REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 1 (2024)
http://www.veterinaria.org
Article Received: 1/4/2024 Revised: 2/5/2024 Accepted: 30/5/2024

Effective Shielding Materials In High Energy Space Radiation Environment (GCR) For Free Space

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Abstract
In the demanding environment of deep space, space radiation poses a significant challenge for human space travel. A recent study introduces a multi-layered shielding approach to minimize exposure to trapped radiation, Solar Particle Events (SPE), and Galactic Cosmic Radiation (GCR). The study utilized a range of shielding materials, including aluminum (Al), HDPE, PMMA, $LiBH_4$, water, and LiH. By calculating the dose equivalent (DE) for each shielding material using the On-line Tool for the Assessment of Radiation In Space (OLTARIS) for the 2010 Solar minimum GCR, researchers determined that LiH outperformed other materials in reducing dose. Furthermore, constructing two combinations of multi-layered shielding materials (Al and shield material) with an areal density of 15 g/cm^2 led to effective dose measurements. Here combination of Al +LiH provide the reduced dose in the free space of GCR environment.

Keywords: GCR, SPE, Deep space, LiH, water, OLTARIS, Effective dose equivalent.

1. Introduction

Space radiation presents a significant challenge for space travel and exploration, threatening both human health and the functioning of electronic equipment. There are two primary types of space radiation: Solar Particle Events (SPE) and Galactic Cosmic Radiation (GCR) (Figure1). GCR is particularly concerning due to its composition of high-energy protons, alpha particles, electrons, and heavy ions with atomic numbers greater than 2. This radiation originates from outside our solar system and poses difficulties in terms of effective shielding. During periods of Solar Minimum, GCR can penetrate deeply into the solar system, increasing the risk it poses to astronauts and spacecraft. Researchers have been exploring various materials and methods to shield against GCR and SPE.

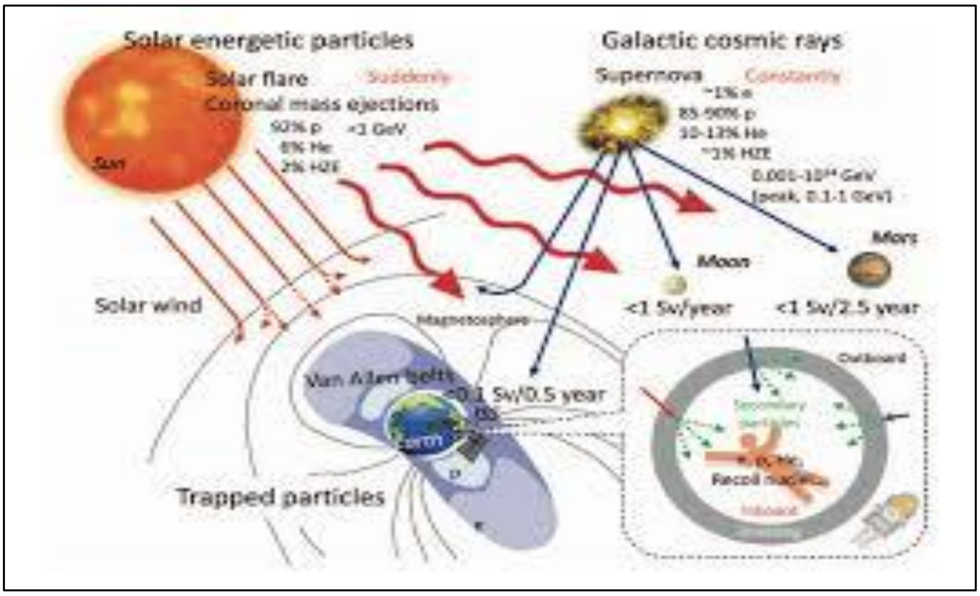

Figure 1: Space Radiation Environment in Free space.

One potential approach that shows promise is active shielding, although it is still in the early stages of development. Going back to the 1960s and early 1970s, scientists began investigating active radiation shielding methods, such as using electromagnetic fields, as an alternative to traditional passive material shielding. Some of these active shielding methods include electrostatic fields, plasma shields, and confined and unconfined magnetic fields. These methods aim to protect astronauts and spacecraft from the harmful effects of space radiation and are an important area of ongoing research and development for long-duration space missions.

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In the 1980s and 1990s, there was an increased focus on researching proton shielding and investigating active methods to protect against high-energy heavy-ion galactic cosmic rays (GCRs) [1]. Researchers discovered that elements with a high charge-to-mass ratio serve as the most effective shielding materials against high Z and E particles (HZE) [2, 3]. Moreover, it was found that mitigating radiation risks from neutrons, gamma rays, and x-rays is challenging in space, as it is not feasible to provide enough shielding material to fully absorb all forms of radiation. Additionally, the changing composition and energy of nuclei resulting from atomic and nuclear interactions influence the relative biological effectiveness of nuclei, and this effect varies with the depth of penetration [4]. The altering Linear Energy Transfer (LET) of each nucleus as it loses energy and slows down within the penetrated material further influences these factors.

Passive shielding designs for spacecraft play a critical role in ensuring the safety and functionality of space missions. These designs must fulfill several essential criteria to be effective. Ideally, they should be multipurpose, adaptable to different applications, cost-effective, non-toxic, durable, and capable of producing minimal secondary radiations [5]. One common material used for spacecraft shielding is aluminum. However, when exposed to galactic cosmic rays (GCR), aluminum can generate highly penetrating secondary radiations such as neutrons and ions. To address this issue, researchers are exploring the use of hydrogen as a promising element for spacecraft shielding. Hydrogen's lightness and high charge-to-mass ratio make it an attractive candidate. Not only does hydrogen effectively slow down GCR through direct ionization, but it also lacks neutrons in its nucleus, thereby preventing the production of secondary neutrons. While hydrogen is not typically used as a standalone structural material for spacecraft, it can be incorporated into other materials to enhance their shielding capabilities. For example, hydrogen can be integrated into structural materials such as water, polyethylene, lithium hydride, and hydrogen-stored boron nitride. Boron and nitrogen, found in hydrogen-stored boron nitride, have high neutron absorption capabilities, making this composite material effective for neutron shielding. In addition to hydrogen-based materials, polybenzoxazine is being explored as a potential candidate for spacecraft shielding [6]. Polybenzoxazine is a hydrogen-rich benzoxazine material known for its low viscosity and good shelf-life, making it a promising option for spacecraft shielding applications.

In a literature survey on radiation shielding materials, various substances such as Aluminum, Liquid Hydrogen, Polyethylene, Water, Liquid Methane, Lithium Hydride, HGNF, Polybenzoxazine, Carbon foam, low and high-density Carbon form, Silicon, Boron Nitride, Kevlar, and Zylon, among others, were recommended. According to Singleterry (2013), liquid hydrogen (number_1 g/cc) is not the most suitable shielding material for missions lasting over 225 days, unlike the favorable performance of water and polyethylene. However, increasing the density of liquid hydrogen to 1g/cc resulted in an improved shielding material compared to water, with polyethylene lasting over 1200 days. Furthermore, when the OLTARIS simulation was applied to the 1977 solar minimum GCR environment, liquid hydrogen demonstrated a significant reduction in dose equivalent compared to polyethylene, water, and aluminum. In experiments conducted at NASA's Space Radiation Laboratory, PE-infiltrated carbon forms, polymer fibers, and fiber-resin were exposed to high-energy O16 beams. Additionally, through OLTARIS simulations, it was determined that polyethylene provided better shielding than Kevlar and Zylon for the 1977 solar minimum GCR [7]. Materials containing hydrogen, boron, and nitrogen were found to be the most effective against GCR and SPE. For the 1997 solar minimum GCR, liquid hydrogen was identified as the top shielding material, followed by BN+20% hydrogen shielding material [8,9]. The dose equivalent of HGNF and Lithium Hydride shielding materials proved to be significantly better than polyethylene. Furthermore, compared to polyethylene, the hydrogen-rich benzoxazine material, polybenzoxazine, exhibits acceptable shielding capabilities [10]. Additionally, polymer and composite materials outperform aluminum as potential GCR shielding materials [11].

Over the years, extensive research has been conducted to estimate radiation doses for different types of space missions, including both crewed and robotic missions. Various studies have shown that cosmic rays contain a wide range of elements, with heavy nuclei being discovered in cosmic radiation over the past 45 years. The fragmentation of heavier nuclei leads to overabundances of "secondary" nuclei in cosmic rays, while elements with high initial ionization potential have decreased in abundance. Understanding the composition of galactic cosmic rays (GCR) is crucial for evaluating the risks associated with space radiation, and accurate measurement of the spectra of elements such as hydrogen, helium, carbon, oxygen, and iron is essential for this purpose. High energy protons and alpha particles in GCR have specific flux ranges, and materials such as aluminum and liquid hydrogen are used to minimize the effects of space radiation. Lithium hydride, with its high hydrogen content, is known for efficiently shielding secondary neutrons. The primary goal of radiation shielding is to optimize the stopping power for GCR ions while limiting the production of harmful secondary radiation and increasing the absorption of radiation, including neutrons. Multi-layered shielding, composed of materials with different atomic numbers (Z values), is employed to protect against radiation exposure.

2. **OLTARIS Simulation for High Energy Space Radiation in Free space:**

In this work, the simulation of Galactic Cosmic Radiation (GCR) are carried out at 1AU in free space.

a) Galactic Cosmic Rays in Free space

In our OLTARIS project [12], we deliberately chose to utilize the sphere geometry option to design the necessary setup meticulously. This decision was driven by the need to accurately capture the Galactic Cosmic Rays (GCR) spectrum in

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free space during the 2010 solar minimum event. To achieve this, we strategically employed the Badhwar O'Neill model [13], explicitly considering the MarsGram parameter at an elevation of 0.0 km. In this work, the results have been produced for a one-day mission. Our primary focus was calculating the precise, effective dose equivalent for a female adult voxel (FAX) phantom.

b) Geometry in Simulation

In this work, we simulate one geometry: sphere geometry consisting of two layers of thickness of 5g/cm^2 aluminium and a second layer of 10g/cm^2 of the chosen material. The table 1 shows the list of shielding materials.

S.No.	**Material Name**	**Chemical Formula**	**Density in g/cm^3**
1	Aluminium	Al	2.7
2	HDPE	C_2H_4	0.96
3	PMMA	$C_5H_8O_2$	1.18
4	Water	H_2O	1
5	Lithium Hydride	LiH	0.82
6	Lithium Borohydride	LiBH4	0.68

Table 1: List of shielding materials chosen.

3. Results

3.1 Effective Dose Equivalent

Figure 2 shows the effective dose equivalent for a radiation shield with a first layer of 5 g/cm^2 aluminium and a second layer of 10 g/cm^2 chosen material.

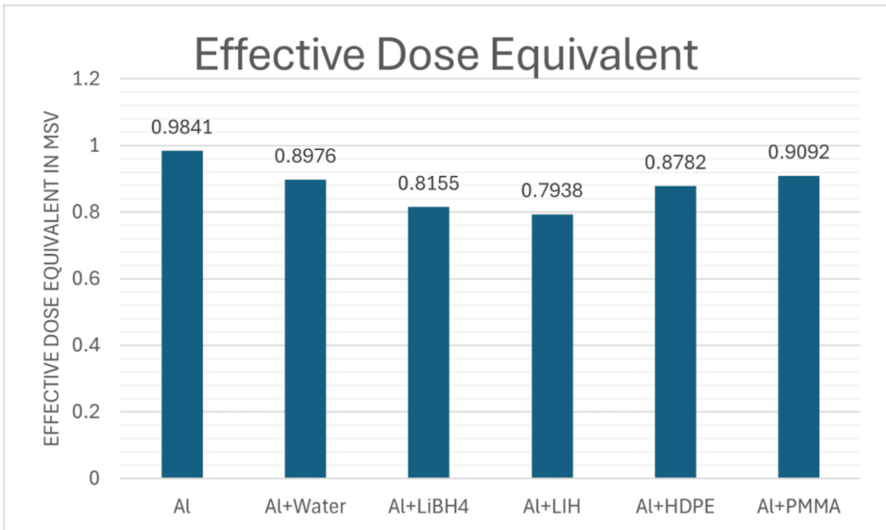

Figure 2: Effective dose equivalent for various shielding materials in combination with Al.

We observed that Al+ LiH produces the least dose. All the materials are more effective than a 15 g/cm^2 Aluminium shield.

3.2 Effective Dose Equivalent for various thickness of Shielding Material

Figure 3 shows the variation of effective dose equivalent produced by various shields with their second layer thickness varying from 0 to 10 g/cm^2.

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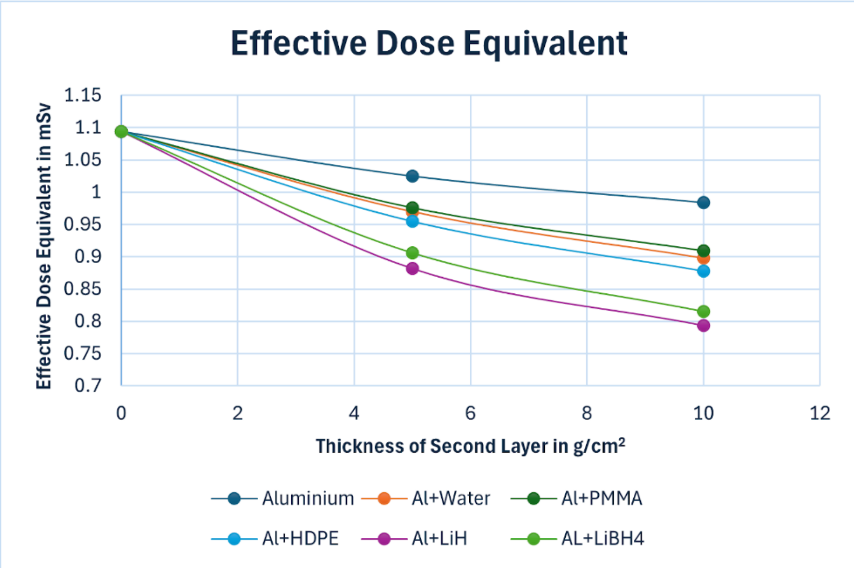

Figure 3: Effective dose equivalent for various shielding materials in combination with Al by varying the thickness of the material.

All the materials perform far better than an aluminium shield of the same thickness. Effectiveness of Al+water is similar to that of polymers. The inorganic compounds chosen transcend the effectiveness of polymers, too. Out of them LiH performs better. It's noteworthy that LiBH4 showed better effectiveness than LiH on Mar's surface [14].

3.3 **Average Dose Equivalent for Al+LiH**

Figure 4 shows the average dose equivalent in various organs produced by a shield of 5 g/cm^2 aluminium and 10 g/cm^2 LiH.

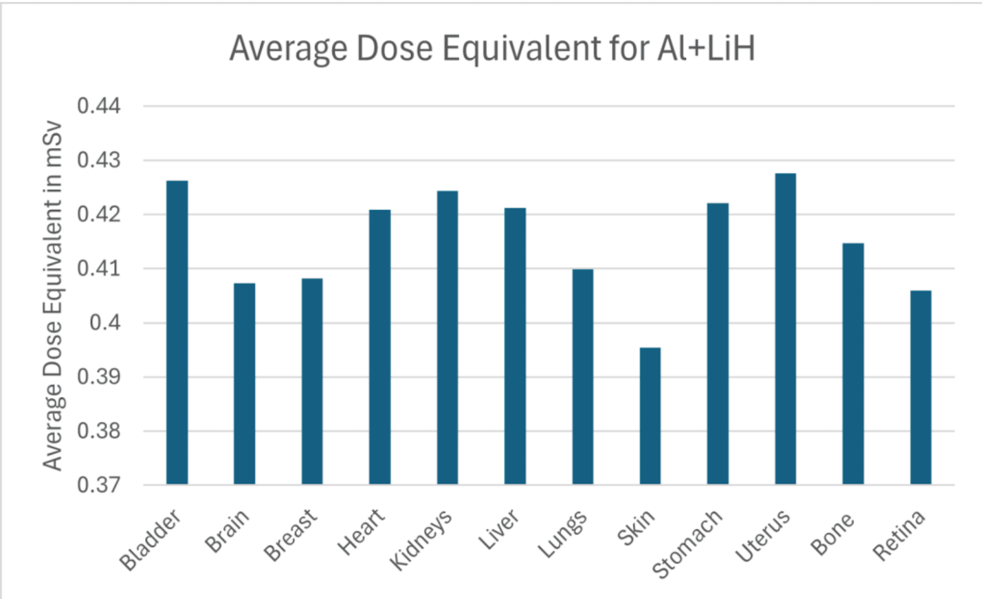

Figure 4: Average dose equivalent for Al+ LiH combination for various organs of Female Phantom.

We observed that in free space, the skin has less dose absorption as compared to another organ of the Female Phantom. More dose is absorbed in uterus and bladder. The dose absorbed in heart, kidneys, liver and stomach is also considerable.

3.4 Flux as a function of energy

Figure 5 shows the variation in flux of proton, neutron, alpha particle and iron with energy for Al+LiH shield in GCR free space environment.

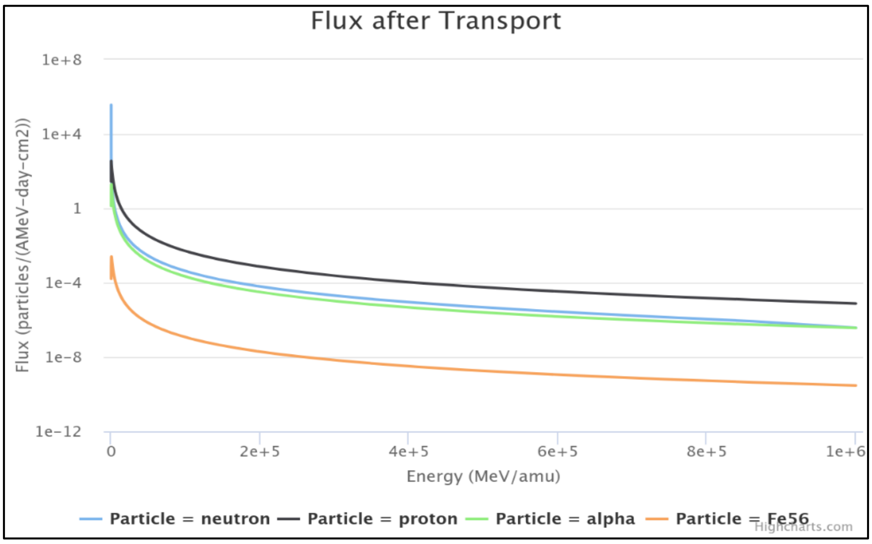

Figure 5: Flux vs energy of particles for proton, neutron, alpha and iron in Al _ LiH combination.

We observed that proton has higher flux than alpha, neutron and iron for higher energies. In addition, the curve for neutron and alpha has similar flux towards the higher energies. The iron has the least flux as compared to other particles.

4. Summary and Conclusion

We used the OLTARIS simulations in this study to calculate the dose equivalent and flux of multi-layered shielding materials in sphere geometry using the 2010 solar minimum GCR environment in free space. It is considered when the solar cycle is at a minimum, and GCR is at maximum. Multi-layered structures of the materials were analyzed to classify important relationships between them. The multi-layered Al+LiH significantly reduces the dose equivalent to the remaining materials.

5. Acknowledgments

We thank MNIT Jaipur for supporting the publications of this research work.

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