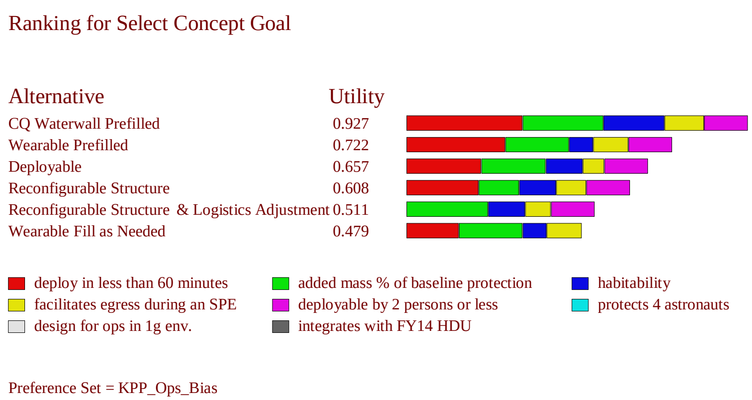

Figure 22

Minimum Deploy Time Emphasis — 70% Radiation Reduction

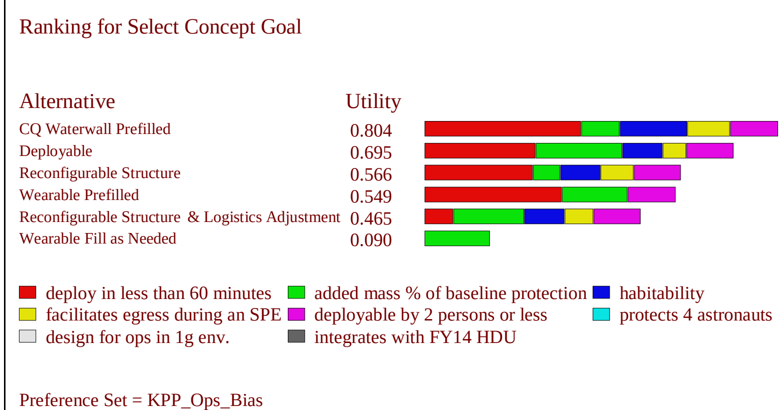

Figure 23

Appendix C – RadWorks Storm Shelter Project Requirements

Reqt #	Shall Statement	Rationale	KPP? (Y/N)	Threshold Value (for KPP)	Goal Value (for KPP)	Verification Success Criteria	Verif. Method
SS001	Storm sheltering shall protect 4 astronauts.	Sheltering must be adequately sized to accommodate all personnel anticipated to inhabit the HDU simultaneously.				Demonstrate that storm sheltering is of sufficient size to accommodate TBR astronauts.	Demonstration
SS002	<Deleted>						
SS003	Storm sheltering shall provide crew protection for a nominal 36 hour habitability period.	Storm sheltering configuration should be reasonable for astronaut habitation given the limited space of the shelter.	No			Astronauts remain sufficiently comfortable and accommodated for a 36 hour SPE.	Demonstration
SS004	Storm sheltering shall be deployed/ assembled in less than 60 minutes.	Sheltering set-up should be easily achievable based on time between warning and SPE event.	Yes	60 min	15 min	Demonstrate that storm shelter can be deployed/assembled in the time required.	Demonstration
SS005	Added mass shall be less than 20% of the raw shielding mass.	Avoidance of parasitic mass.	Yes	20%	10%	Show analysis results that verify adherence to mass requirements.	Analysis
SS006	The astronauts 90% percentile SPE exposure shall be reduced by 50%.	Effective protection will increase allowable astronaut time in space and operational flexibility.	Yes	50%	70%	Analysis results document required SPE protection.	Analysis
SS007	Storm sheltering shall be designed for space operations loads equivalent in a 1-g environment.	For handling demonstration, the operational environment should be replicated as closely as possible. Reduced-g will be tracked analytically.	No			Show analysis results that verify adherence to gravity requirement.	Analysis
SS008	<Deleted>						
SS009	Storm sheltering shall integrate with FY14 HDU configuration.	Storm sheltering must effectively integrate with the HDU without impact to HDU functionality.	No			Demonstrate integration of storm sheltering with HDU.	Demonstration
SS010	A minimum of 3 storm sheltering design concepts shall be identified.	Multiple concepts provide means for users to understand benefits and risks associated with each concept.	No			Show design concepts via CAD models and/or sub-scale models.	Inspection
SS011	Storm shelter features shall facilitate astronaut egress during SPE.	Personnel may need brief access to other areas of the habitat during a storm event for purposes of personal hygiene, to perform a short term maintenance task, or to maintain habitat safety.	No			Demonstrate that storm shelter features facilitate egress during a storm event.	Demonstration
SS012	Deployment/assembly of storm sheltering shall require not more than 2 persons.	So as to have minimum impact on mission operations, it is necessary that the number of persons required for assembly of the storm shelter be minimized.	No			Demonstrate that storm shelter can be deployed/assembled by not more than 2 persons.	Demonstration

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References

[1]NASA, "Habitat Demonstration Unit – Deep Space Habitat", NASA Fact Sheet, FS-2011-08-047-JSC, 2011.

[2]Broyan, J., Ewert, M., "Logistics Reduction and Repurposing Beyond Low Earth Orbit," AIAA-2012-3445 42nd International Conference on Environmental Systems, 17-21 July, San Diego, CA.

[3]Wignarajah, K., Fisher, J., Alba, R., "Development of the Heat Melt Compactor for Management during Long Duration Human Space Flights," AIAA-2012-3545, 42nd International Conference on Environmental Systems, 17-21 July, San Diego, CA.

[4]NASA, "NASA Langley's Multi-Functional Composite and Honeycomb Panels," Technology Gateway: NP-2008-04-77-LaRC, Vol. 1, Issue 21, 2008.

[5]Walker, S., et al., "Radiation Exposure Analyses Supporting the Development of Solar Particle Event Shielding Technologies", AIAA2013-3402 , AIAA 43rd International Conference on Environmental Systems, Vail, CO, 2013.

[6]http://www.sigmaxim.com/Products/SmartAssembly/smartassembly.html

[7]International Commission on Radiological Protection (ICRP), The 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Pergamon Press, New York, 1991.

[8]National Council on Radiation Protection and Measurements (NCRP), "Radiation Protection Guidance for Activities in Low-Earth Orbit," NCRP Report 132, 2000.

[9]Wilson, J. W., et al., "HZETRN: Description of a Free-Space Ion and Nucleon Transport and Shielding Computer Program," NASA TP-3495, 1995.

[10]Slaba, T.C., Blattnig, S.R., and Badavi, F. F., "Faster and more Accurate Transport Procedures for HZETRN," *Journal of Computational Physics*, Vol. 229, 2010, pp. 9397-9417.

[11]Singleterry, R. C., et al., "OLTARIS: On-Line Tool for the Assessment of Radiation in Space," Acta Astronautica, Vol. 68, 2011, pp. 1086-1097.

[12]Kramer, R., et al., "All about FAX: A Female Adult Voxel Phantom for Monte Carlo Calculations in Radiation Protection Dosimetry," *Physics in Medicine and Biology*, Vol. 49, 2004, pp. 5203-5216.

[13]Xapsos, M. A., Barth, J. L., Stassinopoulos, E. G., Burke, E. A., and Gee, G. B., "Space Environmental Effects: Model for Emission of Solar Protons (ESP) - Cumulative and Worst-Case Event Fluences," NASA TP-1999-209763, 1999.

[14]Smith, G. Logical Decision for Windows: Users Manual. Fairfax, VA. http://www.logicaldecisions.com, 2007.