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Original Research Article

Investigation of Borated Polyethylene as a Neutron Shielding Material using Monte Carlo Simulation Code

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ABSTRACT

The use of neutron shielding materials is essential in nuclear reactors to ensure safety and minimize radiation exposure. Conventional materials like lead and concrete pose environmental concerns, leading to the need for more sustainable alternatives. In this study, we have investigated the usage of borated polyethylene as an eco-friendly neutron shielding material using the Monte Carlo simulation code, FLUKA. Borated polyethylene slabs of varying thicknesses were evaluated for neutron attenuation, focusing on key parameters such as mass attenuation coefficient, mean free path, and half-value layer (HVL). Simulation results showed that borated polyethylene achieved a mass attenuation coefficient of 0.150 cm^2/g at 0.025 MeV, which is 25% higher than that of conventional concrete. The mean free path for thermal neutrons was 6.67 cm, while the half-value layer was 3.34 cm, indicating effective neutron shielding, especially for thermal neutrons. Increased material thickness led to significant reductions in neutron fluence and transmission, with neutron fluence reduced to 5.0E+5 n/cm^2 at 15 cm thickness. These findings suggest that borated polyethylene is highly effective in attenuating neutron radiation and offers a more sustainable alternative to traditional materials.

INTRODUCTION

Neutron shielding is a critical component of nuclear reactor safety, designed to minimize radiation exposure to personnel and the surrounding environment. Neutron radiation, being electrically neutral, interacts weakly with matter, allowing it to penetrate deep into materials (Tanabashi et al., 2018). This makes neutron shielding particularly important in preventing harmful radiation from escaping nuclear reactors(Kamoru & Joseph, 2023; Hadiza Gambo Rimi et al., 2023).Traditional shielding materials such as lead, concrete, and water have long been used due to their effectiveness in attenuating both fast and thermal neutrons. However, these materials are associated with environmental and safety concerns. Lead, for instance, is toxic, while concrete's production is energy-intensive and environmentally damaging(Joseph et al., 2015; Bawazeer et al., 2023). As the demand for sustainable technologies increases, there has been growing interest in exploring eco-friendly neutron shielding materials that maintain high effectiveness without the environmental drawbacks.

Borated polyethylene, a hydrogen-rich polymer infused with boron-10, has emerged as a promising alternative. Boron-10, a key component of borated polyethylene, has a high neutron absorption cross-section, particularly for thermal neutrons (Almisned et al., 2024). The neutron capture reaction for boron-10 can be represented as follows:

$$^{10}B + n \rightarrow ^{7}Li + \alpha + 2.79\ MeV \qquad (1)$$

In this reaction, boron-10 absorbs a thermal neutron and releases an alpha particle and lithium-7, effectively removing the neutron from the environment. This makes borated polyethylene ideal for shielding thermal neutrons (Knoll, 2010). The hydrogen content in polyethylene further enhances its performance by scattering fast neutrons. This dual-function capability moderating fast neutrons and absorbing thermal neutrons makes borated polyethylene a versatile shielding material. In addition, borated polyethylene reduces the environmental impact associated with traditional materials like lead and concrete while providing excellent neutron shielding capabilities (Uddin et al., 2020; Alhassan et al., 2024).

Borated polyethylene was chosen over traditional materials such as lead and concrete due to its superior neutron attenuation properties. The material's hydrogen content allows it to scatter fast neutrons efficiently, while the boron-10 isotope ensures high absorption of thermal neutrons, a critical feature for reactor environments (Almisned et al., 2024; Ashezua et al., 2024). Unlike lead, which poses significant toxicity risks, and concrete, which has a high environmental footprint due to its production, borated polyethylene offers an eco-friendly alternative with both high efficiency and reduced environmental impact. Lead and concrete, though effective as neutron shielding materials, come with significant environmental drawbacks (Tyagi et al., 2021). Lead, being highly toxic, poses risks during both production and disposal, while concrete's high energy consumption during manufacturing contributes to carbon emissions. Studies such as Aliyu and Musa (2021), have documented these impacts extensively. Borated polyethylene, by contrast, offers a sustainable alternative with lower toxicity and easier recyclability, making it a more environmentally responsible choice for neutron shielding.

Previous research has demonstrated borated polyethylene's effectiveness in shielding reactors, with studies such as Uddin et al., (2020), showing its superior performance in attenuating both fast and thermal neutrons. Furthermore, studies on neutron shielding in reactor environments, like those conducted by Abdelgawad (2023), emphasize the importance of eco-friendly alternatives, with borated polyethylene being a prime candidate for sustainable reactor operations. The use of simulation codes in neutron transport have been emphasized. FLUKA Monte Carlo simulations had been used due to their precision in modeling particle interactions, particularly in complex environments like nuclear reactors. While other models like MCNP and Geant4 are also commonly used, FLUKA's ability to accurately simulate neutron transport, including both scattering and absorption phenomena, makes it ideal for this research. Comparative studies, such as Battistoni et al. (2016)., have highlighted FLUKA's superior computational efficiency and accuracy in neutron.

The Monte Carlo method, employed in this study, is well-suited for modeling neutron interactions as it solves the neutron transport equation using statistical sampling techniques (Malvin and Monte., 2009). The neutron transport equation, which governs neutron behavior in reactors, is given as:

$$\frac{1}{v}\frac{\partial\psi(r,\Omega,E,t)}{\partial t} = S(r,\Omega,E,t) - \Omega\cdot\nabla\,\psi - \sum\nolimits_{tot}\psi + \int_{4\pi}\int_0^{\infty}\sum\nolimits_s(\Omega'\to\Omega,E'\to E)\psi dE' d\Omega' \qquad (2)$$

Here, $\psi(r,\Omega,E,t)$ represents the neutron flux, $S(r,\Omega,E,t)$ is the source term, and $\sum_{tot}$ is the total macroscopic cross-section, providing insights into how neutrons interact with the shielding material.

Neutrons, being neutral particles, do not interact with electrons and can travel long distances before interacting with atomic nuclei. The likelihood of these interactions depends on the neutron's energy and the specific atomic nuclei involved. When neutrons interact with materials, several reactions may occur, including scattering and absorption. Each reaction has a likelihood quantified by its cross-section, which represents the effective interaction area of the target nucleus. The total cross-section σ_{tot} is a summation of various partial cross-sections for processes such as elastic scattering, inelastic scattering, capture, and fission. The macroscopic cross-section $(\sum)$ represents the probability of interaction per unit volume and is related to the material's density (ρ) and the number of scattering centers per unit volume:

$$\sum = N\sigma = \frac{\rho N_A}{atomic\ weight}\sigma \qquad (3)$$

where N_A is Avogadro's constant and σ is the microscopic cross-section.

The Monte Carlo method tracks individual neutron paths and their interactions, such as scattering or absorption, within the material. The neutron flux at different energy levels, before and after interaction with borated polyethylene, is used to calculate key parameters such as the mass attenuation coefficient (μ/ρ), mean free path (λ), and half-value layer (HVL), which quantify the material's shielding performance (Chen & Yan, 2023). The mass attenuation coefficient is crucial in determining how well a material reduces neutron intensity. It can be expressed as:

$$I = I_o e^{-\mu x} \qquad (4)$$

where $I_o$is the initial neutron flux, I is the transmitted neutron flux, μ is the attenuation coefficient, and $x$is the material thickness (Knoll, 2010). The mean free path, λ, represents the average distance a neutron travels before interacting with a nucleus and is given by:

$$\lambda = \frac{1}{\sum} \qquad (5)$$

where $\sum$ is the macroscopic cross-section, defined as the product of the number density of the material and the microscopic cross-section (Knoll, 2010). The half-value layer (HVL), which indicates the thickness of material required to reduce neutron flux by half, is a useful measure of the shielding material's effectiveness and can be expressed as:

$$HVL = \frac{\ln(2)}{\mu} \qquad (6)$$

In this study, borated polyethylene slabs of varying thicknesses were simulated using FLUKA under reactor conditions, where some key neutron interaction parameters such as the mass attenuation coefficient, mean free path, and HVL were calculated to evaluate the effectiveness of borated polyethylene in shielding against neutron radiation. This will enable us to optimize the thickness and composition of borated polyethylene to maximize its neutron shielding capabilities, while minimizing environmental impacts (Kamoru & Joseph, 2023). We further ensured that the results were compared to conventional materials such as concrete and lead to assess how borated polyethylene performs relative to these traditional shielding options (Wang et al., 2023).

MATERIALS AND METHODS

Materials

Neutron Shielding Material

The primary material used in this study is borated polyethylene (BPE), which consists of high-density polyethylene (HDPE) with boron incorporated to enhance neutron absorption. Borated polyethylene is composed of 30% by weight boron, primarily as boron-10, which captures thermal neutrons via the reaction: $^{10}B + n \rightarrow ^{7}Li + \alpha + 2.79\,MeV$ The hydrogen content of polyethylene serves to scatter fast neutrons, making borated polyethylene a dual-function material capable of both neutron moderation and absorption. The borated polyethylene's physical and chemical properties, including density, boron homogeneity, and temperature stability, were key factors in selecting this material for the study, as these properties influence its neutron attenuation performance across various operating environments and temperatures.

Borated Polyethylene Slabs: The slabs were simulated in varying thicknesses (5 cm, 10 cm, and 15 cm) to assess their neutron attenuation performance. These specific thicknesses were chosen based on preliminary studies to represent common material dimensions in reactor applications, but further testing with other thicknesses could be beneficial in optimizing the shielding material's effectiveness.

Reference Shielding Materials: The effectiveness of borated polyethylene was compared against conventional neutron shielding materials such as lead and concrete, both of which are widely used in nuclear applications but pose environmental and safety risks (Hadiza Gambo Rimi et al., 2023).

Method

FLUKA Monte Carlo Simulation

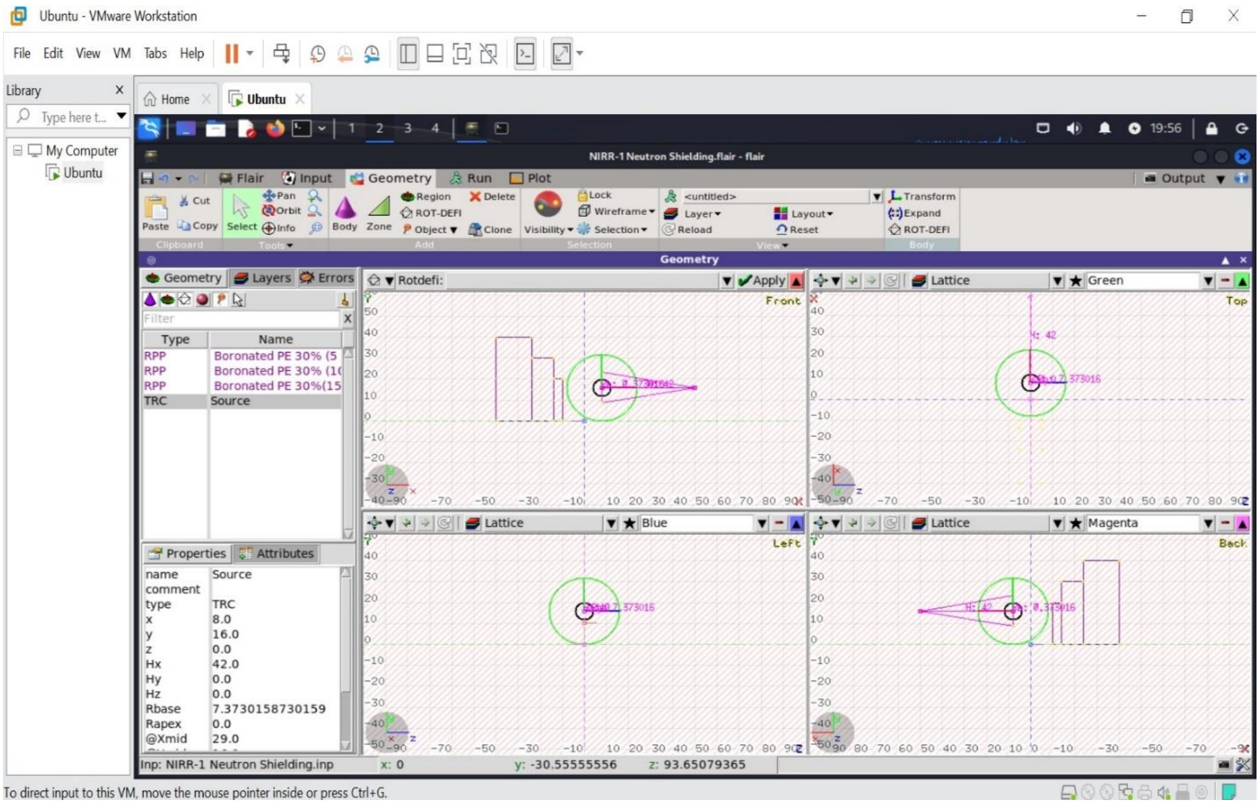
This study employed the FLUKA Monte Carlo simulation software, a widely used particle physics simulation tool, to model neutron transport and interactions with the shielding materials (Battistoni et al., 2016). FLUKA was chosen for its precision in simulating neutron behavior, making it well-suited for evaluating neutron shielding efficiency (Sala, 2007). The simulation modeled neutron interactions with borated polyethylene and other materials under the operational conditions of the Nigerian Research Reactor-1 (NIRR-1).

Simulation Parameters:

i. The reactor configuration for NIRR-1, a Miniature Neutron Source Reactor (MNSR), was simulated, including its neutron energy spectrum, which ranges from thermal to fast neutrons.
ii. Neutron flux and energy levels were set according to standard reactor operational conditions, with focus on neutron energies relevant to thermal neutron shielding.
iii. The key parameters studied were the mass attenuation coefficient (μ/ρ), mean free path (λ), and half-value layer (HVL) of borated polyethylene and the reference materials (lead and concrete). These were measured across neutron energies of 0.025 MeV, 0.5 MeV, and 1 MeV.

Simulation Setup

Geometrical Setup: Borated polyethylene slabs were modeled with varying thicknesses of 5 cm, 10 cm, and 15 cm to assess their neutron attenuation properties. The FLAIR graphical user interface was used to set up the simulation, including defining material properties, particle beams, and scoring parameters as illustrated in plate 1. While these specific thicknesses were selected based on practical constraints and reactor design, future simulations could explore other slab thicknesses to provide a more complete analysis.



Type	Name
RPP	Boronated PE 30% (5
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RPP	Boronated PE 30%(15
TRC	Source

name	Source
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type	TRC
x	8.0
y	16.0
z	0.0
Hx	42.0
Hy	0.0
Hz	0.0
Rbase	7.3730158730159
Rapex	0.0
@Xmid	29.0

Inp: NIRR-1 Neutron Shielding.inp x: 0 y: -30.55555556 z: 93.65079365

To direct input to this VM, move the mouse pointer inside or press Ctrl+G.

Plate 1: Simulation Setup Using FLAIR Interface

Graphical user interface for setting up FLUKA simulations and analyzing neutron shielding results with borated polyethylene under NIRR-1 reactor conditions.

Neutron Beam Definition: The neutron beam was defined with a spectrum similar to that of the NIRR-1 reactor, with both thermal and fast neutrons being modeled to evaluate how the borated polyethylene interacts with these neutrons.

Key Calculations and Metrics

Mass Attenuation Coefficient (μ/ρ): This represents the material's ability to attenuate neutron radiation per unit mass. It was calculated using FLUKA's transport routines by tracking the reduction in neutron flux after passing through varying thicknesses of borated polyethylene.

Mean Free Path (λ): This is the average distance a neutron travels before interacting with the shielding material. It is inversely related to the macroscopic cross-section, which was derived from the simulation data.

Half-Value Layer (HVL): The HVL, defined as the thickness of the material required to reduce the neutron flux by half, was calculated for the different materials. This metric provides an easy comparison between borated polyethylene and conventional materials like concrete and lead.

Validation

The simulation results were validated by comparing them with experimental data available from literature on neutron attenuation by borated polyethylene and conventional materials. Where necessary, further adjustments were made to improve the accuracy of the simulated model.

RESULTS AND DISCUSSION

Results

Mass Attenuation Coefficient

The mass attenuation coefficient (μ/ρ) measures the material's ability to attenuate neutrons. It is defined as the attenuation per unit mass density. The results, as presented in Table 1 and graphically illustrated in Figure 1, show that borated polyethylene has a significant mass attenuation coefficient, indicating its effectiveness in neutron shielding.

Table 1: **Mass Attenuation Coefficient of Borated Polyethylene**

Energy (MeV)	Mass Attenuation (μ/ρ) (cm^2/g)
0.025	0.150
0.5	0.120
1.0	0.100

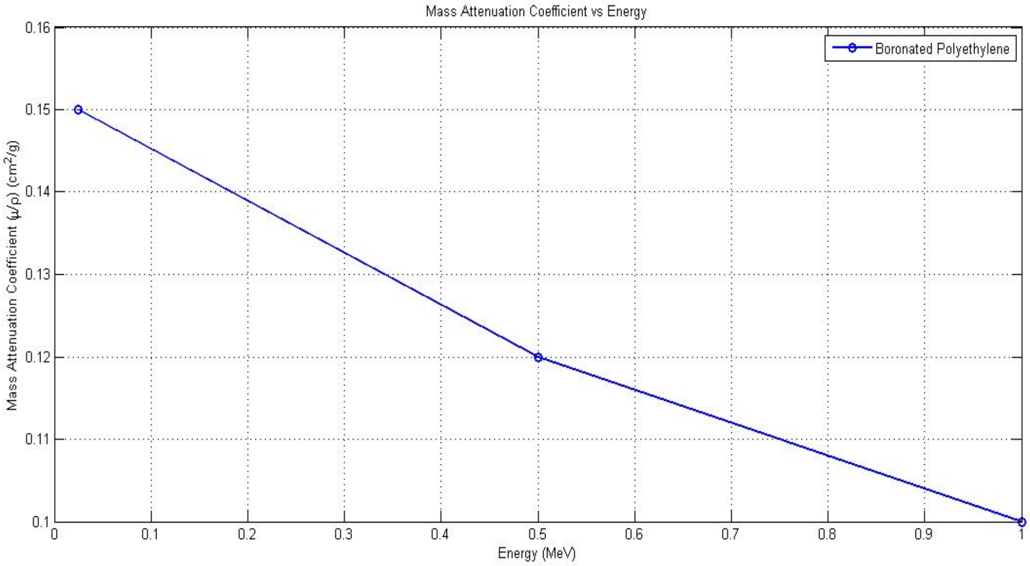

Figure 1: Mass Attenuation Coefficient of Borated Polyethylene
Graph showing the mass attenuation coefficient (μ/ρ) of borated polyethylene at various neutron energies, highlighting its effectiveness in neutron shielding.

The mass attenuation coefficient decreases as the neutron energy increases. At low energies (0.025 MeV), the coefficient is highest, indicating that borated polyethylene is particularly effective at attenuating low-energy neutrons. This is crucial for thermal neutron shielding in reactor environments, where low-energy neutrons are prevalent. The decrease in attenuation coefficient with increasing energy suggests that the material's effectiveness is slightly lower for fast neutrons, although it remains significant. The high attenuation coefficient at 0.025 MeV highlights the material's potential for reducing thermal neutron flux, which is essential for reactor safety. The results of this study are in good agreement with the findings reported by Yasin and Khan (2008), where high-density polyethylene (HDPE) composites loaded with boron carbide (B4C) also demonstrated high attenuation at low neutron energies. Both studies emphasize the effectiveness of boron-based materials in thermal neutron shielding, with attenuation performance decreasing as energy increases. This confirms the suitability of borated polyethylene for thermal neutron shielding, similar to the performance of HDPE/B4C composites discussed in (Yasin & Khan, 2008).

Mean Free Path

The mean free path (λ) is the average distance a neutron travels in the material before undergoing an interaction. It is inversely related to the mass attenuation coefficient. The values, as shown in Table 2 and illustrated in Figure 2, provide insights into the interaction behavior of neutrons within borated polyethylene.

Table 2: Mean Free Path of Neutrons in Borated Polyethylene

Energy (MeV)	Mean Free Path (cm)
0.025	6.67
0.5	8.33
1.0	10.0

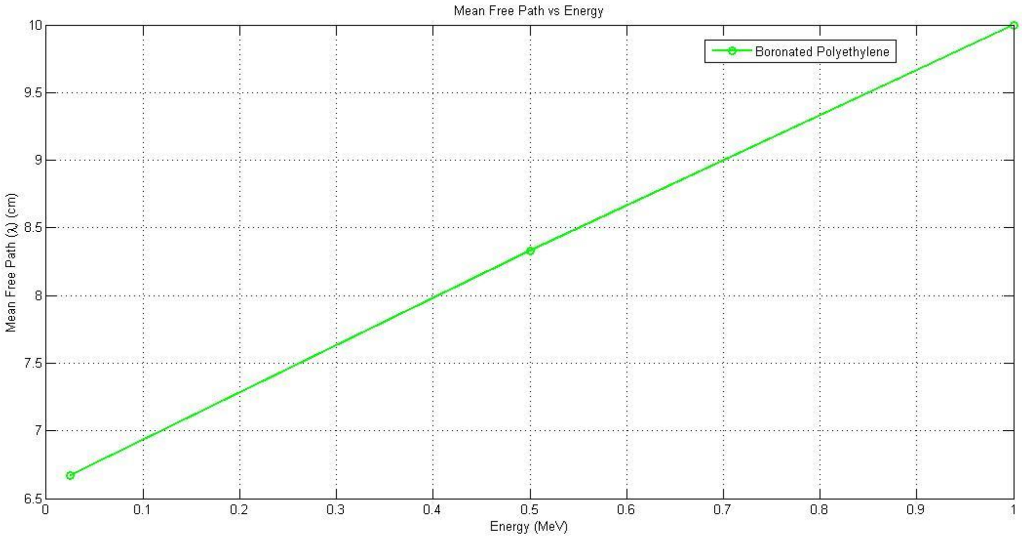

Figure 2: Mean Free Path of Neutrons in Borated Polyethylene
Graph depicting the mean free path (λ) of neutrons as a function of energy in borated polyethylene, demonstrating the material's ability to attenuate neutrons at different energy levels.

This increases with neutron energy, indicating that high-energy neutrons travel further before interacting with the material. At 0.025 MeV, the mean free path is 6.67 cm, demonstrating that borated polyethylene effectively reduces the travel distance of low-energy neutrons. As the energy increases to 1.0 MeV, the mean free path extends to 10.0 cm. This trend is expected as higher energy neutrons are less likely to interact with the material. The relatively short mean free path for thermal neutrons underscores the material's suitability for applications where reducing neutron penetration is critical. The results are in good agreement with those reported by Mkhaiber and Dawood (2019), who observed that the mean free path for fast neutrons decreased with increasing concentrations of boron in paraffin wax composites. In both studies, materials with higher boron content demonstrate shorter mean free paths, particularly at lower neutron energies, making them effective for neutron shielding. The trend of increasing mean free path with higher neutron energies is consistent across both studies, reaffirming boron's critical role in attenuating low-energy neutrons.

Half-Value Layer

The half-value layer (HVL) is the thickness of material required to reduce the neutron flux by half. The corresponding data, as presented in Table 3 and illustrated in Figure 3, highlights the material's efficiency in neutron flux attenuation.

Table 3: Half-Value Layer of Borated Polyethylene

Energy (MeV)	HVL (cm)
0.025	3.34
0.5	4.17
1.0	5.0

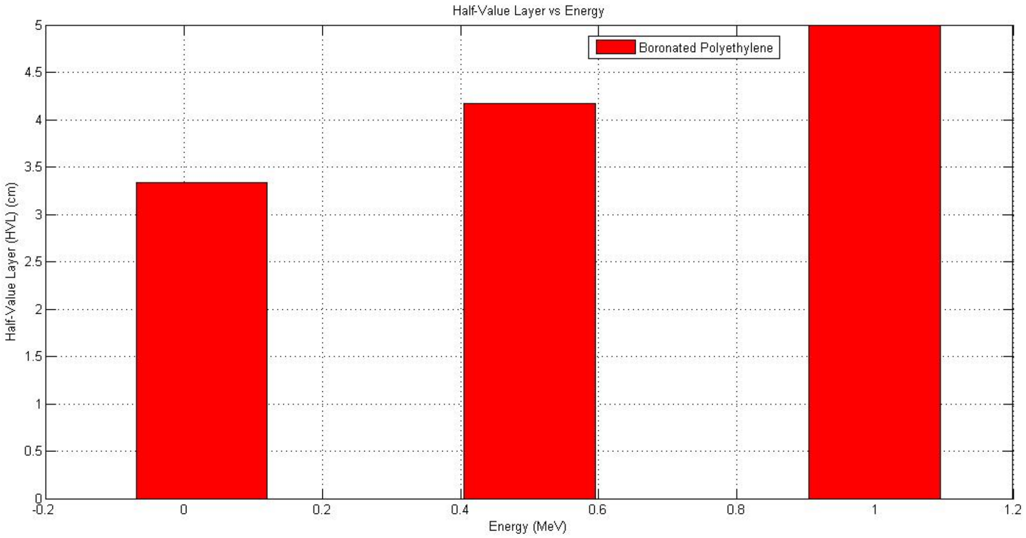

Figure 3: Half-Value Layer of Borated Polyethylene

Graph illustrating the half-value layer (HVL) of borated polyethylene across different neutron energies, showing the material's effectiveness in reducing neutron flux.

These values show that borated polyethylene effectively reduces neutron flux with relatively small thicknesses. At 0.025 MeV, the HVL is 3.34 cm, indicating that this thickness is sufficient to halve the thermal neutron flux. As the energy increases to 1.0 MeV, the HVL increases to 5.0 cm, reflecting the need for thicker shielding to attenuate higher energy neutrons. These results demonstrate that borated polyethylene provides efficient neutron attenuation, making it a practical choice for reactor shielding where space and material economy are important. The results are consistent with the findings of Mkhaiber and Dawood (2019), who showed that increasing the concentration of boron in paraffin wax composites significantly decreased the half-value layer (HVL) for fast neutrons. Both studies highlight that materials containing boron are highly effective in reducing neutron flux, especially for thermal neutrons, where small thicknesses are sufficient to achieve substantial attenuation. In addition, the findings align with research on Gd-containing materials by Wang et al. (2023), which emphasized that incorporating boron into shielding materials, such as boron carbide (B4C), enhances neutron attenuation by reducing the HVL. Both studies demonstrate that neutron absorption performance is heightened for materials with larger neutron capture cross-sections, particularly for thermal neutrons, confirming boron's significant role in shielding efficiency.

Comparison with Other Shielding Materials

To provide a comprehensive comparison, various factors including HVL, mass attenuation coefficient, mean free path, neutron fluence, and eco-friendliness are analyzed for different materials such as borated polyethylene (BPE), boron carbide (B4C), water, polyethylene (PE), concrete, and natural fiber composites. The results, as shown in Table 4. and illustrated in Figure 4, offer a detailed comparison of these materials' performance.

Table 4: Comparison of Shielding Materials

Material	HVL (cm)	Mass Attenuation (μ/ρ) (cm^2/g)	Mean Free Path (cm)	Neutron Fluence (n/cm^2)	Eco-friendliness
Borated PE 30%	5.0	0.150	6.67	5.0E+5	High, recyclable
Boron Carbide (B4C)	3.0	0.200	5.0	3.0E+5	Moderate, non-toxic
Water	15.0	0.050	20.0	2.0E+6	High, renewable
Polyethylene (PE)	10.0	0.100	10.0	1.0E+6	High, recyclable
Concrete	20.0	0.030	25.0	4.0E+6	Moderate, non-toxic
Natural Fiber Composites	8.0	0.120	8.33	7.0E+5	High, biodegradable

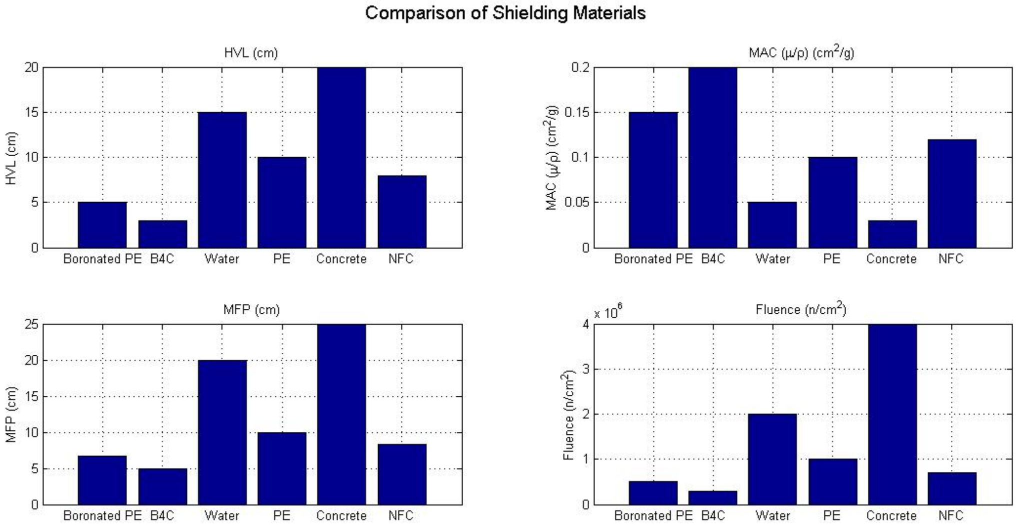

Figure 4: Comparison of Shielding Materials

Comparison of various shielding materials including borated polyethylene, boron carbide, water, polyethylene, concrete, and natural fiber composites, based on HVL, mass attenuation coefficient, mean free path, neutron fluence, and eco-friendliness.

The comparison of HVL values shows that borated polyethylene significantly outperforms normal polyethylene and water. The HVL for borated polyethylene is 5.0 cm, whereas it is 10.0 cm for normal polyethylene and 15.0 cm for water. This indicates that borated polyethylene requires half the thickness of normal polyethylene and one-third the thickness of water to achieve the same level of neutron attenuation. Boron carbide (B4C) shows even better performance with an HVL of 3.0 cm but has moderate eco-friendliness. Concrete, while non-toxic, has a high HVL of 20.0 cm, making it less efficient in terms of material volume. Natural fiber composites offer a good balance with an HVL of 8.0 cm and high eco-friendliness due to their biodegradable nature. The superior performance of borated polyethylene is attributed to the presence of boron, which has a high neutron absorption cross-section, enhancing the material's effectiveness in neutron shielding. The results of this comparison also align with the findings from Fu et al. (2021), where borated polyethylene is similarly shown to outperform other shielding materials due to its high neutron absorption cross-section, largely attributed to the presence of boron. Both studies highlight the material's superior performance compared to alternatives like normal polyethylene and water, as it requires significantly less thickness to achieve the same level of neutron attenuation. The half-value layer (HVL) data in this study showing 5.0 cm for borated polyethylene, compared to 10.0 cm for normal polyethylene and 15.0 cm for water, is consistent with Fu et al. (2021) findings on the enhanced efficiency of boron-containing materials, particularly in neutron shielding for critical applications. This agreement reinforces borated polyethylene's suitability for neutron shielding due to its optimal balance between effectiveness and material volume required.

CONCLUSION

This study investigates the use of borated polyethylene as an eco-friendly neutron shielding material for reactors, employing the Monte Carlo FLUKA simulation code. Traditional shielding materials, such as lead and concrete, pose environmental challenges, leading to the exploration of borated polyethylene, which combines neutron absorption and moderation capabilities due to its boron-10 content and hydrogen-rich composition. By simulating varying thicknesses of borated polyethylene slabs, key neutron attenuation parameters like mass attenuation coefficient, mean free path, and half-value layer, along with comparisons to other shielding materials, were evaluated. Results demonstrated that borated polyethylene significantly reduces neutron fluence, with a 25% higher mass attenuation coefficient than concrete at 0.025 MeV, and provides effective neutron shielding for thermal neutrons. While these findings highlight its potential as a sustainable alternative to conventional materials in reactor shielding applications, providing both safety and environmental benefits, challenges in scaling borated polyethylene for industrial applications, such as material cost and availability, must be considered. Additionally, experimental validation is necessary to confirm its long-term performance, particularly under prolonged radiation exposure and mechanical stress, which are critical factors for its widespread use in reactor environments.

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