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Trade Study of System Level Ranked Radiation Protection Concepts for Deep Space Exploration

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Abstract

A strategic focus area for NASA is to pursue the development of technologies which support exploration in space beyond the current inhabited region of low earth orbit. An unresolved issue for crewed deep space exploration involves limiting crew radiation exposure to below acceptable levels, considering both solar particle events and galactic cosmic ray contributions to dosage. Galactic cosmic ray mitigation is not addressed in this paper, but by addressing credible, easily implemented, and mass efficient solutions for the possibility of solar particle events, additional margin is provided that can be used for cosmic ray dose accumulation. As a result, NASA's Advanced Engineering Systems project office initiated this Radiation Storm Shelter design activity. This paper reports on the first year results of an expected 3 year Storm Shelter study effort which will mature concepts and operational scenarios that protect exploration astronauts from solar particle radiation events. Large trade space definition, candidate concept ranking, and a planned demonstration comprised the majority of FY12 activities. A system key performance parameter is minimization of the required increase in mass needed to provide a safe environment. Total system mass along with operational assessments and other defined protection system metrics provide the guiding metrics to proceed with concept developments. After a downselect to four primary methods, the concepts were analyzed for dosage severity and the amount of shielding mass necessary to bring dosage to acceptable values. Besides analytical assessments, subscale models of several concepts and one full scale concept demonstrator were created. FY12 work terminated with a plan to demonstrate test articles of two selected approaches. The process of arriving at these selections and their current envisioned implementation are presented in this paper.

Introduction

NASA's goal for exploration of space outside the protection of Earth's magnetic field requires demonstration of technologies which can mitigate the effects of radiation dosage to crew members. The Advanced Exploration Systems [AES] technology program organizes developments for crew systems, vehicle systems, and operations. It also encompasses the use of robotic precursor missions to gain knowledge prior to or in place of the need to assign crew to a particular mission. Defined within the AES Crew Systems project is a task to develop radiation protection systems and define their integration with proposed mission operations. Shielding, analysis tools, and advanced dosimetry sensors are technology development study areas in this, the AES Radiation Works (RadWorks) project.

In this paper, the RadWorks Storm Shelter development sub-task is reported on. Status for the first year of a three year effort is presented. Storm Shelter work includes modeling and assessment of radiation sheltering techniques from a system viewpoint with emphasis towards fast track prototyping. Initially, a large systems solution trade space is subjectively assessed, competing figures of merit are weighted, and concept approaches are ranked. Selection of a path forward is discussed with this qualitative ranking in place to characterize concept pros and cons. Decision analysis leads to a focus on several types of protection options and these options are expanded upon with more detailed analysis and again a decision analysis to choose the preferred path for second year development and demonstration. Assessment includes system mass impacts on the decision process; mass metrics are based upon shielding thickness requirements determined by detailed radiation transport analyses. First year activities also included demonstrations of sub-scale prototyping. Second year deliverables will consist of full scale prototyping for multiple approaches while the final products at the end of the third year are envisioned to be an integration of one or two solutions into a full scale deep space exploration demonstration item with an associated usage logistics assessment. This paper is a summarization of inputs from the large multidisciplinary team gratefully acknowledged in Appendix A.

Large Trade Space Screening

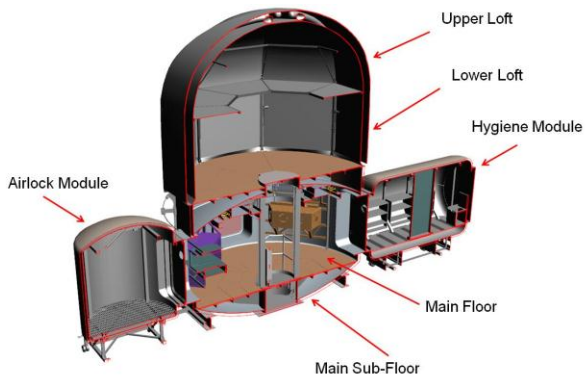


Figure 1 - HDU, Baseline Crew Quarters Arrangement

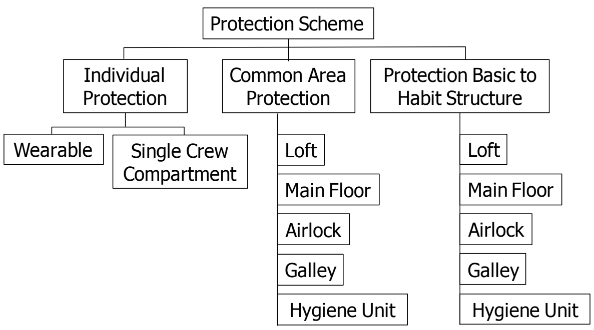


Figure 2 - Large Trade Space

There is a rich history of technical approaches which suggest means to provide radiation protection for astronauts living in transfer and habitation space vehicles [NRC2008] [RUC2012] [CLO2005]. For the RadWorks Storm Shelter team, the approach was to integrate an appropriate selection of protection schemes in the vehicle environment of NASA's Habitat Demonstration Unit (HDU) [HDU2010]. Considered in that integration are the effects of mass, operational logistics and radiation protection as they influence the selection of a "best" protection approach. Initial activities in FY2012 involved team based multi-reviewer subjective screening of many existing radiation protection techniques which have been envisioned in past NASA studies. This large trade space screening activity developed a characterization of screening methodologies based upon how various systems are constructed and operated. Because technically detailed CAD models of the HDU existed from previous work, and such models were required to perform radiation transport analyses, the Storm Shelter team utilized the HDU as a vehicle to assess storm shelter integrations within. Figure 1 shows an interior arrangement for the HDU.

Figure 2 shows the trade tree utilized by the storm shelter team to categorize and discuss potential protection approaches. To minimize the size of a region which must be protected, the idea of shielding crew members only rather than a larger surrounding volume seemed inherently worthy. Such approaches are captured as "Individual Protection" concepts. Another efficient volumetric packaging method is to combine all crew into a small area and shield only that region; such approaches are categorized as being in a "Common Area". Considering the operational constraints imposed upon crew for either of these first two approaches, the third leg of the tree focuses on concepts which shield large portions of the overall vehicle and pose no particular operational demands on the crew. The actual trade tree depicted in Figure 2 was captured down to seven levels of hierarchy using a commercial trade tool analysis program [VIS2008].

The event scenario that is prescribed for comparison of all approaches is that of providing required protection to four crew for a 36 hour period from the danger imposed by a Solar Particle Event (SPE). The crew has a maximum of one hour to prepare and inhabit the protected area; a time of less than 15 minutes is tracked as an ultimate performance metric goal. In terms of mass as a performance metric, a very aggressive mass savings goal is pursued. It is required that the system protection mass be only 20% of what is required to protect crew if the crew is integrated into a habitat similar to the current International Space Station crew quarters approach. Crew quarters positioned on the structural wall of the habitat, and protected with polyethylene, provide this baseline mass measure. An ultimate goal for protection mass penalty at or below 10% is also tracked as a higher performance metric.

Team discussion and concept ranking sessions were held early so that a multi-view stakeholder background would influence the chosen path towards a preliminary selection of concepts. A commercial decision analysis program [LOG] was used to track the ranking of protection categories as judged against system performance metrics. Multiple stakeholder rankings of decision metrics were averaged to provide a single input to the decision analysis. The multiple criteria for concept ranking were weighted in two different manners to understand how concept selection may change if mass savings are deemed of greater program value. Table 1 shows the factors used to weight figure of merit summations for the two preference sets. Even weighting of all figures of merit is compared to using a weighted summation with preference towards emphasizing the importance of mass savings.

Table 1- Large Tradespace Metric Weighting Factors

	Weighting - Preference Set	
Measure	Mass Performance	Even Weighting
Mass	1/2	1/3
Operational Assy. Time	1/3	1/3
Crew Functionality	1/6	1/3

Figure 3 shows the ranking of alternatives based upon the two weighting preference sets. Ranking shows that despite set preference, the pre-integrated waterwall for a two person crew quarters is a highly preferred approach (utility of .834 and .826). A water based wearable bladder ranks second if Mass Performance weighting is desirable (utility of .748). Deployable fabric/tent is least favorably ranked with utility values of .616 and .579. Water bladder based wearables are generally highly rated and capture a personal protection concept. In the main section, reposition of panels and logistics is moderately rated but is noted as useful for capturing a non-water wall solution. The pre-integrated blind concept was not as highly rated, but was the top rated concept in what is considered the "Deployable" category. Though numeric in presentation, this early screening process was subjective; its value was in organizing the discussion of the proposed concepts for consideration of the pros and cons of each. Subsequent discussion between LaRC technical personnel and program management resulted in creating four general categories which are taken forward for greater analytical assessment; they are 1) Wearable 2) Deployable 3) Crew Quarters Centric, and 4) Reconfigured Components.

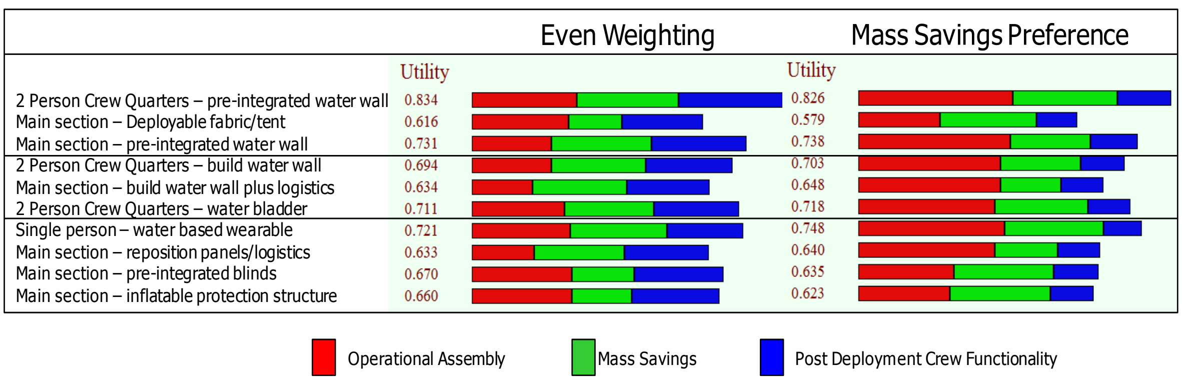


Figure 3 – Level 1 trade tree ranking for multiple sets of decision ranking metrics

Concept Definition

Having decided upon a general approach using four types of protection, and for purposes of radiation transport analysis, sample concepts had to next be refined to a point of definition where they could be integrated into a Computer Aided Design (CAD) representation. CAD incorporation is required to perform radiation transport analysis of the crewed habitat. Physical properties primarily in terms of mass, geometry, and location are required within a virtual mockup dedicated to a radiation analysis process. CAD models were matured to facilitate parasitic mass analyses and scaled demonstration developments as well. This section describes the concepts matured through the design phase which were subsequently used for the radiation and mass analyses.

Wearable:

Wearable approaches take little general habitat volume and can utilize different types of logistics to provide sheltering thickness to a garment. A sleeping bag type implementation was chosen for analysis and demonstration purposes of a wearable garment protection system (Figure 4). Such an enhanced sleeping garment, utilized within a habitats crew quarters means work and sleep activities, can be accommodated in a space proven to be habitable and productive for the duration of an SPE. Additionally, sleeping bags are designed in this case to be worn in the sense that the lower leg may extend thru the garment such that protection could be maintained during translation through the habitat and use of the astronauts feet for motion/anchoring is available.

Two approaches to wearable concepts are included in the storm shelter protection options. One uses an integrated water bladder for protection and the other uses a pouch system to contain water, food and Heat Melt Compacted (HMC) [SHU2012] bricks. The water bladder sleeping bag seeks to leverage the existing sleeping bag/restraint system available to the crew, and also available contingency life support water, to reduce required additional mass. Water 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 is included to provide head and neck (thyroid) protection. The bladder within the sleeping bag covers the body from the head to the knees maintaining complete protection of blood-forming organs but providing some relief to the overall amount of inertial mass which the occupant must deal with.

Operationally, food and water pouches would be preassembled and packaged such that the system could easily be pulled from storage and quickly attached to the sleeping bag/restraint. Packaging would be arranged so that food and water pouches could be exchanged, used or replaced with the HMC bricks as needed.

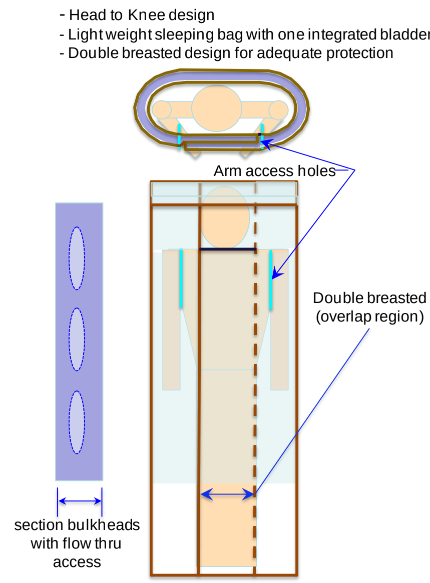


Figure 4 - Water bladder based sleeping bag concept

Deployable:

Deployable concepts feature a structural frame deployment utilizing available materials (e.g., logistics, water, trash, etc.) to protect a region of a habitat interior. Initial concepts considered included "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 CTBs, termed Multi-use CTBs (MCTB) [SHU2012]. HMC bricks, food, and water provisions provide fill material for a deployable SPE protection shelter. Kinematic structures such as pop-up ribbing to support a radiation protection cover material were also discussed.

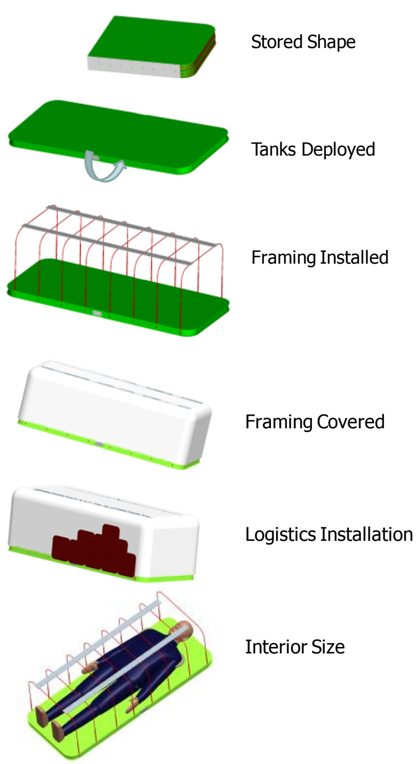


Figure 5 - Deployable Concept

Deployable analysis focused on an individual shelter leveraging contingency water and logistics. Figure 5 shows the features of the individual deployment shelter concept. A hinged water tank holds contingency water and the support elements used to create the deployed structure. Shelter frame supports assemble onto the unfolded assembly to support positioning of a frame covering which holds the protection elements. HMC bricks, CTB's, food storage etc. could be pre-integrated into sheets which would be attached to the deployed shelter framing.

Crew Quarters Centric:

The Crew Quarters centric approach was rated as a very likely location for radiation protection. It was then chosen as the location to demonstrate use of a water wall. Figure 6 shows a single ISS-type crew quarter which would be constructed from structural panels which also contain contingency life support water. To preserve the inner mold line of the original design, wall thickness increases are applied outward. A major advantage of crew quarters-based shelters is that the space within the crew quarters has been designed and proven for durations of occupation approaching the length of an SPE. Crew activity functions such as clerical work, reading as well as sleeping are already provided for in this living space and crewmembers are accustomed to working within this enclosure.

An additional savings could be provided if multiple crew quarters can be ganged together, sidewall to sidewall. Adjacent sidewalls would not have to be a radiation wall, reducing the number of surfaces requiring protection. Also, from a radiation protection perspective, placing the crew quarters as close to the center of the habitat as possible is useful because it then accommodates component storage between the outer wall of the habitat and the outer most wall of the crew quarters.

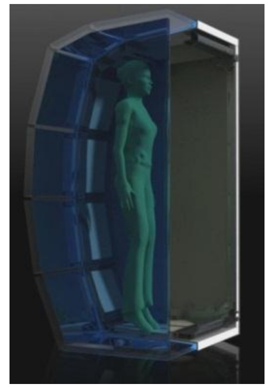


Figure 6 - Crew Quarters Centric Shielding

Reconfigured Components:

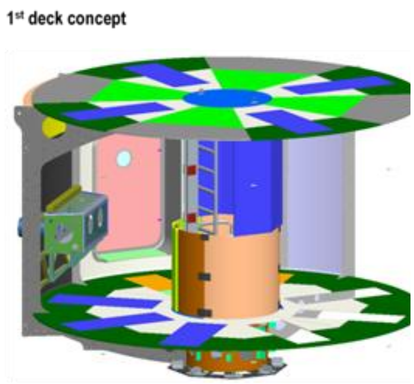


Figure 7 - Reconfigured Components Main Deck

Reconfiguring of components to create a Storm Shelter was accomplished by the incorporation of dual use structural panels and associated repositioning of logistics. This approach is based on structural panels that can quickly be removed without tools and assembled together to construct a radiation shelter. Figure 7 shows an HDU section with with the “dual-use” waterwall floor panels highlighted in blue. These panels are attached to sub-flooring structure using “no-tools” fasteners. Assembly of the panels into a radiation shelter is accomplished with “no-tools” fasteners such as push-button quick-release pins and locking push-pull quick release pins. Some of the main section panels are shown as removed from their flooring positions and reassembled around the elevator shaft to create a centrally protected region. In this case panels are hung from ceiling hard-points and pinned securely to the lower lift gate structure.

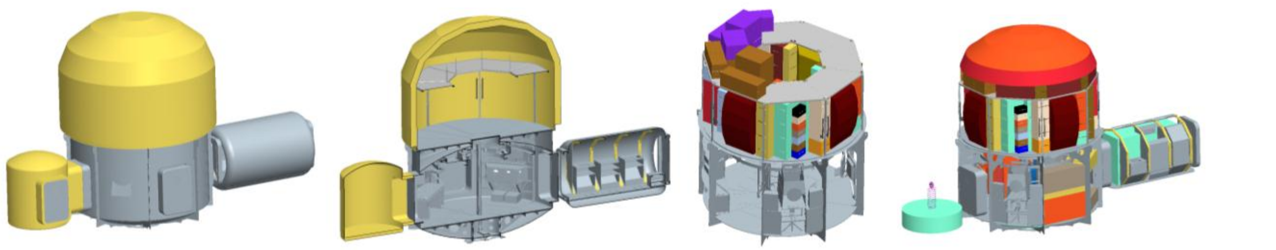
For panels which are not intended to be moved, they can still serve to hold contingency logistics and serve both structural and radiation protection functions. Such panels, which makeup the remaining central enclosure access and additional structure are shown in green and brown. The “Reconfigurable Components” option is the only concept analyzed which focuses on providing a common protection area for all four crew members. Attaching logistics such as CTB’s to the repositioned panels further enhances radiation protection capability of this design with little parasitic mass penalty.

Radiation Analyses

Details of the concept radiation analyses for the RadWorks Storm Shelter project are to be published in References [WAL2013A] and [WAL2013B]. A summary of that work is presented here to show the levels of protection required, in terms of mass, for the competing protection schemes.

The shielding efficacy of each concept was evaluated in terms of a reduction in astronaut radiation dosage. Two requirements for dosage reduction were assessed, a threshold value of 50% and a goal of 70%. Shielding meets the required percentage exposure reduction if the effective dose for the crew inside the concept is less than 50%, or 70%, of the baseline value of a habitat in an ISS style crew quarters placement. Baseline values of 450 mSv in the crew quarters and 361 MSv in the main section of the HDU were determined to base dosage reductions upon. Note that baseline masses for the ISS style initial condition were determined to be 1500 lbm for the 50% reduction level, and 4000 lbm for the 70% reduction level. Dosage is determined based on the effective dose for a 50th percentile female astronaut in the habitat in its normal configuration and then repeating the calculation for the same astronaut within the habitat reconfigured to include the shielding concept.

Of note and as explained in [WAL2013A] shielding requirements are driven in large part by the choice of the SPE model used as a design basis, with the astronaut position in the habitat playing a significant but smaller roll. A design basis SPE for exploration missions has not yet been identified. A design basis SPE as determined by [XAP2009] was used for this study. This is a conservative dosage level as compared to alternative SPE models, Xapsos yielded greater than a 50% increase in crew dosage as compared to a King '72 model for nominal crew stationed in the main section of the HDU. Logistics and element subsystems can provide much natural radiation protection. The HDU model was populated with appropriate consumables and equipment, as shown in Figure 8. Presented in this figure is the basic CAD model used for radiation transport analyses. Protection concepts, crew, and logistics are appropriately added to this basic model to assess radiation material thickness requirements of the competing concepts. Calculated masses, summarized and Table 2, are the primary input to calculation of each concepts parasitic mass requirement.



Panel 1 – Overall View **Panel 2 – Inside Cutaway** **Panel 3 – Logistics Added** **Panel 4 - Subsystems Added**

Figure 8 - HDU CAD Simulation for Radiation Analyses

Table 2 – Protection Requirements Based on Radiation Transport Analysis

		Water Wall Thickness (in)		Total Mass for 4 Astronauts (lbm)	
		50%	70%	50%	70%
Wearable					
	Wearable Shield in Crew Quarters	2.1	5.0	1527	3636
	Wearable Shield in Main Section	2.8	6.1	2036	4436
		Food/Brick Layer Thickness (g/cm^2)		Total Mass for 4 Astronauts (lbm)	
Deployable		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
		Water Wall Thickness (in)		Total Mass of Water (lbm)	
Crew Quarters Centric		50%	70%	50%	70%
	Original Position	2.7	7.7	3119	8942
	Moved Inward	0.49-0.84	4.95-5.12	676	5827
	Doubling Up	0-0.82	3.50-4.93	379	2656
		Water Wall Thickness (in)		Total Mass of Water (lbm)	
Reconfigured Components		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

Operational Features & Solar Particle Event Timelines

Operational approach timelines for use of a shelter concept during an SPE are required to judge performance against a Key Performance Parameter, the requirement that the: "*Storm Shelter shall be deployed/assembled in Less Than 60 Minutes*". For each approach, it is assumed that at time zero a call is made to take shelter. At this time there is one crew member in the lower loft, two in the main section of the habitat and one in the hygiene unit. For each shelter concept a series of tasks were defined which take each astronaut from event notification to a protected state. Some tasks may occur in parallel and some in serial. Task timeline assessments were prepared and Figure 9 shows an assessment result example for the case of having four crew quarters with pre-integrated water walls. The astronaut in the loft region can move quickly to the crew quarters and be in a protected state in approximately two minutes. Simultaneously, one astronaut in the main section can proceed to the loft region followed by the second person who was originally located in the main section. The fourth person is assumed to move quickly to the main section, but must wait three minutes before moving to the loft and subsequently taking shelter in a crew quarters. Total time for this event is seven minutes.

Task Name	Duration (minutes)
SPE Crew Quarters – Pre-integrated Water wall	7
loft person	2
move to crew quarters	1
inhabit crew quarters	1
main section personnel	5
person 1	3
move to loft	2
inhabit crew quarters	1
person 2	3
move to loft	2
inhabit crew quarters	1
hygiene person	7
move to main level	1
move to loft	2
inhabit crew quarters	1

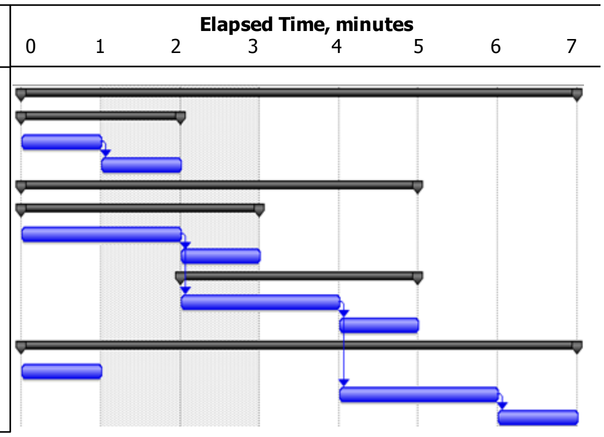


Figure 9 - Event Timeline - Crew Quarters Centric

The sleeping bag wearable concept was assessed in two different operational scenarios. One which assumes the sleeping bags are prefilled with water prior to declaration of an SPE, and one where each sleeping bag must be filled with water from the habitat life support system upon event notification. For the prefilled scenario, the crew person in the loft proceeds directly to his CQ to don the sleeping bag and hood protection. Some timing cushion is provided in moving astronauts thru the central corridor from the other locations to perform the same act. The main section crew next move to their respective Loft CQ's locations followed finally by the crew member who was in the hygiene portion of the habitat. Total time estimated to implement this solution is 15 minutes. Operating in this manner assumes the water used for protection is contingency water and is not required for on-demand access by the habitat's Environmental Control and Life Support System (ECLSS). The second sleeping bag wearable operational assessment was made assuming the water bladders used for protection would have to be filled from primary water prior to donning for the SPE. It is assumed adequate water exists in the primary ECLSS and those four ports are simultaneously utilized, one by each astronaut, to fill his sleeping bag. The sleeping bags are in storage in vicinity of the water supply and taken out for use during an event. Upon filling one's sleeping bag, the astronaut proceeds to his crew quarters for a primary location during the event. Some mobility while wearing the sleeping garment is provided by this approach. This approach is assessed at 36 minutes for deployment time.

The deployable shelter is removed from a position of utilization such as existing nominally as a partition or tabletop. It is unfolded and the skeleton structure erected which can then be covered with a pre-filled flexible wall made of pockets of food or HMC bricks, depending on how far into a mission it is before an SPE occurs. It is assumed in this operational approach that all four deployable shelters are assembled simultaneously by its respective future resident. This approach is assessed at 26 minutes for deployment time.

Table 3 - Concept Deployment Times

	Deployment time, minutes
Wearable Prefilled	15.0
Wearable Fill as Needed	36.0
Deployable	26.0
CQ Waterwall Prefilled	7.0
Reposition Panels	27.0
Reposition Panels and Logistics Adjustment	60.0

A more operationally intensive approach, though one that provides for common location of all four crew members in a centrally located shelter, is that of using repositioned structural panels to create such a shelter region. To implement this concept, crew members are assigned simultaneous tasks including removal of panels from a habitat floor or wall and positioning these 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 assessed at only 27 minutes. An additional deployment time was assigned to this approach where instead of having pre-filled water based panels, normal structural panels with scarring for logistics attachment is assumed. This was advantageous from a mass savings potential, but was judged to place deployment time at the upper end of useful utility, 60 minutes. Table 3 summarizes the assessment of SPE timelines for each protection approach.

Parasitic Mass Estimations

Mass estimations for the storm shelter protection options are derived from two primary sources. First is the basic structure and hardware associated with supporting and providing a means to implement the chosen protection material, second is the protection material itself, which has been quantified by the radiation analyses previously described. In this section, these two contributions are summed and compared for each concept. Parasitic mass is then calculated for each concept. Items, which would be on-board for any other purpose, though used for radiation protection, are not counted as parasitic mass. The primary example of this is "contingency water". Such water was baselined at 1300lbm for our presumed Deep Space Habitat DSH design mission. Additonal water, which is included because of radiation protection needs, is counted as parasitic even though it may be useful in an emergency if sufficient access to it is provided.

Table 4 - Parasitic Mass Summary

		Protection mass			
	Prescribed Radiation Reduction	Basic Protected Mass	Basic Parasitic Mass	Predicted Parasitic Dry Mass	4 person parasitic mass
		Single Person Mass			
Wearable	50%	534	17	19	805
Wearable	70%	977	19	21	2577
Deployable	50%	636	131	196	784
Deployable	70%	1531	131	196	784
Crew Quarters	50%	545	41	62	246
Crew Quarters	70%	1832	41	62	4763
		Four person mass divided by 4			
Repositioned Panels, no logistics	50%	909	44	52	1619
Repositioned Panels, no logistics	70%	1930	44	52	5703
Repositioned Panels, and logistics	50%	230	44	52	209
Repositioned Panels, and logistics	70%	1032	44	52	2113

Mass tables were assembled for each of the concept approaches for both the 50% and 70% levels of radiation reduction protection. These detailed tables are not included in this report, but their highlights are now discussed and summations presented in Table 4. Use of the wearable garment in the main section of the habitat requires 2.8 inches of water for the 50% radiation reduction condition and 6.1 inches for the 70% condition. There is a miniscule dry mass requirement for the wearable approach, but considering the contingency mass water limit the parasitic masses are significant at 805 lbm and 2577 lbm for the 50 and 70% radiation reductions. If wearable usage is restricted to within a lower loft located crew quarters the 2.8 and 6.1 inch numbers drop to 2.1 and 5.0 inches respectively.

Mass calculation for the deployable concept is based on the operational scenario where each crew uses a single deployed apparatus. Because the deployable concept is designed with a fixed 2.0in. size water wall, which does not exceed the contingency water mass allotment, there was no parasitic water mass to declare. The remaining five sides of the deployed enclosure are assumed to be shielded with logistics 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 concept is constant between conditons of 50% or 70% dosage reduction. The validity of such assumptions is a subject for future consideration.

For the current analysis, sufficient food is available in terms of mass to support the shielding of the deployable concept prior to HMC brick creation. Timing of logistics availabilty, considering initial stored locations, and use rates would really be required to develop scneario showing exactly how items like food, HMC bricks, and contintency water can be accessed for radiation protection. Discrete Event Simulation analysis was recognized as a good quantitative means for characterizing component usage over a mission timeline.

For the Crew Quarters Waterwall shelter concept, nominally each crew member is housed in their own crew quarters during an SPE. This approach does show a higher declared parasitic mass for the 70% radiation reduction requirement than for the 50% case. As the shielding in this concept is provided by water, and a large amount of water is required for the 70% condition, 4500 lbm out of a required 5825lbm of water is parasitic. Of note also is the condition of utilizing two single Crew Quarters to house two crew each for the SPE event. In this operational scenario the shielding required mass reduction is on the order of 30% for the 50% radiation reduction case and 50% for the 70% radiation reduction.

Utilizing the reconfigured component approach, the HDU central corridor is reconfigured to simultaneously support housing of four crew members during the SPE. Water is chosen as the protection mechanism and there is resulting parasitic water at both radiation protection levels. If at the same time logistics are used to supplement the repositioned panels, parasitic water mass drops to 0 for the 50% radiation reduction case and drops from 5500lbm to 1900 lbm for the 70% condition.

Table 5 - Summary of Protection Mass Requirements

	50% effectivity, 1500 lbm base mass		70% effectivity, 4000 lbm base mass	
Concept	mass, lbm	mass_ratio	mass, lbm	mass_ratio
Wearable	805	0.54	2577	0.64
Deployable	784	0.52	784	0.20
CQ_waterwall	246	0.16	4763	1.19
Structural Panel Reuse	1619	1.08	5703	1.43
Structural Panel Reuse_with logistics	209	0.14	2113	0.53

The 4 person parasitic mass is tracked in Table 4 to provide input to Table 5. Table 5 provides a summary of the masses required for protection for the concepts under consideration, and the ratio of that mass to the baseline mass. Both 50% and 70% radiation reduction conditions are presented. As defined in the radiation analysis process, 1500 lbm is the reference baseline radiation protection mass required for the 50% radiation reduction analysis and 4000 lbm is the baseline for 70% radiation reduction. Calculated protection mass is normalized by the baseline numbers in order to rate concepts against the percentage based Key Performance Parameter for radiation protection mass.

Table 6 - Concept Demonstration Methods, FY12

		Wearable	Deployable	Crew Quarters Centric	Reconfigure Components
Demonstration Method	Virtual Mockup	√	√	√	√
	Animation	√	√	√	√
	Tabletop Model	√	√	√	√
	Full Scale Mockup	√	—	Begun	Details taken from another AES project

Concept Demonstrations

Figure 10 – 1/8 Scale model of the HDU DSH configuration, highlighting use of repositioned structural panels

A primary deliverable for the Storm Shelter FY '12 project consisted of providing physical demonstration items for at least two concepts. Along with the physical demonstration item emphasis, additional demonstration methods assisted in forming the basis from which to assess each approaches project metric pros and cons. The full set of demonstration items finally provided is shown in Table 6.

CAD models were developed for each approach. These virtual mockups defined size, mass, and placement of all components which make up a protection approach. They are used for concept communication and numerically for radiation protection design in conjunction with the radiation transport analysis process.

Figure 11 – Full scale model of a wearable water wall based sleeping garment

Another demonstration/assessment tool was to create three dimensional printing and associated sub-scale fabricated models depicting the primary aspects of each approach. Figure 10 shows the tabletop model for the HDU DSH configuration as created utilizing three dimensional printing. Coloration of components is used to distinguish types of structural components. The blue floor panels may be relocated to build a protected region around the central core of the HDU. The green panels are existing panels which are considered to be of a waterwall structural concept. Not shown are the crew quarters, also modeled as 1/8 scale components which can be placed in the tabletop model. Positioning at the ISS location, adjacent to the loft outer wall and also at the protection advantageous position closer to the HDU central core is possible.

Figure 12 – x scale model of a wearable water wall based sleeping garment

The wearable water filled concept was developed at full scale level, Figure 11, as well as initially with sub-scale level fabrications, Figure 12. The wearable sleeping bag includes a removable bladder, Figure 13, to simulate the storage of water as its means of providing crew protection. Only air was used as a filling medium for an assessment of bulk operational issues. Water containment issues will be looked at in the continuing work effort.

Figure 13 – Water wall bladder insert for the wearable garment

Figure 14 shows the components of the deployable concept at various stages of deployment. This is also a primarily 3D printed model of 1/8th scale. In this arrangement, three deployable habitats have been combined to provide a table top surface useful for a meeting space in a DSH vehicle element. One of the deployable items is shown being unfolded and then framed with the logistics supporting framework. The red and blue Food/water or HMC brick pouches cover the framework.

The crew quarters centric approach met with consistent group acceptance as a likely protection region. It may be considered a region where several methods of protection could be demonstrated, water walls, deployed partitions, sleeping garments. Another full scale demonstration item created for FY12 was thus a wooden mockup of a typical ISS style crew quarters, Figure 15. This mockup will be further developed in FY13 to begin to better understand the logistics of crew interaction with chosen protection items.

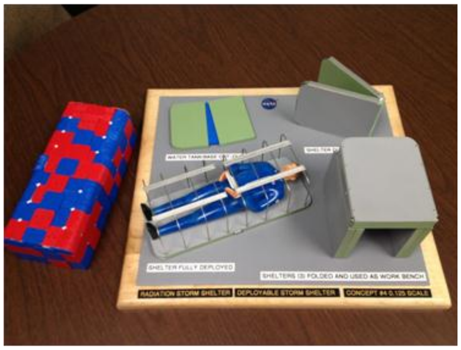


Figure 14 – 1/8th scale model of the Deployable Protection Concept

Finally, for presentation and outreach opportunities, a descriptive poster [Appendix B] [LaRC2012] and four minute animation [VID2] were made available to describe the RadWorks Storm Shelter work for the year. The animation depicts a deep space habit subject to an SPE and the selection and implementation of representative concepts from the four defined categories of Wearable, Deployable, Crew Quarters Centric, and Reconfigurable Components. These outreach items, including the subscale and full scale models, were utilized at a NASA LaRC Open House [LARC2012] to describe to the general public the severity of the need to provide radiation protection to astronauts on a deep space exploration mission and to show how protection methods can be consistently assessed.

Concept Selection - Decision Analysis

Figure 15 - Full Scale Crew Quarters Logistics Mockup

RadWorks Storm Shelter design engineering in coordination with detailed concept radiation analysis provides a consistent basis for quantification of performance parameters that can be used to compare and contrast the system performance of competing storm shelter approaches. System performance evaluation is made by considering the importance of each of a chosen set of performance Figures of Merit (FOMs). The *Logical Decisions* software program is again used to perform concept rankings in a variety of interpretive ways. To make these rankings first the relative importance of the rating FOMs are defined. Four FOM weighting approaches were used to rank the importance of one requirement relative to another, Table 7. These weightings are the "preference sets" defined within the decision analysis software.

Table 7 - Figure of Merit Weighting Preference Sets

	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

Using multiple weighting preference sets provides rigor with respect to concept selection. If the same concept(s) always appear at the top of a ranking despite the rating set chosen, it is a more programmatically robust selection. 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. Baseline weighting places equal emphasis on mass savings and deployment time. The Mass Savings and Deployment Time weighting sets then provide more value to concepts which minimize mass or deployment time respectively.

Each scored FOM provides additional "utility" to a candidate alternative. Utility as utilized by RadWorks is a quantity which can range between between 0 and 1, between zero and full utility. Raw scores such as percent mass savings or deployment time are assigned a utility value thru a utility function. The weighted summation of all FOM utility values provides a concept's integrated utility rating.

Before the weighted summation utility integration can be performed, each alternative must be scored for each FOM. We have shown how raw score values are derived for the deployment time and mass savings figures of merit. Table

8 shows these values in data columns three and four for each of six alternative concept approaches. Additionally raw scoring is shown for the other six FOMs. The utility scores are then summed up on a preference set weighted average basis.

Table 8 - 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 env.	integrates with FY14 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
Reposition Panels	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
Reposition Panels and Logistics Adjustment	4.0	0.6	60.0	14	Yes	Yes	0.6	2.0

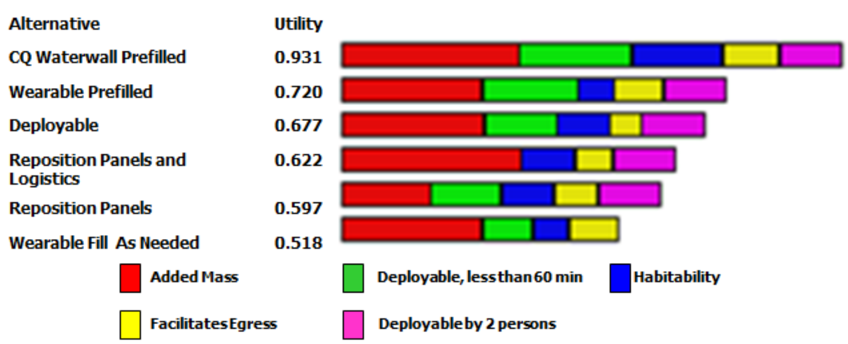


Figure 16 - Typical utility ranking figure of merit breakout for the mass savings preference weighting set and the 50% radiation reduction requirement

Figure 16 shows a utility scoring breakout for the case where a 50% radiation dosage reduction is required and the preference weighting set selected is skewed towards the importance of saving mass. The Crew Quarters water wall concept garners the most utility with most of that utility coming from mass savings, short deployment time and habitability.

A summary of final utility scores for the four FOM preference weighting sets and the two radiation reduction requirements is provided in Table 9. The Crew Quarters Waterwall stands out as being the top utility ranked concept for all FOM weighting sets and for both levels of radiation reduction requirement. The prefilled wearable approach is generally second in utility, exchanging ranking with a deployable approach for conditions of greater protection requirement. A reconfigured panel approach is not

Table 9 - System Performance Utility Rankings

	Weighting Set and Radiation Protection Level							
	all FOMs equal		Baseline weights		Preference for Mass Savings		Preference for Deployment Time Savings	
	50% Radiation Reduction	70% Radiation Reduction	50% Radiation Reduction	70% Radiation Reduction	50% Radiation Reduction	70% Radiation Reduction	50% Radiation Reduction	70% Radiation Reduction
Concept								
Wearable - Prefilled	0.835	0.435	0.719	0.521	0.720	0.540	0.722	0.549
Wearable filled on demand	0.666	0.678	0.489	0.130	0.518	0.195	0.479	0.090
Deployable	0.800	0.820	0.669	0.712	0.677	0.734	0.657	0.695
Reconfigure Panels	0.788	0.766	0.616	0.568	0.622	0.535	0.608	0.566
Reconfigure Panels and Logistics	0.766	0.741	0.580	0.528	0.597	0.552	0.511	0.465
Crew Quarters water wall	0.963	0.898	0.933	0.794	0.931	0.748	0.927	0.804
	Rank	1	2	3	4			

far behind the deployable ranking with some exception for the case of requiring 70% radiation reduction and mass efficiency. Note also that for the case of 50% radiation reduction, the selection of the top 4 concepts is independent of weighting set. This provides some good feeling that for this level of reduction, that concept ranking would satisfy multiple habitat development stakeholders. Wearables drop to mid to low ranking for the 70% radiation conditions. For 70% radiation reduction, 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. Also it can be concluded that filling wearables on an as needed basis does not appear as an attractive option.

The value in determining quantitative rankings for concept selections is not primarily to arrive at a numerically determined solution, but rather to show in a clear manner the pros and cons of each concept, with respect to performance parameters and weighting considerations to program managers. Management can be briefed on the technically derived rankings so that they understand the issues covered in the analysis. Consideration of other program factors such as the influence of technologies from other development programs can then be considered in planning on what concept(s) to spend future resources and development efforts. The RadWorks Storm Shelter technical and management personnel collaborated on this forward planning and chose to continue development of demonstration items for a Crew Quarters Centric and a Deployable approach. The crew quarters approach is easily justified by the utility ranking process. The deployable approach was chosen because it actually was reworked to consider aspects of protection items from a reconfigured panel approach with incorporation of additional logistics. The wearable prefilled approach was not selected for further demonstration because a great deal of progress, to a full scale demonstration item, was already achieved during the FY12 activity. Similar use of water, food and HMC brick protection items will be incorporated into both the Crew Quarters Centric and Deployable approach. The wearable approach, actually well rated for the 50% radiation reduction condition, is seen as a useful means to provide augmentation to the other two chosen concepts. The Repositioned Components approach, was somewhat poorly rated, but is unique in that it was the only approach which creates a single protection region for the full crew. This design aspect will be incorporated into the ongoing deployable approach. Also the incorporation of logistics reconfiguring, which showed as of great importance for higher radiation dosage will be incorporated into FY13 activities.

Summary and Future Work

Some summarization of this projects work can be made which are felt to be useful for forward work planning and for general consideration in future DSH element design work.

- Formal decision analysis 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 useful for communication of technical design issues with project managers has been created. The process assists in quantifying storm shelter performance from a system level viewpoint.
- Especially for cases of greater radiation dosage reduction requirements, it is mass advantageous to keep crew surrounded by logistics and element sub-systems for as much time as possible. As a design example, crew quarters located down the center of a cylinder with logistics surrounding them in an annular manner could be a more advantageous arrangement than the typical ISS design with crew quarters on the perimeter of the habitat element.
- Reuse of logistics material and dual use structures can be counted on to reduce parasitic mass needs. Ex: Design of protection mechanism storage for food/water bag, and HMC bricks which can accommodate any of these packages over the timeline of a mission is an important consideration.
- Water shielding is non-parasitic only if the water can be used for habitat living functions. To be useable as non-parasitic the water must be extractable from the water wall such as by a collapsing bladder w/pumping, or a positive expulsion device.
- Knowledge of the amounts of logistics on hand through a mission timeline though not assessed is noted to be important to show that sufficient radiation protection is available for reconfiguration during an SPE which could occur at any timepoint in a long mission. One way to assess this may be to perform mission Discrete Event Simulation (DES) to quantify logistics, food, water, and waste product usage over time. DES 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 items located.

- In comparison to water, HMC brick shielded designs were not considered parasitic. This was purely a judgment made for the assessment work done in FY12. Because of this note that conditions which require large amounts of shielding water, such as for 70% radiation reduction, fared poorly on a mass savings basis for water as opposed to HMC bricks.
- It is not required and likely not effective that only one solution approach be utilized to reduce radiation exposure. Subject to the goal of minimizing mass it is recognized that simultaneous utilization of protections may be possible. Particularly, an individual wearable garment is easily utilized by a crew member inside an additionally protected region such as a protected crew quarters or a deployed or fabricated shelter region.

The focus of continuing Storm Shelter work will be to develop selected radiation protection concepts to a degree that they can be integrated into a demonstration DSH element where human in loop simulations of operational logistics can be played out. Based on the Storm Shelter work of FY12 it was decided that in FY 13 the Crew Quarters Centric and Deployable/Logistics based concepts will be developed to the point of demonstration outside of a defined habitat element. In FY14 it is planned that one or both of these concepts will be further developed to be operable as a human-in-loop simulation element, integrated into a full vehicle DSH simulator. Possible redirection to a Waypoint Spacecraft element from the HDU will also be instrumental in redefining the shelter concept implementations and their operational requirements. The HDU DSH configuration could be replaced by an element or elements derived from existing ISS pressurized elements. In the coming year of activity [FY13] there is a need to increase shelter concept definition with respect to required subsystem interface requirements and operational constraints concerning mechanical, power, water, ventilation, heat, humidity, lighting, and communication interfaces.

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Appendix A

NASA LaRC - Radiation Storm Shelter Team

	Name	Responsibility	Affiliation
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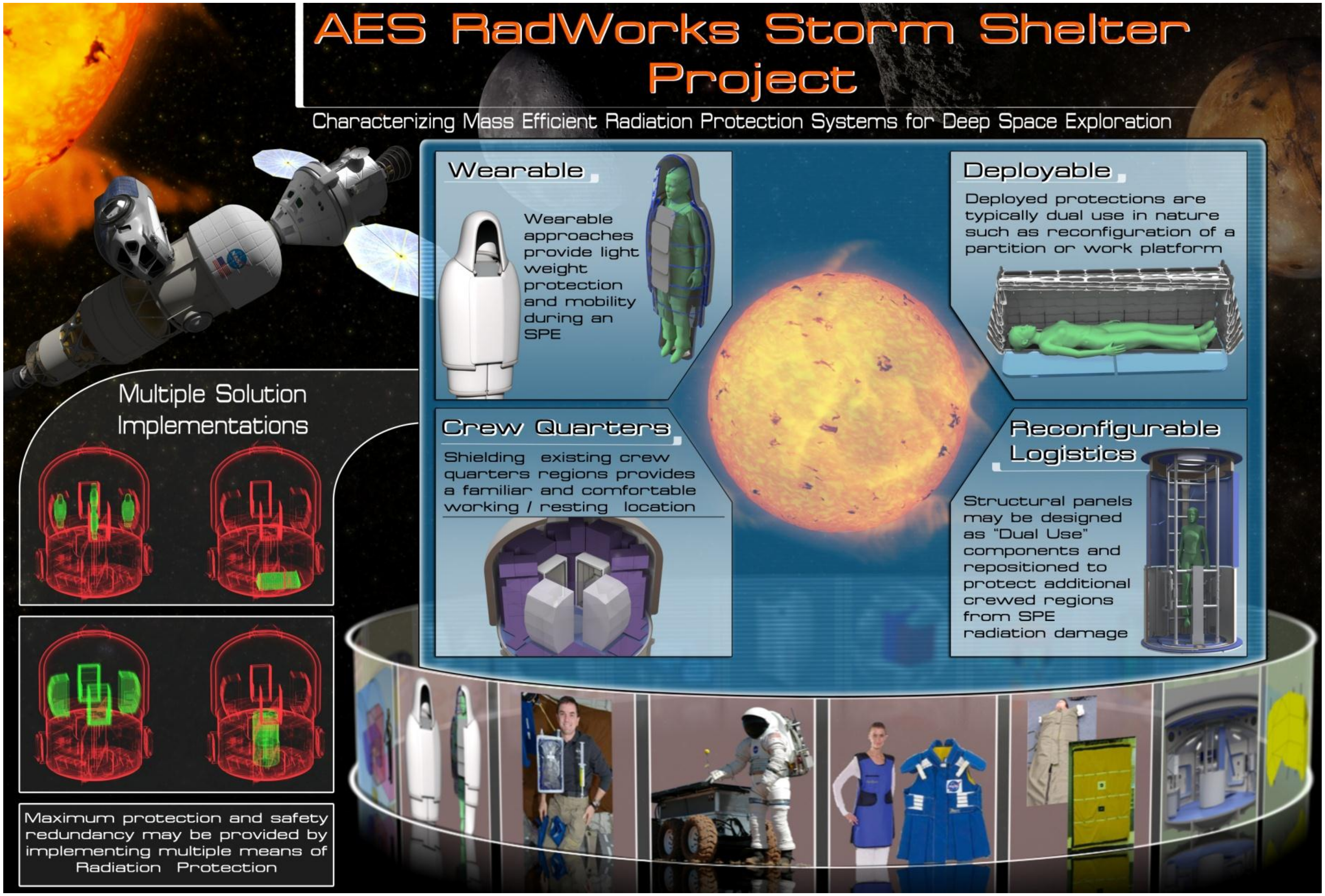
Rob	Andrews	Fabrication	NASA LaRC – Engineering Directorate
Sherry	Araiza	Resource Analyst	NASA LaRC – Space Technology and Exploration Dir.
David	Castle	CQ Centric Design	NASA LaRC – Engineering Directorate
Jeff	Cerro	Conceptual Design and Eval	NASA LaRC – Systems Analysis and Concepts
Martha	Clowdsley	Radiation Analysis	NASA LaRC – Research Directorate
Heidi	Connolly	Configuration Management	Analytical Mechanics Associates, Inc.
Adam	Gallegos	CAD modeling	Lockheed Martin Corp.
Nicole	Hintermeister	Scheduling	AMA Space Systems, Inc.
Sam	James	Fabrication	NASA LaRC – Engineering Directorate
Tommy	Jordan	Element Lead	NASA LaRC – Engineering Directorate
Mike	Langford	Reconfigurable Components Design	NASA LaRC – Engineering Directorate
Vincent	Le	Deployable Concept Design	NASA LaRC – Engineering Directorate
David	Moore	Deputy Project Manager	NASA LaRC – Engineering Directorate
Ken	Neubauer	Risk Management	Futron Corporation
Lee	Noble	Systems Engineering and Int	NASA LaRC – Engineering Directorate
Shawn	Scharf	Risk Management	Futron Corporation
Ed	Shea	Risk Management	Futron Corporation
Matt	Simon	Habitat Design - SME	NASA LaRC – Systems Analysis and Concepts
Debi	Tomek	Project Manager	NASA LaRC – Space Technology and Exploration Dir.
Steve	Walker	Radiation Analysis	Old Dominion University
Judith	Watson	Wearable Concept Design	NASA LaRC – Research Directorate

Appendix B


AES RadWorks Storm Shelter Project
Characterizing Mass Efficient Radiation Protection Systems for Deep Space Exploration
Wearable
Wearable approaches provide light weight protection and mobility during an SPE
Deployable
Deployed protections are typically dual use in nature such as reconfiguration of a partition or work platform
Crew Quarters
Shielding existing crew quarters regions provides a familiar and comfortable working / resting location
Reconfigurable Logistics
Structural panels may be designed as "Dual Use" components and repositioned to protect additional crewed regions from SPE radiation damage
Multiple Solution Implementations
Maximum protection and safety redundancy may be provided by implementing multiple means of Radiation Protection

Biography:

Jeff Cerro has over 30 years of experience at the NASA Langley Research Center. He is currently a structural mass properties and vehicle systems analyst in the Vehicle Analysis Branch. He works to support NASA initiatives in the areas of space exploration and orbital access. In 2012 Mr. Cerro was a team member on the Advanced Exploration Systems, Radiation Storm Shelter analysis team. He led activities in the systematic trade space assessment of solution approaches to maintain acceptable space radiation dosage for astronauts destined to perform deep space exploration missions. This document is a consolidation of the work performed on that task by the RadWorks Storm Shelter team members identified in the Appendix of this report. Mr. Cerro is a registered Professional Engineer with a Masters in Mechanical Engineering from Rensselaer Polytechnic Institute. He is currently active in the SAWE in advancing society goals in creating accredited mass properties standards, and in moving towards a future of greater digital distribution of society publications. Additionally, Mr. Cerro is a senior member of the American Institute of Aeronautics and Astronautics.