An Analysis of the Material Best Suited to Replace Aluminum for Radiation Shielding Aboard Spacecraft for Moon Missions

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Abstract. Space radiation is one of the most significant barriers to space travel, and without improved radiation-shielding materials, there are severe limitations to deeper space exploration and longer space missions in general. The two most practically problematic sources of radiation in the solar system are galactic cosmic radiation (GCR) and solar particle events (SPEs). Aluminum has long been a spacecraft material of choice since it is relatively light-weight and has good structural stability. Given aluminum's insufficient radiation-shielding properties, radiation was evidently not a serious consideration during previous moon missions. In 2025, NASA plans to launch a 30-day long moon mission called Artemis 3, where astronauts will to the south pole of the moon and conduct experiments for 6 days. This paper evaluates polyethylene and liquid hydrogen against aluminum as shielding materials for a mission with similar parameters to the Artemis 3. The materials are evaluated based on weight as well as their ability to shield from galactic cosmic radiation and solar particle events. Shielding effectiveness against GCR and SPEs is evaluated from simulations which predict dose equivalent versus material thickness in the presence of high GCR and SPE environments. Weight is ultimately evaluated based on the density of the materials. Results show that liquid hydrogen is a significantly better shielding material in response to both GCR and SPEs for a given thickness, and it is tentatively concluded that liquid hydrogen contributes less weight to the spacecraft. Although liquid hydrogen is highly flammable, it also has potential use as a fuel for final burn. In light of these findings, liquid hydrogen is found to be the better solution due to its better shielding properties than polyethylene.

1. Introduction

Space radiation is one of the most significant barriers to space travel, and without improved radiation shielding materials, there are severe limitations to deeper space exploration and longer space missions in general [1]. Nasa has identified four primary biomedical risks that may pose significant health concerns to astronauts exposed to interplanetary radiation environments: carcinogenesis, degenerative tissue effects, central nervous system decrements, and acute radiation syndrome [2]. Especially in a time when space travel is seeing a notable resurgence, it is imperative that the threat of space radiation is dealt with as soon as possible. Aluminum has long been a spacecraft material of choice since it is relatively light-weight and has good structural stability [1]. Materials used in 1969 for the hull of the Apollo service module, command module, and lunar module were primarily composed of aluminum [3]. However, radiation shielding was not considered an operational issue during the Apollo missions [4], especially given aluminum's poor radiation-shielding properties (as will be illustrated in section 3). The scientific literature has revealed that hydrogen-rich materials appear to be effective in radiation shielding [5], and NASA has shown interest in two materials in particular: polyethylene [6], and liquid hydrogen[7]. In 2025, NASA plans to launch the Artemis 3 moon mission. This will be their first manned mission to the moon since the Apollo 17 mission in 1972 [8]. This paper will evaluate polyethylene and liquid hydrogen against aluminum as shielding materials for a mission akin to the Artemis 3. The materials will be evaluated based on their weight as well as their ability to shield from galactic cosmic radiation and solar particle events.

2. Background

2.1 Ionizing vs. Non-Ionizing, Primary vs. Secondary Radiation

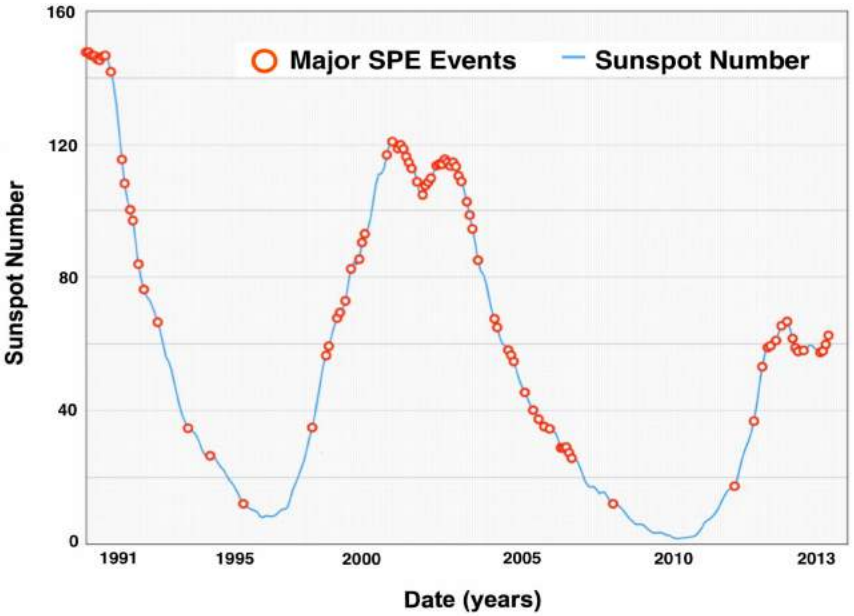
Radiation can either be particulate or electromagnetic (EM) in nature. Radiation is ionizing if the incident radiation is capable of separating electrons from their nuclei [9]. Naturally, ionizing radiation contains more energy than non-ionizing radiation. Electromagnetic waves with a frequency greater than or equal to that of x-rays are ionizing, and subatomic particles with energies above certain thresholds are ionizing. Examples of particulate ionizing radiation include alpha particles, beta particles, and neutron radiation, which are high-speed helium nuclei, electrons or positrons, and neutrons respectively [9]. When ionizing radiation comes into contact with material such as the hull of a spacecraft or human skin, it is also capable of splitting the nuclei of said material (also known as nuclear fragmentation), which produces very harmful secondary radiation particles and EM waves in addition to the primary radiation [2].

2.2 The Radiation Environment in the Solar System

For space missions, there are kinds of radiation which pose the greatest risk to astronauts: Van Allen radiation belts, galactic cosmic radiation (GCR), and solar particle events (SPEs) [10]. All of these kinds of radiation are ionizing. Note that although general solar activity contributes to the radiation environment of the solar system, it is not (in of itself) problematic for space missions. GCR describes particulate radiation which originates from nearby galaxies and dying stars outside our solar system, traveling at near the speed of light. The GCR spectrum is 98% hadrons, and 2% electrons and positrons (beta particles). The hadron component is 87% high energy protons, 12% alpha particles, and 1% heavy ions [11].

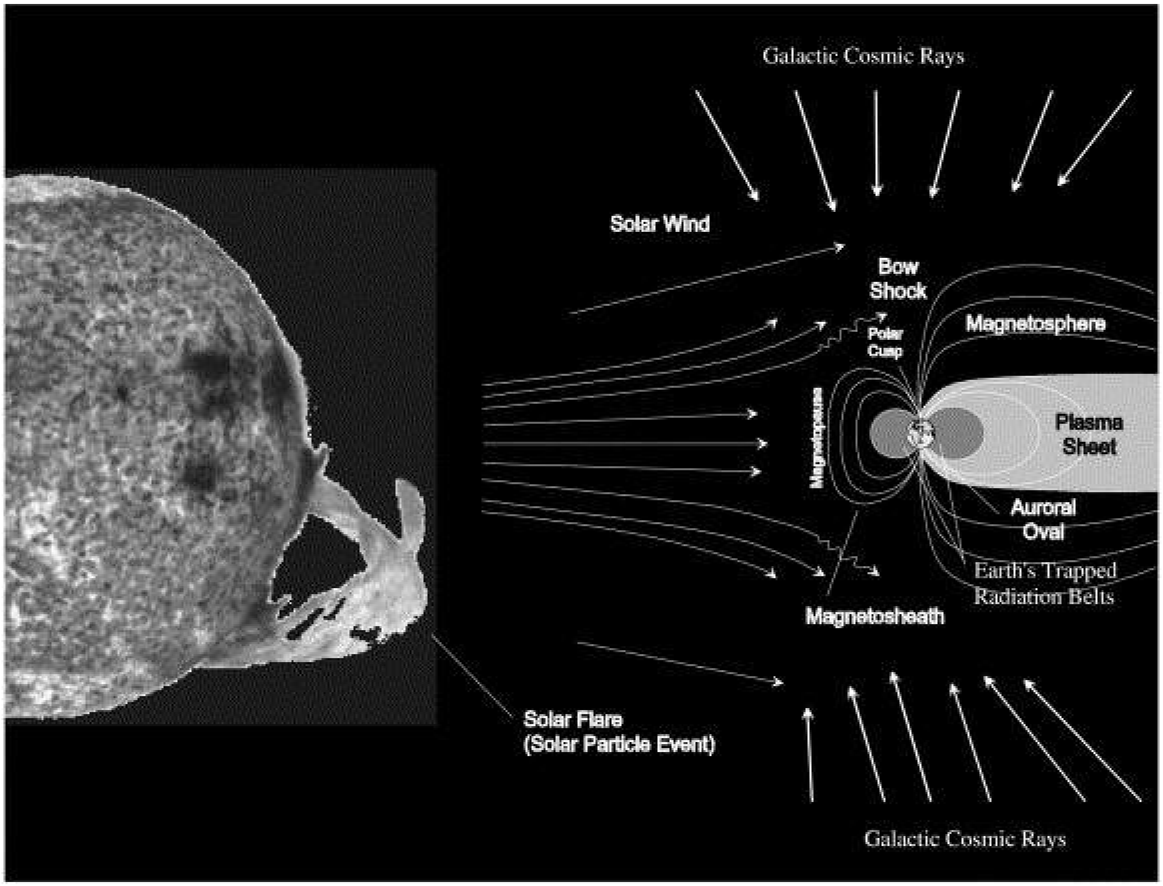
Solar particle events are acute events such as solar storms, coronal mass ejections (CMEs), and solar flares. These events mainly produce protons with kinetic energies below a few hundred MeV. These events are rare, yet quite hard to predict [12]. Solar particle events also consist of electrons and heavier nuclei [1]. General solar activity refers to the EM and particulate radiation constantly emitted by the sun, and the activity levels change over the course of an 11 year period of time known as the solar cycle. This cycle is coupled with a reversal of the sun's magnetic-field orientation. Solar maximum and solar minimum refer to the periods of time when general solar activity levels are higher and lower respectively [10]. The frequency of SPEs is proportional to sunspot activity, which also varies in adherence with general solar activity levels. Thus the SPE occurrences wax and wane with the solar cycle [2]. In addition, GCR intensity is shown to be inversely proportional to solar intensity during the 11-year cycle, decreasing by a factor of two during solar maximum. Note that the phase of the solar cycle, however, does not determine the intensity of the SPEs [2]. Figure 1 illustrates the positive correlation between sunspot activity and SPE occurrences.

Figure 1. Major SPEs in Conjunction with Sunspot Activity (in Sunspot Number) Since 1991 [2]



The Earth's magnetosphere is able to shield the earth and its atmosphere from the vast majority of the solar system's radiation environment, with small amounts able to penetrate [13]. By-products of collisions between this radiation and particles of earth's atmosphere produce high-energy subatomic particles which get trapped in orbit around the earth by earth's magnetosphere, known as the Van Allen Belts [13]. The inner belt consists mainly of high energy protons while the outer belt consists mainly of high-energy electrons [10].

Figure 2. An Illustration of the Van Allen Belt Regions as well as how GCR and Solar Energetic Particles are Deflected by Earth's Magnetosphere [11]



2.3 Dosimetry

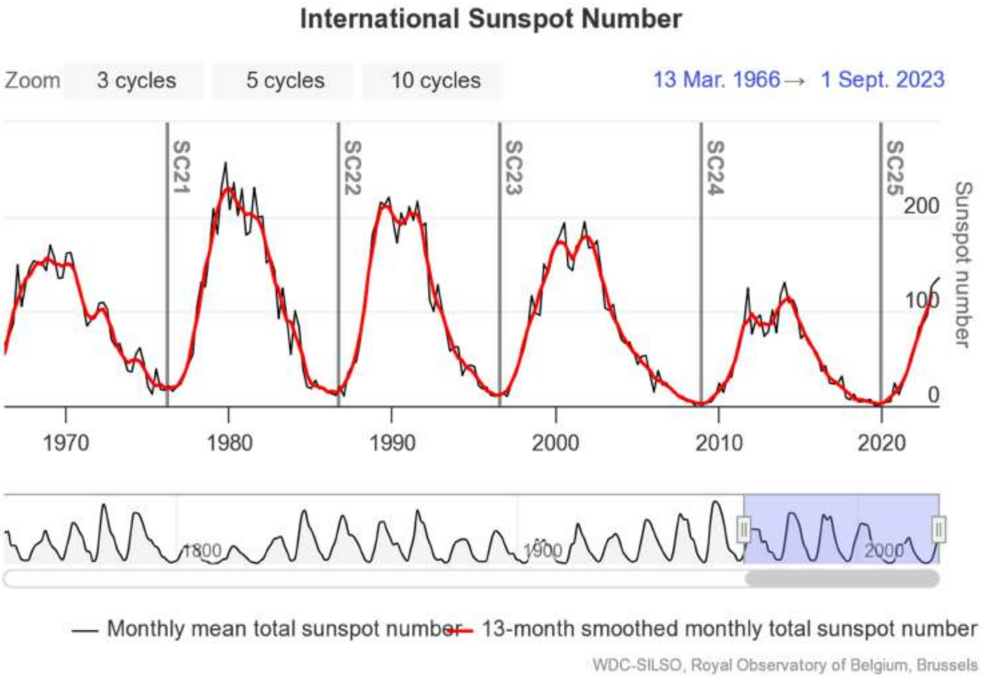
One way of measuring radiation exposure is with absorbed dose, which is the amount of radiation energy absorbed in a given amount of mass and commonly measured in rad or Gray (Gy). Note that 1 Gray is equal to 100 rad [13]. The "Dose Equivalent" parameter exists to account for the difference in harmful effects produced by equal absorbed doses of different kinds of radiation by representing the biological effect of a given dose [13]. Dose equivalent is measured in Sieverts (Sv), and dose equivalent is the main parameter of interest in this paper when it comes to measuring radiation exposure since the biological consequences of a given dose of radiation are the main concern. NASA's exposure limits for a 30-day space mission are: 1 Sv to the eye-lenses, 1.5 Sv to the skin, 0.25 Sv to the blood-forming organs (BFO), 0.25 Sv to the heart, and 0.5 Sv to the central-nervous-system (CNS) [10]. One millisievert (mSv) is approximately the exposure one would get from three chest x-rays [9]. The average dose-equivalent experienced by the astronauts during the Apollo 11-17 missions ranged from 5.4-108 mSv to the skin. Solar maximum GCR and Van Allen belt radiation are mainly what contributed to the exposure during these missions [13]. One of the most powerful SPEs on record occurred between the Apollo 16 and 17 missions in August of 1972. Calculations for the exposure levels of astronauts (had there been a mission at the time) to the August 1972 SPE suggest that astronauts would have been exposed to somewhere between 0.110-9.53 Sv to the skin, 0.101-3.83 Sv to the eyes, and 0.024-0.217 Sv to BFO [11]. The lower ends of those ranges correspond to if the astronauts were caught by the SPE during a space-walk (where the only shielding present is the spacesuit), and the higher end corresponds to if they were sheltered within the most densely shielded part of their spacecraft [11].

2.4 Radiation exposure concerns with the Artemis 3 Mission

NASA plans to launch the Artemis 3 moon mission in 2025; their first crewed mission to the moon since the Apollo 17 mission in 1972. The Artemis 3 mission is projected to be about four weeks in duration, where astronauts will land on the moon's surface to explore and conduct research on the south pole of the moon for roughly six days [14]. The Apollo missions in the 1960s and 1970s are the most similar past missions to the Artemis 3, so the radiation exposure risk to the astronauts during Artemis 3 is initially estimated based on exposure levels during the Apollo missions. However, radiation-exposure levels during the Apollo moon missions were quite low [13]. This is because there were no SPEs which occurred during the Apollo moon missions in the late 1960s and early 1970s, and the radiation exposure levels would have undoubtedly been higher had an SPE occurred [4]. As it stands, there is not sufficient evidence to suggest that radiation exposure will be an issue for the Artemis 3.

Although there were no SPEs which occurred during those Apollo moon missions, the later missions occurred during solar maximum (see Figure 3), and one of the most powerful SPEs on record occurred between the Apollo 16 and 17 missions in August of 1972 (as mentioned in section 2.3). Calculations for the exposure levels of the astronauts presented in section 2.3 suggest that the astronauts would likely have suffered from fatal acute radiation sickness [11]. Seeing as how the Artemis 3 moon mission scheduled for 2025 is projected to occur during a solar maximum (see Figure 3), insufficient radiation shielding poses life-threatening danger to the astronauts should a SPE occur. Therefore, SPEs are what ultimately justify the necessity for improved radiation shielding in this case.

Figure 3. Solar Activity (shown in sunspot number) vs Time from Late 1960s to Present [15]



2.5 Solutions and Criteria

A notable trend is that the smaller the nucleus of the shielding material, the better it is able to shield for a given material thickness [16]. Hydrogen is particularly effective at dealing with heavy ions from GCR, and stopping high-speed protons which are the main component of radiation found in SPEs [1]. Liquid hydrogen would then theoretically be one of the best choices of shielding material. This is also evident since NASA already has a patent on several implementations of liquid hydrogen for radiation shielding of spacecraft [7]. Among solid radiation-shielding materials, polyethylene is one of the most investigated since it has the highest hydrogen content among all polymers, and has already been certified for use aboard the International Space Station (ISS) [6]. Therefore, polyethylene and cryogenic liquid hydrogen are selected as second solutions.

The three criteria that will be used to evaluate the solutions are: weight of the material, shielding effectiveness against galactic cosmic radiation and shielding effectiveness during solar particle events. Even though the SPEs are what ultimately justify the need for a better shielding material, GCR still poses a notable risk to the astronauts. It follows that the effectiveness of each material relative to GCR and SPEs must be analyzed. The weight criterion is considered simply because the shielding must also weigh as little as possible to maintain the fuel efficiency of the spacecraft.

3. Analysis

3.1 Galactic Cosmic Radiation

To evaluate a material's performance against GCR, it suffices to evaluate its performance in space during solar minimum since that is when GCR intensity is the highest as discussed in section 2.2. The data presented in Figures 4, 5, 6 and 7 is based on computer simulations. These simulations assume that there is a human organ which is being shielded by one of the materials of interest under the specified solar-minima radiation conditions. The figures below present curves which illustrate dose equivalent experienced by the organ for a given thickness of the shielding material. Note that for the following figures, material thickness, depth, and areal density are all equivalent.

The data in Figure 4 was based on simulations of the GCR environment from the 2010 solar minima in the vicinity of the earth, but still outside the protection of Earth's magnetosphere [1]. The data presented in Figure 5 represents a simulation of the materials' performance on the lunar surface during the 1977 solar minima. Although Figure 5 presents dose equivalent for the skin particularly, Tripathi et al. [17] display similar curves relating dose equivalent to material thickness for most other organs as well, all showing similar results. In Figure 5, "Al 2219" represents aluminum.

Figure 4. Dose Equivalent versus Shielding Material Thickness during a Simulation of the 2010 Solar Minimum [1]

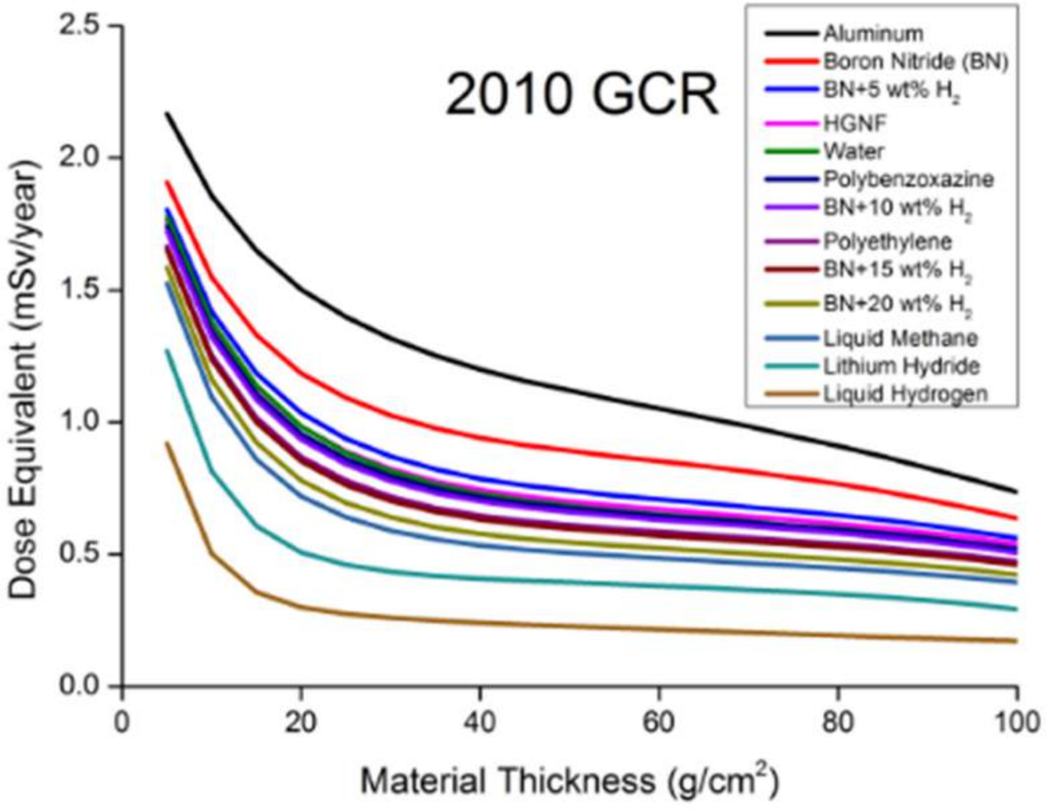
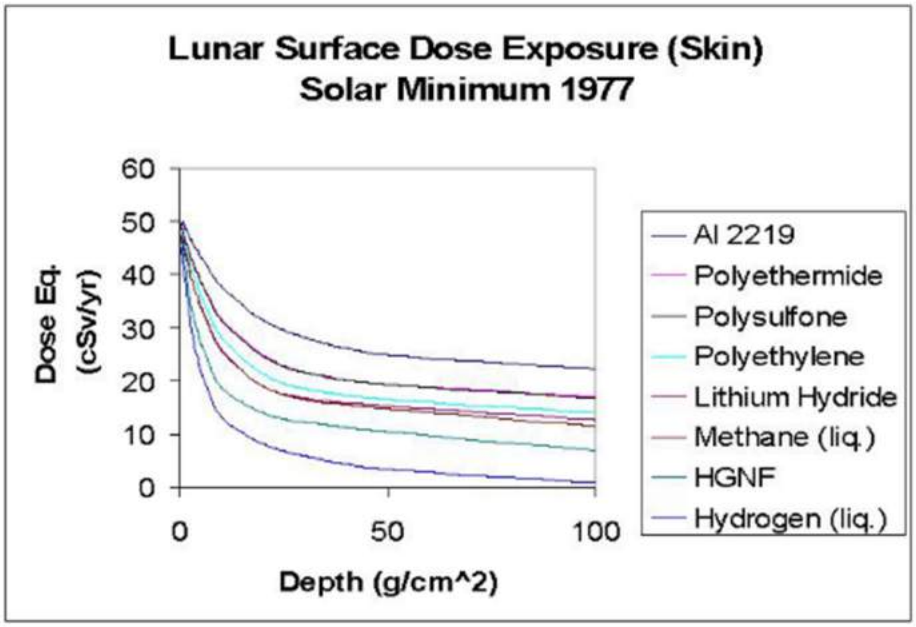


Figure 5. Dose Equivalent versus Shielding Material Thickness during a Simulation of 1997 Solar Minimum on the Lunar Surface [17]



The data presented in Figure 6 is from simulations of the GCR environment during a solar minimum in free space. In Figures 6 and 8, "MDPE" stands for "medium density polyethylene" and thus represents polyethylene [6]. Data presented in Figure 7 is from simulations of the 1997 GCR environment in free space [18]. In Figures 7 and 9, "LH_2" refers to liquid hydrogen and "PE" refers to polyethylene.

Figure 6. Dose Equivalent versus Shielding Material Thickness during a Simulated GCR Environment [6]

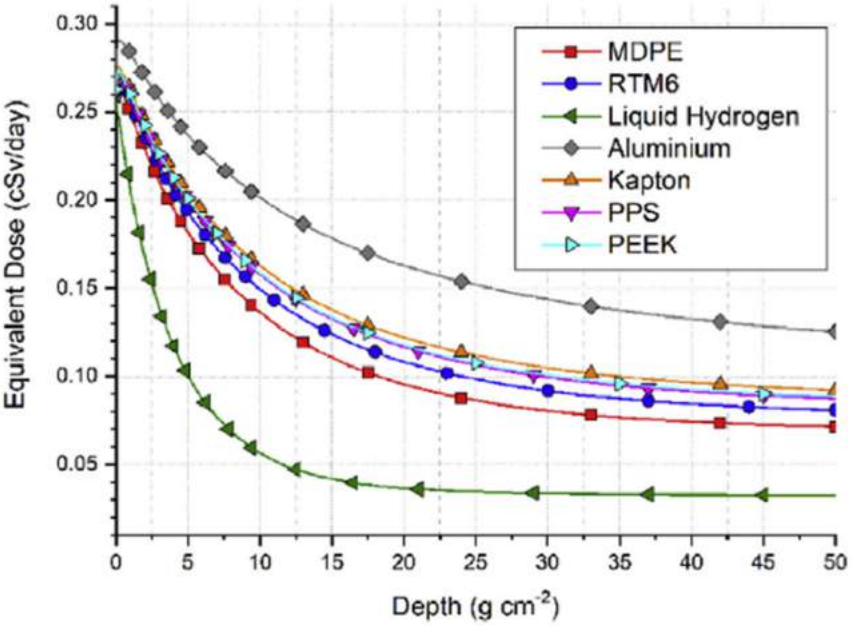
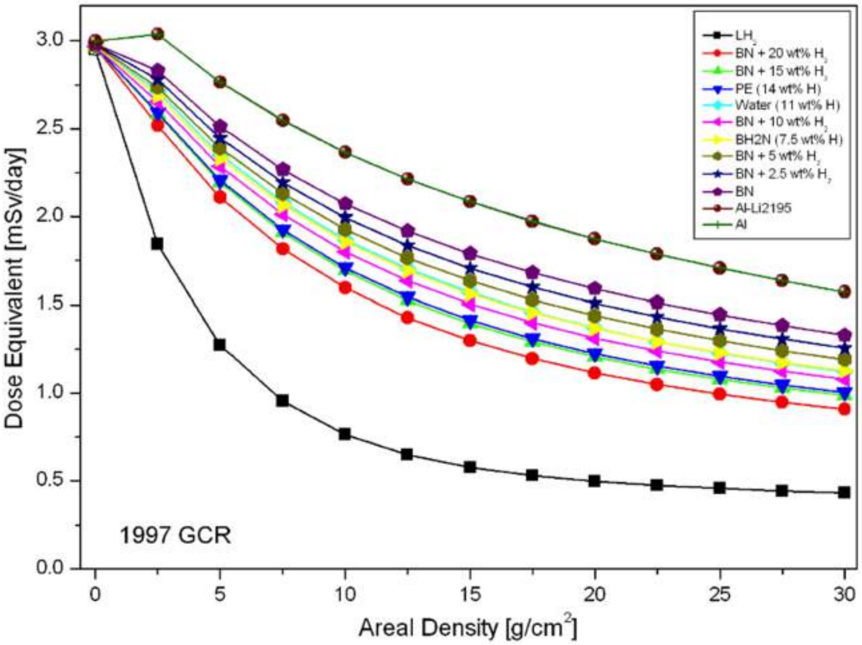


Figure 7. Dose Equivalent versus Shielding Material Thickness during a Simulated 1997 Solar Minimum Environment [18]



3.2 Solar Particle Events

The shielding effectiveness of the materials in question against solar particle events is also analyzed through simulations with the same method as in section 3.1, except the radiation environments considered are those during SPEs instead of solar minima. Table 1 and Figure 9 display effective dose versus material thickness [19], and dose equivalent versus material thickness [18] respectively during simulations of the August 1972 SPE in free space. Effective dose refers to the average dose equivalent experienced across different organs [19]. In Table 1, cSv refers to centisievert. The data from Figure 8 is derived from a simulation that reconstructed the Carrington event: a solar storm in 1859 considered the largest SPE occurring in modern civilization [6].

Table 1. Effective Dose versus Material Thickness during a Simulation of the 1972 SPE (adapted from [19])

	Effective Dose (cSv)		
X, g/cm^2	**Liquid Hydrogen**	**Polyethylene**	**Aluminum**
0	**354**	**354**	**354**
5	**11.9**	**43.7**	**66**
10	**1.9**	**13.4**	**24**
20	**0.2**	**3.15**	**6.3**

Figure 8. Dose Equivalent versus Material Thickness during a Simulation of the 1859 Carrington Event [6]

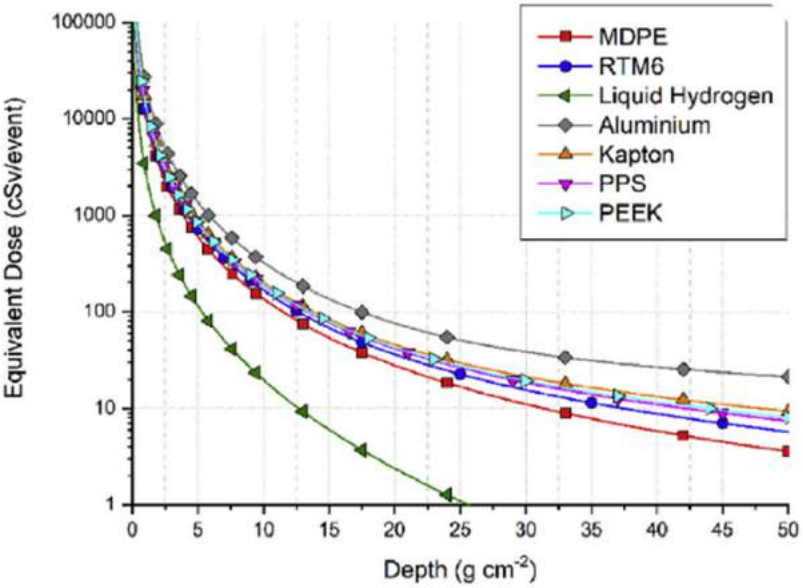
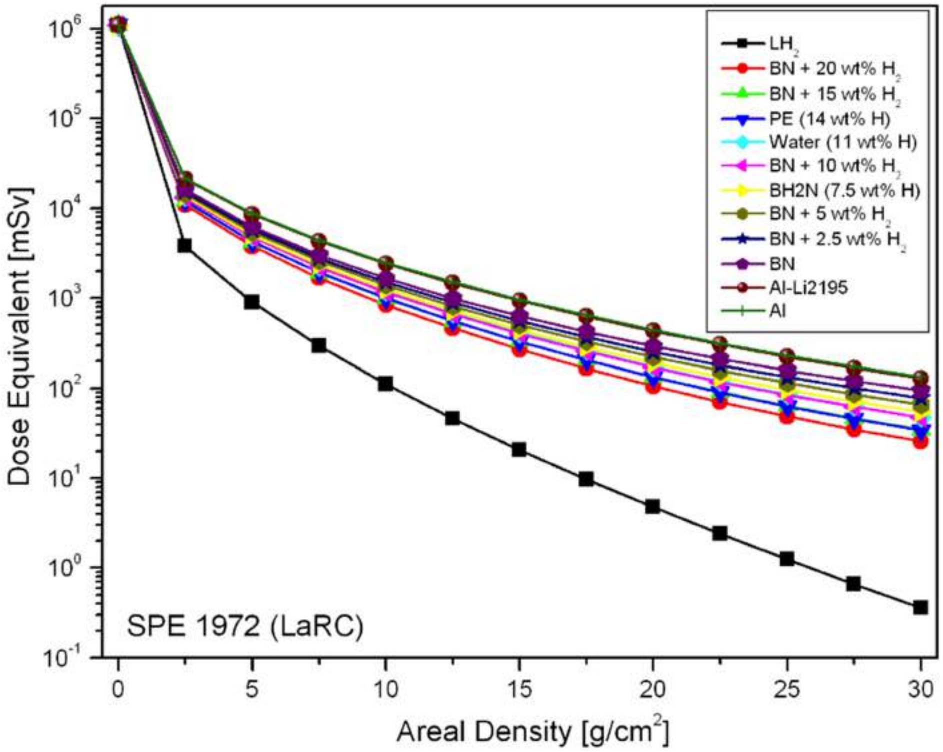


Figure 9. Dose Equivalent versus Material Thickness for a Simulation of the 1972 SPE [18]



3.3 Weight

Since liquid hydrogen will be kept in a tank at 20 K [7], its density is found to vary based on pressure conditions from approximately 72 kg/m^3 at 10 MPa to 81 kg/m^3 at 105 MPa [20]. The density of aluminum is approximately 2700 kg/m^3, and the density of polyethylene ranges from 910 to 960 kg/m^3 [21]. Since the previous data on radiation shielding shows that liquid hydrogen is already more effective for a given thickness, we can conclude that liquid hydrogen contributes less weight to the spacecraft. However, the hydrogen would be stored in a cryogenic tank inside the spacecraft, which will add notable weight [16]. Ultimately, the mass of the cryo-tank itself depends on its size, which in turn depends on how much liquid hydrogen is necessary for the mission. This can be determined by first calculating the desired thickness of shielding - denoted “T” in kg/m^2 – which ensures that radiation exposure is below permissible limits during the entire mission assuming an SPE occurs. Then the total surface area of the spacecraft which needs shielding must be calculated - denoted “SA” in m^2. Multiplying “T” by “SA” will yield the total mass of hydrogen that is needed. However, this analysis depends on too many other situation-specific parameters in practice (such as the exact implementation of liquid hydrogen shielding to be used), and is therefore beyond the scope of this paper.

4. Discussion

The data from the figures and tables of sections 3.1 and 3.2 illustrate that liquid hydrogen is the best at shielding from SPEs and GCR. The conclusion at the beginning of section 3.3 is resorted to (hesitantly but for simplicity), which reveals that liquid hydrogen shielding contributes less weight to the spacecraft. This is reasonable despite the mass of the cryo-tank playing a factor in practice since liquid hydrogen’s density is less than one tenth that of polyethylene, and is already significantly more effective at shielding for a given thickness as previously shown. These results produce the following decision matrix in Table 2.

Table 2. The Decision Matrix

Material	GCR shielding	SPE shielding	Weight
Polyethylene			
Liquid Hydrogen	+	+	+
Aluminum			

As criteria, shielding against GCR and SPEs were considered, but shielding against Van Allen belt radiation was not considered because Van Allen belt radiation does not practically present concerns during moon missions. NASA has been able to find the trajectory that avoids the thickest, most radioactive part of the belts, and determined the speed of the spacecraft which allows the astronauts to pass through the belts in the least amount of time. While the Van Allen belts are lethal, they can only pose significant health risks to the astronauts after a significant amount of exposure time [22].

Worth noting is that liquid hydrogen can also be used as a fuel for the spacecraft for a final burn. This dual use increases the overall effectiveness of liquid hydrogen by weight [7]. It should also be noted that liquid hydrogen is also a challenging material to implement because of production hardships and its flammability [23].

5. Limitations

Limitations to the analysis in this paper are mainly from two sources. The first is the accuracy of the simulations in predicting the effectiveness of the shielding materials of interest. Future study should be conducted with these materials physically to determine if the results reported in this paper can be repeated experimentally. The second is hinted to in section 3.3 where we conceded that more work must be done to deduce which solution contributes less weight to the spacecraft. Evidently, we don’t discuss the exact methods of implementation for liquid hydrogen and polyethylene shielding in this paper, and mostly refer to material properties alone to come to our conclusions. If we were to consider exact shielding implementations, other variables would arise that could influence the conclusion in this paper. It is particularly the sheer overwhelming data supporting liquid hydrogen as a superior shielding material which gives us confidence that there exists a practical implementation of it that will perform better against any possible implementation that uses solely polyethylene. Some implementations also use both materials, which we did not consider here.

6. Recommendations

This paper has evaluated polyethylene and liquid hydrogen against aluminum as shielding materials for a moon mission similar to the Artemis 3. The materials were compared by weight as well as their ability to shield from Galactic Cosmic Radiation and Solar Particle Events. The main purpose of this paper is to evaluate materials based on their radiation shielding effectiveness, and sections 3.1 and 3.2 illustrate that liquid hydrogen is significantly superior to polyethylene. In section 4 we tentatively concluded that liquid hydrogen also contributes less weight to the spacecraft. Ultimately, liquid hydrogen is the contender since it has better radiation shielding properties than polyethylene.

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