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Investigation of The Shielding Properties of Hydrides as a Shielding Material for Space Radiation Protection Using Geant 4 Montecarlo Simulation

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Abstract
Space radiation environment is composed of energetic particles which can deliver harmful doses of radiation that may lead to acute radiation sickness and even death for insufficiently shielded crew members. The process of space radiation shielding can play a key role in reducing the radiation encountered in deep space. This research investigated the shielding effectiveness of NH_3BH_3, $LiAlH_4$, PE, NH_3, $NaBH_4$, and MgH_2 as a function of stopping power. It also calculated the absorbed dose of the materials when exposed to ^{28}Si ions with energy levels of 1 GeV, and 2 GeV using Geant4 Monte Carlo Simulation. The energy levels are around the peak of the Galactic Cosmic Rays (GCR) energy spectrum. The attenuation of the incident particle is very high in materials with large hydrogen fraction. NH_3BH_3 having a hydrogen concentration of 19.63% provides good shielding effectiveness in the stopping power and the dose deposition parameter which makes it a better shielding material than the conventional material PE and other hydrides.

Keywords: Geant 4, Galatic Cosmic Rays (GCR), Solar Particle Events (SPE), stopping power, absorbed dose.

INTRODUCTION
Space radiation is made of three kinds of radiation: particles trapped in the Earth's magnetic field, particle that shot into the space during solar flares (solar particle event) and galactic cosmic rays. Space radiation is different from the kinds of radiation we experience here on Earth (NASA, 2017).

Space radiation in the solar system consist of Galactic cosmic rays (GCR) and solar particle event (SPE), space radiation is acknowledged to be a threat to human's health and also the spacecraft located in international space station (ISS). The station operates in Low Earth Orbit (LEO), therefore manned spacecraft are partly protected from cosmic rays and solar particle by the geomagnetic field (Naito *et al.,* 2021). Galactic cosmic rays spectrum mainly consists of charged particles. The nuclear component consists of 87% protons, 12% of α-particles and 1% heavier nuclei. (Naito *et al.,* 2020).

High atomic number and high energy (HZE) particles from He to Fe nuclei in GCRs increases radiation risks. HZE particles contribute substantially to the radiation dose due to high Linear

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Energy Transfer (LET) resulting in significant biological effects even if contribution of HZE particles to the GCR composition are small (Cucinotta, 2014).

The space radiation environment constitutes a substantial health concern for individuals engaged in space exploration, primarily characterized by the prevalence of galactic cosmic rays (GCRs) and solar energetic particles (SEPs). These radiation sources are universally recognized as the foremost threats to human well-being during space missions. While the geomagnetic field does offer partial protection to astronauts in Low-Earth Orbit (LEO), such as those aboard the International Space Station (ISS), forthcoming extended missions to destinations like the Moon, NASA's Deep Space Gateway, and Mars pose heightened radiation hazards due to the limited magnetic field in those regions. The radiation risks inherent to space are further accentuated by the presence of protons and high-energy particles with high atomic numbers (HZE particles) ranging from helium (He) to iron (Fe) nuclei, constituting integral components of galactic cosmic rays (GCRs) (Heinbockel *et al.*, 2006).

As asserted by Durante (2014), passive shielding emerges as a viable and pragmatic strategy for mitigating radiation hazards faced by space crews. Given the inherent technical challenges of completely arresting HZE (high atomic number and energy) particles within shielding materials, a practical approach involves the absorption of lower energy particles within the material and the subsequent fragmentation of HZE particles into lighter counterparts. This fragmentation effectively reduces their linear energy transfer (LET) and diminishes their contribution to the overall radiation dose.

METHODOLOGY

Shielding parameters

Stopping Power

Given a certain type of energetic particle and target material, stopping power is given by (L'Annunziata, 2003) as

$$S = \frac{dE}{dx} \tag{1}$$

Absorbed dose

The quantity absorbed dose has been defined to describe the quantity of radiation for all types of ionizing radiation, including charged and uncharged particles; all materials; and all energies. Absorbed dose is a measure of the biologically significant effects produced by ionizing radiation. The absorbed dose is given by

$$D = \frac{dE}{dm} \tag{2}$$

The unit of asorbed dose is Gray, abbreviated Gy (Ahmad *et al.*, 2022)

MATERIALS

The material for this study is motivated by their hydrogen-rich compositions and distinct physical and chemical properties, which offer varied potential for effective radiation shielding in space. Hydrogen-rich materials are particularly valued for space applications due to their high hydrogen content, which makes them effective at attenuating high-energy particles from Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE).

Table 1 List of materials and their properties

Materials	Chemical Formula	Density (gcm^{-3})	Hydrogen Concentration (%)
Polyethylene	PE	0.94	14.40
Lithium Aluminium Hydride	$LiAlH_4$	0.91	10.6
Sodium Borohydride	$NaBH_4$	1.07	10.7
Ammonia	NH_3	0.70	17.19
Magnesium hydride	MgH_2	1.45	7.67
Ammonia Borane	NH_3BH_3	0.74	19.63

NUMERICAL SIMULATION

Geant4 Monte Carlo simulation was used to investigate the radiation shielding properties of hydrides compared to the conventional material of PE by considering the stopping power and the absorbed dose of the materials. The radiation production and transport calculations were performed using the geant4 source code v10.05.p02 making use of the reference physics model "Shielding". To commence the simulation, the electromagnetic example (TESTEM5) was simulated utilizing the pre-existing default macros. These macros encompass a variety of parameters that can be adjusted as needed, the target materials, energy range, primary particle and material thickness were modified from the macro commands. To calculate the stopping power, the target material was modified using the macro file testem in det and setAbsMat. The energy levels of 100 MeV-2 GeV was modified in the macro files gun and write the energy with its unit in code /gun/energy 200 MeV. Additionally, the absorbed dose was calculated by modifying the thickness in testem setAbsThick in code /setAbsThick 5 cm from 0 to 40 cm for the primary particle (Si ion) that is been modified in gun-particle-ion 14 28 and for energy 1 GeV and 2 GeV in gun energy. For every target material, output data were equally essential and indispensable. The calculated values of the stopping power was stored in a designated file. Additionally, a concise documentation outlining the essential details was saved in the MAC FILE.

RESULTS AND DISCUSSION

Stopping Power

The stopping power calculated based on the simulations in Geant4 by projecting the incident ion (^{28}Si ion) against the selected materials are given in Table 3.1 along with the varying incident energies.

Table 2 Variation of Stopping power of the selected materials

Energy (Mev)	NH_3BH_3	$LiAlH_3$	NH_3	PE	$NaBH_4$	MgH_2
100	49610	49520	49300	46370	46200	32910
200	44860	44560	43260	41020	40980	27110
300	39640	39100	38090	36220	35920	23180
400	34930	34530	33930	32320	31220	20620
500	31640	30960	30560	29130	28930	18650
600	28980	28580	27780	26490	26310	17450
700	26810	26540	25450	24270	24120	15800
800	24960	24380	23480	22390	22260	14750
900	22910	22490	21790	20770	20660	13840
1000	21470	21010	20320	19370	19270	13050
1100	20100	19830	19030	18140	18050	12350
1200	18920	18290	17890	17060	16970	11740
1300	17570	17020	16890	16100	16020	11180
1400	16660	16210	16000	15250	15170	10690
1500	15870	15300	15200	14490	14410	10240
1600	14940	14490	14470	13800	13720	9828
1700	14010	13990	13820	13170	13100	9452

1800	13610	13410	13220	12600	12530	9108
1900	12920	12880	12680	12080	11910	8790
2000	12290	12230	12180	11600	11240	8497

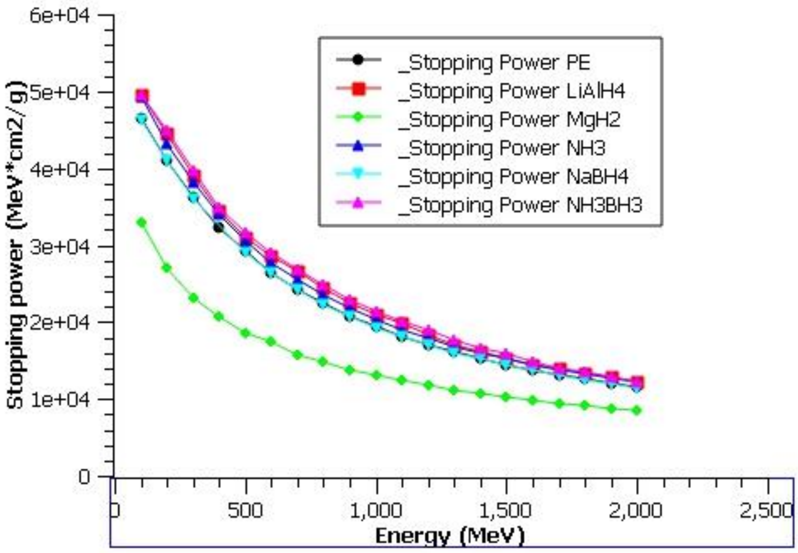

Fig 1: Variation of Stopping Power as a function of energy of each material for 100 MeV-2GeV

In Fig 1, the graphic representation illustrated the variations in stopping power when a mono-energetic pencil beam composed of ^{28}Si ions interacts with shielding materials within the energy range of 100 MeV to 2 GeV. As depicted in figure 1, The results, ranked from best to worst in shielding effectiveness, are as follows: NH_3BH_3 (Ammonia Borane), $LiAlH_4$ (Lithium Aluminum Hydride), NH_3 (Ammonia), PE (Polyethylene), $NaBH_4$ (Sodium Borohydride), and MgH_2 (Magnesium Hydride).

In the context of high-energy particle interaction, the phenomenon of energy dissipation while traversing materials is distinguished by a distinct energy dependence. At elevated initial energy levels, the rate of energy loss per unit distance traveled (dE/dx) remains relatively modest. Initially, high-energy particles encounter minimal energy reduction owing to their considerable kinetic energies. However, as they encounter the constituents of the material, such as electrons and nuclei, the energy loss amplifies. This interaction becomes increasingly pronounced as the particles decelerate and their energies align with the summit of the energy loss. As illustrated in figure 1, there is an observable declining trend in the stopping power as the incident energy increases.

NH_3BH_3 emerged as the most effective shielding material among the tested substances. Its superior performance can be attributed to its high hydrogen content and density, which are crucial factors in attenuating GCR radiation. Hydrogen-rich materials are known to be effective at reducing secondary neutron production, which is a significant concern in space radiation shielding. The boron content in NH_3BH_3 likely contributes additional neutron absorption, enhancing its overall shielding capability. The neutron absorption capability of boron, particularly its isotope ^{10}B, is well-documented for enhancing radiation shielding. Boron's ^{10}B isotope has a high neutron capture cross-section, meaning it can absorb neutrons effectively, thus reducing secondary neutron production, which is particularly valuable in space radiation shielding applications. (Zeitlin *et al.*, 2006). Studies confirm that materials incorporating boron are valuable in mixed radiation fields, as boron can capture low-energy neutrons through nuclear reactions such as $^{10}B(n,\alpha)^{7}Li$. This reaction releases an alpha particle and lithium, which can further attenuate radiation by absorbing neutron energy (Cucinotta *et al.,* 2015). $LiAlH_4$ was the second most effective material, slightly less effective than NH_3BH_3. NH_3 performed moderately well, ranking third. Its effectiveness can be attributed to the high hydrogen content, but the lack of lighter elements like boron or lithium reduces its ability to absorb secondary radiation, making it less effective than NH_3BH_3 and $LiAlH_4$. Polyethylene (PE), a conventional material widely used in space applications, ranked fourth. While PE is effective due to its high hydrogen content, the results suggest that it is outperformed by certain hydrides, particularly those containing elements like boron or lithium that enhance neutron absorption. Polyethylene has been used as a standard shielding material, as shown in studies by Cucinotta *et al*., (2015) and Guetersloh et al. (2006). While effective, PE's hydrogen concentration is lower than that of NH_3BH_3, and without neutron absorbers, it is outperformed by other materials such asNH_3BH_3, $LiAlH_4$ and NH_3. $NaBH_4$ showed less shielding effectiveness compared to the other hydrides, ranking just above MgH_2. The boron content provides some neutron absorption capability, but the lower hydrogen density and overall atomic composition seem to limit its effectiveness. Finally, MgH_2 ranked the lowest in shielding effectiveness the absence of elements that can capture secondary neutrons and low hydrogen concentration make it less effective compared to the other materials studied.

Overall, the results indicate that hydrides, particularly those containing boron or lithium, offer superior GCR radiation shielding compared to conventional materials like polyethylene. The high hydrogen content, combined with the presence of neutron-absorbing elements, is critical in enhancing the shielding effectiveness of these materials.

3.2 Absorbed dose

When assessing the effectiveness of materials for shielding against Galactic Cosmic Rays (GCR), the absorbed dose is a critical factor. Various materials, each with unique atomic compositions and densities, exhibit different levels of effectiveness in reducing the impact of GCR. The ranking of these materials from lowest to highest absorbed dose provides insight into their shielding capabilities, particularly for applications in space exploration where exposure to GCR is a significant concern.

Table 3 Comparison of Absorbed dose at 1 GeV

Thickness (cm)	**NH_3BH_3**	**$LiAlH_3$**	**NH_3**	**PE**	**$NaBH_4$**	**MgH_2**
0	0	0	0	0	0	0
5	2.289e-07	2.054e-07	1.704e-07	1.571e-07	1.105e-07	5.936e-08
10	1.144e-07	1.027e-07	8.522e-08	7.854e-08	5.525e-08	2.968e-08
15	7.629e-08	6.847e-08	5.681e-08	5.236e-08	3.683e-08	1.979e-08
20	5.722e-08	5.135e-08	4.261e-08	3.927e-08	2.762e-08	1.484e-08
25	4.578e-08	4.108e-08	3.409e-08	3.142e-08	2.21e-08	1.187e-08
30	3.815e-08	3.423e-08	2.841e-08	2.618e-08	1.842e-08	9.894e-09
35	3.27e-08	2.934e-08	2.435e-08	2.244e-08	1.578e-08	8.48e-09
40	2.861e-08	2.568e-08	2.131e-08	1.963e-08	1.381e-08	7.42e-09

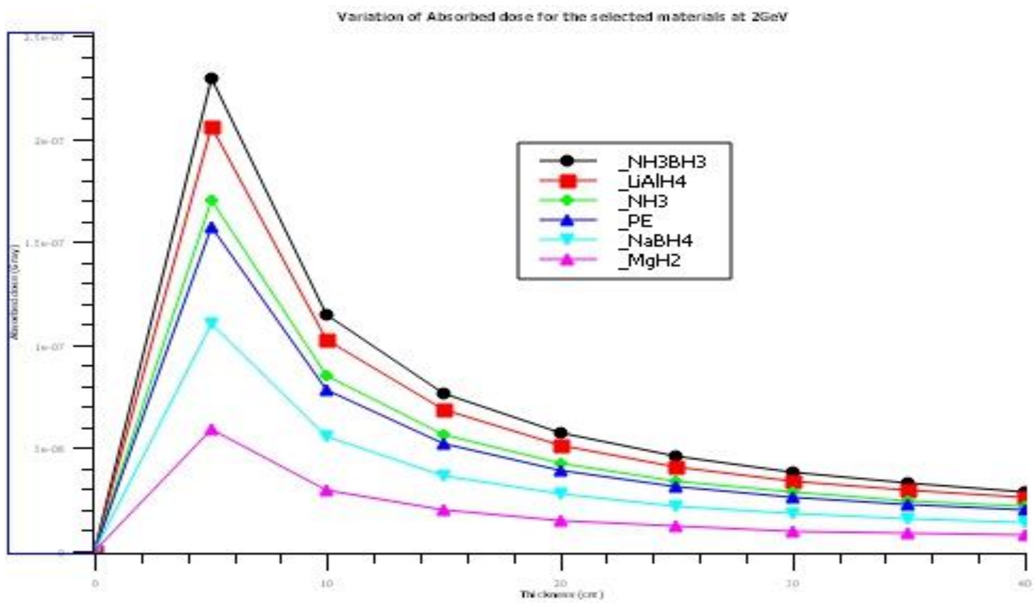

Fig 2 Variation of Absorbed Dose as a function of the thickness of all the materials at 1 GeV

Table 4 Comparison of Absorbed dose at 2 GeV

Thickness (cm)	NH_3BH_3	$LiAlH_3$	NH_3	PE	$NaBH_4$	MgH_2
0	0	0	0	0	0	0
5	4.578e-07	4.108e-07	3.142e-07	3.409e-07	2.21e-07	5.936e-08
10	2.289e-07	2.054e-07	1.571e-07	1.704e-07	1.105e-07	2.968e-08
15	1.526e-07	1.369e-07	1.047e-07	1.136e-07	7.366e-08	1.979e-08
20	1.144e-07	1.027e-07	7.854e-08	8.522e-08	5.525e-08	1.484e-08
25	9.155e-08	8.216e-08	6.283e-08	6.818e-08	4.42e-08	1.187e-08
30	7.629e-08	6.847e-08	5.236e-08	5.681e-08	3.683e-08	9.894e-09
35	6.539e-08	5.869e-08	4.488e-08	4.87e-08	3.157e-08	8.48e-09
40	5.722e-08	5.135e-08	3.927e-08	4.261e-08	2.762e-08	7.874e-09

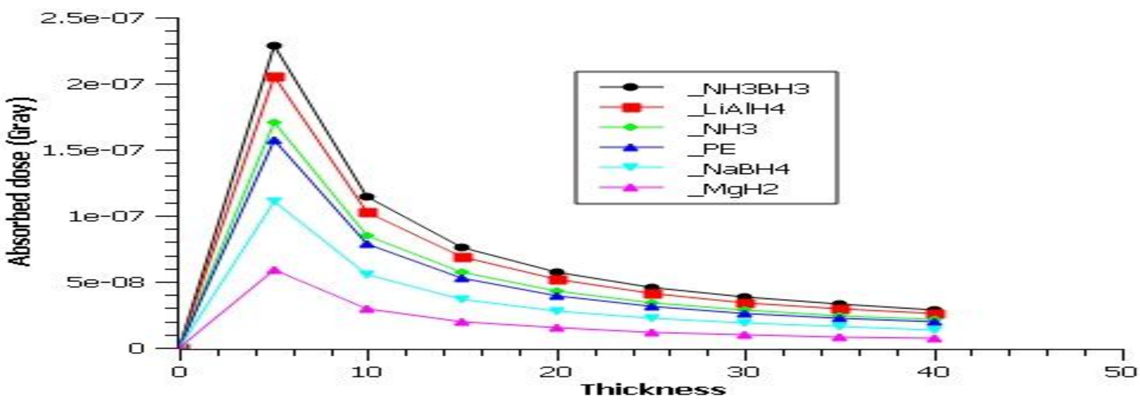

Fig 3 Variation of Absorbed Dose as a function of the thickness of all the materials at 2 GeV

This result confirms that NH_3BH_3 is highly effective in shielding against GCR. Its effectiveness is primarily due to its high hydrogen content, which is critical for slowing down and absorbing cosmic rays. The boron atoms in the compound may also contribute to neutron absorption, further enhancing its shielding properties. $LiAlH_4$ follows closely behind NH_3BH_3, which is consistent with expectations.NH_3 ranks third, indicating that while it has a decent hydrogen content, its lower density compared to the hydrides reduces its overall effectiveness. While PE is a good shield, especially considering its practicality and ease of use, the hydrides and ammonia outperform it due to their optimized combination of high hydrogen content, favorable density, and lighter atomic structure. The presence of heavier elements like sodium in $NaBH_4$ reduces its effectiveness as a GCR shield. MgH_2 is the least effective material in this group.

CONCLUSION

This study thoroughly evaluated the Galactic Cosmic Ray (GCR) radiation shielding properties of various hydrides in comparison to the conventional material, polyethylene (PE), using Si-28 ion interactions as a model. The analysis focused on key parameters such as stopping power and absorbed dose, both crucial in assessing the effectiveness of these materials in space radiation shielding.

The results demonstrated that hydrides, particularly NH_3BH_3 (Ammonia Borane) and $LiAlH_4$ (Lithium Aluminum Hydride), significantly outperformed polyethylene in terms of both stopping power and absorbed. NH_3BH_3, in particular, emerged as the most effective shielding material, largely attributed to its optimal composition for attenuating high-energy particles. Overall, the findings suggest that advanced hydride materials, especially those containing boron or lithium, hold significant potential for improving radiation protection in space environments. These materials could offer enhanced safety for astronauts and equipment by providing superior shielding against harmful cosmic radiation compared to conventional materials like polyethylene. Further research and development of these hydrides could lead to more effective and lightweight shielding solutions for future space missions.

REFERENCES

Ahmad, I., Abdullahi, M.M., Musa, A. (2022). Simulation of material properties for effective space radiation shielding using Geant 4. *Bayero journal of Physics and Mathematical* Sciences *13(1):* 191-198

Cucinotta, F. A. (2014). Space Radiation Risks for Astronauts on Multiple International Space Station Missions. *PLOS ONE* 9(4), 16–23. https://doi.org/10.1371/journal.pone.0096099

Cucinotta, F. A. (2015). A new approach to reduce uncertainties in space radiation cancer risk predictions. *PLOS ONE, 10*(3), e0120717. https://doi.org/10.1371/journal.pone.0120717

Durante, M. (2014). Space radiation protection: Destination Mars. *Life Sciences in Space Research,* 1(1), 2–9. https://doi.org/10.1016/j.lssr.2014.01.002

Guetersloh, S., Zeitlin, C., Heilbronn, L., Miller, J., Komiyama, T., Fukumura, A., Iwata, Y., Murakami, T., & Bhattacharya, M. (2016). Polyethylene as a radiation shielding standard in simulated cosmic-ray environments. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 252*(2), 319-332. https://doi.org/10.1016/j.nimb.2006.08.019

Heinbockel, J. H., Wilson, J. W., Blattnig, S. R., Qualls, G. D., Badavi, F. F., & Cucinotta, F. A. (2006). HZE ion fragmentation cross-section sensitivity and propagated errors in HZE exposure estimates. *Radiation Measurements, 41*(9–10), 1103–1114. https://doi.org/10.1016/j.radmeas.2006.02.002

L'annunziata, M. F. (2003). Nuclear radiation, its interaction with matter and radioisotope decay. *Handbook of Radioactivity Analysis, 1–121.* doi:10.1016/b978-012436603-9/50006-5

Naito, M., Kitamura, H., Koike, M., Kusano, H., & Kusumoto, T. (2021). Applicability of composite materials for space radiation shielding of spacecraft. *Life Sciences in Space Research*, 31(April), 71–79. https://doi.org/10.1016/j.lssr.2021.08.004

Naito, M., Kodaira, S., Ogawara, R., Tobita, K., Someya, Y., Kusumoto, T., Kusano, H., Kitamura, H., Koike, M., Uchihori, Y., Yamanaka, M., Mikoshiba, R., Endo, T., Kiyono, N., Hagiwara, Y., Kodama, H., Matsuo, S., Takami, Y., Sato, T., & Orimo, S.(2020). Investigation of shielding material properties for effective space radiation protection. *Life Sciences in Space Research*, 26(May), 69–76. https://doi.org/10.1016/j.lssr.2020.05.001

NASA. (2017, April 13). *Why Space Radiation Matters - NASA*. NASA. https://www.nasa.gov/missions/analog-field-testing/why-space-radiation-matters/

Origins, Predictability, and Consequences. Elsevier Inc. https://doi.org/10.1016/B978-0-12812700-1.00017-0