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Investigation of Lithium Metal Hydride Materials for Mitigation of Deep Space Radiation

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Radiation exposure to crew, electronics, and non-metallic materials is one of many concerns with long-term, deep space travel. Mitigating this exposure is approached via a multi-faceted methodology focusing on multi-functional materials, vehicle configuration, and operational or mission constraints. In this set of research, we are focusing on new multi-functional materials that may have advantages over traditional shielding materials, such as polyethylene. Metal hydride materials are of particular interest for deep space radiation shielding due to their ability to store hydrogen, a low-Z material known to be an excellent radiation mitigator and a potential fuel source. We have previously investigated 41 different metal hydrides for their radiation mitigation potential.[1,2] Of these metal hydrides, we found a set of lithium hydrides to be of particular interest due to their excellent shielding of galactic cosmic radiation. Given these results, we will continue our investigation of lithium hydrides by expanding our data set to include dose equivalent and to further understand why these materials outperformed polyethylene in a heavy ion environment. For this study, we used HZETRN 2010, a one-dimensional transport code developed by NASA Langley Research Center, to simulate radiation transport through the lithium hydrides. We focused on the 1977 solar minimum Galactic Cosmic Radiation environment and thicknesses of 1, 5, 10, 20, 30, 50, and 100 g/cm^2 to stay consistent with our previous studies. The details of this work and the subsequent results will be discussed in this paper.

Nomenclature

CNT = nanoporous carbon composite
GCR = galactic cosmic radiation
GeV = unit of measure of energy (Gigaelectron volt)
HDPE = high density polyethylene
HZETRN = High charge and Energy (HZE) Transport (TRN) code
ISS = International Space Station
Low-Z = an element with low atomic number
MeV = unit of measure of energy (Megaelectron volt)
MH = metal hydride
MOF = metal organic framework
SPE = solar particle event

I. Introduction

One of the many challenges of deep space flight is the radiation environment that vehicles must withstand. In particular, galactic cosmic radiation (GCR), a constant background source of radiation in deep space, is difficult to shield against, requiring large thicknesses of material to provide any measurable difference in the dose to crew and

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electronics. The materials that have proven to be the best radiation mitigators are low-Z materials, such as high-density polyethylene (HDPE). However, large amounts of HDPE for purely shielding purposes (parasitic shielding) leads to extra mass in a vehicle that can increase launch costs significantly. Thus, finding materials with multipurpose uses and developing a multifaceted shielding approach is far more mass and cost efficient.

In keeping with this philosophy of using multipurpose materials, we investigated materials from other industries that could increase the quantity of low-Z elements into materials. In particular, we focused on the fuel cell industry that was developing fuel cells for automobiles and studied the materials that could be infused with higher concentrations of hydrogen, but were more difficult for the hydrogen to be extracted later on. Initially, we investigated three classes of materials: metal hydrides (MH), metal organic frameworks (MOF), and nanoporous carbon composites (CNT).

In our first study[1], we examined a total of 64 materials, 10 of which were MOF, 14 of which were CNT, and 40 of which were MH. We focused on a hard solar particle event (SPE), the October 1989 series of events, as the radiation environment. We then compared the resultant doses for these materials against aluminum and high-density polyethylene (HDPE). Aluminum was chosen as the common space vehicle structural material and HDPE was chosen as the typical “gold standard” radiation shielding material. In this case, we found that one MOF, one MH, and seven CNTs outperformed HDPE, leading us to conclude that the CNT-type material would be more beneficial for radiation mitigation against a hard SPE. However, in deep space missions with large timelines, the SPE exposure can be sufficiently mitigated with radiation-optimized design, such as placing large tanks and other massive logistics around the habitable volume and core electronics.[3-5] Thus, the more difficult environment to shield against is the GCR environment due to extremely penetrating, high-energy particles.

Therefore, in our second study[2], we investigated the same 64 materials in the 1977 solar minimum GCR environment, which is considered a worst case for GCR. We, again, compared the doses to aluminum and HDPE. In this case, we found one MOF, seven MHs, and seven CNTs outperformed HDPE. It was interesting to note that in the GCR case, several more MHs outperformed HDPE than in the SPE case. Furthermore, when reviewing the MHs, we found that those MHs that contained lithium were the ones that outperformed HDPE. Additionally, when we compare the doses of the CNTs to the MHs (Figure 1), we find that several of the MHs are also better radiation mitigators than the CNTs for this environment. Given these findings, we want to understand why the lithium metal hydrides have lower doses in a GCR environment, as well as whether this trend holds for GCR exposure in tissue (dose equivalent). The following paper focuses on these next steps of the investigation.

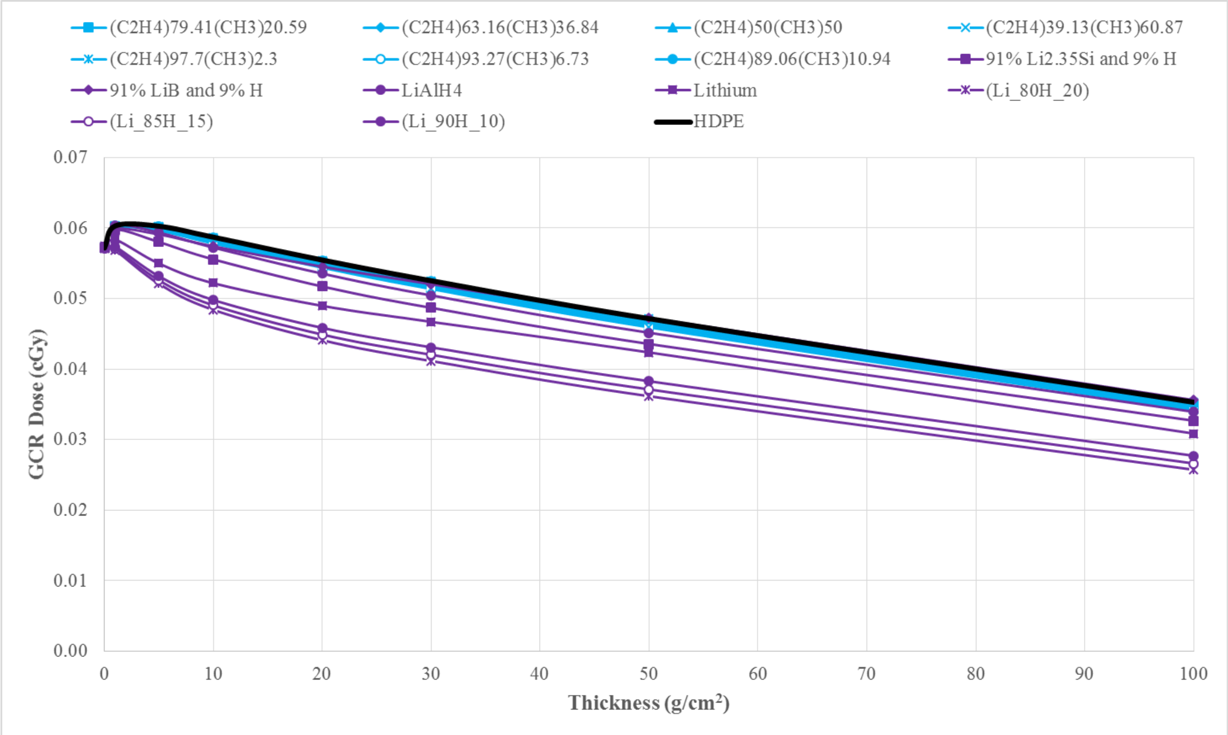

Figure 1: Comparison of GCR dose of the CNTs that outperformed HDPE with MHs that outperformed HDPE. All the CNTs are in the blue color and all the MHs are in the purple color. For comparison, HDPE is in black.

II. Background

The radiation environment of interest in this study is the galactic cosmic radiation (GCR) environment. GCRs are particles that are a constant background source of radiation to vehicles in deep space. The relative abundance of elements within the GCR environment are similar to what is found in the solar system (Figure 2). These elements range from low atomic number, such as protons, to high atomic number, such as iron. In general, there is a higher abundance of particles at the low atomic numbers than at the high atomic numbers.

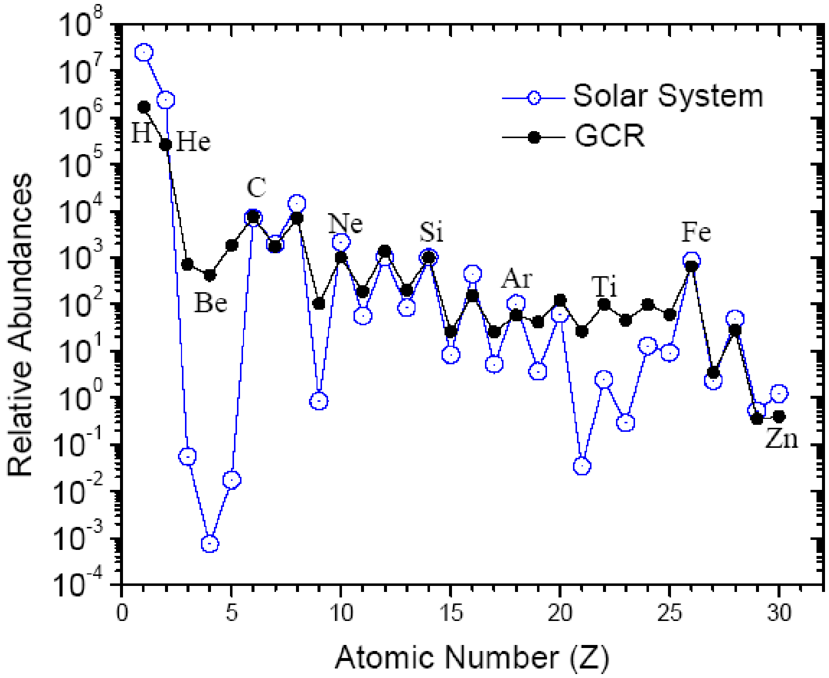

Figure 2: Relative abundance of GCRs as compared with the solar system[6].

GCRs are also anti-correlated with the solar cycle. Thus, when the sun is experiencing high activity, the GCR intensity is lower, and vice versa (Figure 3). The decrease in the GCR intensity at solar maximum is due to the interaction of solar particles with the GCR particles, thus slowing them down or stopping them completely. GCRs also contain particles with very high energy, as can be seen in Figure 3, with ranges from 10 MeV to several GeV.

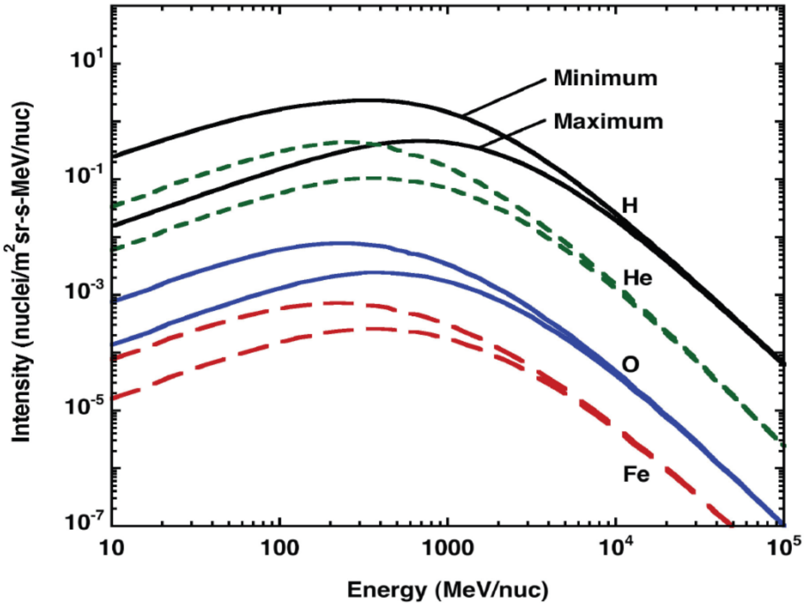

Figure 3: Differential fluence of several GCR elemental species (hydrogen, helium, oxygen, and iron) for both solar minimum and solar maximum[7].

The materials being investigated in this study are metal hydrides, with a particular interest in the subset of lithium metal hydrides. Metal hydrides are metallic compounds that have a bond with an anion of hydrogen. These compounds are typically non-stoichiometric and have variable amounts of hydrogen within the metallic lattice structure. For radiation purposes, the desire is to have as much hydrogen within the lattice as possible. The lithium metal hydrides in this study comprises lithium and hydrogen, with the exception of two of the compounds, also containing aluminum and silicon, respectively.

III. Materials and Methods

Six lithium metal hydrides were investigated, along with lithium, aluminum, and high-density polyethylene (HDPE). The element lithium was included as the base metallic material for the lithium metal hydrides. Aluminum represents the typical spacecraft material used in vehicles throughout historical human spaceflight. HDPE is the current standard parasitic shielding material commonly used on spaceflight vehicles, such as the International Space Station (ISS). The details of these materials are shown in Table 1.

Table 1: Materials investigated with chemical composition and density.

Condition	Chemistry	Density (g/cm^3)
Spacecraft Material	Al	2.70
Shielding Material	C_2H_4	0.94
Base	Li	0.53
H	91% $Li_{2.35}Si$ and 9% H	0.84
H	$LiAlH_4$	0.92
H	80% Li and 20% H	0.57
H	85% Li and 15% H	0.56
H	90% Li and 10% H	0.55
H	95% Li and 5% H	0.54

To perform the simulation, HZETRN 2010[8-12] was used as the transport code. This code was developed at NASA Langley Research Center and is based a one-dimensional space-marching formulation of the Boltzmann transport equation with a straight-ahead approximation. The environment chosen was the 1977 solar minimum GCR to stay consistent with our previous study and the shielding profile investigated was 1, 5, 10, 20, 30, 50, and 100 g/cm^2. For this paper, we are interested in the dose equivalent with a tissue detector to determine whether the trend seen in the dose from our previous study[2] remains. In addition, to understand why the lithium hydrides outperform HDPE, we studied the secondary flux in each of these materials.

IV. Results and Discussion

A. Dose Equivalent Results

The first part of this study was to examine the dose equivalent in these materials to see whether they exhibited the same trend as in our previous study[2]. The results are shown in (Figure 4).

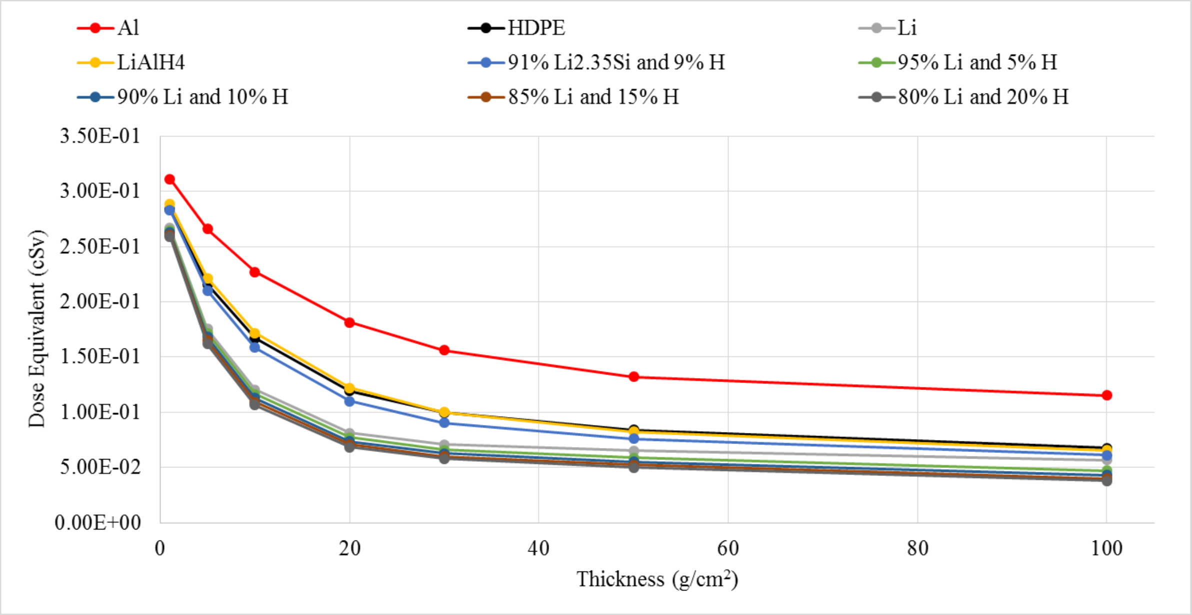

Figure 4: Dose equivalent results.

The figure shows that all the lithium hydride materials outperform aluminum and HDPE, with the exception of $LiAlH_4$, which has similar radiation mitigation properties as HDPE for dose equivalent. The lithium hydride that also contains silicon is similar to HDPE in radiation mitigation properties as well. All the materials that only contain lithium and hydrogen are better radiation mitigators overall, particularly in the shielding range of 1-50 g/cm^2. At higher thicknesses, there are not any additional shielding benefits. These are similar results to what we found with the absorbed dose in our previous study, further indicating that lithium hydrides could be of particular interest for GCR mitigation.

B. Secondary Flux Results

The second part of our study focused on determining why the lithium hydrides outperform HDPE. For this part of the investigation, we examined the flux in the material at a particular thickness, 20 g/cm^2. We chose this thickness because it is representative of a typical spacecraft thickness.

HZETRN 2010 provides the flux of 59 different species for GCR environments. Initially, we considered the entire 1977 GCR energy spectrum. However, it was difficult to separate out which part of the flux was due to secondary radiation production and which part of the flux was due to the primary radiation. Thus, we reduced the input GCR environment to the energy range from 10 to 100 MeV to better show flux purely resulting from secondary radiation production. In Figure 5, we show the first six species (out of 59 species total) of this reduced energy GCR environment. As you can see, the primary particles are from protons and alphas, with the majority from the protons.

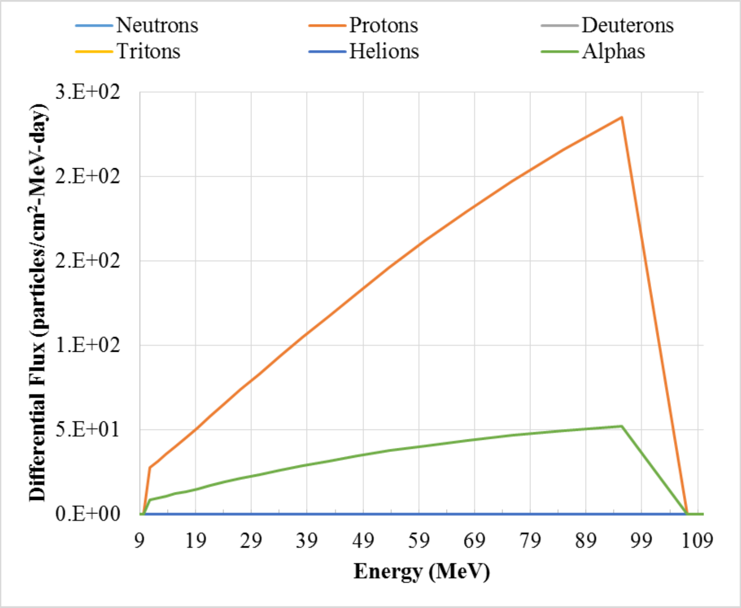

Figure 5: First six species of the reduced energy GCR input spectrum used in HZETRN 2010.

The following results (Figure 6 and Figure 7) contain those species that had fluxes greater than zero. Given that the input spectrum comprises protons and alphas, all the other fluxes presented in the results are purely due to secondary radiation production from the primary radiation interacting with the material. Additionally, considering the magnitude of the differential flux for the primary radiation (Figure 5) and the magnitude of the flux for protons in Figure 6 and alphas in Figure 7 at 20 g/cm^2 in the material, suggests that the material absorbed all the primary radiation. Thus, the flux at 20 g/cm^2 is due to secondary production from the primary radiation interacting with the material.

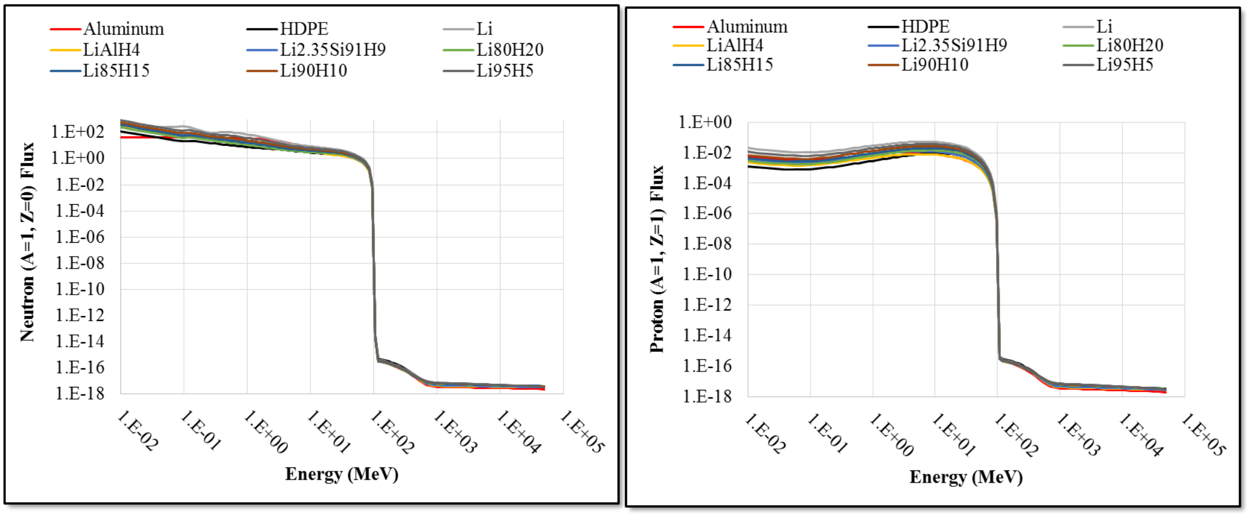

Figure 6: Secondary flux in materials at 20 g/cm^2 thickness. The neutron flux is shown in the left panel and the proton flux is shown in the right panel.

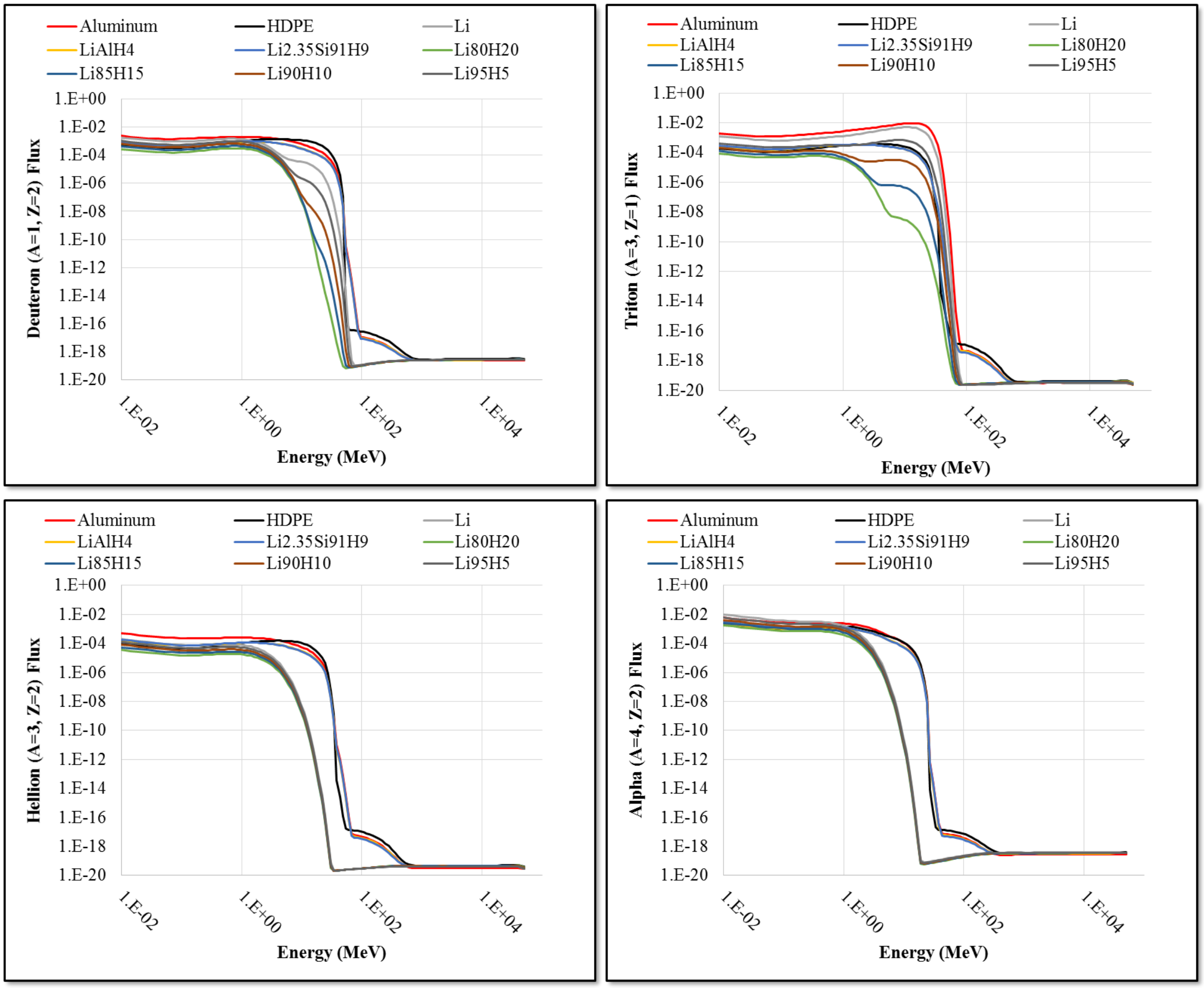

Figure 7: Secondary flux in materials at 20 g/cm^2 thickness. The deuteron flux is shown in the top left panel, the triton flux is shown in the top right panel, the hellion flux is shown in the bottom left panel, and the alpha flux is shown in the bottom right panel.

Our initial hypothesis was that the superiority of the lithium hydrides was due to the combination of lithium being a good neutron absorber and hydrogen being an exceptional radiation mitigator. However, when considering the results in Figure 6, we see that there is no difference between aluminum, HDPE, and the lithium hydrides with respect to neutron production for the reduced energy range of the GCR environment. Similarly, there is no difference in the materials for proton secondary production.

Rather, in Figure 7, we see differences associated with deuteron, triton, hellion, and alpha production amongst the materials. If we consider the deuteron, hellion, and alpha flux, we see similar trends to those presented in Figure 4 with the dose equivalent. The triton flux does not show the same kind of trend when considering those materials that have higher percentages of lithium (Li or Li95H5). Thus, given these results, we conclude that the reason why these lithium hydrides outperform HDPE is that they do not produce as many secondary deuteron, triton, hellion, and alpha particles that contribute to the overall dose or dose equivalent at the detector.

Similar trends exist in these six species when the entire GCR energy spectrum is considered, but it is unclear which aspect of the flux is primary radiation or secondary radiation. These results can be found in the Appendix for comparison (Figure 8 and Figure 9).

V. Conclusion

This study was a follow on to two previous studies examining the radiation mitigation potential of multifunctional, metal hydride materials. In particular, we focused on lithium metal hydrides exposed to a worst-case GCR environment that produced favorable results in our previous studies. The first part of the study considered the dose equivalent of these materials. We found similar trends, as was shown in the previous studies, revealing that lithium metal hydrides outperform the current standard radiation shielding material of HDPE. The second part of the study asked the question why lithium hydrides outperform HDPE. By examining the secondary radiation production in these materials, we conclude that lithium hydrides are superior to HDPE due to the lower production of particular secondary radiation products, namely deuterons, tritons, hellions, and alphas. Given these results, we recommend that future vehicle designs and shielding configurations for deep space missions with long durations consider the use of lithium hydrides as multifunctional materials that could be advantageous for shielding against GCR environments.

Appendix

The following results (Figure 8 and Figure 9) demonstrate the fluxes in the materials of this study at 20 g/cm^2 when the entire energy spectrum for the 1977 solar minimum GCR environment is used as the input to HZETRN 2010. Figure 8 reveals that there is no difference in the fluxes between the metal hydrides and aluminum or HDPE for neutrons and protons. Figure 9 reveals similar results to Figure 7 in that the lithium metal hydrides have a lower incidence of deuteron, triton, hellion, and alpha fluxes when compared with aluminum and HDPE, particularly at energies below a few hundred MeV.

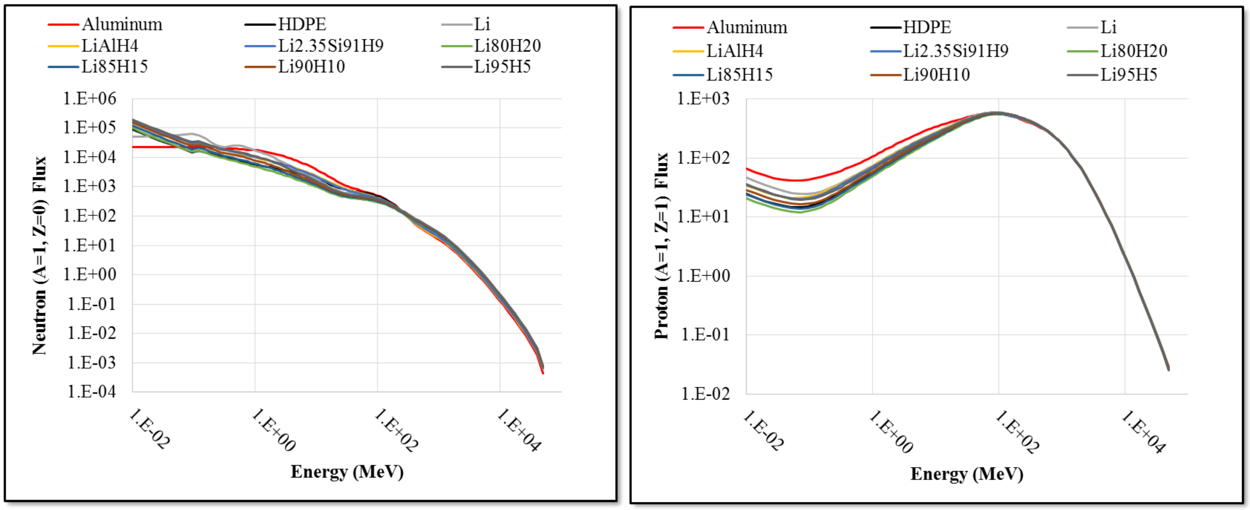

Figure 8: Flux in materials at 20 g/cm^2 thickness with the full energy range of the 1977 GCR input spectrum. The neutron flux is shown in the left panel and the proton flux is shown in the right panel.

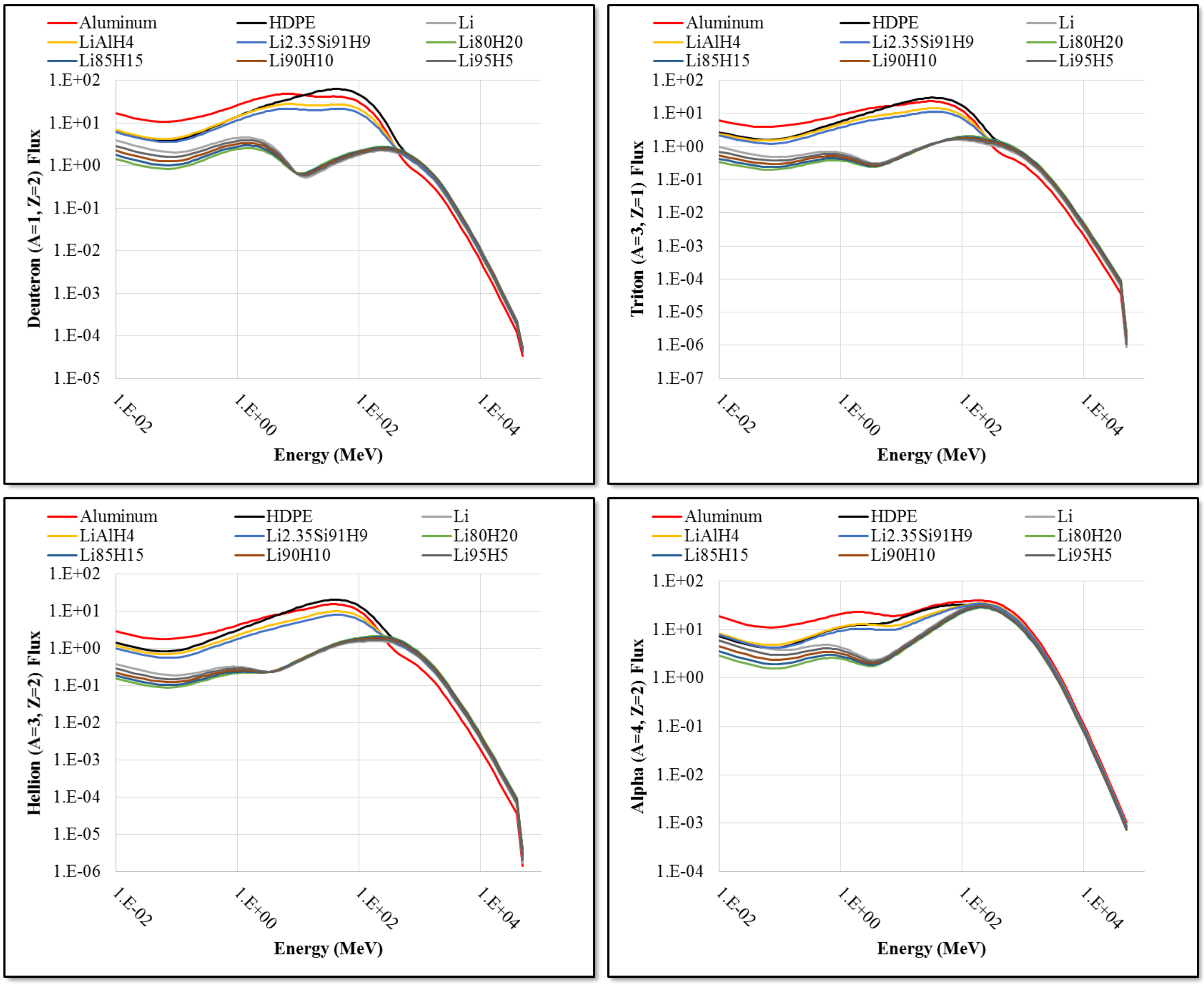

Figure 9: Flux in materials at 20 g/cm^2 thickness with the full energy range of the 1977 GCR input spectrum. The deuteron flux is shown in the top left panel, the triton flux is shown in the top right panel, the hellion flux is shown in the bottom left panel, and the alpha flux is shown in the bottom right panel.

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