Water Walls Radiation Shielding: Preliminary Beam Testing of Ersatz Solid Waste Simulant

Jack Miller[1]
Guest Scientist, Lawrence Berkeley National Laboratory, Berkeley CA 94720

Marc M. Cohen[2]
Astrotecture – Marc M. Cohen Architect PC, Palo Alto CA 94306

Jurek Parodi[3]
University Space Research Association, Moffett Field CA 94035

A major attribute of the Water Walls Life Support Architecture is its potential to provide radiation shielding in addition to its air revitalization, climate control, contaminant control, and waste processing functions. This section describes the method and results of a series of preliminary particle beam tests conducted in the HIMAC Accelerator in Chiba, Japan. These tests are preliminary in the sense that the researchers' intent was to acquire sufficient data to begin modeling the shielding properties of the Water Walls passive membrane bag components, including their biological product contents. The experiments tested algae simulant (nori seaweed), bone simulant, and fecal simulant. The tests measured relative dose to benchmark models of the effectiveness of these materials. The long-term goal of this research is to establish the radiation shielding properties of the Water Walls materials and components within the configuration of a space habitat or spacecraft.

Nomenclature

$CaSO_4$	=	Calcium Sulfate, gypsum, or "astronaut bone precipitate"
CRaTER	=	Cosmic Ray Telescope for the Effects of Radiation
FO	=	Forward Osmosis
GCR	=	Galactic Cosmic Ray
^{4}He	=	the most abundant nucleus of helium
HIMAC	=	Heavy Ion Medical Accelerator in Chiba Japan.
LET	=	linear energy transfer, the deposition of energy as a GCR particle passes through a material.
MeV	=	MegaVolts, the energy carried by a particle at relativistic velocities.
MeV/nucleon	=	the energy carried by an atomic nucleus divided by the number of nucleons
NIAC	=	NASA Innovative and Advanced Concepts program
^{28}Si	=	the most abundant nucleus of silicon
SPE	=	solar particle event, a major source of GCRs.
WW	=	Water Walls Life Support Architecture

I. Introduction

THE purpose of this research is to determine the results of a relatively small thickness of the Water Walls materials. The radiation particles that hit the WW material will have passed through 8 to 10 g/cm^2 of spacecraft structure and stowage, so the particles will have begun to lose energy and shed nuclear fragments. The approach to modeling is to consider how the three-particle/energy combinations in our tests translate to represent the full radiation spectrum, which contains dozens of ions across a wide range of charges and energies. The objective is to

[1] Nuclear Physicist, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, miller@lbl.gov.
[2] President, Astrotecture, 4260 Terman Drive No. 104, Palo Alto, CA 94306-3864 USA, marc@astrotecture.com. http://www.astrotecture.com.
[3] Project Engineer, NASA Ames Research Center, MS 239-15, Moffett Field, CA 94035, jurek.parodi@nasa.gov

measure and/or model how that full energy spectrum, passing through the spacecraft structure, equipment, and stowage, will interact with the WW materials, and how the various WW materials will perform as an additional shielding layer.

Mass is a critical limiting factor in spacecraft design; adding material solely for shielding is "parasitic" and not favored. This mass penalty has not been a major factor in human space exploration thus far, with missions to date were inside the radioprotective effects of the Earth's magnetic field (*e.g.* ISS) or of short duration (Apollo). Unshielded radiation exposure in future explorations will prove vastly greater.

Water Walls Life Support Architecture provides "nonparasitic" radiation shielding in addition to its life support functions. Water Walls materials are particularly conducive to the radiation protection function because they are largely hydrogenous, and hydrogenous materials are the most efficient by mass at reducing the radiation dose from highly ionizing atomic nuclei (including protons). It is possible for the crew to reposition shielding bags as the supply increases or conditions, stowage, or outfitting change.

Composition and density of the WW subsystems will vary over time and location. Elemental composition will be stable in the system, so it is not a concern. However, variations in chemical composition and density of the waste progressing through the system affects the degree of radiation protection, and need to be taken into account. This assessment can be accomplished through models now under development (*e.g.* NASA-LaRC and NASA-MSFC) to integrate radiation transport physics into the vehicle design process

The most damaging ionizing radiation comes from solar protons and heavier nuclei in the Galactic Cosmic Rays (GCR). Particles that hit the WW material will have already passed through about 10 g/cm^2 of spacecraft structure and stowage, so they will have begun to lose energy, and GCR nuclei will shed nuclear fragments. It is not feasible to replicate the full space radiation field in the laboratory, so NASA adopted the approach to develop radiation transport models using data from laboratory measurements. The input data are measured nuclear interaction cross-sections; the models are benchmarked against accelerator measurements of radiation transport of selected particles and energies. Thus, a relatively small number of judiciously chosen particle-energy combinations can represent the full space radiation spectrum, which contains dozens of ions across a wide range of charges and energies with the WW materials, and how those materials will perform as an added shielding layer.

This research began when the NASA Innovative and Advanced Concepts Program (NIAC) awarded a Phase I grant to the Water Walls Life Support Architecture, for which Michael Flynn at NASA Ames Research Center is the PI and Marc M. Cohen of Astrotecture™ is the Co-I.[4] The initial concept proposed a passive, forward osmosis (FO) membrane-based technology to replace conventional electro-mechanical life support systems that are complex, expensive, heavy, and all too prone to failure. The Water Walls team was able to obtain additional funding to conduct radiation testing on several samples of Water Walls-related materials.

Providing radiation shielding is an important benefit of the Water Walls Architecture concept. It confers the advantage of shielding that is "non-parasitic," that is, it affords another important function besides being inert mass. Water Walls materials are particularly conducive to the radiation protection function, because, they are largely hydrogenous, and hydrogenous materials are the most efficient by mass at reducing radiation dose from highly ionizing atomic nuclei (including protons).

A. Key Concepts

To understand the Water Walls team's approach to radiation shielding research, it is helpful to present a few key concepts. These central concepts include ionizing radiation, radiation dose, relative dose, and the space radiation environment.

Ionizing Radiation: Particles (including photons) that have sufficient energy to ionize, or liberate electrons from atoms or molecules, potentially producing chemical and/or biological effects detrimental to life.

Radiation Dose: The energy deposited in matter (e.g. tissues and organs) by ionizing particles.

Relative Dose: For purposes of this study we define the relative dose to be the ratio of the energy deposited in the downstream detector with and without the target material. For example, a change of 1.13 denotes a 13% increase in dose with the material in place, compared to the unshielded dose. (This effect is typical when the shielding is relatively thin compared to the range of the particles. As the shielding thickness is increased, the dose with shielding will be less than without shielding, and the relative dose will be less than 1).

---

[4] NASA Ames Contract NNA13AA38C for the 2012 NIAC grant: Water Walls Architecture: Massively Redundant and Highly Reliable Life Support for Long Duration Exploration Missions.

Space Radiation Environment: The space radiation environment consists of charged particles, neutrons and photons. The charged particles are of both solar (mainly protons) and extra-solar origin (protons, helium and heavier nuclei). The radiation types of principle concern for missions outside low Earth orbit (LEO) are protons emitted during solar particle events (SPE) and protons and heavier charged particles in the galactic cosmic radiation (GCR).

II. Experiment Design

Given the constraints of limited beam time, the objective of this experiment was to establish a methodology for future tests, and to obtain a baseline by measuring the effect on representative components of space radiation of a relatively thin WW layer consisting of two forward osmosis bags containing fecal simulant (FIGURE 1) developed at NASA Ames Research Center by the team of Dr. Kanapathipillai Wignarajah's (Wignarajah, Litwiller, Fisher, Hogan; 2006). It consists of miso, peanut oil, propylene glycol, psyllium husks, salt, urea, and yeast.

Developing this methodology will enable the Water Walls team to apply standard models and techniques for measuring radiation transport properties (Guetersloh *et al*., 2006; Miller *et al*., 2003; Miller *et al*. 2009; Zeitlin *et al*. 2006). This baseline measurement, in combination with model calculations, will guide future measurements with sufficient WW thicknesses to measurably reduce radiation dose. As expected from basic physics considerations and in agreement with model calculations, the slowing of the ions in thin materials results in higher dose than if there were no shielding. This important result highlights the importance of providing the right materials and thicknesses of shielding. In a spacecraft, the WW materials will not be the only material present. In fact, the WW will reside inside a spacecraft structure that will provide approximately 10g/cm2 of shielding from the many layers of material that make up the module.

FIGURE 1. Fecal Simulant Bags for Radiation Beam Testing. Simulant prepared by Jurek Parodi, Serena Trieu, and Kevin Howard, University Space Research Association at Ames Research Center.

The next steps to evaluate the WW test data will be: to factor it into the larger spacecraft structure and materials, and to model the performance of the WW material in both the spacecraft structure and the actual space radiation environment. After making these calculations it will be possible to make some estimates of the radiation dose to the crew for practical thicknesses of WW material. However, to obtain good results that can tell us if there is an optimal thickness of WW material in terms of cost-benefit and effectiveness per unit mass, or for a given thickness, it will be necessary to conduct much more extensive testing. The essential approach for this testing will be to subject each material in a graduated range of thicknesses to particle beams to see how the shielding effect varies with thickness. This assessment is very important, because the effectiveness of shielding does not scale linearly with thickness. Instead it is a very complex process that will require testing and analysis for each of the WW materials.

A. Ersatz Solid Waste/Fecal Simulant Composition.

We followed this procedure to make 500g of solid waste ersatz:

In a 1 L beaker, we combined 143g of yeast and 95.5g of ground psyllium husk, both dry ingredients. In a second beaker, we melt 95.5g of polyethylene glycol, which is in solid state at room temperature, by putting it in an oven at a temperature of 60°C, which is its melting point. In a third beaker, we combined 95.5g of peanut oil and 24.0g of miso, mixing them until the latter was fully incorporated. Then we poured 46.5mL of deionized water and the peanut oil/ miso mixture into the beaker containing the liquid polyethylene glycol, mixing until we obtained a homogeneous solution. Finally, we slowly added the latter mixture into the beaker containing the yeast/psyllium husk solution while mixing thoroughly. At this point eh ersatz was ready to use.

We inserted a mass comprised between 900g and 1100g of solid waste ersatz into the product side of each X-Pack bag and we put the three bags into a vacuum oven at a temperature of 120°C, which is lower than the heat stability of PVC that constitutes the walls of the X-Pack. We let the bags dry overnight. We closed the ports on the product side of the bags to avoid any loss of ersatz but we left open the ports on the feed side in order to let any gas or vapor out.

TABLE 1. Ingredients for 500g of solid waste ersatz

Mass	Percent of Composition	Component	Manufacturer	Product Name
143 g	28.60%	Active Dry Yeast	Fleischmann's	Bread Machine Yeast
95.5 g	19.10%	Polyethylene Glycol	Sigma-Aldrich	P3515
95.5 g	19.10%	Ground Psyllium Husk	Yerba Prime	Psylliium Husks Powder
95.5 g	19.10%	Peanut Oil	Sigma-Aldrich	P-2144
24.0 g	4.80%	Miso	Hikari Miso	Organic Miso, White Type
46.5 g	9.30%	Deionized Water		

TABLE 2a. Elemental Weight by Percent of Each Ingredient, Interpreted from Nabity et al (2008)

Ingredient		C	H	N	O	S	Total %
Dry Active Yeast		45.16	6.92	6.83	37.99	0.05	96.95
Psyllium Husk		40.87	6.33	0.51	50.07	0.05	97.83
Polyethylene Glycol		49.61	9.45	0.03	40.97	0.01	100.07
Peanut Oil		77.72	11.85	0.03	11.18	0.01	100.79
Miso		29.89	7.21	4.09	46	0.03	87.22
Inorganics		*	*	*	*	*	*

TABLE 2b. Elemental Weight by Percent of Each Ingredient in the Simulant Mixture, Interpreted from Nabity et al (2008)

Ingredient	Percent of Mixture	C	H	N	O	S	Total %
Dry Active Yeast	30%	13.55	2.08	2.05	11.40	0.02	29.09
Psyllium Husk	20%	8.17	1.27	0.10	10.01	0.01	19.57
Polyethylene Glycol	20%	9.92	1.89	0.01	8.19	0.00	20.01
Peanut Oil	20%	15.54	2.37	0.01	2.24	0.00	20.16
Miso	5%	1.49	0.36	0.20	2.30	0.00	4.36
Inorganics	5%	*	*	*	*	*	*
Total Major Elemental Consitutents %		48.68	7.96	2.37	34.14	0.03	93.18

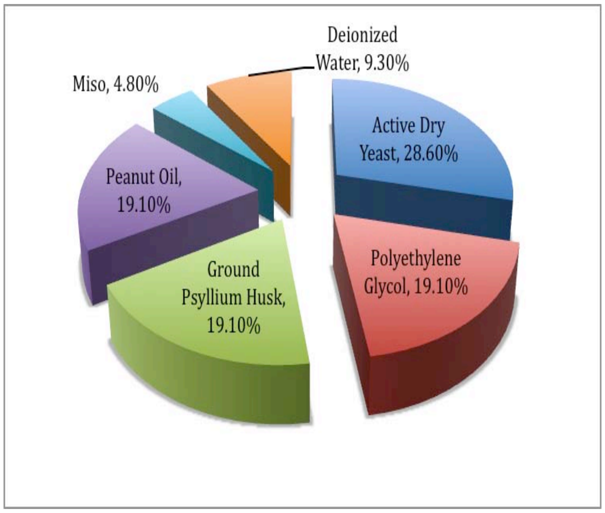


FIGURE 2. Pie chart representation of the Ersatz Solid Waste/Fecal Simulant composition prepared at NASA Ames Research Center in 2013.

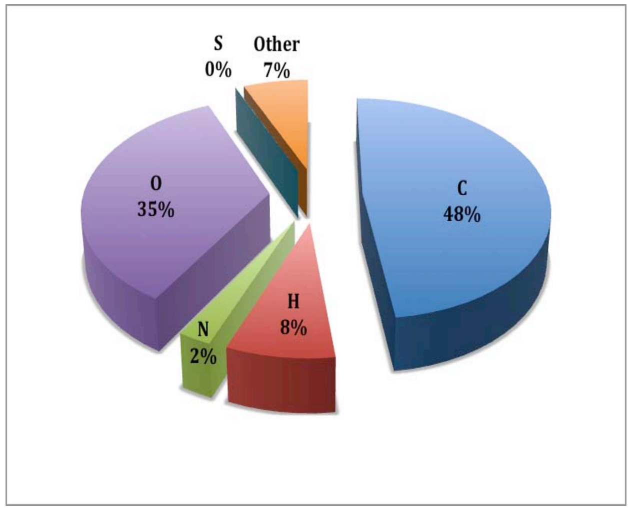


FIGURE 3. Pie Chart Representation of the Elemental Composition of the Ersatz Solid Waste/Fecal Simulant interpreted from Nabity et al (2008)

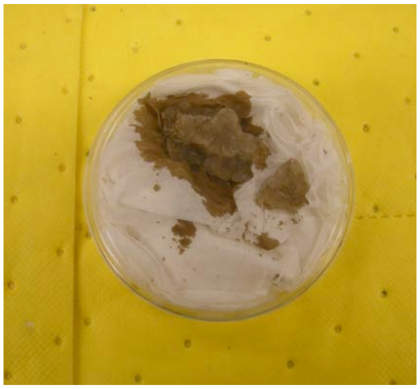
FIGURE 2 shows a pie chart representation of the ingredients in this composition. This result agrees closely with Nabity et al's (2008) preparation of the Wignarajah et al (2006) simulant. Nabity et al conducted an elemental analysis of the simulant, as shown in TABLES 2a and 2b and FIGURE 3. The significance of the elemental analysis is that in a closed system such as Water Walls, the total elemental composition remains constant, despite chemical processes or changes such as photosynthesis or the nitrogen cycle (urine > urea > brine > ammonium > nitrite > nitrate). Another observation is that in the elemental analysis in FIGURE 3, there appears a fairly low hydrogen content at 8%. Our interpretation of such a proportion, based upon our own experience of overdrying the simulant is that the Nabity et al version was also very dry. Such dry solid wastes offer reduced radiation shielding potential insofar as the water content with an abundance of loosely bonded hydrogen atoms afford the best way to absorb LET. Increasing the water content offers the potential of improving potential radiation protection.

B. Other Materials

Other WW-related materials that we began testing in Chiba included $CaSO_4$ (gypsum, a surrogate for "astronaut bone" precipitate) and nori seaweed to represent dried algae. FIGURE 4a shows a sample of the "astronaut bone" collected from the ISS urine processor, which it had clogged. FIGURE 4b shows the gypsum board samples we used to represent the astronaut bone precipitate.

"Astronaut Bone" Gypsum Solid Precipitates:
70% Calcium Sulfate (CaSO4·~0.5H2O), (CaSO4·2H2O)
20% Calcium Carbonate (CaCO3)
10% Organic Precipitates

For Phase 2, we are planning to expand on this effort to obtain sufficient beam time at HIMAC and/or one or more other accelerators to do further, and much more systematic testing of the WW materials. This data will enable the Water Walls team to make some definitive interpretations of the best ways in which to apply and use the Water Walls architecture to provide radiation shielding.



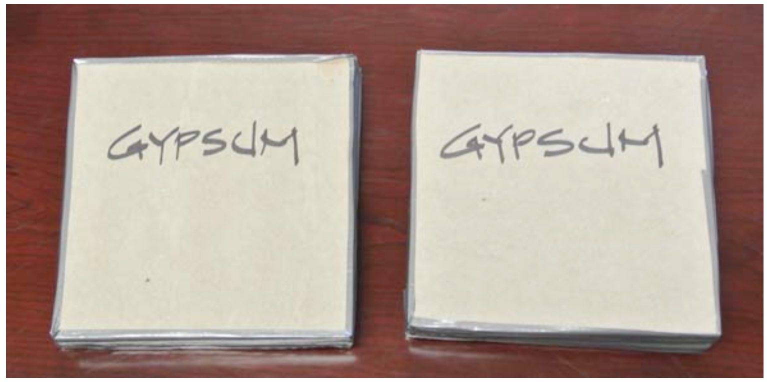


FIGURE 4a "Astronaut Bone" $CaSO_4$.

FIGURE 4b Gypsum "sheetrock" coupons used to simulate panels of "astronaut bone."

III. Summary of Radiation Tests at NIRS HIMAC, May 2013

This section describes the key findings from HIMAC in Chiba Japan in May of 2013. Other results appear in the tables in the APPENDIX.

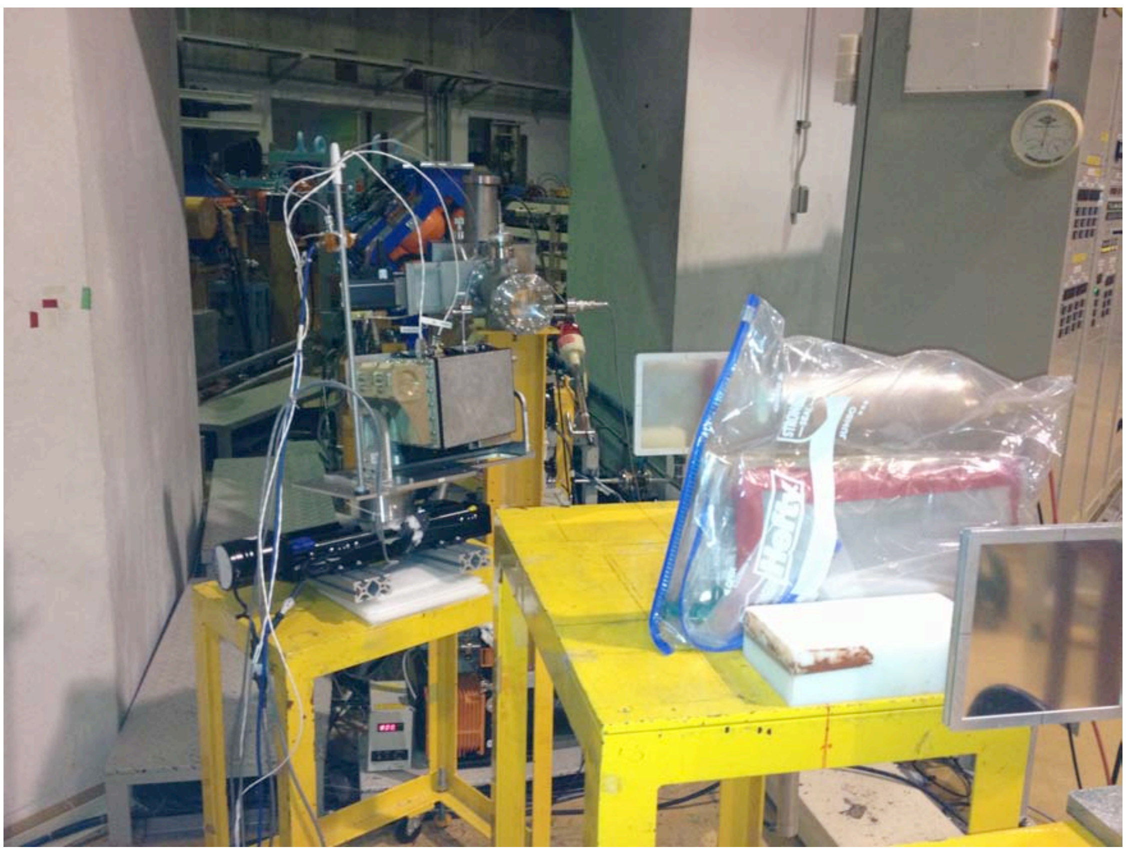


FIGURE 5. Detection system for the 160 MeV proton and 800 MeV/nucleon ^{28}Si tests. The beam exits through the circular window just above the center of the frame, passes through the square trigger scintillator, two forward osmosis bags and the second scintillator, which records energy deposition.

A stack of two forward osmosis bags containing 4-8 g /cm^2 fecal simulant were exposed to particle beams representative of significant components of the space radiation field: 160 MeV protons (SPE) 230 MeV/nucleon ^{4}He, and 800 MeV/nucleon ^{28}Si (GCR). The detection system consisted of a plastic scintillation trigger counter, followed by the target, and a second counter, either a plastic scintillation counter (for the proton and silicon measurements) (FIGURE 5) or a solid-state detector (for the helium measurements) (FIGURE 6). The solid-state detector was part of the CRaTER radiation instrument currently in lunar orbit. An engineering model of the instrument was made available to us through the generosity of the CRaTER collaboration.

Particles passing through the plastic scintillator produced a light pulse that a photomultiplier tube converted to a voltage pulse and digitized. Particles passing through the solid-state detector produced electron-hole pairs, which were concerted to voltage and digitized. Coincident signals in the two detectors indicated the passage of a beam particle through the target, and the voltage in the second detector (either scintillator or solid state) was proportional to energy deposited and therefore radiation dose. Energy deposition with the simulant target present and without the simulant target present provides a measure of the change in dose after passage through the fecal simulant.

FIGURE 6. Detection system for the 230 MeV/nucleon ^{4}He tests. Here the beam direction goes from right to left. The beam passes through the trigger scintillator, two forward osmosis bags and the CRaTER instrument at the left of the frame.

TABLE 3 shows the fecal simulant results. From these results it can be seen that simulant in the small amounts used here actually increases dose. This is expected, because as particles slow down their energy loss increases. The next step in the radiation studies is to use models and additional data to extrapolate these results to realistic shielding scenarios in which forward osmosis bags in various stages of processing are combined with proposed spacecraft hull materials and internal structures to determine the thicknesses and combinations of shielding materials that will optimize dose reduction within mass constraints. For protons, the desired endpoint is particle stopping; for heavier ions the endpoint is fragmentation to a sufficient degree that while secondary and higher order particles are not stopped, the total dose is reduced. The fact that in these tests the increase in proton dose is greatest is consistent with the need for a relatively thick storm shelter to protect against SPE.

TABLE 3.
Exposure data for the fecal simulant target compared to the unshielded control.

Particle Beam	ΔE(downstream)/ΔE(upstream)
160 MeV protons	1.41
230 MeV/nucleon ^{4}He	1.13
800 MeV/nucleon ^{28}Si	1.03

FIGURE 7 shows data for the 800 MeV/nucleon silicon beam with no target and with the simulant target. Two effects can be seen: first the slight shift to higher linear energy transfer (LET) with the simulant present is consistent with energy loss of the beam in the simulant. Second, the shoulder on the left side of both curves is indicative of fragmentation of the beam into an aluminum nucleus and a proton. The shoulder is the aluminum; the proton peak is too small to be seen above the background. (Note that there is also a shoulder in the target out distribution—this is indicative of fragmentation of the beam in the beam line elements, the detectors and the air.) As shielding material is added, the fragmentation peaks would become more pronounced and the primary (silicon) peak less so; while the surviving primary particles would still each deposit more energy than the unshielded particles, the total dose, integrated over all the fragments, would be decreased over the unshielded case. The onset of that effect can be seen here: the aluminum fragment has lower linear energy transfer (LET) than the unshielded silicon beam.

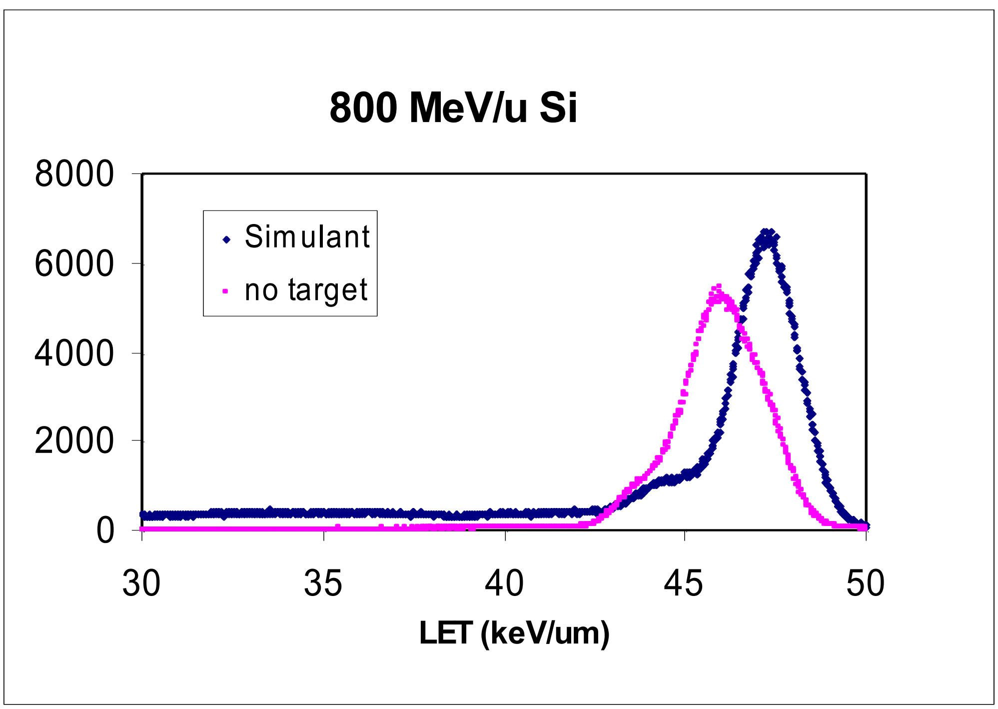


FIGURE 7. Plot of number of events vs. linear energy transfer (LET) in keV/μm. The primary silicon ions have slightly higher energy loss (and thus contribute more dose) than the unshielded ions after passing through the simulant, but the fragments—the shoulder at the left—contribute less to the dose. Increasing the shielding thickness will produce more fragments and lower total dose than the unshielded ions.

IV. Significance of the Results

The objective of this test regime was to determine what a minimal layer of WW materials might contribute to radiation shielding effects inside a space vehicle. The incoming particles that hit the WW materials would already have passed through approximately 8 to 10g/cm^2 of spacecraft structural material, external MMOD protection, and internal stowage, equipment racks, and other non-WW material. The incoming particles will have begun losing energy through ionization energy loss and the generation of secondary particles. Thus it will be a somewhat less energetic proton or GCR particle that actually hits the WW shielding material on the interior.

The significance of FIGURE 7 is that it shows the approximately 10% increase in dose/fragmentation in the fecal simulant target. This result shows that the WW material is making an impact upon the Si particles. Incrementally increasing the shielding areal density will eventually cause the secondary particles to be completely absorbed within the thickness of the shielding material, thereby helping further to reduce the overall dose exposure.

APPENDIX TABLE 2 (Appendix) shows the results for the mid-range 230 MeV/n ^{4}He. This is the particle and energy with which we tested the broadest range of WW materials. The nori (a stand-in for algae) and the gypsum produced a larger effect than the fecal simulant. Of course, we will need to calculate sizing factors for the actual areal densities of these shielding coupons, but the results are intriguing. What if algae give a better shielding performance than the seemingly denser fecal simulant?

It is important to understand this shielding experiment as the first of several steps – if not many steps. First, the WW team will need to translate these three particle and energy exposures to a representation of a portion of the actual radiation spectrum in space, which is made up of dozens if not hundreds of different particles at a wide range of energies. Second, we need to factor that representative data into a computational model of the full spectrum coming into the spacecraft and hitting the WW materials. Third, we need to interpret these results in terms of crew radiobiological absorbed dose exposure. The aim is to keep the crew exposure below the maximum allowable for crew exposure over the period of the mission, and what may be more important, under the career allowable dose.

These steps will involve additional work, including a second, much more comprehensive round of radiation shielding tests at HIMAC and perhaps at the higher energy NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory, and possibly with other particles and energies at other accelerators. These data provide a baseline to begin modeling the performance of the materials within the larger spacecraft environment.

A final realization from these results is that we may have over-dried the simulant, depriving it of some of the water content that would have afforded better radiation shielding through absorption of LET.

Appendix

This paper reviews only the Water Walls fecal simulant-related results, but it records the other data for future examination. This appendix presents all the data obtained in the beam testing at the HIMAC facility during the May 2013 test runs. These test runs consisted of particle tests for protons at 160MeV/p, 230 MeV/nucleon ^{4}He, and 800 MeV/nucleon ^{28}Si. The only material for which the team obtained results at all three energies was fecal simulant. Other Water Walls-related materials that we tested include nori and gypsum at 230 MeV/nucleon 4He. Additional materials tested came from other sources including Armortex fiberglass, CCAT CC-1 Carbon-filled Carbon (black carbon-carbon), and Ultramet Ultrafoam from the Habot project (Cohen, 2004 July).

APPENDIX TABLE 1.
HIMAC Test Data for Materials Exposed to 160 MeV Protons

Material	Relative Dose
fecal simulant	1.41
Armortex fiberglass	1.52
CCAT	1.41
Ultrafoam	1.12

APPENDIX TABLE 2. Test Data for Materials Exposed to 230 MeV/n ^{4}He.	
Material	Relative Dose
fecal simulant	1.13
nori	1.17
gypsum	1.17
10 g/cm^{2} food/cellulose/plastic	1.12
10 g/cm2 plastic/Bosch carbon	1.20

APPENDIX TABLE 3. Test Data for Materials Exposed to 800 MeV/n ^{28}Si.	
Material	Relative Dose
fecal simulant	1.03

Acknowledgments

We wish to thank Michael Flynn and Mark Kliss in the NASA Ames Bioengineering Branch for their encouragement and support. We further thank Patricia Williams in Ames Contracts for her forbearance, patience, and support. We thank Kanapathipillai Wignarajah for his advice, persistence, and support. We thank Cary Zeitlin for his assistance. We also thank the CRaTER collaboration for allowing us the use of the solid-state detector in the CRaTER instrument and the HIMAC staff for providing the three particle beams.

References

Cohen, Marc M. (2004 July). Carbon Radiation Shielding for the Habot Mobile Lunar Base (SAE 2004-01-2323). *34th International Conference on Environmental Systems (ICES),* Colorado Springs, Colorado, USA, 19-22 July 2004. Warrendale, Pennsylvania, USA: Society of Automotive Engineers.

Cohen, Marc M.; Flynn, Michael T.; Matossian, Renée L. (2012 May). Water Walls Architecture: Massively Redundant and Highly Reliable Life Support for Long Duration Exploration Missions (GLEX-2012.10.1.9x12503). *Global Space Exploration Conference (GLEX)*, Washington, DC, USA, 22-24 May 2012. Paris, France: International Astronautical Federation.

Cohen, Marc M.; Matossian, Renée L.; Mancinelli, Rocco L.; Flynn, Michael T. (2013 July). Water Walls Life Support Architecture (AIAA 2013-3517). 43rd International Conference on Environmental Systems (ICES), Vail, Colorado, USA, 14-18 July 2013. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Flynn, Michael T.; Delzeit, Lance; Gormly, Sherwin; Hammoudeh, Mona; Shaw, Hali; Polonsky, Alex; Howard, Kevin; Howe, A. Scott; Soler, Monica; Chambliss, Joe (2011 July). Habitat Water Wall for Water, Solids, and Atmosphere Recycle and Reuse (AIAA 2011-5018). *41st International Conference on Environmental Systems (ICES)*, Portland, Oregon, USA, 17-21 July 2011. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Flynn, Michael T.; Soler, Monica; Shull, Sara; Broyan, James Lee, Jr.; Chambliss, Joe; Howe, A. Scott; Gormly, Sherwin; Hammoudeh, Mona; Shaw, Hali; Howard, Kevin (2012 July). Forward Osmosis Cargo Transfer Bag (AIAA 2012-3599). *42nd International Conference on Environmental Systems (ICES),* San Diego, California, USA, 15-19 July 2012. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Guetersloh, Stephen. B.; Zeitlin, Cary.; Heilbronn, L. H.; Komiyama, T.; Fukumura, A.; Iwata, Y.; Murakami, T.; Bhattacharya, M. (2006). Polyethylene as a radiation shielding standard in simulated cosmic-ray environments, *Nucl. Instr. and Meth. B* 252, Issue 2, 319-332.

Miller, Jack; Zeitlin, Cary.; Cucinotta, Francis. A.; Heilbronn, L. H.; Stephens, D.; Wilson, John. W. (2003). Benchmark Studies of the Effectiveness of Structural and Internal Materials as Radiation Shielding for the International Space Station, *Radiat. Res.* 159, 381-390.

Miller, Jack; Taylor, L.; Zeitlin, Cary.; Heilbronn, L. H.; Guetersloh, S. B.; DiGiuseppe, M.; Iwata, Y.; Murakami, T. (2009). Lunar soil as shielding against space radiation, *Radiat. Meas. 44 163.*

Nabity, James A.; Andersen, Erik W.; Engel, Jeffrey R.; Wickham, David T.; Fisher, John W. (2008). Development and Design of a Low Temperature Solid Waste Oxidation and Water Recovery System, (SAE 2008-01-2052). *38th International Conference on Environmental Systems (ICES),* Warrendale PA: Society of Automotive Engineers.

Wignarajah, Kanapathipillai; Litwiller, Eric; Fisher, John W.; Hogan, John (2006, July). Simulated Human Feces for Testing Human Waste Processing Technologies in Space Systems (SAE 2006-01-2180), *36th International Conference on Environmental Systems (ICES)* Norfolk VA, USA 17-20 July 2006. Warrendale PA, USA: Society of Automotive Engineers.

Zeitlin, Cary; Guetersloh, S. B.; Heilbronn, L. H.; Miller, Jack. (2006). Measurements of materials shielding properties with 1 GeV/nuc ^{56}Fe. *Nucl. Instr. and Meth. B* 252, Issue 2, 308-318.