Comparative Simulation of Boron Nitride and Aluminum Shielding Effectiveness against Galactic Cosmic Rays in Free Space

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Abstract

OLTARIS simulations were used to examine how effectively various shielding materials, such as Aluminium and Boron Nitride, protect against deep space radiation, or Galactic Cosmic Rays (GCRs), in different space environments, namely Free Space, Lunar Surface and Martian Surface [1] .As we venture deeper into space, radiation poses a significant concern for both mission sustainability and astronaut safety. While Earth is protected by its magnetic field and dense atmosphere, deep space exposes humans to high levels of ionizing radiation from galactic cosmic rays (GCRs) and solar particle events (SPEs). Unlike, Aluminium (Al), Boron nitride (BN) has emerged as a promising alternative due to its low atomic number, superior thermal stability, and effective radiation attenuation, while also generating fewer secondary particles under high-energy exposure. Its low mass further enables the design of lighter structural materials, making it highly suitable for space applications. [2]

Despite being indirectly ionizing, neutrons can interact with biological tissue nuclei to create secondary charged particles like recoil protons and heavy ions. Because of their high linear energy transfer (LET), these secondaries have the potential to inflict serious biological injury, including cellular dysfunction and DNA double-strand breaks [3].

Keywords

nucleons; nuclei; magnetosphere; radiation; dose; dose equivalent; flux; nuclear fragmentation; high-energy particles; dose equivalent; differential flux; areal density; shielding efficiency; secondary radiation; space radiation transport; deep space missions

Abbreviations

Al – Aluminium; BN – Boron Nitride; CME – Coronal Mass Ejection; GCRs – Galactic Cosmic Rays; SPEs – Solar Particle Events; LEO – Low Earth Orbit; Al – Aluminium; BN – Boron Nitride; LET – Linear Energy Transfer; SEPs – Solar Energetic Particles; ISS - International Space Station; HZE – high atomic number and high energy

Introduction

The International Space Station (ISS) currently serves as a hub for manned space exploration, with missions soon extending to the Moon and beyond. Astronauts aboard the ISS are exposed to space radiation, which includes highly charged, energetic particles capable of causing significant biological and technological harm. Situated in LEO, the ISS benefits from the protective influence of Earth's geomagnetic field, which offers substantial shielding against Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs). However, beyond LEO, this magnetic protection is greatly diminished or absent, resulting in a far more hostile and challenging radiation environment for future deep space missions. [1] Radiation hazards in space are significantly influenced by protons and high atomic number, high energy (HZE) particles—ranging from helium (He) to iron (Fe) nuclei—found in galactic cosmic rays (GCRs). While protons constitute the majority of GCRs (approximately 87%), it is the HZE particles, with their high linear energy transfer (LET) and substantial biological impact, that contribute disproportionately to the overall radiation dose. These particles pose a considerable threat to both human health and spacecraft systems during long-duration space missions. Radiation shielding is one of the key strategies being explored to protect crew members from harmful space radiation. [4]

To optimize shielding strategies for future space missions, this review examines key factors such as the relationship between dose equivalent and areal density, as well as the flux of various particle types as a function of kinetic energy. The first section outlines the simulation platform used to generate the required data, while the second presents and discusses the resulting findings and their implications for spacecraft radiation protection.

Radiation Environment in Space

In deep space, the radiation environment is dominated by galactic cosmic rays (GCRs) and solar particle events (SPEs), both of which contribute significantly to long-term exposure risks. GCRs consist of high-energy nuclei—mostly protons, but also heavier ions such as helium, carbon, and iron (Fe^{56})—that originate from outside the solar system. SPEs, on the other hand, are sporadic bursts of energetic particles emitted by the Sun, especially during solar flares and coronal mass ejections.

Unlike in low Earth orbit, where Earth's magnetic field offers partial protection, spacecraft beyond LEO is directly exposed to these high-energy particles. The result is a complex radiation field capable of damaging biological tissue and degrading electronic systems. Particularly concerning are the high atomic number and high energy (HZE) particles, which can penetrate shielding and create secondary radiation, such as neutrons and heavy recoils, upon collision with spacecraft materials.

These conditions make radiation shielding a critical aspect of mission design. An ideal shielding material must be effective across a wide energy range, limit the production of biologically harmful secondaries, and remain lightweight to meet structural constraints. Therefore, understanding how different materials perform under GCR conditions—especially for primary particles like protons, alpha particles, and Fe^{56}—is essential to enabling safer long-duration space missions.

Materials and Methods

Materials

The dose equivalent was calculated using shielding materials with areal densities ranging from 5 to 15 g/cm². Boron Nitride (BN, 2.1 g/cm³) and Aluminium (Al, 2.7 g/cm³) were among the materials analyzed due to their relevance in spacecraft construction. BN was specifically considered for its lower secondary particle production and better attenuation properties compared to Al as discussed earlier.

Additionally, the particle flux as a function of kinetic energy was examined for protons, alpha particles, and iron-56 (Fe^{56}) nuclei. These particles were selected to represent the primary components of the space radiation environment, covering a broad spectrum of energies and biological impact. Together, these analyses offer insights into the effectiveness of various shielding materials under realistic space radiation conditions.

Simulation Platform

The OnLine Tool for the Assessment of Radiation In Space (OLTARIS) is a web-based simulation platform developed by NASA to evaluate the impact of space radiation. It is widely used to assess radiation effects on various mission components, including electronics, spacesuits, habitats, and spacecraft structures.

OLTARIS is composed of two key components: a web interface and a computational execution environment. OLTARIS enables simulations of radiation exposure scenarios involving solar particle events (SPEs) and galactic cosmic rays (GCRs). It employs the High Charge and Energy Transport (HZETRN) algorithm for accurate modelling of radiation transport through shielding materials. To simulate a realistic deep-space environment, the BON2020 model was applied, representing GCR spectra under solar minimum conditions (φ = 400 MV), when radiation intensity is typically highest.

The simulation considered exposure to protons, alpha particles, and iron-56 (Fe^{56}) nuclei—particles that dominate the GCR spectrum and contribute significantly to biological dose. Key output parameters included dose equivalent (based on ICRP 60 recommendations), differential particle flux versus kinetic energy, and tissue dose. In this study, the target was defined as human tissue, enabling biologically relevant interpretation of the shielding results, although OLTARIS also allows simulations for silicon, which is useful for assessing impacts on electronic components.

Designed with modern software techniques and user-defined flexibility, OLTARIS offers a high degree of accuracy and adaptability for evaluating shielding strategies and mission planning under varying space radiation conditions. [2]

Simulation Geometry

In this study, shielding performance was assessed using a spherical geometry to better represent the isotropic nature of cosmic radiation exposure. Simulations were conducted for total shielding thicknesses of 5, 10, and 15 g/cm². Aluminum (Al) and boron nitride (BN) were selected as candidate materials, and each configuration was modeled using both OLTARIS and HZETRN transport codes. For practical interpretation, 10 g/cm² of aluminum corresponds to approximately 3.7 cm in physical thickness, while the same areal density of boron nitride corresponds to about 4.8 cm, based on its typical density of 2.1 g/cm³. The chosen thickness levels enabled evaluation of how dose equivalent varies with increasing areal density. Comparative results from OLTARIS and HZETRN were analyzed to assess consistency between the transport models.

Results & Discussions

Dose Equivalent Analysis

Simulations were performed using OLTARIS to evaluate the shielding effectiveness of aluminum (Al) and boron nitride (BN) in a free space environment, focusing on how radiation exposure varies with increasing material thickness. The results, presented in Figure 1, show the dose equivalent for both materials plotted against areal density.

The dose equivalent (measured in sieverts, Sv) quantifies the biological impact of ionizing radiation by combining the absorbed dose with a radiation weighting factor, which accounts for the type and energy of the incident radiation. Areal density (g/cm²) represents the mass of shielding material per unit area, calculated as the product of a material's physical thickness and density. It serves as a key parameter in evaluating shielding performance, especially in the context of space missions where mass efficiency is critical.

At an areal density of 0 g/cm², both aluminum (Al) and boron nitride (BN) exhibit nearly identical dose equivalent values, representing unshielded exposure to galactic cosmic rays (GCRs). As areal density increases, BN consistently demonstrates a steeper decline in dose equivalent compared to Al, indicating superior attenuation of ionizing radiation. A slight rise in Al's curve at low densities may suggest the generation of secondary radiation, such as neutrons or nuclear fragments, resulting from interactions with high-energy particles.

Throughout the studied range (up to 15 g/cm²), the gap between BN and Al steadily widens, with BN maintaining significantly lower dose equivalent values at each increment. This trend highlights BN's higher shielding efficiency per unit mass, underscoring its potential as a more effective and lightweight material for space radiation protection—particularly in missions where both mass constraints and biological safety are of critical importance.

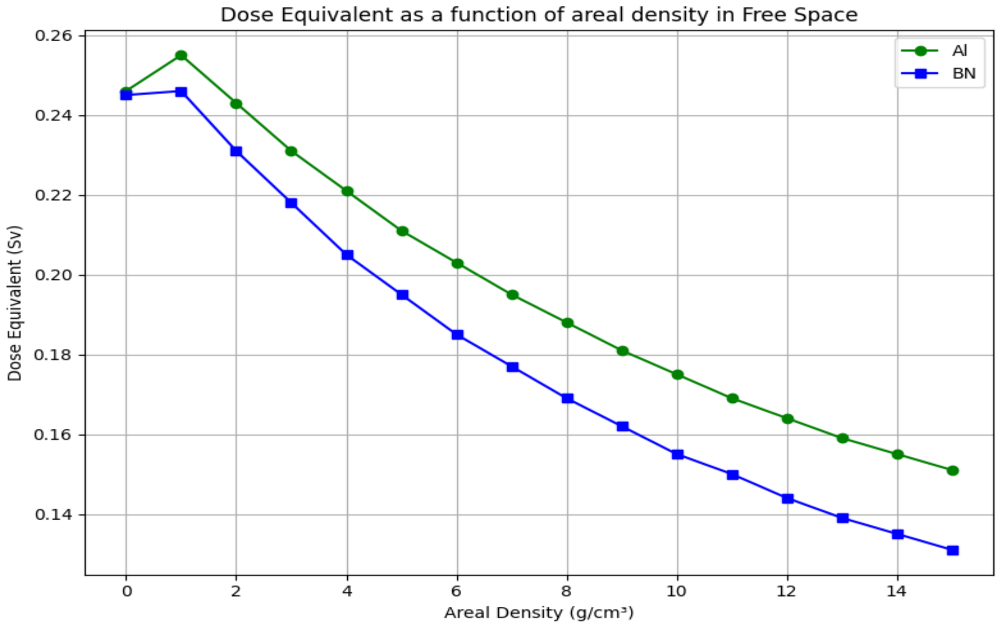


Figure 1: Dose Equivalent v/s Areal Density

Particle Flux Analysis

Beyond integrated dose metrics, analyzing the differential flux of individual galactic cosmic ray (GCR) components—protons, alpha particles, and iron-56 (Fe^{56})—provides a particle-resolved view of shielding performance. Since each particle type interacts differently with matter based on its charge, mass, and energy, this spectral analysis helps reveal how effectively different materials attenuate incoming radiation across a wide energy range. Understanding how these particles propagate through shielding not only refines estimates of radiation risk but also sheds light on the energy-dependent behaviour of transmitted and secondary radiation—both crucial for optimizing material selection in future space missions.

Overall, the differential flux analysis aligns with dose equivalent results, reaffirming that BN exhibits superior shielding performance across the energy spectrum, with notable effectiveness in the biologically significant low- to mid-energy ranges.

Proton Flux Analysis

As shown in Figure 2, the differential flux of protons after transport through aluminum (Al) and boron nitride (BN) was evaluated over a wide kinetic energy range. Both materials follow similar overall spectral trends; however, BN consistently exhibits lower proton flux, particularly in the low-energy region. This suggests that BN more effectively attenuates low-energy protons, which are of greater biological significance due to their high linear energy transfer (LET) and ionizing potential.

In the moderate energy range, where the flux reaches its peak, the curves for BN and Al begin to converge, although BN continues to maintain a slight advantage. This indicates enhanced shielding capability even for mid-energy protons. The peak corresponds to the energy window where most transmitted protons emerge post-shielding.

At higher energies, both materials demonstrate a rapid decrease in proton flux, with minimal distinction between them. This is expected, as very high-energy protons are more penetrating, making them harder to shield regardless of material.

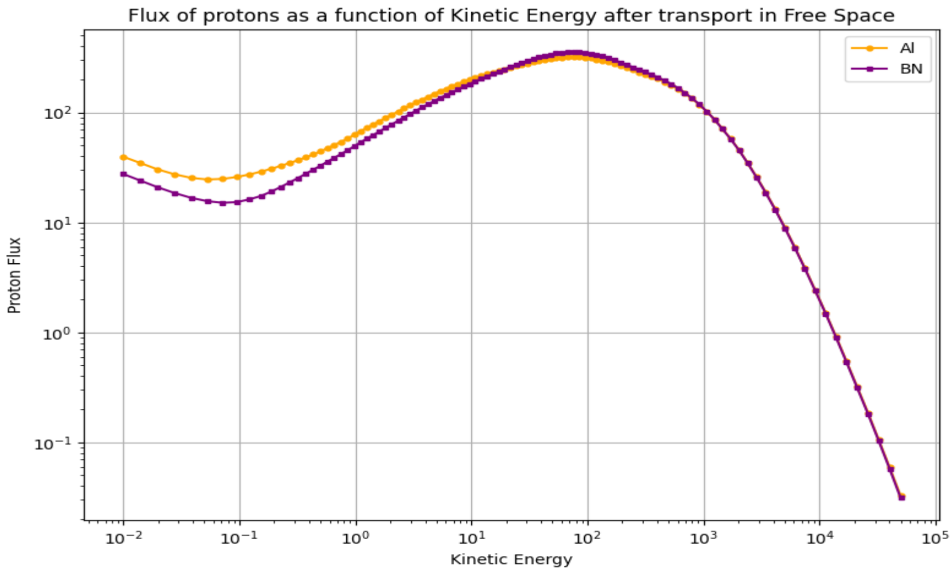


Figure 2: Proton Flux v/s Kinetic Energy

Alpha Particle Flux Analysis

The differential flux of alpha particles after passing through aluminum (Al) and boron nitride (BN) shielding in free space is shown in Figure 3. As with protons, the comparison reveals how each material attenuates radiation across a wide energy spectrum.

In the low-energy range, BN exhibits lower alpha flux than Al, indicating more effective suppression of these particles early in the energy spectrum. Since alpha particles carry twice the charge and four times the mass of protons, they have higher ionizing potential, making this region particularly important for biological shielding.

In the moderate energy region, a wave-like fluctuation in the flux is observed, reflecting complex interactions such as scattering, secondary particle generation, or energy loss processes within the shielding material. Here too, BN generally maintains a slight advantage, as its curve remains marginally below that of Al throughout most of the range.

At higher kinetic energies, both flux curves converge and decline sharply, consistent with the trend observed for protons. At this stage, the difference in attenuation capability between the two materials diminishes, as high-energy alpha particles are increasingly difficult to stop.

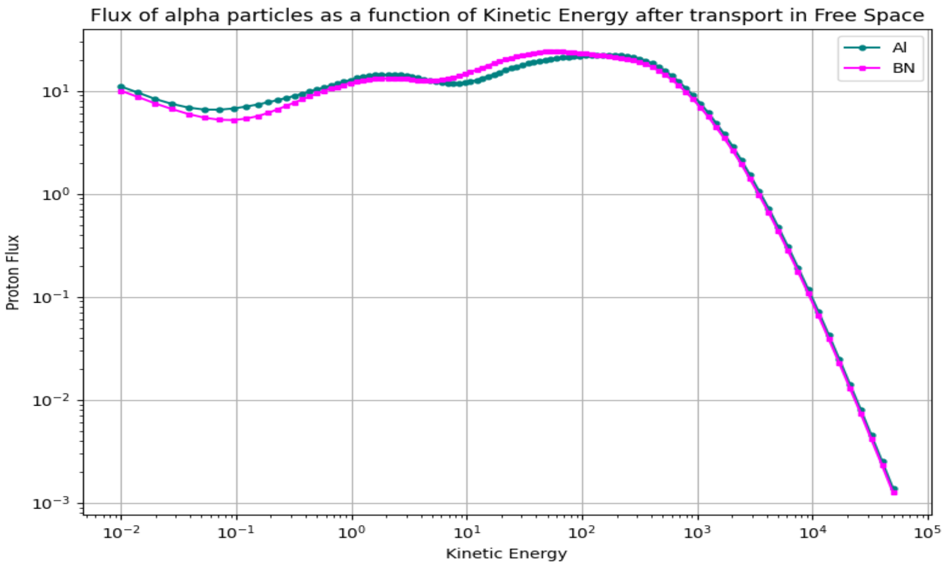


Figure 3: Alpha Particle Flux v/s Kinetic Energy

Iron (Fe^{56}) Flux Analysis

The differential flux of iron-56 (Fe^{56}) nuclei after passing through aluminum (Al) and boron nitride (BN) shielding is presented in Figure X. As one of the heaviest and most biologically hazardous components of galactic cosmic rays (GCRs), Fe^{56} plays a critical role in assessing deep-space radiation risks.

In the low-energy region, BN exhibits noticeably lower iron flux compared to Al. This indicates greater attenuation of low-energy heavy ions, which are particularly damaging due to their high charge and dense ionization tracks. BN's performance in this region suggests reduced generation of harmful secondary radiation.

As the kinetic energy increases, both materials show a characteristic rise in transmitted flux, reaching a peak region where the majority of Fe^{56} nuclei penetrate the shielding. Even at this peak, BN maintains a consistent advantage, showing lower flux levels than Al and thus better shielding efficiency against high-charge, high-mass particles.

At very high energies, the curves begin to converge, reflecting the inherent difficulty of attenuating ultra-relativistic ions. Nonetheless, BN continues to perform marginally better throughout the spectrum.

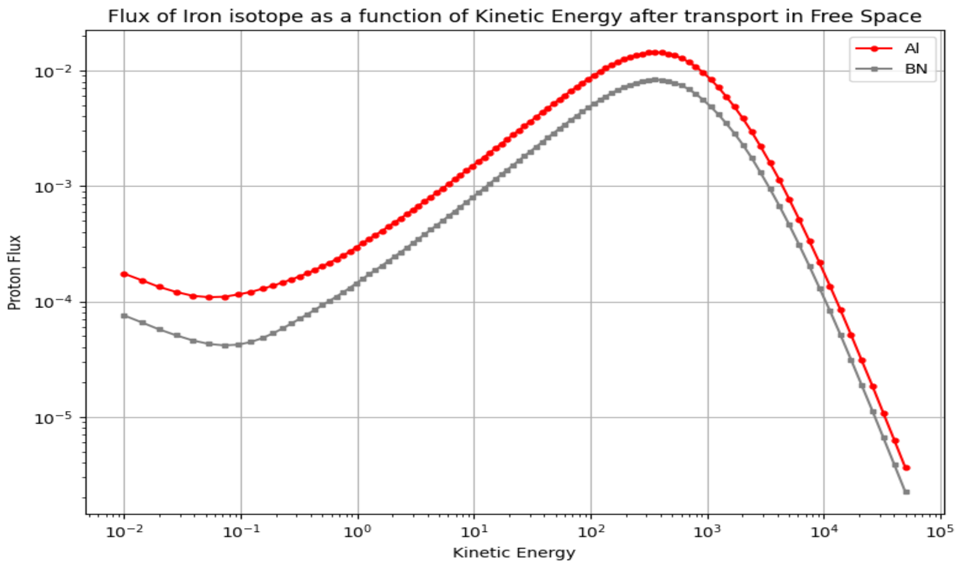
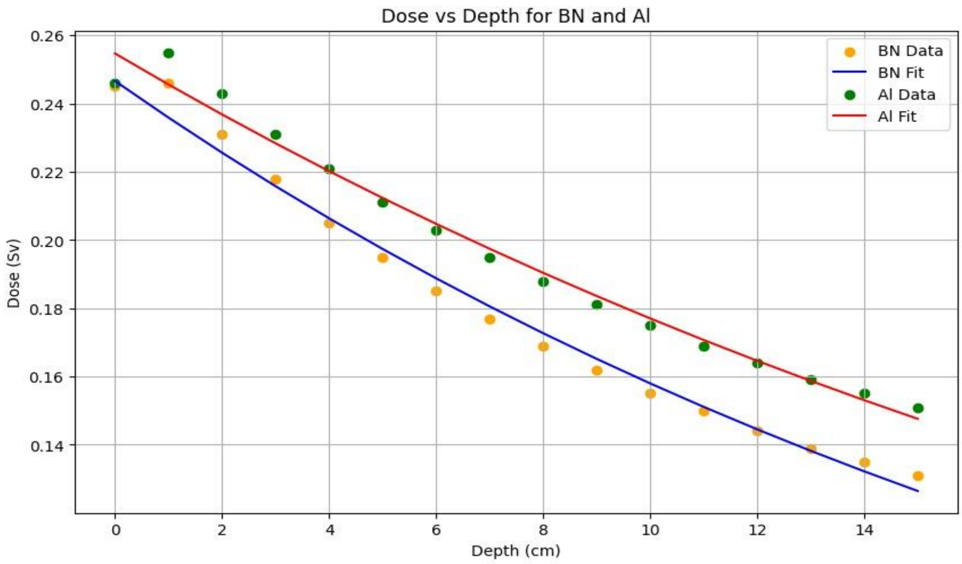


Figure 4: Iron (Fe56) Flux v/s Kinetic Energy

Linear Regression

This plot shows how radiation dose changes with shielding depth for boron nitride (BN) and aluminum (Al), using a linear regression fit. In both cases, the trend slopes downward, meaning that as the thickness (or areal density) of the material increases, the dose equivalent drops. Put simply, more shielding means less radiation. The line for BN drops more steeply than the one for Al, showing that BN blocks radiation more effectively for each unit of thickness. This means you'd need less BN than Al to get the same level of protection—an advantage that can save both weight and cost, which are crucial factors in spacecraft engineering.



Limitations and Future Work

This study offers valuable insights into the shielding performance of boron nitride (BN) and aluminum (Al); however, several limitations should be acknowledged. The simulations were conducted for a fixed one-day mission duration, which simplifies the analysis but does not account for long-term cumulative radiation exposure encountered during extended space missions. Additionally, the simulations focused solely on human tissue as the target, which is essential for biological assessment but does not represent radiation impacts on spacecraft electronics—materials like silicon would be critical to consider in future studies.

Another limitation lies in the use of uniform, single-material shielding. While this allows for straightforward comparison, real-world applications often involve multi-layered or composite shielding systems designed to optimize mass, attenuation, and secondary radiation suppression. Exploring such configurations—especially those combining BN with hydrogen-rich or low-Z materials—could yield improved protection.

Moreover, the current study was restricted to the free space radiation environment. Future simulations should be extended to include planetary surfaces such as the Moon or Mars, where environmental factors like regolith and local field interactions can alter radiation transport. Although OLTARIS is a robust simulation tool, experimental validation remains essential. Ground-based accelerator tests or in-situ data from space missions will help verify simulation accuracy and support the practical development of shielding technologies.

In this context, India's Gaganyaan mission, the country's first human spaceflight program led by ISRO, offers a valuable opportunity for real-world validation of shielding models. With planned crewed operations in low Earth orbit (LEO), Gaganyaan could serve as a platform to deploy and evaluate dosimetry systems, monitor space radiation exposure, and test advanced shielding materials under operational conditions. Integrating such studies into the mission could help bridge the gap between simulation and application, while also contributing to the global understanding of radiation protection for future deep space exploration.

Conclusion

This study set out to explore the comparative shielding effectiveness of boron nitride (BN) and aluminum (Al) against galactic cosmic rays (GCRs) under free space conditions. Leveraging the capabilities of the OLTARIS simulation platform, the analysis focused on both dose equivalent and differential flux across key GCR components—protons, alpha particles, and iron-56 (Fe^{56})—to evaluate how each material performs under varying radiation intensities and areal densities.

The results strongly indicate that BN offers superior radiation protection across all studied metrics. It consistently achieved lower dose equivalents and attenuated particle flux more effectively than Al, particularly within the low- to mid-energy spectrum, where biological impact is most severe. These findings not only highlight BN's attenuation efficiency but also its capacity to reduce secondary radiation—an important factor often overlooked in traditional shielding materials.

Beyond its shielding efficiency, BN's material characteristics—such as lower density, higher thermal stability, and minimal secondary particle production—make it a compelling choice for spacecraft applications where mass and safety constraints are critical. Its performance advantage over Al suggests that BN could play a central role in enabling safer and more sustainable long-duration human missions beyond low Earth orbit. [5]

Looking ahead, future investigations could expand on these findings by considering multi-layered configurations, exploring performance under planetary surface conditions, and integrating real-world validation through upcoming space missions. As India advances toward its Gaganyaan crewed flight program, such missions present a timely opportunity to test and refine shielding [5]strategies in orbit, bridging the gap between simulation and application.

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