Evaluation of Multi-Functional Materials for Deep Space Radiation Shielding

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Abstract

The space radiation environment presents numerous space exploration challenges in achieving crew health protection and minimal onboard systems effects while guaranteeing mission success. In this paper we discuss the deep space radiation environment, which includes both the galactic cosmic radiation (GCR) and solar particle events (SPEs), and methods of mitigating the dangers of that radiation. Thus, we have examined several radiation-mitigating materials, including composite materials that also have exhibited other desirable multi-purpose engineering properties such as structural, thermal management, and debris protection. We have also investigated the use of "Z-graded" materials by performing parametric studies using a combination of layered materials and thicknesses. Several select materials have been ground-tested at key particle accelerator facilities and the results validated using high energy particle transport/dose computer codes. The evaluated materials were chosen for their potential use as a radiation shielding material, but other considerations such as multi-functionality, safety, cost, and weight were also included in this study. The preliminary results of these analyses are discussed and presented in this paper.

Introduction

NASA's current focus is on returning to the moon and establishing a long-term human presence there. To do this, NASA must design an outpost such that the crew is able to live and work in a safe and productive manner. One of the main safety concerns to crew and electronics is the harsh radiation environment that exists on the lunar surface, and the focus of this paper is methods by which to mitigate some of that radiation.

Deep Space Radiation Environment

The deep space radiation environment consists of two types of radiation, galactic cosmic rays (GCR) and solar particle events (SPE). Both types of radiation consist of particles traveling at very high energies, and both are modulated by the solar cycle.

Galactic Cosmic Rays

Galactic cosmic rays (GCR) originate outside of the solar system and travel at extremely high energies, such that they can penetrate through the solar wind and reach lunar or Martian surfaces. The composition of GCRs is of protons and heavy ions. In comparison to SPEs, GCRs do not contain as many particles, and thus do not produce as much dose. However, the heavy ions contained within GCRs can produce biological mutations such that late effects, such as cancers, are a concern with prolonged exposures.

Another concern with GCRs is that they travel at such high energies that it is extremely difficult to passively shield against them. Additionally, the heavy ion particles from GCRs interact intensely with materials that they are passing through and create a secondary radiation shower, which enhances the amount of radiation to which the crew is exposed.

Solar Particle Events

In contrast to GCRs, large solar particle events (SPE) are typically correlated with coronal mass ejections (CME) that arise from coronal holes. These holes are areas in the solar corona with intense magnetic activity. During the eleven year solar cycle, SPEs occur most frequently and with highest intensity during the period of solar maximum, which is when the sun is most magnetically active. However, even in periods when the solar cycle is at a minimum, SPEs can occur, although typically at a lower intensity and less frequently. These large events typically consist of a large number of protons traveling at high energies, can last anywhere from a few hours to several days, and can produce large amounts of dose to crew members.

While SPEs produce a larger dose when compared to GCRs, they can be effectively shielded with the use of passive shielding. This is due to lower energies of SPEs and the type of particles, protons rather than heavy ions, which are interacting with materials.

Methods of Radiation Mitigation

The main method of mitigating the radiation exposure to crew is through passive shielding. It is generally known that materials with high hydrogen content are better radiation mitigators than those materials with low hydrogen content. This typically translates into looking at polymeric materials when considering solids, and water if considering liquids. Additionally, all materials produce some amount of secondary radiation shower. However, metals may produce more secondary radiation when compared to polymers and water. Thus, for radiation shielding purposes, it is important to consider high-hydrogen polymeric materials as radiation mitigators.

Furthermore, it will be advantageous to use polymeric materials that can be dually functional rather than only as parasitic shielding. From an integration perspective, having multifunctional materials in any lunar surface element will ultimately decrease mass and increase useable volume to the crew, which fiber reinforced polymeric composites may provide. These are materials with a matrix, typically an epoxy, and fibers embedded in the matrix. These materials are typically very strong, and based on the purpose and design of the composite, can have different strengths in different directions. Thus, for this study, fiber reinforced polymeric composites were also considered as multi-functional radiation mitigators.

Another type of polymeric composite material in development by NASA's Langley Research Center is being developed as an enhanced radiation shielding material that can be reconfigured to any location within a pressurized lunar element where crew might be located. This material is classified as a soft-good material and could be used as a blanket, flexible wall or ceiling, or a reconfigurable cargo transfer bag.

In an earlier paper (Bartholet, et al., 2004), one of the authors (WA) showed the advantage of using several layered materials, called "graded-Z shielding," ["Z" for atomic weight] to not only mitigate the radiation, but also determine the minimum shielding weight, which can also reflect a potential cost savings. One particular graded-Z design (PE/Pb/Al) was shown (for electron environments) to reduce weight anywhere from 65% to 21% the weight of a comparable aluminum shield. Ideally, one uses a 3-layered material configuration with the outer layer composed of a low-Z material, the middle layer containing a high-Z material, and the inner layer being a low-Z material. The "graded-Z" shielding approach has its best utility in an intense electron environment such as is found in the magnetosphere of Jupiter. Here, we are primarily interested in attenuating the production of secondary bremsstrahlung and photoelectrons. More on graded-Z shielding will be discussed in greater detail in a later section of this paper.

Another method that may be beneficial in helping to shield against GCRs is the reuse of cargo transfer bags as a radiation mitigation method. These bags are used to bring logistical items to the surface for the crew, and several bags are used to accomplish this. The bags are made of soft good material, and are typically disposed of once emptied. Rather than disposal of the bags, they can be reused by filling them with regolith and placing them on the outside of an inhabited structure, such as the habitat. Over time, walls with significant thicknesses can be created to add additional shielding to the crew.

Radiation-Mitigating Materials

This preliminary investigation of radiation mitigating materials was performed using the HZETRN 2005 code (Clowdsley, 2006), a radiation transport/dose code developed at NASA'S Langley Research Center. Additionally, a Band (Band, et al., 1993) function fit was used for the October 1989 solar proton event (SPE) calculations. Tylka and Dietrich (2008) have performed extensive analyses of the major SPE's dating back to 1956. Historically, the scientific community has used an exponential in particle rigidity (momentum) fit based on the GOES satellite data (the >30 and >100 MeV data points) and extrapolated the particle (proton) energy spectrum out to approximately 2 GeV. Whereas, Tylka and Dietrich (2008) have utilized the GOES MEPAD, GOES HEPAD, and ground-based neutron monitor data to completely describe the entire proton energy spectrum using the Band function, which is a double power law in rigidity fit. Furthermore, Atwell (2008) and Atwell, et al. (2008) have shown the exponential in rigidity fitting method grossly under-estimates the actual radiation exposure received from the SPE.

The materials investigated for radiation mitigation fall into three categories: high-hydrogen content materials, composite materials, and Z-graded materials. The data presented at this time are preliminary simulation data, and further work will need to be completed to validate the results.

High-Hydrogen Content Materials

These materials were selected for the study because they represented high-hydrogen polymeric materials and some of them included potential enhanced radiation shielding benefits from added elements in the material. The base material in the enhanced polymeric materials is polyethylene with additives of lithium and boron. These additives were interesting because boron and lithium are neutron-absorbing materials, and there may be a concern with secondary neutrons on the lunar surface. The enhanced materials are compared against neat polyethylene and aluminum, which are typical baseline materials for shielding studies.

In the figure below, the dose vs. depth of the materials are compared. The condition for which the simulation data is gathered is a worst year case, meaning a large SPE occurs (October 1989 event) and there is a one year exposure to GCR radiation during solar minimum.
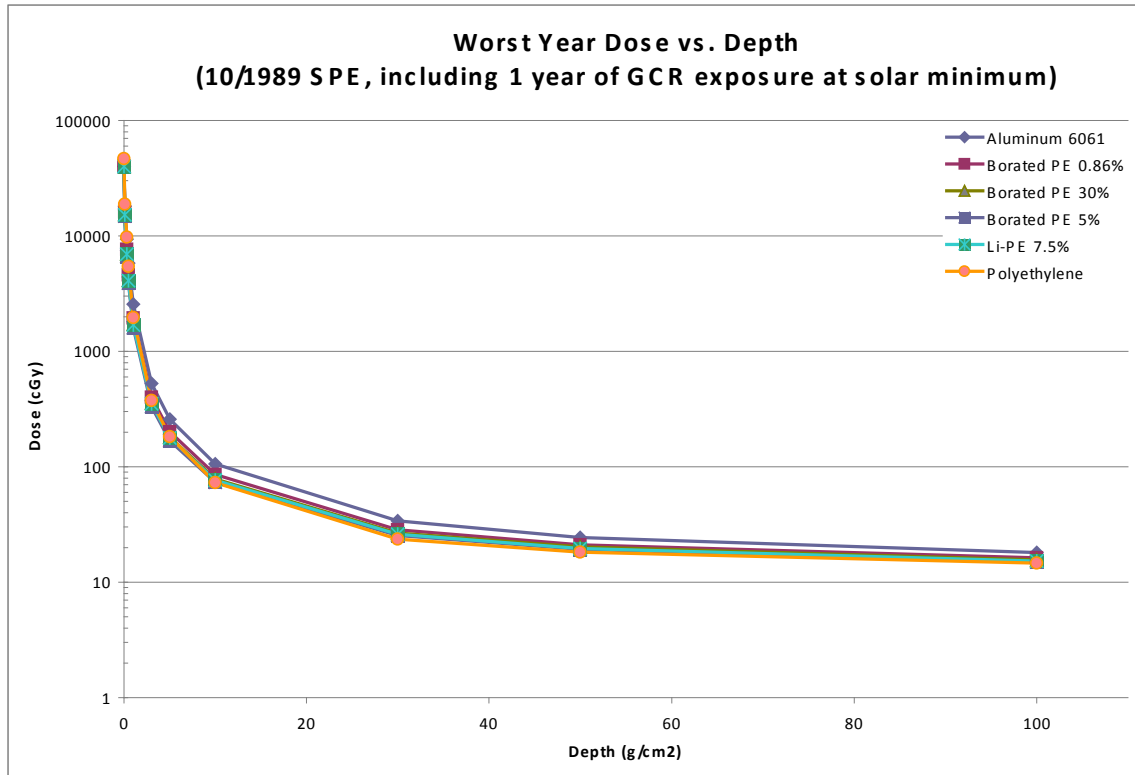
Figure 1: Worst Year dse vs. depth for several high-hydrogen content materials.

As can be seen from the figure, all the polymeric materials represented show a decreased absorbed dose when compared with aluminum. When compared with neat polyethylene, those with additives show an increased absorbed dose. The lithium-infused polyethylene seems to have about the same absorbed dose as the 5% borated polyethylene. Also, the borated polyethylene materials seem to have an optimum amount of boron infused within them. This can be seen better on a zoomed-in version of Figure 1, as shown below.
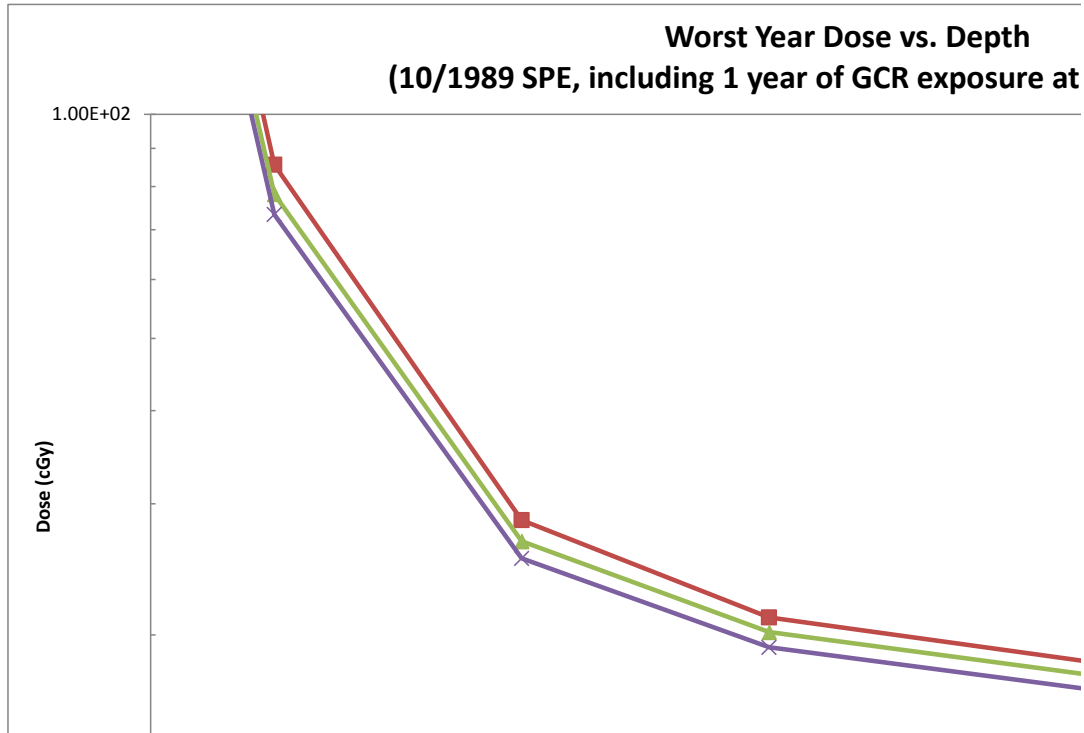
Figure 2: Comparison of borated polyethylene at worst year.

In this comparison, it is evident that both the 0.86% and the 30% borated polyethylene are higher doses when compared with the 5% borated polyethylene. This suggests that there may be an optimum amount of boron that can be used in the material to provide the most advantageous shielding.

While high-hydrogen content polymers, such as polyethylene, are excellent radiation mitigators, they tend to be dead weight when used on spacecraft solely for radiation shielding purposes. Therefore, it is advantageous to consider other polymeric materials that can also be dually functional.

Fiber Reinforced Polymeric Composites

As mentioned previously, fiber reinforced polymeric composites were chosen for their multifunctionality as high-strength materials that may also provide radiation mitigation, when compared to metals. For this preliminary study, a select number of materials were chosen for their potential use on lunar surface elements. These materials are the following: a boron fiber prepreg, a boron/carbon prepreg, four different carbon fiber prepreg systems, a high modulus polypropylene/carbon prepreg, Kevlar prepreg, Nextel prepreg, and a Spectra prepreg. The dose vs. depth for these materials in a worst year case (10/1989 SPE and one year GCR exposure during solar minimum), is shown below.
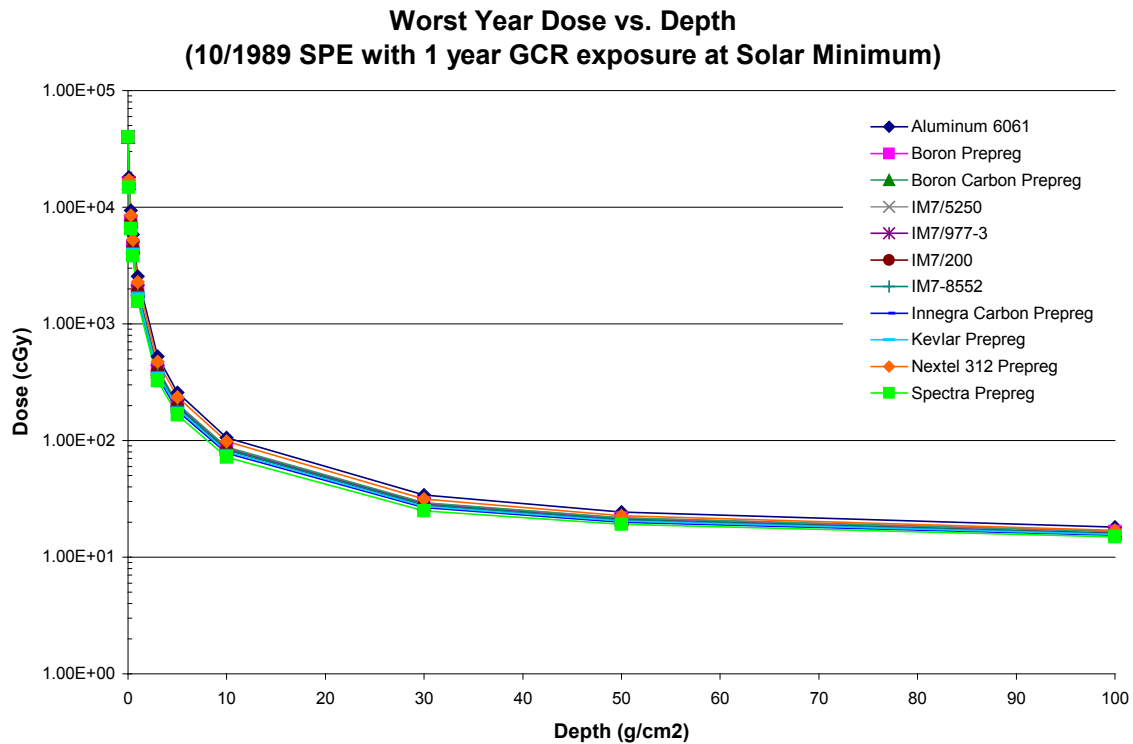
Figure 3: Worst year dose vs. depth for several fiber reinforced composite materials.

Although difficult to identify, all the polymeric fiber-reinforced composite materials investigated here are better radiation mitigators when compared to aluminum at the same areal density. Nextel seems to have similar radiation mitigation properties as aluminum, as it contains a relatively high concentration of aluminum in the material. The other polymeric fiber reinforced composites are very similar in their radiation mitigation properties. The one showing the least amount of absorbed dose is the Spectra material, as it is composed of mostly polyethylene fiber.

Of these materials, the carbon fiber composites are currently drawing the most interest for lunar structural applications. Those composites containing boron have an enhanced benefit of additional stiffness, and potential neutron absorbing properties for radiation mitigation. Focusing on this subset of all the fiber reinforced composites examined in this preliminary study, it is seen that they are all very similar in their radiation mitigation properties (Figure 4).
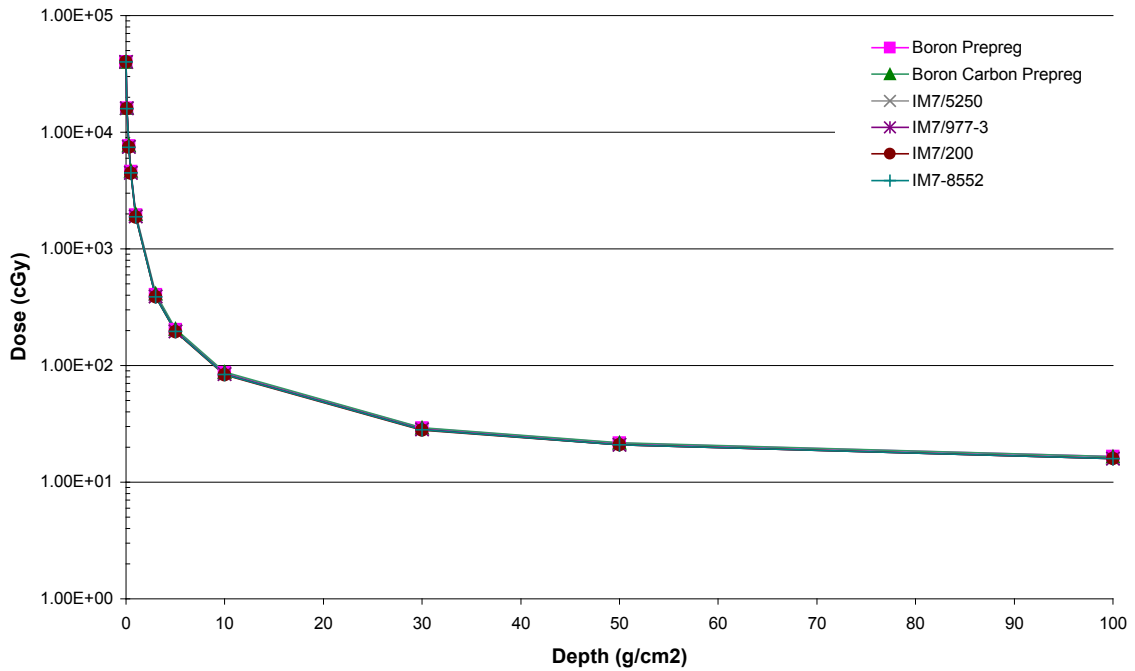
Figure 4: Radiation mitigation properties of boron and carbon fiber composites systems.

From this view, it is difficult to see if there is any variability between the materials being studied. However, in looking at a close-up version of this figure, it is shown that there is a slight variation in the radiation mitigation properties of the materials.
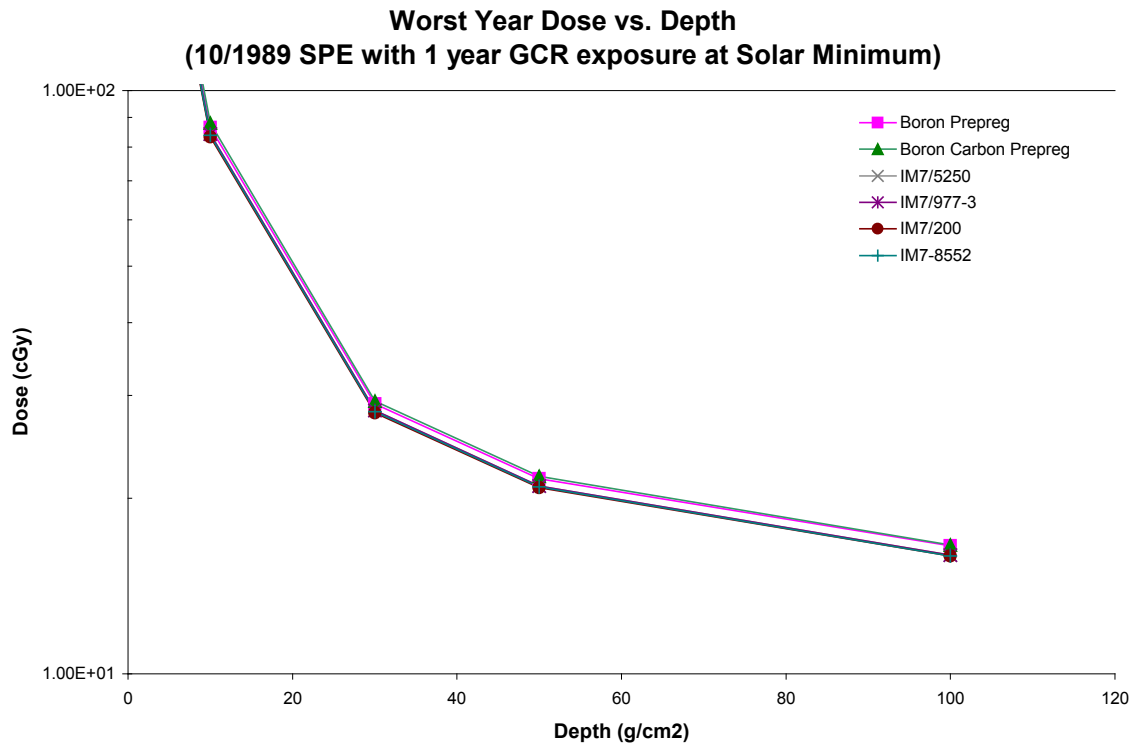
Worst Year Dose vs. Depth
(10/1989 SPE with 1 year GCR exposure at Solar Minimum)

Figure 5: Close up examination of boron and carbon fiber composites

In this zoomed-in version of Figure 4, it is shown that the borated prepregs are actually slightly higher in dose than the carbon fiber composites. Each individual carbon fiber composite is indistinguishable from the others, and this is most likely due to an unknown exact composition for each material.

Graded-Z Materials

As mentioned earlier, the use of graded-Z material shielding was originally proposed for mitigating high-energy electrons. However, the use of graded-Z material shielding for protons can also be utilized. Since high-energy protons produce secondary particles including neutrons through nuclear reactions in the outer layered material, the approach would be to have a middle layer of a material doped with lithium or boron, since these two elements both have high neutron capture cross-sections. We plan to design several graded-Z shielding configurations and test their radiation mitigation potential both experimentally and computationally.

Data from Bill

Preliminary Ground Testing

One of the challenges in working with several of the materials included in this study is that many of the materials are proprietary and it is difficult to obtain exact chemical

makeup of the materials. Therefore, the inputs to the HZETRN transport code are approximations based on information available, and consequently the outputs from the code are also approximations. Thus, it is necessary to validate the output data with experimental data before making any conclusions.

As part of this study, some preliminary ground testing also took place to begin to validate the transport data obtained from HZETRN. Principal investigator, Dr. Richard Wilkins and co-PI, Dr. Brad Gersey, Prairie View A & M University, completed a proton radiation shielding study for three materials. For the December run, University of Southern California Ph.D. student and NASA aerospace engineer at Johnson Space Center, Kristina Rojdev, accompanied the PIs to gain experience in performing radiation shielding experiments.

Materials Selected

Two of the materials selected were polyethylene composites, one doped with 5.5% boron (Figure 8) and the other with 7.5% lithium (Figure 6). The radiation mitigation properties of these materials were first studied via transport modeling, as discussed earlier, which led to their selection for experimental observations. Both of these were manufactured by Shieldwerx Inc., Rio Rancho, NM. The third material was a 60% beryllium – 40% aluminum alloy (Figure 7) manufactured by Brush Wellman, Inc., Warren, MI. There were also coupons of neat polyethylene and aluminum that were chosen to gather baseline data of typical spacecraft materials.

Figure 6: Sample coupons of lithium doped polyethylene (92.5% polyethylene, 7.5% lithium). The samples had dimensions of 15.24 cm x 15.24 cm (6" x 6") and the blocks were of various thicknesses. There are a total of ten coupons.

Three sets of material sample coupons were acquired for the shielding experiments; each set was made to allow stacks of the materials with areal density thicknesses of approximately 1, 5, 10, 15, and 20 g/cm^2, typical values for spacecraft structures. A tissue equivalent proportional counter (TEPC) was used to measure absorbed dose and dose equivalent from a 190 MeV proton beam impinging on the shield samples, an energy representative of solar protons.

During three visits to the Loma Linda University Medical Center (LLUMC) proton synchrotron, experiments using the five thicknesses of the commercial shield samples, as well as equivalent thicknesses of neat polyethylene and aluminum (for comparison to common spacecraft materials), were performed. Preliminary data on thin samples of the boron- and lithium-doped polyethylene composites show shielding performance similar to comparable thicknesses of neat polyethylene and aluminum, which is an expected

result. Any significant differences that may exist are expected to be manifested in the data from experiments with thicker samples. A complete analysis of the data for all samples tested will be included in a final report.
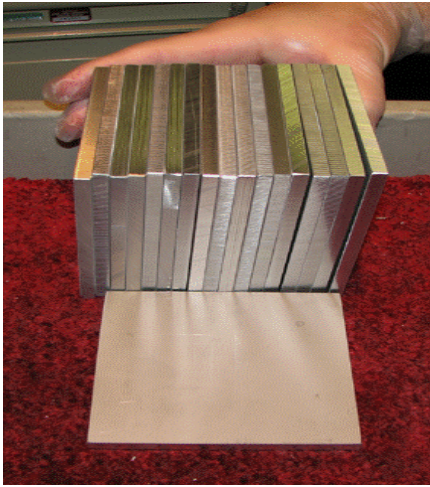

Figure 7: Sample coupons of the Be-Al alloy (60% Be, 40% Al). The sample coupons had the dimensions of 10.16 cm x 10.16 cm x 0.635 cm (4" x 4" x 0.25"). There are a total of 18 coupons.
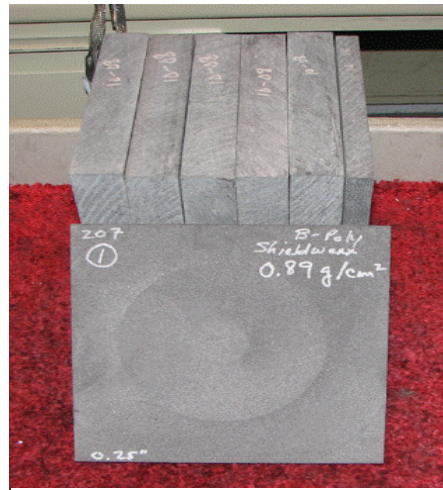

Figure 7: Sample coupons (6"x6") of boron doped polyethylene (94.5% polyethylene, 5.5% boron). There are a total of seven coupons.

Test Procedures

The experimental configuration used for the reported experiments is shown in Figure 9 and Figure 10. The proton beam exits from the left to the right through the square-shaped beam port. To the right of the Be-Al shield stack in Figure 9 is the TEPC dosimeter head. Figure 11 shows one of the shield targets and the Tissue Equivalent Proportional Counter (TEPC) in the experimental area.

The radiation beam used consisted of protons with nominal extracted energies of 200 MeV. In any accelerator experiment, the nominal extracted energy of a particle is higher than the final energy of the particle at the experimental area. This is due to various instrumentation and materials (including air) intervening in the particle path. Because of data rate processing restrictions inherent in the TEPC system, it was necessary to utilize low proton fluence
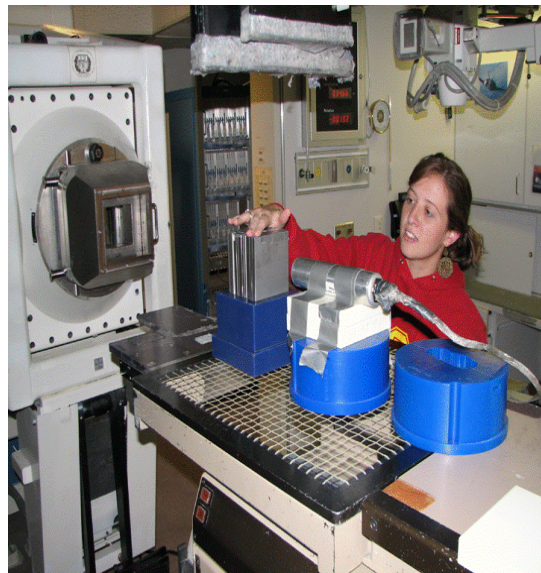
Figure 8: A stack of the Al-Be samples being prepared by Kristina Rojdev for an experimental run at the Loma Linda proton facility on the morning of December 13, 2008.

(approximately 200 protons/cm2/spill) for this shielding study. A novel synchrotron beam configuration was utilized to provide this low proton fluence. This beam configuration performed well, and will be perfectly reproducible for future shielding experiments.
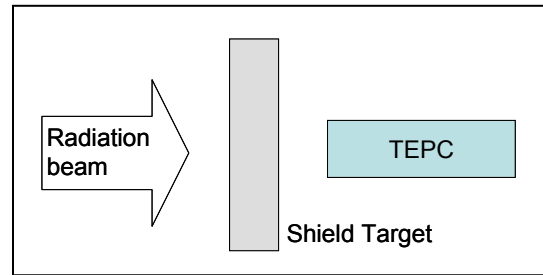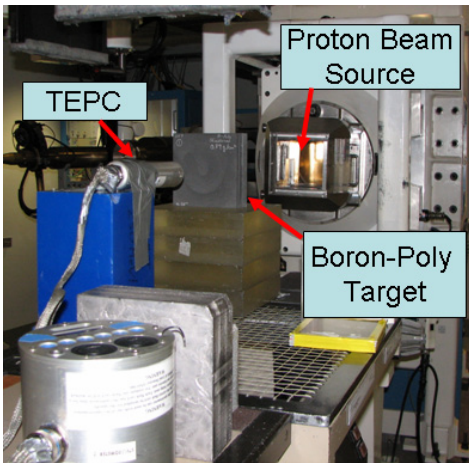

Figure 9: Expermental configuration.

Figure 10: boron-poly shield target and TEPC in the experimental area at LLUMC. The proton beam travels from the beam source toward the left of the photograph. The silver cylinder at the lower left hand corner is the TEPC spectrometer.

Preliminary Results

The preliminary results of some of the shielding experiments are summarized in Table 1. The "None" target material is for a measurement taken with the TEPC of the nominal values of absorbed dose and dose equivalent for the proton beam itself with no intervening shield target. This measurement provides a normalization point for convenient comparisons to study the effect of beam interactions with the shield targets. Given the limited time, it was decided to measure the thin targets and as many neat HDPE thicknesses as possible for initial comparisons. The instrument error for the TEPC is approximately 8%.

It should be noted that the TEPC data for the Li-polyethylene target of density thickness of about 1 g/cm^2 was corrupted and was not usable. This target will be re-measured during subsequent experiments.

Table 1: Summary of absorbed dose and dose equivalent for the shield targets studied.

Target Material	Density Thickness (g/cm2)	Absorbed Dose (µGy/Spill)	Dose Equivalent (µSv/Spill)
None	0.00	1.96	3.14
HDPE	0.92	2.01	3.18
HDPE	5.52	2.11	3.19
HDPE	10.12	2.22	3.31
HDPE	14.72	2.56	3.68
Al	0.86	1.83	2.94
Al	5.16	2.09	3.06
Li-Poly	5.06	2.12	3.31
Boron -Poly	0.89	1.92	3.14
Boron -Poly	5.35	2.10	3.31

Figure 12 and Figure 13 give a graphical representation of the data displayed in Table 1. For the thicknesses studied, the HDPE data shows a slight increase on absorbed dose and dose equivalent due to a decrease in average proton energy as the particles traverse the thickness of the shield. However, as the Bragg peak is passed, the dose measurements should decrease rapidly for the thicker targets (of all the materials) and highlight any substantial differences in the shielding characteristics of the materials. These are the reasons why the proton energy was chosen and the thicknesses of the targets.
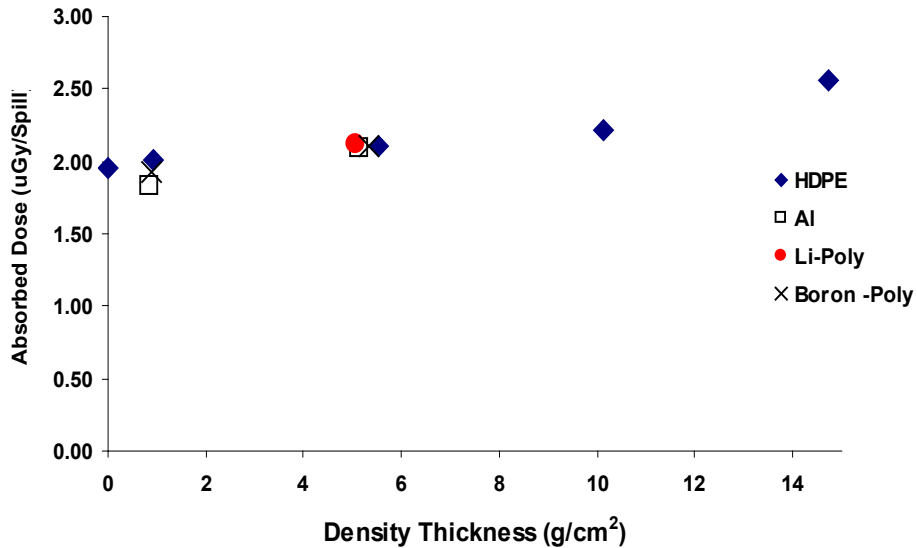
Figure 11: Absorbed dose per proton spill as measured by the TEPC for the targets described in Table 1.
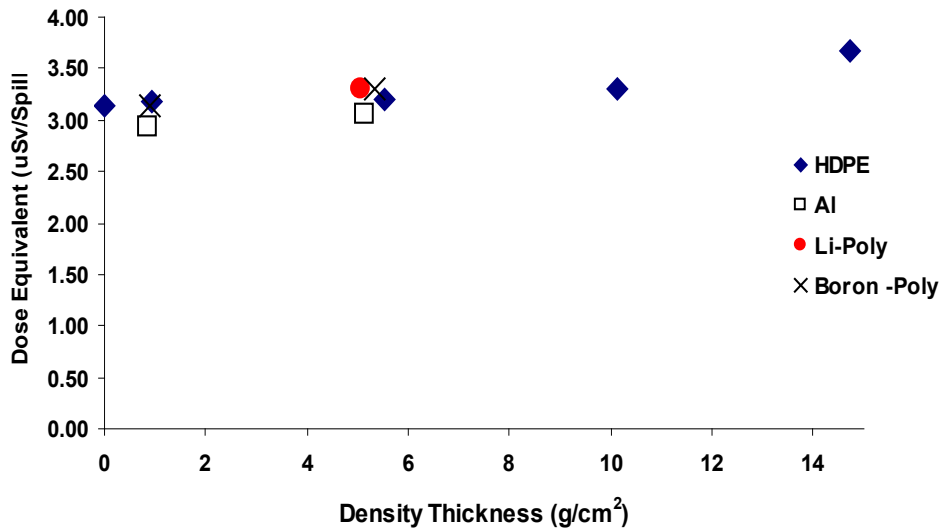
Figure 12: Dose equivalent as measured by the TEPC per proton spill for the targets described in Table 1.

The data is given in absorbed dose and dose equivalent per proton "spill" (Each spill represents a group of protons generated by the accelerator during one duty cycle). The

exact number of protons per spill was not able to be measured for this experiment. A reliable conversion should result from proton counting measurements being analyzed from this run.

For the areal density thicknesses reported, there are no substantial differences in absorbed dose and dose equivalent as measured by the TEPC for all the materials studied. There is some indication in the "5 g/cm^2 data point" for the various materials that some differences may be emerging which indicate the importance for the measurements on the thicker samples.

We investigated thicker thicknesses (>5 g/cm^2) computationally using the HZETRN 2005 code and the Band function fit for the 19-24 October 1989 SPE. We determined that both of the doped polyethylene materials were better radiation-mitigators than Al-Be with polyethylene (5.5% B) being the best of the three materials tested. This is quite apparent in Figure 14 and Figure 15, which shows the absorbed dose and dose equivalent, respectively, as a function of material thickness.
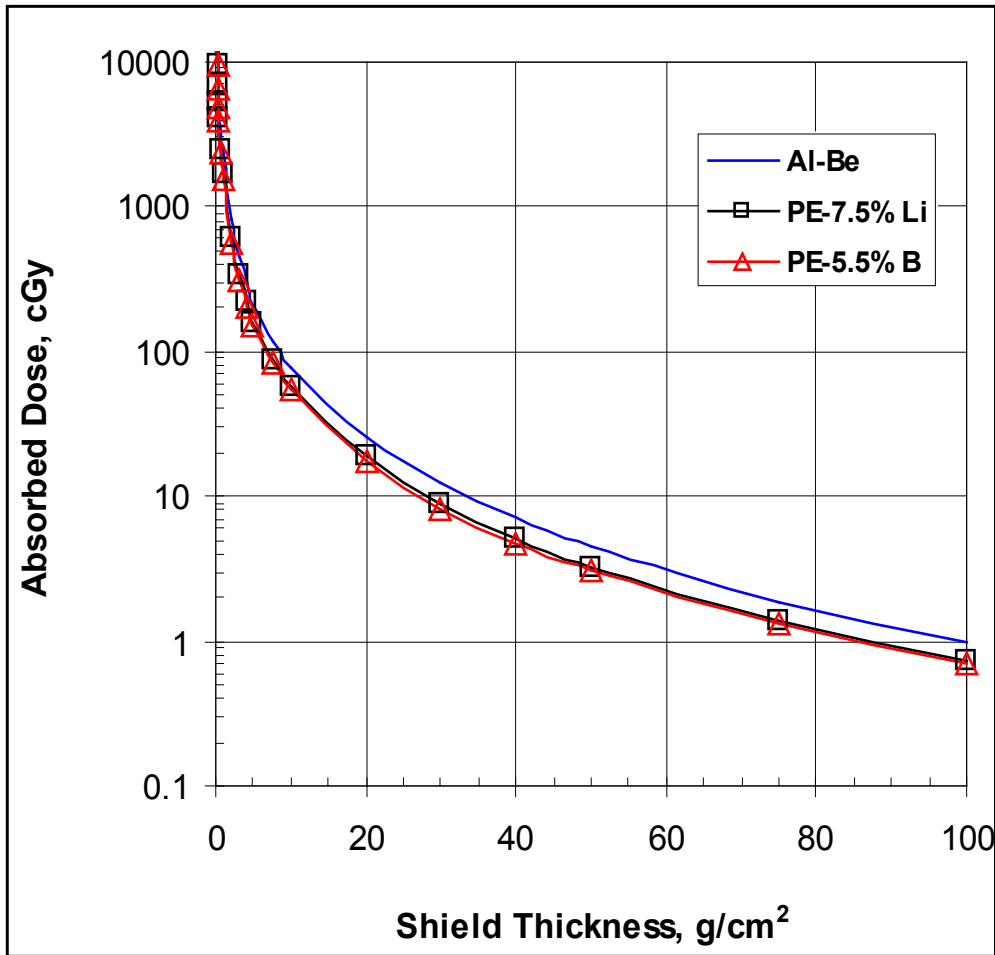
Figure 13: An absorbed dose comparison of the three test materials from the 19-24 October 1989 SPE.
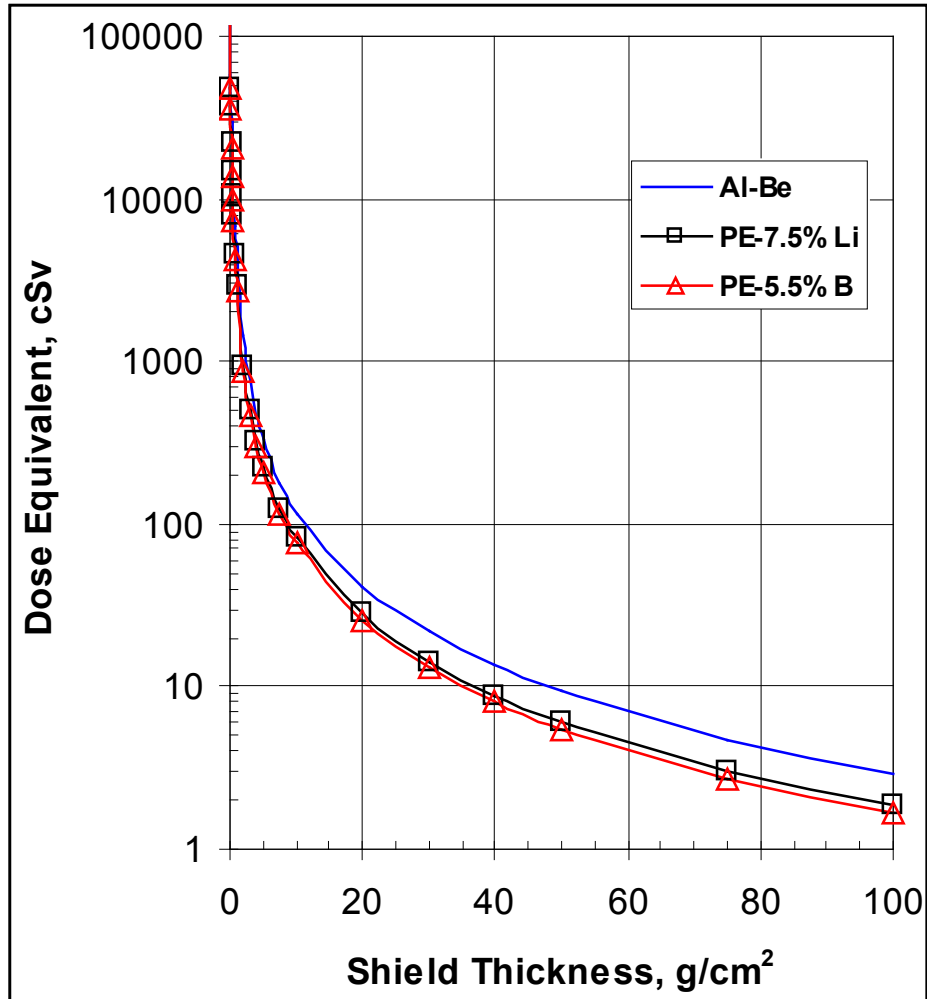
Figure 14: A dose equivalent comparison of the three test materials from the 19-24 October 1989 SPE.

Multifunctionality Properties

As mentioned earlier, the fiber reinforced polymeric composites were chosen for added benefits of multifunctionality. Primarily, these materials were chosen for their high strength characteristics, which lend themselves to primary and secondary structures that require high strength materials. However, several of these materials are also used commercially for items such as bullet proof vests, and thus may lend themselves to additional space applications such as micrometeorite shielding or surface ejecta shielding.

For primary and secondary structural applications, the materials that may be the most suited are the boron fiber prepreg, the boron/carbon prepreg, and the four different carbon fiber prepreg systems. Their strength properties are tabulated below.

One thing to note is that there are more than one set of properties for the IM7/8552 carbon/resin system and the IM7/5250 carbon/resin system. This shows that depending

on the design of the layup involved, there can be different strength properties. Typically, the strength of the composite materials comes from the fibers in the material. Therefore it makes sense that those materials in a zero degree unidirectional layup, where the fibers are taking the load, are much stronger than those materials in a 90 degree unidirectional layup, where the matrix takes the load. Those materials that have woven fibers are stronger than materials in a 90 degree unidirectional layup, but not nearly as strong as those in a zero degree unidirectional layup. Woven fibers can be thought of as an average of the two directions of unidirectional fibers and woven fibers tend to have very similar strength characteristics in both directions, making it more of a homogeneous material when compared to unidirectional composites. Thus, composites are unique in that you can design the layup to provide the strength in the directions that it is most required.

Also, it is important to mention that for the IM7/5250 system, both notched and unnotched properties are reported. While this is fairly difficult information to obtain, it is useful for understanding how a hole or impact to the material might change the design or use of the material in a design. Typically, notched strength properties will be much less when compared to unnotched properties, as is shown in the table below for IM7/5250.

Table 2: Strength properties of composite materials for primary and secondary structures.

Materials	Compressive Modulus [Gpa]	Compressive Strength [Mpa]	Tensile Modulus [Gpa]	Tensile Strength [Mpa]
Aluminum 6061	-	206.8	67.98	241.3
IM7/8552 (uni prepreg) 0 deg mech. Props.	150	1690	164	2724
IM7/8552 (uni prepreg) 90 deg mech. Props.	-	-	12	111
IM7/8552 (woven prepreg) 0 deg mech. props	-	-	85	1090
IM7/8552 (woven prepreg) 90 deg mech. props.	-	-	80	945
IM7/Cytec 5250 (uni tape)	158	1620	162	2618
IM7/Cytec 5250 (uni tape) (Orientation: +45,0,-45,90) (notched properties)	57	310	63	441
IM7/977-3 (uni tape) (notched properties not given)	154	1680	162	2510
Boron/Carbon Fiber Composite (uni tape)	240	2760	240	1900
Boron Fiber Composite (uni tape)	210	2930	195	1590

In the above table, aluminum is also included as a baseline spacecraft material. When compared to aluminum, and considering unnotched properties in a zero degree layup, the strength of the composites far surpass the strength of the aluminum. Therefore, these materials have the potential to provide high strength for structural applications.

The other materials that were investigated as part of this study are the high modulus polypropylene/carbon prepreg, Kevlar prepreg, Nextel prepreg, and a Spectra prepreg. Strength information on these materials was not available for this study; however, these materials are known to be used commercially for items such as bullet proof vests. Thus, it may be possible to also use these materials for micrometeorite protection or surface ejecta protection of different elements on the lunar surface.

Preliminary Conclusions

The conclusions given here are preliminary conclusions based upon the data that was gathered for this study. Additional work needs to be completed before definitive conclusions can be drawn.

When considering the simulation data gathered on borated polyethylene and comparing it to neat polyethylene, it was shown that the borated polyethylene still produced a higher absorbed dose. Given that boron is a neutron absorbing material, it would be expected that the borated polyethylene would produce a lower absorbed dose than the neat polyethylene, as it would be able to absorb the secondary neutrons produced during the transport of primary radiation through the thickness. However, the simulation data showed that it was not so. This could be due to the approximations made in the chemical composition input to HZETRN, which would then produce an approximate output. It could also be that the neutron production during transport through these materials did not produce very many neutrons and thus the benefit of the boron was not shown. It may be necessary to do a follow on study in which these materials are placed in a relatively heavy neutron environment, such as on the lunar surface and exposed to the neutron albedo from GCR interaction with lunar regolith. However, the simulations did show that in comparison to aluminum, borated polyethylene, lithium doped polyethylene, and neat polyethylene produced less absorbed dose than aluminum and are thus better radiation mitigators.

A similar trend was shown when considering carbon fiber composites when compared to borated carbon fiber composites. Although the distinction was not as great, the borated composites were slightly higher in absorbed dose when compared to carbon fiber composites. Again, as these materials are proprietary, the exact chemical composition is unknown, and thus the input and outputs are strictly approximations. Given this information, no definitive conclusions can be drawn until ground studies have proven that the trend follows what is shown in the simulation studies.

When comparing the different percentages of doped polyethylene, there seemed to emerge an optimization in terms of the amount of boron in the material. This current study showed that 5% borated polyethylene was a better mitigator than 30% or 0.86%

borated polyethylene. Future studies may want to delve deeper into studying the amount of boron contained in polyethylene to better pinpoint what the optimum amount might be for radiation mitigation.

Also, when considering the simulations performed on the same materials being studied for the ground testing, it is clearly shown that the lithium doped polyethylene and the borated polyethylene are much better radiation mitigators than the aluminum beryllium alloy. Given that the ground testing data has not been finalized as of yet, there is no validation of this simulation study. Once the ground testing data is completed, there will be a follow on to this paper discussing the validation of the simulation data to the ground testing data.

Forward Work

The work described in this paper is preliminary work that will need expansion before any real conclusions can be drawn. In terms of the type of forward work that needs to be completed, there are three categories: material chemical characterization, ground testing, and ray tracing of lunar element models for which these materials may be used.

Currently, the input information gathered for HZETRN transport data was based on approximations derived from the published information on the materials. This only outputs an approximation to what the absorbed dose might be, given the accuracy of the input information. Thus, it is imperative to perform characterization on the materials to better understand their chemical compositions, which is important input information for transport simulations.

Ground testing is another important method of validating the transport data collected from HZETRN. The ground testing information included in this paper is only the preliminary data gathered, and much more testing is needed before a conclusion about the mitigation properties of the material or the validation of the simulations can be given in full.

Finally, an extension of this work to full ray tracing of lunar element models will greatly enhance the understanding of the doses the crew may be exposed to, given the design of the lunar element and the different materials we may use to enhance that design. This will also lend itself to additional studies on ways to improve the radiation shielding design of the lunar element by using different materials, graded-Z layering of such materials to be more advantageous, or repurposing used items, such as cargo transfer bags, to be used for radiation shielding purposes.

Summary

In summary, several methods of radiation mitigation were discussed and follow on work to these preliminary studies is suggested. Of the methods presented, a preliminary small-scale trade study was performed on several materials that could provide radiation mitigation properties to shield crew from harmful radiation exposures. As part of this trade study, materials with high-hydrogen content and added materials such as boron and lithium were examined to see if there was an enhanced benefit from the boron or lithium.

Fiber reinforced polymeric composites were also examined for radiation mitigation properties, as well as high strength applications. Last, Z-graded materials were evaluated for their radiation mitigation properties in comparison to typical spacecraft materials.

In addition, select materials were chosen for a preliminary experimental shielding study, and the preliminary data gathered from this exposure is compared against simulation data. This experimental study will be expanded upon in future work to further validate simulation data at higher thicknesses.

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3. Band, D., et al., "BATSE Observations of gamma-ray burst spectra I. – Spectral diversity", *Astrophysical Journal,* **413**, 281-292, 1993.

4. Allan Tylka and William Dietrich, "Proton Spectra in Ground-Level Enhanced (GLE) Solar Particle Events," 37th Committee on Space Research (COSPAR) Scientific Assembly, Montreal, Canada, 2008.

5. William Atwell, " I have the Title in my office – I'll get tomorrow," Boeing Technical Excellence Conference (BTEC-16), Costa Mesa, CA, 9-12 February 2009.

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Evaluation of Multi-Functional Materials for Deep Space Radiation Shielding

Kristina Rojdev, NASA-JSC and USC PhD student
William Atwell, The Boeing Company
Richard Wilkins, Prairie View A&M
Brad Gersey, Prairie View A&M
Francis F. Badavi, NASA LaRC

2009 NSMMS
Henderson, NV
22-26 June 2009
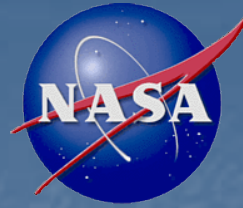
Outline

- **Deep Space Radiation Environment**
- **Methods of Radiation Mitigation**
- **Radiation Mitigating Materials**
- **Multi-Functionality Properties**
- **Preliminary Ground Testing**
- **Forward Work**
- **Preliminary Conclusions**
- **Summary**

Deep Space Radiation Environment

http://msis.jsc.nasa.gov/images/Section05/Image186.gif
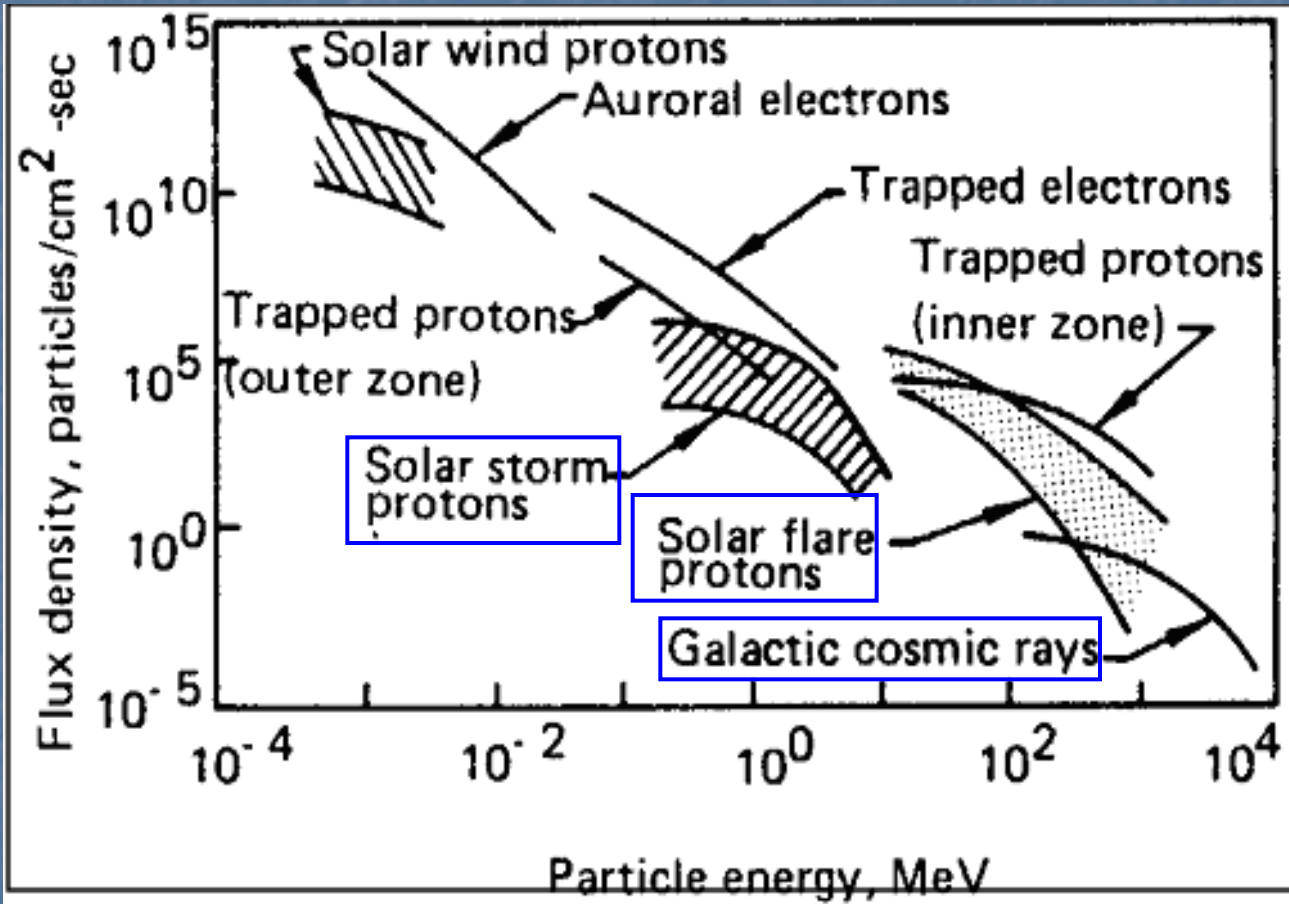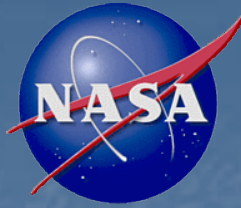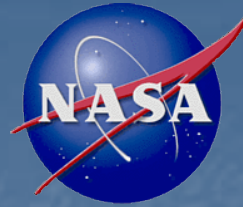
Methods of Radiation Mitigation

- Passive shielding through using radiation mitigating materials
  - High-hydrogen polymeric materials
  - Z-graded materials
  - Fiber-reinforced composite materials

- Repurposing of items
  - Cargo transfer bags

Radiation Mitigating Materials: Preliminary Simulation Study

- HZETRN 2005 radiation transport code
- Band function fit of October 1989 event
  - Band function is a double power law in rigidity fit
  - describes the entire proton energy spectrum
- Materials studied
  - High-hydrogen polymers
  - Z-graded materials
  - Fiber-reinforced polymeric composites

Radiation Mitigating Materials: High-Hydrogen Polymers
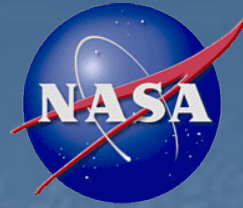
- Baseline shielding material
  - Polyethylene
- Neutron absorbing additives
  - Borated Polyethylene – 0.86%
  - Borated Polyethylene – 30%
  - Borated Polyethylene – 5%
  - Lithium-doped Polyethylene – 7.5%
- Baseline spacecraft material
  - Aluminum

Radiation Mitigating Materials: High-Hydrogen Polymers

Worst Year Dose vs. Depth
(10/1989 SPE, including 1 year of GCR exposure at solar minimum)

Legend:
- Aluminum 6061
- Borated PE 0.86%
- Borated PE 30%
- Borated PE 5%
- Li-PE 7.5%
- Polyethylene

Y-axis: Dose (cGy)
X-axis: Depth (g/cm2)

Radiation Mitigating Materials: High-Hydrogen Polymers

Worst Year Dose vs. Depth
(10/1989 SPE, including 1 year of GCR exposure at solar minimum)

Legend:
- Borated PE 0.86%
- Borated PE 30%
- Borated PE 5%

Y-axis: Dose (cGy), from 1.00E+01 to 1.00E+02
X-axis: Depth (g/cm2), from 0 to 100
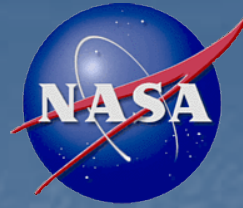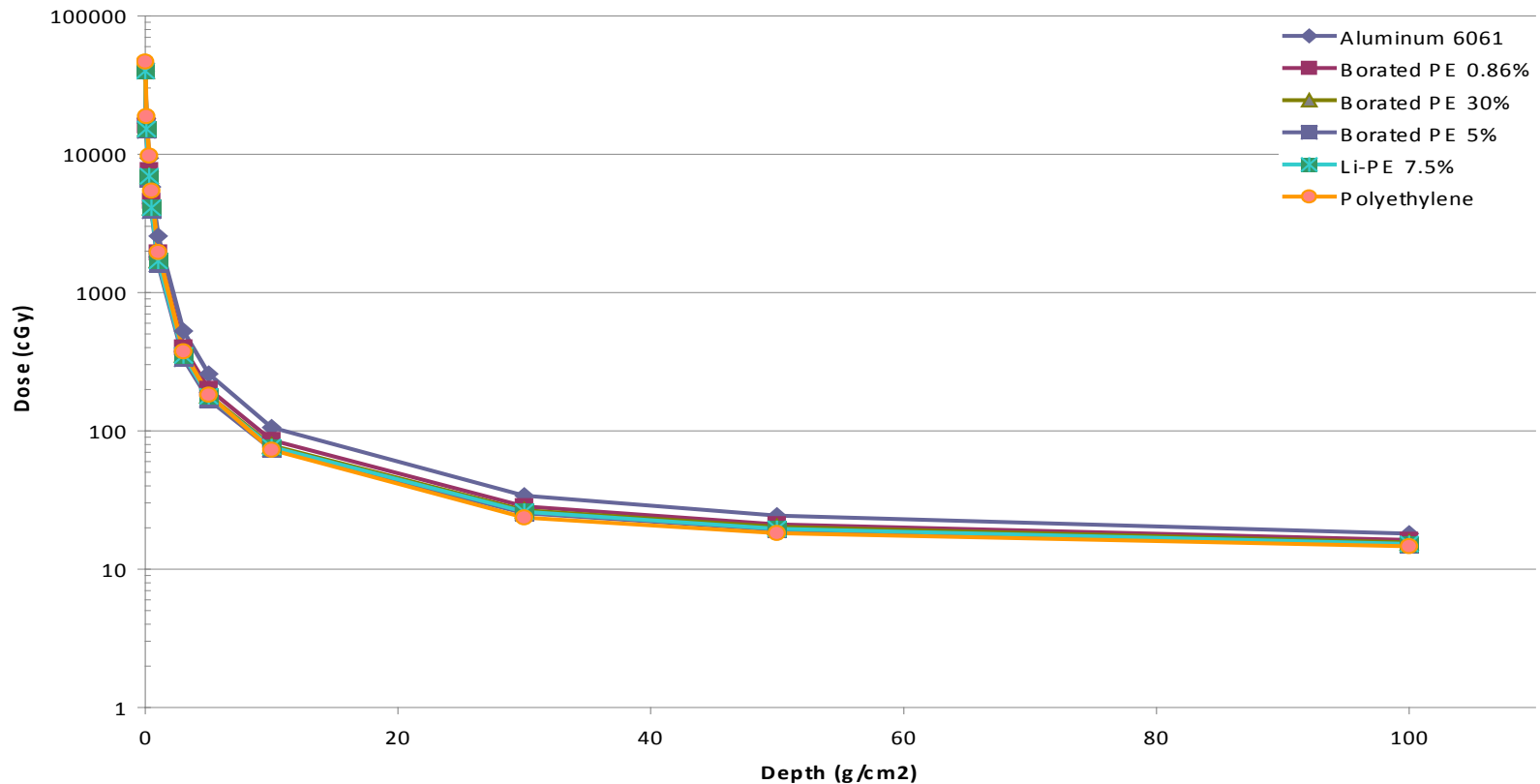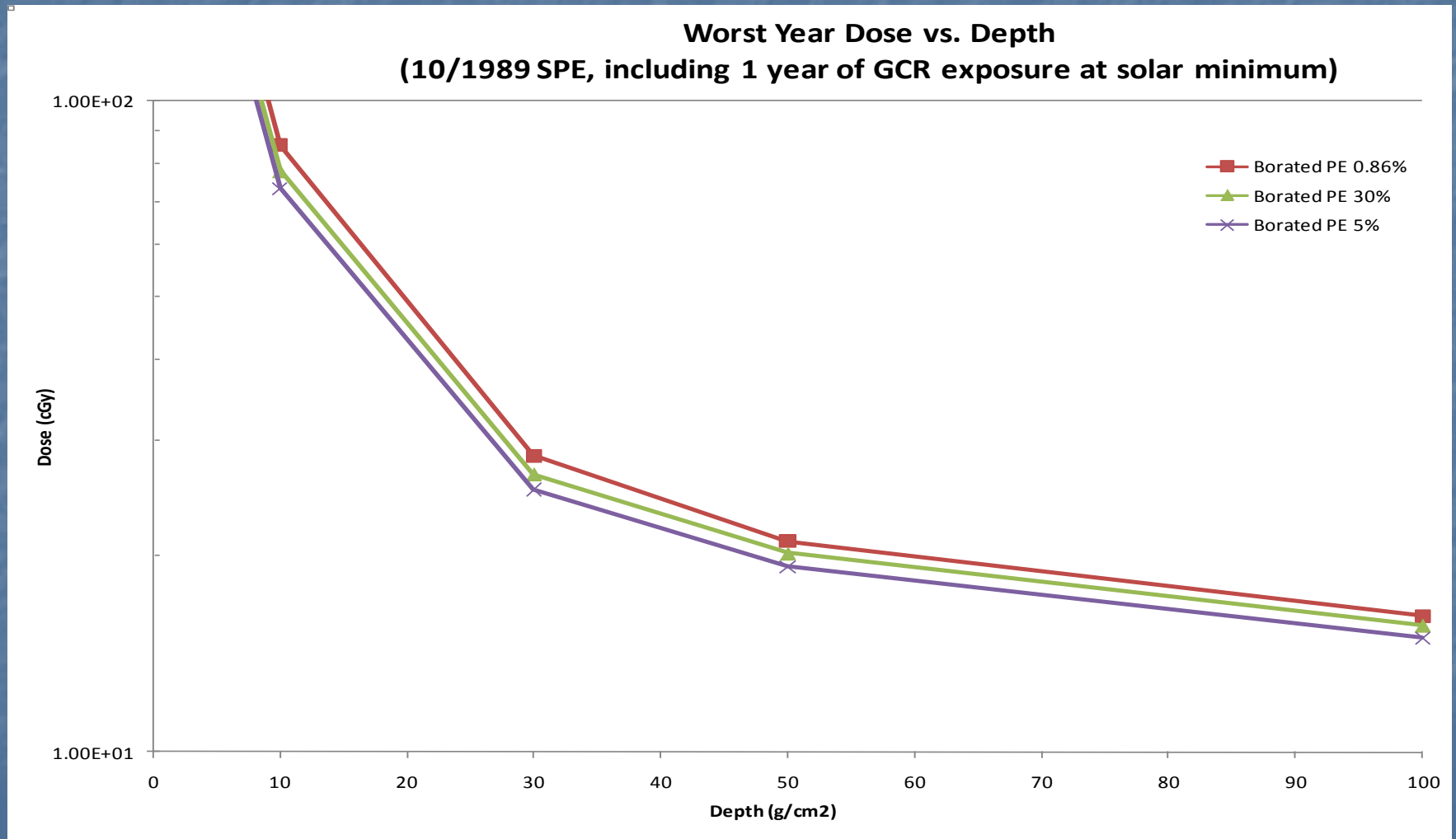
Radiation Mitigating Materials: Graded-Z Materials
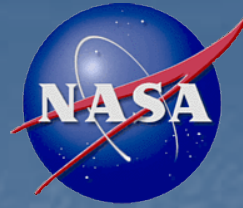
- Need from Bill – Sample run completed – need to plot the data

Radiation Mitigating Materials: Fiber-Reinforced Polymeric Composites
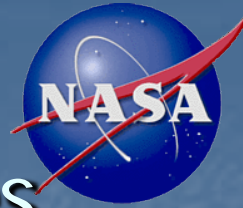
- Carbon fiber composites
  - IM7/5250
  - IM7/977-3
  - IM7/200
  - IM7/8552
- Borated composites
  - Boron prepreg
  - Boron/Carbon prepreg

- Other fiber composites
  - Innegra/Carbon prepreg
  - Kevlar prepreg
  - Nextel 312 prepreg
  - Spectra Prepreg
- Baseline spacecraft material
  - Aluminum

Radiation Mitigating Materials:
Fiber-Reinforced Polymeric Composites

Worst Year Dose vs. Depth
(10/1989 SPE with 1 year GCR exposure at Solar Minimum)

Radiation Mitigating Materials: Fiber-Reinforced Polymeric Composites
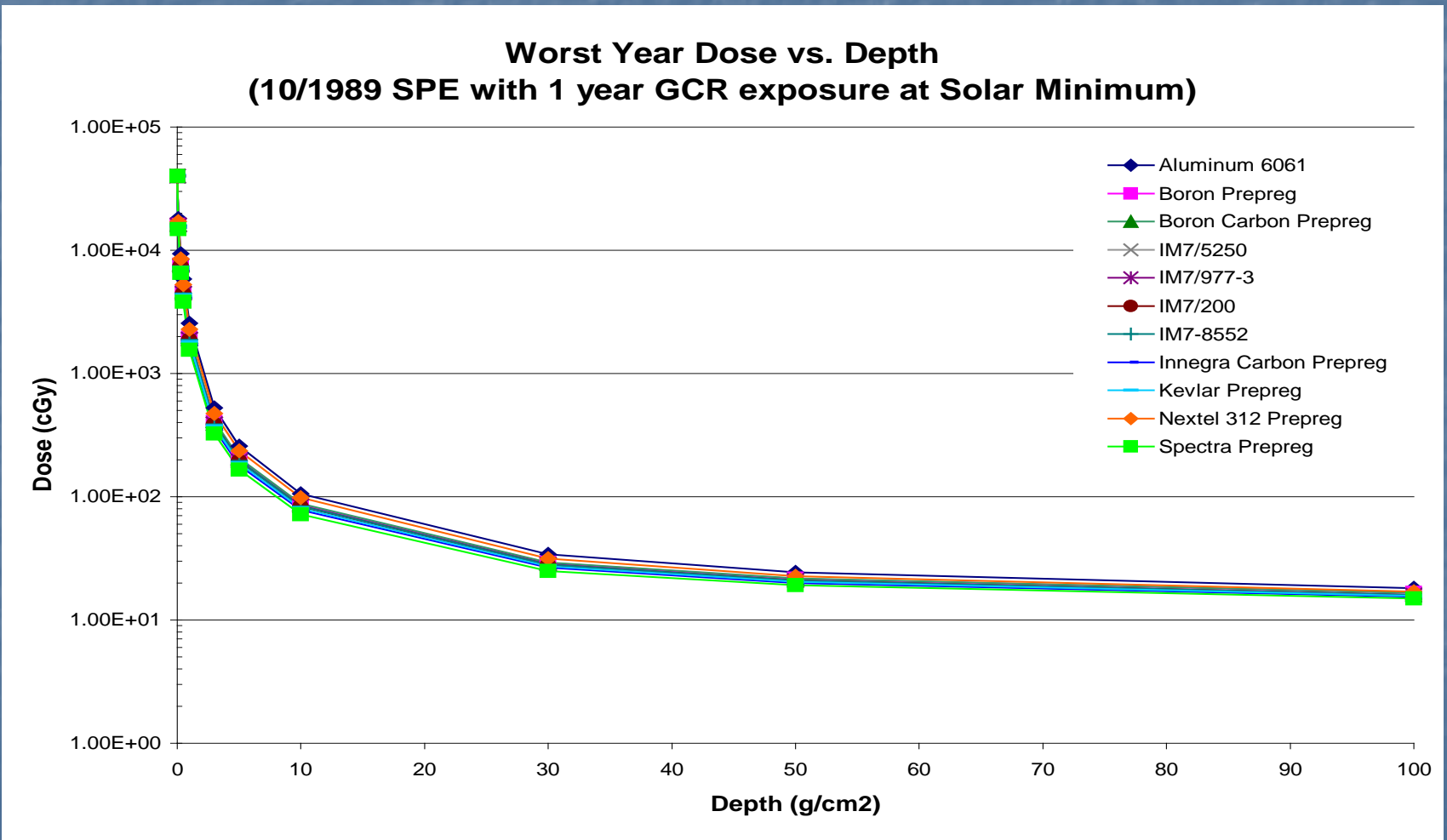
Worst Year Dose vs. Depth
(10/1989 SPE with 1 year GCR exposure at Solar Minimum)

Radiation Mitigating Materials:
Fiber-Reinforced Polymeric Composites

Worst Year Dose vs. Depth
(10/1989 SPE with 1 year GCR exposure at Solar Minimum)

Mutli-functionality Properties: Fiber-Reinforced Polymeric Composites

- **High-strength for primary and secondary structural applications**
  - Carbon fiber prepregs
    - IM7/8552
    - IM7/5250
    - IM7/977-3
  - Borated prepregs
    - Boron prepreg
    - Boron/Carbon prepreg

Mutli-functionality Properties: Fiber-Reinforced Polymeric Composites

Materials	Compressive Modulus [Gpa]	Compressive Strength [Mpa]	Tensile Modulus [Gpa]	Tensile Strength [Mpa]
Aluminum 6061	-	206.8	67.98	241.3
IM7/8552 (uni prepreg) 0 deg mech. Props.	150	1690	164	2724
IM7/8552 (uni prepreg) 90 deg mech. Props.	-	-	12	111
IM7/8552 (woven prepreg) 0 deg mech. props	-	-	85	1090
IM7/8552 (woven prepreg) 90 deg mech. props.	-	-	80	945
IM7/Cytec 5250 (uni tape)	158	1620	162	2618
IM7/Cytec 5250 (uni tape) (Orientation: +45,0,-45,90) (notched properties)	57	310	63	441
IM7/977-3 (uni tape) (notched properties not given)	154	1680	162	2510
Boron/Carbon Fiber Composite (uni tape)	240	2760	240	1900
Boron Fiber Composite (uni tape)	210	2930	195	1590

Mutli-functionality Properties: Fiber-Reinforced Polymeric Composites

- Commercial ballistic applications
  - Innegra/Carbon prepreg
  - Kevlar prepreg
  - Nextel prepreg
  - Spectra prepreg
- Possible space application
  - Micrometeorite and surface ejecta shielding
  - Other impingement protection
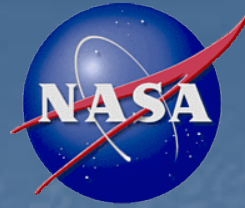
Preliminary Ground Testing

- Co-Principal Investigators – Prairie View A&M
    - Dr. Richard Wilkins
    - Dr. Brad Gersey

- Loma Linda University Medical Center proton synchrotron
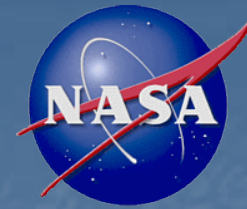
Preliminary Ground Testing

- **Materials Selected**
  - Borated polyethylene – 5.5%
  - Lithium doped polyethylene – 7.5%
  - 60% Beryllium – 40% Aluminum alloy
  - Neat polyethylene
  - Aluminum

Li-PE – 7.5%
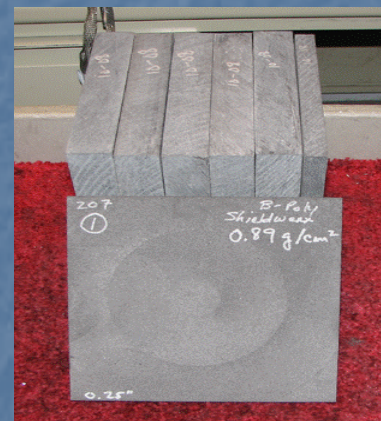
B-PE – 5.5%
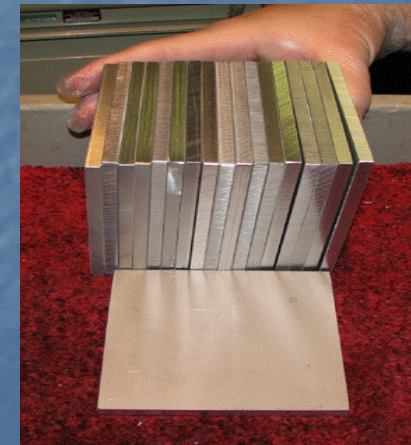
Al-Be
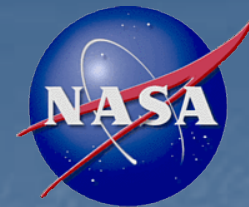
Preliminary Ground Testing
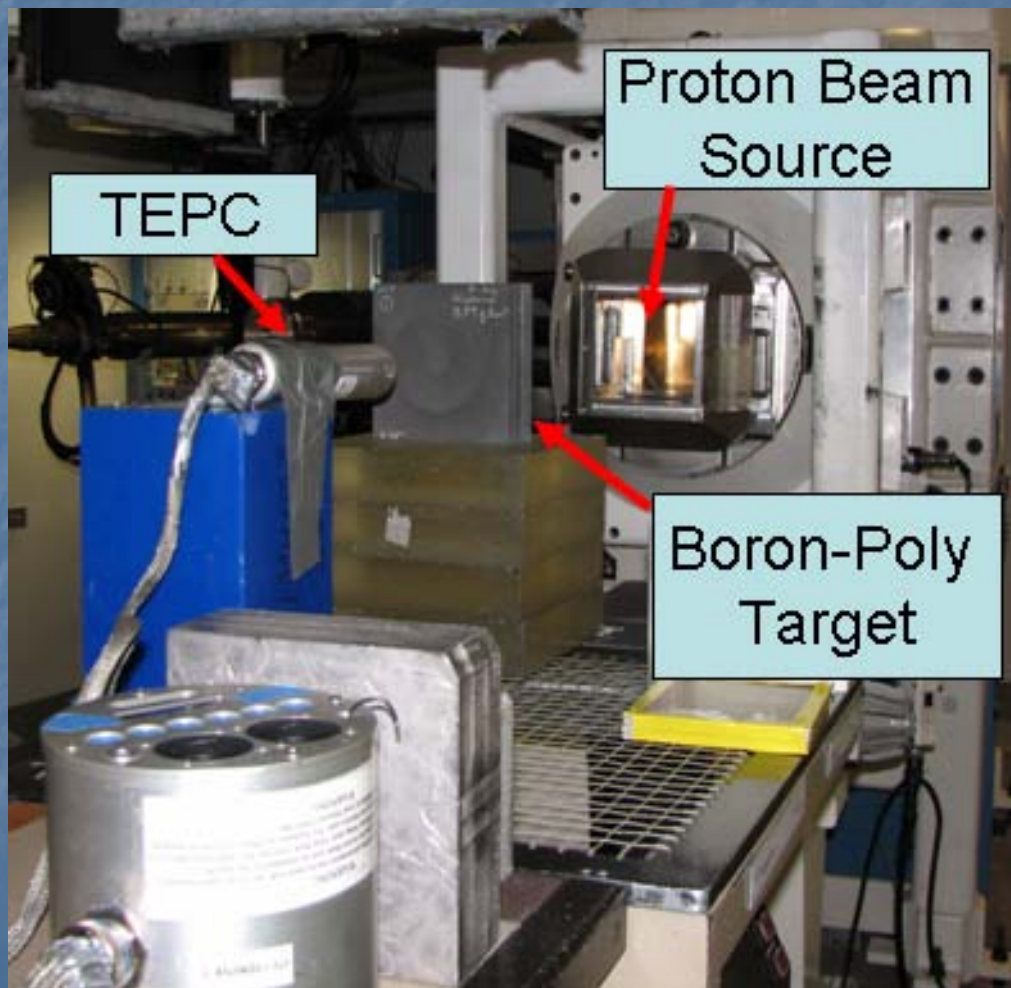
- Experimental setup
  - Tissue Equivalent Proportional Counter (TEPC)
  - ~200 MeV proton beam
 - Low proton fluence (200 protons/cm^2/spill)
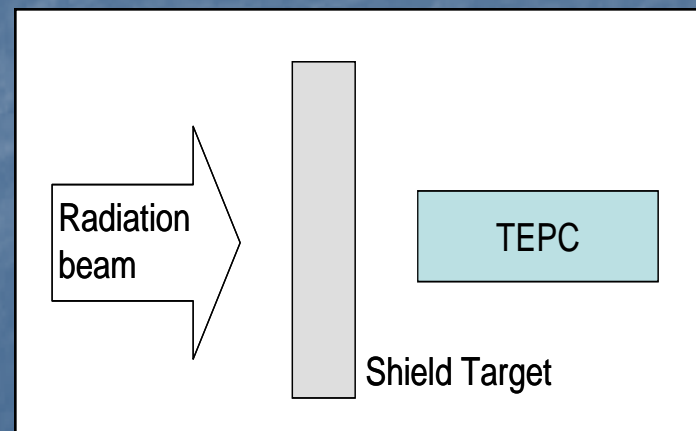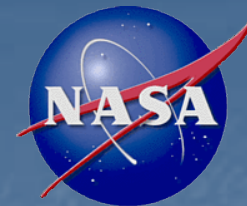
Preliminary Ground Testing

Target Material	Density Thickness (g/cm2)	Absorbed Dose (μGy/Spill)	Dose Equivalent (μSv/Spill)
None	0.00	1.96	3.14
HDPE	0.92	2.01	3.18
HDPE	5.52	2.11	3.19
HDPE	10.12	2.22	3.31
HDPE	14.72	2.56	3.68
Al	0.86	1.83	2.94
Al	5.16	2.09	3.06
Li-Poly	5.06	2.12	3.31
Boron -Poly	0.89	1.92	3.14
Boron -Poly	5.35	2.10	3.31

1. Preliminary data – analysis of Al-Be data "in work"

2. TEPC data for Li-poly target of 1 g/cm^2 was corrupted

3. NONE – measurement taken with TEPC of nominal values of absorbed dose and dose equivalent for proton beam only with no shield target
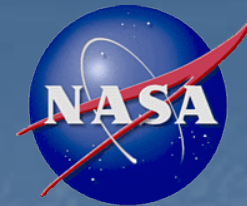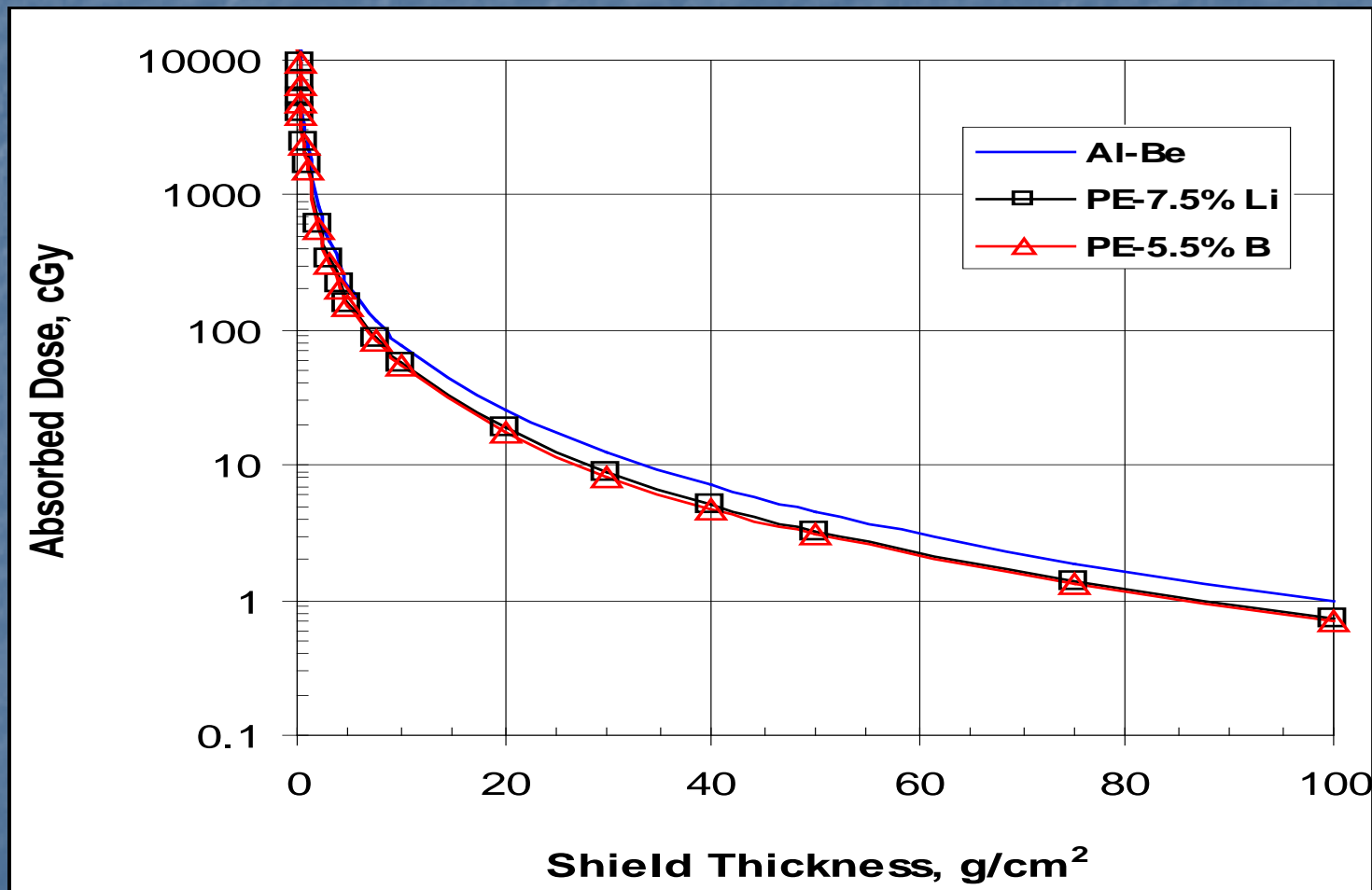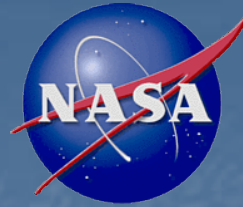
Preliminary Ground Testing

**Absorbed Dose measured by the TEPC**
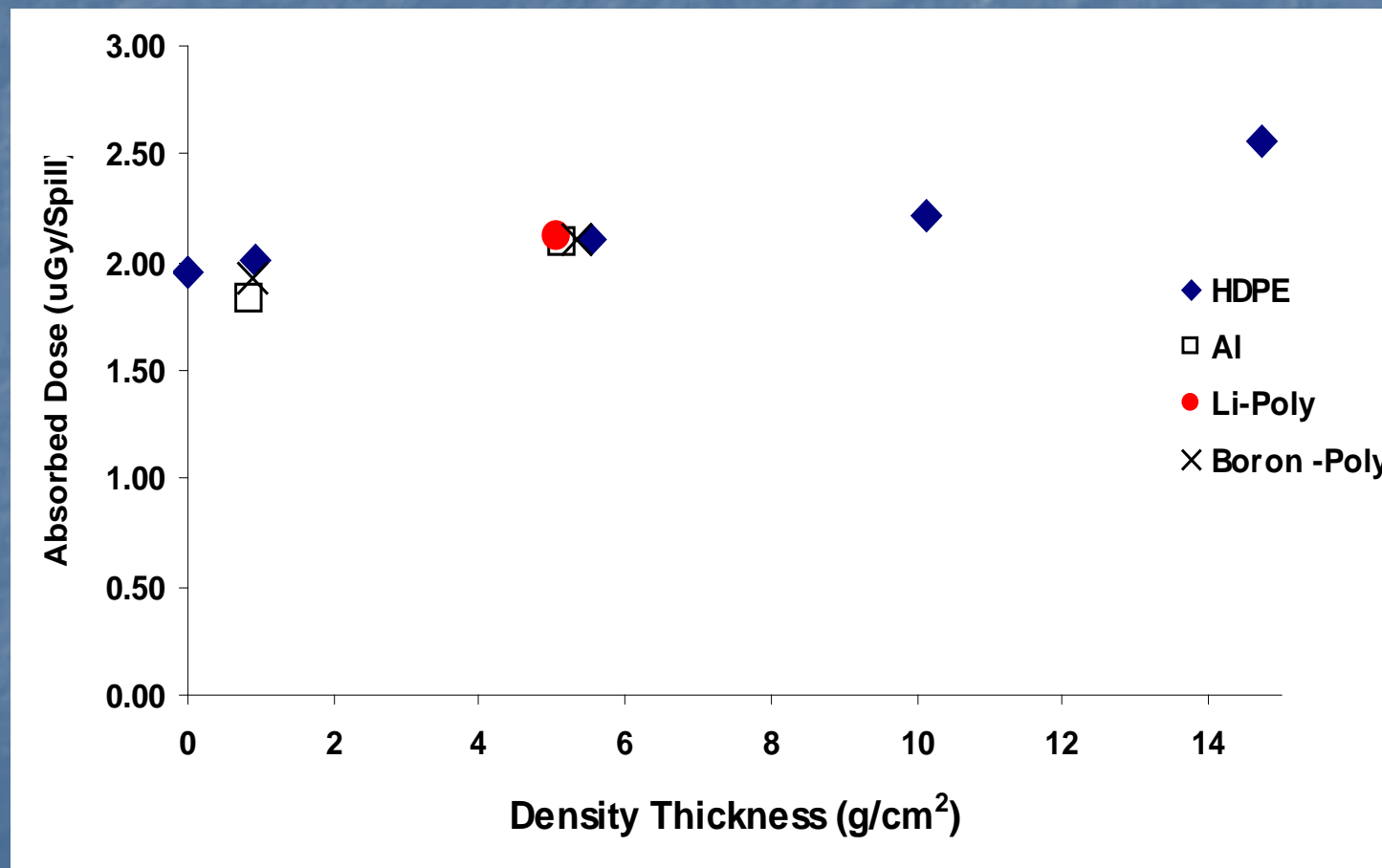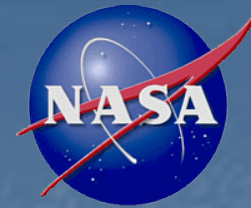
Preliminary Ground Testing

Preliminary Conclusions

- Borated polyethylene showing higher absorbed dose values when compared with neat polyethylene
  - Input information to HZETRN was approximate, thus output was also approximate
  - Neutron production during transport through thicknesses might have been low, thus not showing the full benefit of the borated material
    - May need to complete further studies on these materials in heavy neutron environment
- Similar trend with carbon fiber composites and borated composites in that the borated composites produced high absorbed doses
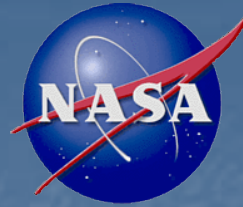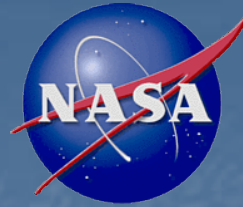
Preliminary Conclusions

- Potential optimization in the amount of boron doped in polyethylene
  - This study showed 5% borated polyethylene as a better radiation mitigator when compared with 30% and 0.85% doping
- Simulations of materials used in ground study showed lithium-doped polyethylene and boron-doped polyethylene as better radiation mitigators when compared with aluminum-beryllium alloy
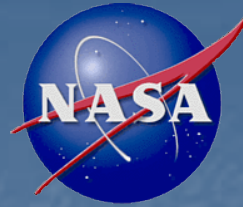
Forward Work

- **Material chemical characterization**
  - Provide more accurate simulation studies of composite materials
- **Ground testing**
  - Validate simulation studies
  - Provide concrete conclusions about radiation mitigation properties of these materials
- **Ray tracing of lunar element models**
  - Enhance understanding of doses to which crew exposed
  - Allow better understanding of how multi-functional materials can be used in designs of lunar elements
  - Study how items within lunar elements can be repurposed for use as radiation shields

Summary

- Small scale trade study of materials for radiation shielding
  - High-hydrogen polymers
  - Z-graded materials
  - Fiber-reinforced polymer composites
- Discussed multi-functionality of fiber-reinforced polymer composites
- Preliminary results of ground testing data

Questions