

RESEARCH ARTICLE

Photon and Fast-Neutron Shielding Characteristics of BaO–Bi₂O₃–TeO₂ Glasses

A. A. Asiri^{1*}, Ahmed Y. A. Mohamed²

ABSTRACT: This study evaluates the photon and fast-neutron shielding characteristics of three BaO–Bi₂O₃–TeO₂ glasses, labelled S1, S2, and S3, using Phy-X/PSD software. The nominal compositions were 25BaO–5Bi₂O₃–70TeO₂, 20BaO–10Bi₂O₃–70TeO₂, and 5BaO–15Bi₂O₃–80TeO₂, with measured densities of 5.427, 5.546, and 6.371 g/cm³, respectively. Key parameters including mass attenuation coefficient, linear attenuation coefficient, half-value layer, tenth-value layer, mean free path, effective atomic number, effective electron density, equivalent atomic number, atomic cross-section, and electronic cross-section were calculated across the photon-energy range of 0.015–15 MeV. Buildup factors, both exposure and energy absorption, were assessed at penetration depths from 0.5 to 40 mean free paths. Fast-neutron removal cross-sections were determined as 0.095, 0.094, and 0.107 cm^{−1} for S1, S2, and S3, respectively. The mass attenuation coefficients decreased with increasing photon energy, reaching a minimum in the few-MeV range before rising slightly toward 15 MeV. Among the three compositions, S3 demonstrated the highest linear attenuation coefficient, effective atomic number, effective electron density, equivalent atomic number, and fast-neutron removal cross-section, while also exhibiting the lowest half-value layer, tenth-value layer, and mean free path. When compared with commercial shielding glasses and selected concretes, the investigated glasses showed superior attenuation performance in terms of half-value layer and mean free path. Buildup factors increased with penetration depth and displayed pronounced maxima at low energies. Overall, S3 offered the most favorable combination of photon attenuation and fast-neutron removal properties among the compositions studied.

Keywords: BaO–Bi₂O₃–TeO₂ Glasses; Phy-X/PSD; Photon Shielding; Fast-Neutron Removal Cross-Section; Mass Attenuation Coefficient; Buildup factor

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1. INTRODUCTION

The growing reliance on ionizing radiation across medical diagnostics, radiotherapy, nuclear power generation, and industrial radiography has intensified the demand for effective shielding materials that can protect personnel and sensitive equipment from harmful exposure [1]. While traditional shields based on lead and concrete have served

these purposes for decades, their limitations, including the toxicity of lead, the opacity of concrete, and the substantial thickness required for adequate attenuation, have motivated a sustained search for alternative materials with superior shielding performance and improved practical characteristics [2]. Glass-based shields have attracted particular attention in this context because they combine optical transparency with the mechanical robustness and compositional flexibility of oxide glasses, enabling their use in applications where visual monitoring or light transmission is required alongside radiation protection [3].

Among the various glass-forming systems explored for radiation shielding, tellurite-based glasses have emerged as especially promising candidates. Tellurium dioxide (TeO₂) can form stable glasses with a wide range of modifier and

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heavy-metal oxides, and the resulting materials typically exhibit high densities, good thermal stability, and excellent transmission in the visible and near-infrared regions [4]. These attributes are directly relevant to shielding applications, since photon attenuation depends strongly on the electron density and atomic number of the constituent elements, and higher densities generally translate into shorter half-value layers and mean free paths for a given material thickness [5]. The incorporation of heavy-metal oxides such as Bi₂O₃ into the tellurite network is particularly advantageous because bismuth, with its high atomic number ($Z = 83$), contributes substantially to photoelectric absorption at low photon energies and to pair production at higher energies, thereby enhancing the overall attenuation capability of the glass [6].

The BaO-Bi₂O₃-TeO₂ ternary system offers a particularly attractive platform for designing shielding glasses because it allows the simultaneous variation of barium, bismuth, and tellurium content within a single glass-forming composition. Barium oxide (BaO) acts as a network modifier that can influence the density and structural compactness of the glass, while Bi₂O₃ serves as a heavy-metal oxide that increases both density and effective atomic number, and TeO₂ provides the glass-forming backbone [7]. By systematically varying the proportions of these three oxides, it becomes possible to tailor the shielding characteristics of the resulting glasses in a controlled manner. Previous studies on related bismuth-borate-tellurite systems have demonstrated that the replacement of TeO₂ with BaO can improve gamma-ray shielding performance, as evidenced by higher mass attenuation coefficients and effective atomic numbers coupled with lower half-value layers and mean free paths [8]. However, the specific BaO-Bi₂O₃-TeO₂ compositions examined in the present work, in which the Bi₂O₃ content increases from 5 to 15 mol% while the BaO content decreases from 25 to 5 mol% and the TeO₂ content rises from 70 to 80 mol%, have not been systematically evaluated for their combined photon and fast-neutron shielding properties.

The assessment of a material's shielding effectiveness requires the calculation of multiple parameters that together describe how photons and neutrons interact with the material across a broad energy spectrum. The mass attenuation coefficient (MAC) and linear attenuation coefficient (LAC) quantify the probability of photon interaction per unit mass and per unit thickness, respectively, and serve as the foundation for deriving other shielding metrics [9]. The half-value layer (HVL) and tenth-value layer (TVL) express the thickness required to reduce the photon intensity to one-half and one-tenth of its original value, while the mean free path (MFP) represents the average distance a photon travels between interactions [10]. The effective atomic number (Z_{eff}) and effective electron density (N_{eff}) provide insight into the average interaction behaviour of the composite material, and the equivalent atomic number (Z_{eq}) allows the material to be compared with elements for the purpose of buildup factor calculations [11]. The atomic cross-section (ACS) and electronic cross-section (ECS) offer further detail on the microscopic interaction probabilities, while the exposure

buildup factor (EBF) and energy absorption buildup factor (EABF) account for the contribution of scattered photons that accumulate within finite shielding thicknesses and can significantly alter the effective dose behind a shield [12]. For neutron shielding, the fast-neutron removal cross-section (FNRC) is the key parameter, as it quantifies the probability that a fast neutron will be removed from the primary beam through scattering and absorption processes [13].

Computational tools have become indispensable for the efficient evaluation of these parameters across wide energy ranges. The Phy-X/PSD software, developed by Sakar and co-workers, provides a user-friendly online platform for calculating a comprehensive set of photon shielding and dosimetry parameters, including MAC, LAC, HVL, TVL, MFP, Z_{eff} , N_{eff} , EBF, EABF, and fast-neutron removal cross-sections, over continuous energy ranges from 1 keV to 100 GeV [14]. The software has been validated against established databases such as XCOM and has been widely employed in recent studies of glass, alloy, and composite shielding materials [15]. Its ability to generate data for arbitrary compositions and densities makes it particularly well suited to the systematic comparison of glass series in which composition and density vary simultaneously.

The novelty of the present work lies in the systematic evaluation of the BaO-Bi₂O₃-TeO₂ ternary glass system for combined photon and fast-neutron shielding applications, with a specific focus on how the coupled variation of Bi₂O₃, BaO, and TeO₂ content, together with the accompanying density increase from 5.427 to 6.371 g/cm³, influences the full suite of shielding parameters. While individual parameters such as MAC or HVL have been reported for related tellurite glasses, a comprehensive analysis that integrates photon attenuation metrics, buildup factors, and fast-neutron removal cross-sections within a single compositionally controlled series remains limited. Furthermore, the comparison of the calculated shielding performance of these glasses with commercial shielding glasses (RS-253-G18, RS-360, RS-520) and selected concrete materials (chromite, ferrite, magnetite, barite) provides a practical benchmark that has not been previously established for this particular glass series.

In this paper, we report the photon and fast-neutron shielding characteristics of three BaO-Bi₂O₃-TeO₂ glasses with nominal compositions of 25BaO-5Bi₂O₃-70TeO₂ (S1), 20BaO-10Bi₂O₃-70TeO₂ (S2), and 5BaO-15Bi₂O₃-80TeO₂ (S3). Phy-X/PSD software was used to calculate the mass attenuation coefficient, linear attenuation coefficient, half-value layer, tenth-value layer, mean free path, effective atomic number, effective electron density, equivalent atomic number, atomic cross-section, and electronic cross-section over the photon-energy range 0.015–15 MeV. The exposure buildup factor and energy absorption buildup factor were evaluated over penetration depths of 0.5–40 mfp. Fast-neutron removal cross-sections were determined for each glass and compared with values for commercial shielding glasses and selected concrete materials. The results are discussed in terms of the compositional and density variations across the S1–S3 series, with particular attention

to identifying the composition that offers the most favorable combination of photon attenuation and fast-neutron removal properties.

2. EXPERIMENTAL DETAILS

2.1. Glass composition and densities

The investigation focused on three tellurite glasses within the BaO–Bi₂O₃–TeO₂ ternary system. Tellurite-based glasses are particularly suitable for shielding studies because TeO₂ can form stable glasses with a wide range of modifier and heavy-metal oxides. In this system, BaO acts as a network modifier, Bi₂O₃ serves as a heavy-metal oxide that increases both density and effective atomic number, and TeO₂ provides the glass-forming backbone. The target compositions, expressed in mol%, were 25BaO–5Bi₂O₃–70TeO₂ (designated S1), 20BaO–10Bi₂O₃–70TeO₂ (S2), and 5BaO–15Bi₂O₃–80TeO₂ (S3). The measured densities of these glasses were 5.427, 5.546, and 6.371 g/cm³ for S1, S2, and S3, respectively. The increase in density from S1 to S3 reflects the higher Bi₂O₃ content and the corresponding reduction in BaO.

Table 1 summarizes the sample codes, nominal compositions, and densities. The elemental weight fractions employed in the subsequent calculations are presented in Table 2. As the Bi₂O₃ content increased from S1 to S3, the weight fraction of bismuth rose from 0.1206 for S1 to 0.2212 for S2 and further to 0.3055 for S3. Conversely, the barium weight fraction declined from 0.1981 for S1 to 0.1453 for S2 and 0.0335 for S3. For each composition, the elemental weight fractions in Table 2 sum to unity. These fractions were used as input for the shielding calculations described in the following subsection.

Table 1. Sample codes, nominal compositions (mol%), and densities of the investigated glasses.

Sample code	Composition (mol%)	Density, ρ (g/cm ³)
S1	25BaO–5Bi ₂ O ₃ –70TeO ₂	5.427
S2	20BaO–10Bi ₂ O ₃ –70TeO ₂	5.546
S3	5BaO–15Bi ₂ O ₃ –80TeO ₂	6.371

2.2. Shielding calculations

Photon-shielding parameters were computed with the Phy-X/PSD software package over a photon-energy range of 0.015–15 MeV [1]. This energy range encompasses the regions of interest for medical, industrial, and nuclear applications, covering the dominance of photoelectric

absorption at low energies and the increasing contributions of Compton scattering and pair production at higher energies. The parameters obtained included the mass attenuation coefficient (MAC, μ_m), linear attenuation coefficient (LAC, μ), half-value layer (HVL), tenth-value layer (TVL), mean free path (MFP), effective atomic number (Z_{eff}), effective electron density (N_{eff}), atomic cross-section (ACS), electronic cross-section (ECS), equivalent atomic number (Z_{eq}), and the geometric-progression (G–P) fitting coefficients necessary for buildup-factor calculations. The mass attenuation coefficient and linear attenuation coefficient are fundamental quantities from which the other parameters are derived, while Z_{eff} and N_{eff} provide insight into the average interaction behavior of the composite glass. The linear attenuation coefficient was calculated from the mass attenuation coefficient and the measured density using:

$$\mu = \mu_m \rho \quad (1)$$

Where μ is the linear attenuation coefficient (cm^{−1}), μ_m is the mass attenuation coefficient (cm²/g), and ρ is the density of the glass (g/cm³). The half-value layer, tenth-value layer, and mean free path were derived from the linear attenuation coefficient as follows:

$$HVL = \ln(2) / \mu \quad (2)$$

$$TVL = \ln(10) / \mu \quad (3)$$

$$MFP = 1 / \mu \quad (4)$$

The exposure buildup factor (EBF) and energy absorption buildup factor (EABF) were determined using the G–P fitting method at penetration depths of 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 10, 15, 20, 25, 30, 35, and 40 mean free paths [2]. The G–P fitting approach is widely used for generating buildup factors because it accurately reproduces the energy and depth dependence of scattered photon contributions. These depths cover the range from thin shields to thick shields relevant to practical applications. The fast-neutron removal cross-section, Σ_R , was evaluated for each glass from the elemental weight fractions. This parameter is a key indicator of a material's effectiveness in attenuating fast neutrons. The mixture rule used for this purpose is given by:

$$\frac{\Sigma_R}{\rho} = \sum_i w_i \left(\frac{\Sigma_R}{\rho} \right)_i \quad (5)$$

Where w_i represents the elemental weight fraction and $(\Sigma_R/\rho)_i$ is the mass fast-neutron removal cross-section of the i -th element. The Phy-X/PSD software implements standard formulations and has been validated against established databases, ensuring the reliability of the computed values. The computed parameters were used to assess the shielding performance of the three glasses.

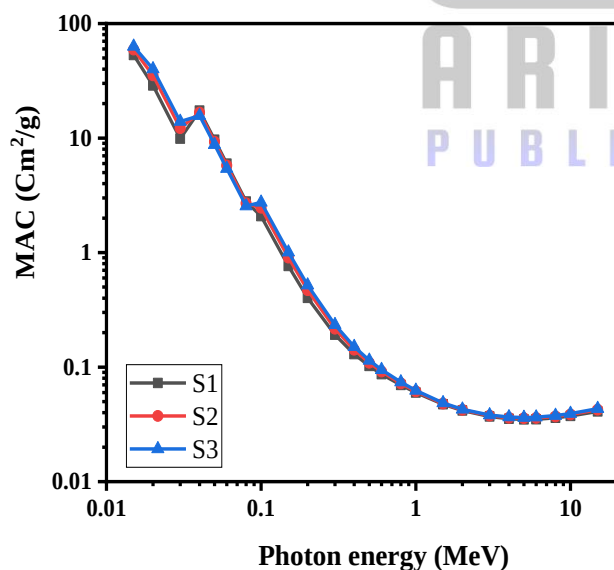
Table 2. Densities and elemental weight fractions of S1, S2, and S3.

Sample code	Density, ρ (g/cm ³)	Ba	O	Bi	Te
S1	5.427	0.1981	0.1661	0.1206	0.5153
S2	5.546	0.1453	0.1609	0.2212	0.4726
S3	6.371	0.0335	0.1637	0.3055	0.4974

3. RESULTS AND DISCUSSION

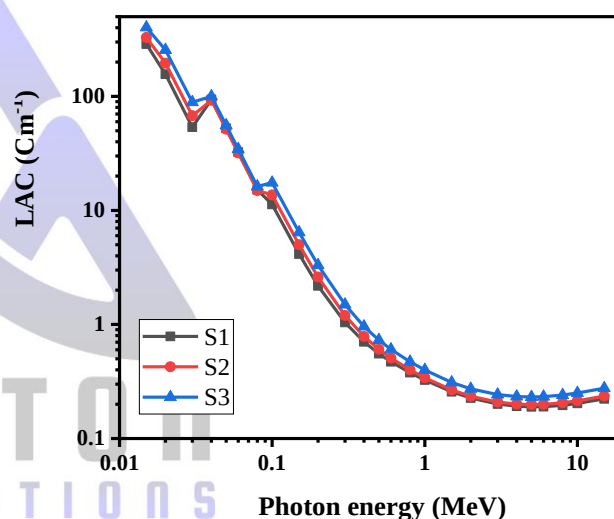
3.1. Mass and linear attenuation coefficients

The mass attenuation coefficients (MAC) calculated for the three BaO-Bi₂O₃-TeO₂ glasses exhibit a pronounced dependence on photon energy, as shown in Figure 1. Across the entire energy range from 0.015 to 15 MeV, the MAC values decrease markedly with increasing photon energy, reach broad minima in the few-MeV region, and then increase slightly toward 15 MeV. At the lowest energy examined, 0.015 MeV, the MAC values are 53.016, 59.164, and 63.100 cm²/g for S1, S2, and S3, respectively. These high values at low energies reflect the dominance of photoelectric absorption, which scales approximately with Z^{4-5}/E^3 , where Z is the effective atomic number and E is the photon energy [1]. Because S3 contains the highest bismuth content and the lowest barium content, its effective atomic number is greater than those of S1 and S2, leading to enhanced photoelectric absorption and consequently the highest MAC values at low energies.

**Fig. 1.** Mass attenuation coefficient of S1, S2, and S3 as a function of photon energy.

As photon energy increases, the MAC values decrease sharply, and between 4 and 6 MeV, they reach approximately

0.035–0.036 cm²/g for S1 and S2 and 0.036–0.037 cm²/g for S3. In this intermediate energy region, Compton scattering dominates the interaction process, and the mass attenuation coefficient becomes largely independent of atomic number, depending instead on the electron density of the material. At 15 MeV, the MAC values are 0.041, 0.042, and 0.043 cm²/g for S1, S2, and S3, respectively. The slight increase at the highest energies can be attributed to the onset of pair production, which becomes energetically allowed above 1.022 MeV and gradually increases in importance with increasing photon energy [2].

**Fig. 2.** Linear attenuation coefficient of S1, S2, and S3 as a function of photon energy.

Two low-energy discontinuities are visible in Figure 1, one between 0.03 and 0.04 MeV and another between 0.08 and 0.10 MeV. These discontinuities correspond to the K-shell absorption edges of bismuth (K-edge at approximately 0.0905 MeV) and tellurium (K-edge at approximately 0.0318 MeV), where the photoelectric cross-section increases abruptly as the photon energy exceeds the binding energy of the K-shell electrons [3]. Although the MAC curves for the three glasses remain relatively close to one another because the parameter is normalized by mass, S3 consistently exhibits the highest MAC values over most of the evaluated range, particularly at 0.015–0.03 MeV and at energies above 0.1 MeV. This behavior confirms that the replacement of BaO with Bi₂O₃ and the simultaneous increase in TeO₂ content

enhance the photon attenuation capability of the glass on a per-unit-mass basis.

The linear attenuation coefficient (LAC) provides a more direct measure of the shielding effectiveness of a material because it incorporates the density of the glass. As shown in Figure 2, the LAC values follow the same overall energy dependence as the MAC values, decreasing rapidly from low energies to a minimum in the few-MeV region before increasing slightly at higher energies. However, unlike the MAC, the LAC values exhibit clear separation among the three glasses across the entire energy range. This separation arises from the differences in density, which increase from 5.427 g/cm³ for S1 to 5.546 g/cm³ for S2 and 6.371 g/cm³ for S3. At 0.015 MeV, for example, the LAC values are approximately 287.7, 328.1, and 402.0 cm⁻¹ for S1, S2, and S3, respectively, reflecting the combined effects of higher density and higher effective atomic number in S3. At 1 MeV, the LAC values decrease to approximately 0.36, 0.38, and 0.42 cm⁻¹ for S1, S2, and S3, respectively. The consistent order S3 > S2 > S1 across the entire energy range demonstrates that the compositional and density modifications in the present series lead to a systematic improvement in photon attenuation performance.

3.2. Half-value layer, tenth-value layer, and mean free path

The half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP) are inversely related to the linear attenuation coefficient and therefore exhibit the opposite energy dependence. As shown in Figures 3–5, these parameters rise rapidly from low photon energies to the few-MeV region, then vary more gradually before decreasing toward 15 MeV. The three glasses consistently follow the order S3 < S2 < S1 for HVL, TVL, and MFP across the entire energy range. This ordering reflects the superior attenuation capability of S3, which arises from its higher density and higher effective atomic number relative to S1 and S2.

At 15 MeV, the HVL values are 3.111, 2.941, and 2.508 cm for S1, S2, and S3, respectively. The corresponding TVL values are 10.335, 9.769, and 8.331 cm, while the MFP values are 4.489, 4.243, and 3.618 cm. These results indicate that S3 requires the smallest thickness among the three glasses to reduce the uncollided photon intensity by one-half or one-tenth, and it also has the shortest average distance between photon interactions. The practical implication is that a shielding barrier constructed from S3 would be thinner and lighter than one made from S1 or S2 for the same level of attenuation, which is advantageous in applications where space and weight are constrained [4].

The comparison presented in Figures 3 and 5 shows that the investigated glasses exhibit lower HVL and MFP values than several commercial shielding glasses and concrete materials, including RS-253-G18, RS-360, RS-520, chromite,

ferrite, and magnetite, over the examined energy range. The most pronounced difference is observed relative to RS-253-G18, whose HVL and MFP increase more rapidly above approximately 2 MeV [5]. This finding suggests that the BaO-Bi₂O₃-TeO₂ glasses, particularly S3, offer competitive or superior shielding performance compared with established reference materials. However, these comparisons should be interpreted with caution, and the compositions, densities, and sources of the reference materials should be documented in the final manuscript to ensure a fair and meaningful comparison.

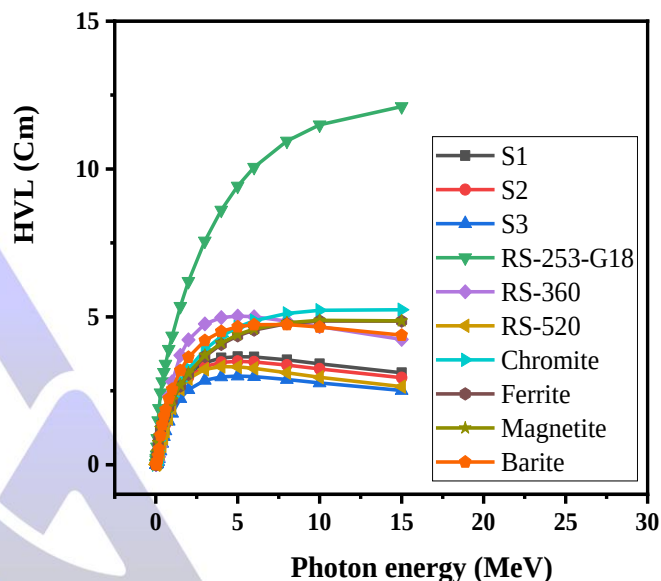


Fig. 3. Half-value layer of S1, S2, and S3 compared with commercial shielding glasses and concretes.

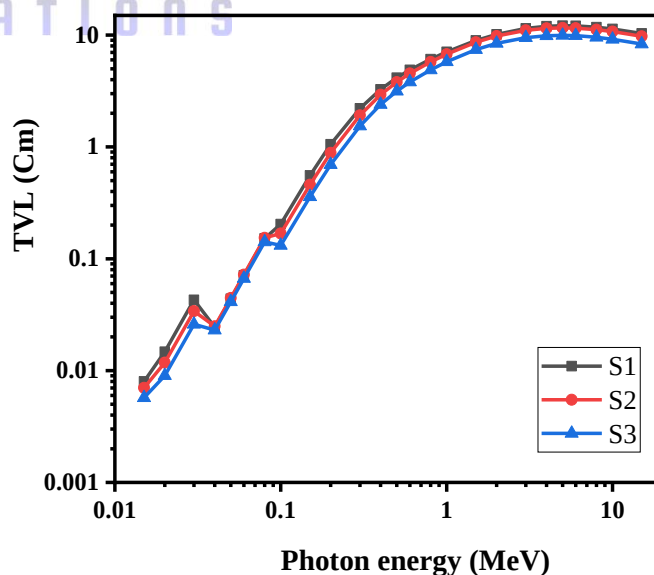


Fig. 4. Tenth-value layer of S1, S2, and S3 as a function of photon energy.

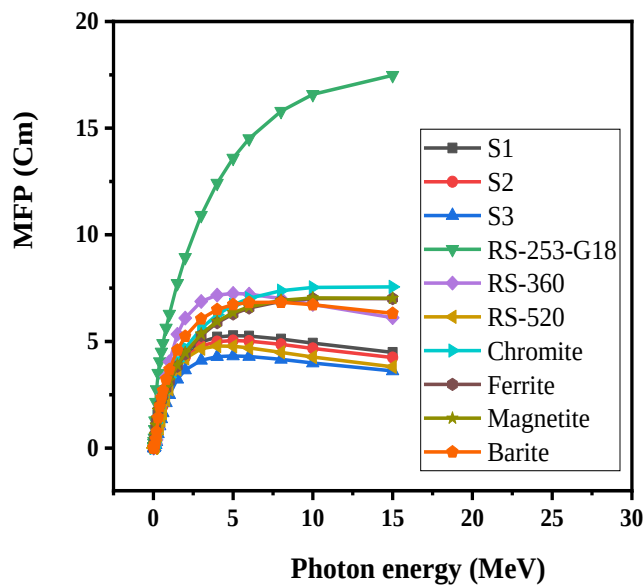


Fig. 5. Mean free path of S1, S2, and S3 compared with commercial shielding glasses and concretes.

3.3. Effective atomic number, effective electron density, and equivalent atomic number

The effective atomic number (Z_{eff}) provides a useful measure of the average interaction behaviour of a composite material and is particularly valuable for understanding the energy-dependent shielding characteristics of glasses. As shown in Figure 6, Z_{eff} is highest at low photon energies, decreases toward a minimum near 1–1.5 MeV, and increases again toward 15 MeV. At 0.015 MeV, the Z_{eff} values are 56.75, 60.86, and 63.87 for S1, S2, and S3, respectively. The maximum values occur at 0.02 MeV and are 59.55 for S1, 64.72 for S2, and 68.15 for S3. These maxima arise from the K-shell absorption edges of tellurium and bismuth, which enhance photoelectric absorption at energies just above the edge energies. The minimum values occur near 1–1.5 MeV, where Compton scattering dominates and the Z_{eff} becomes less sensitive to compositional variations. Above this minimum, Z_{eff} increases toward 15 MeV as pair production begins to contribute.

Throughout the calculated range, S3 exhibits the largest Z_{eff} values, followed by S2 and S1. This ordering is consistent with the increasing bismuth content and decreasing barium content from S1 to S3, since bismuth ($Z = 83$) has a much higher atomic number than barium ($Z = 56$) and tellurium ($Z = 52$). The higher Z_{eff} of S3 explains its superior photon attenuation performance, particularly at low and high energies where photoelectric absorption and pair production are the dominant interaction mechanisms.

The effective electron density (N_{eff}) follows a similar energy-dependent trend, as shown in Figure 7. At 0.02 MeV, the N_{eff} values are 5.90×10^{23} , 6.19×10^{23} , and 6.50×10^{23} electrons/g for S1, S2, and S3, respectively. These values

decrease to minima near 1–1.5 MeV, ranging from 2.66×10^{23} to 2.78×10^{23} electrons/g. At 15 MeV, N_{eff} increases to 3.85×10^{23} , 3.93×10^{23} , and 4.02×10^{23} electrons/g for S1, S2, and S3, respectively. The higher N_{eff} values for S3 across the energy range reflect its higher electron density, which contributes to the enhanced Compton scattering probability at intermediate energies.

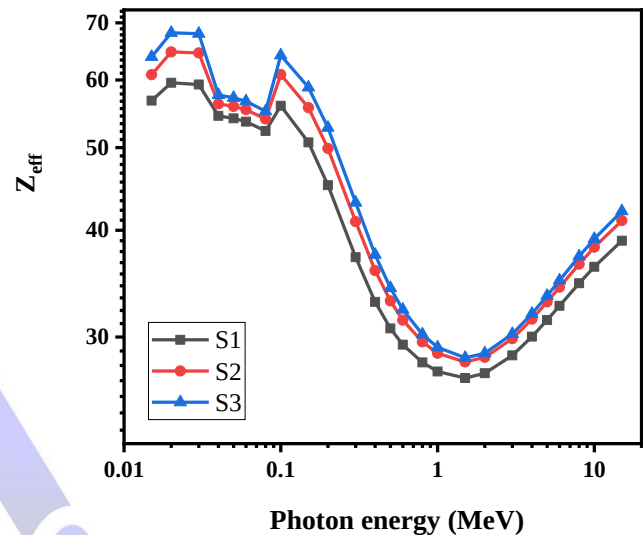


Fig. 6. Effective atomic number of S1, S2, and S3 as a function of photon energy.

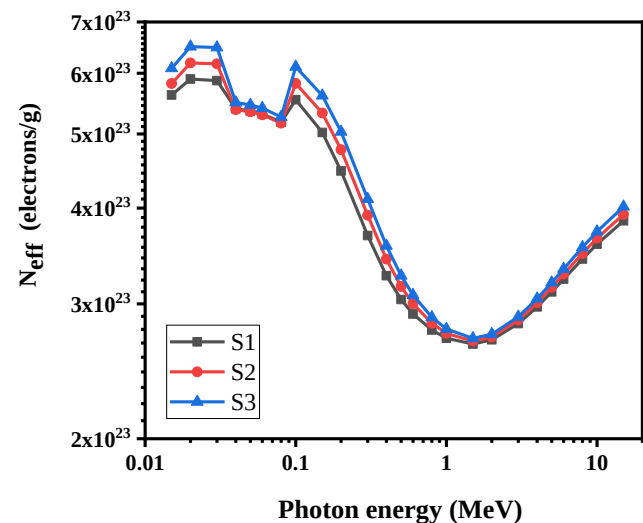


Fig. 7. Effective electron density of S1, S2, and S3 as a function of photon energy.

The equivalent atomic number (Z_{eq}) exhibits a distinct energy dependence, as shown in Figure 8 and summarized in Tables 3–5. Z_{eq} increases from 27.12, 28.33, and 29.03 at 0.015 MeV for S1, S2, and S3, respectively, to maximum values of 56.41, 60.66, and 63.48 at 1 MeV. The values then decrease to 46.43

for S1, 49.07 for S2, and 50.67 for S3 at 15 MeV. A marked increase occurs between 0.03 and 0.04 MeV, followed by another increase between 0.08 and 0.10 MeV. These increases coincide with the K-shell absorption edges of tellurium and bismuth, respectively, and reflect the abrupt changes in the photoelectric cross-section at these energies. S3 has the highest Z_{eq} throughout the calculated energy grid, consistent with its higher bismuth content and higher density.

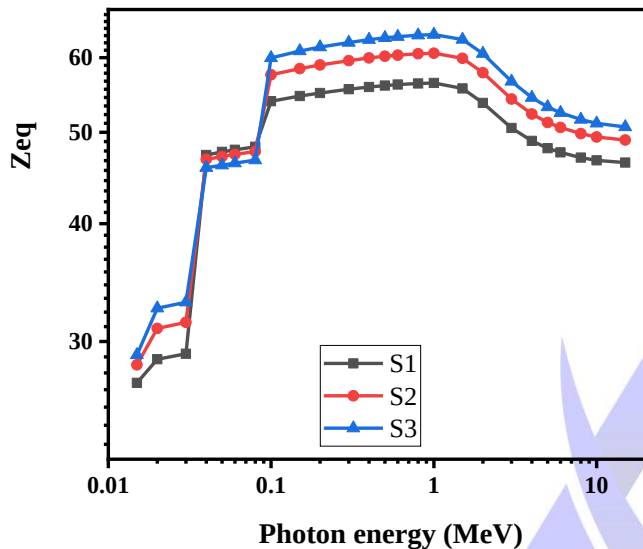


Fig. 8. Equivalent atomic number of S1, S2, and S3 as a function of photon energy.

3.4. Atomic and electronic cross-sections

The atomic cross-section (ACS) represents the effective cross-sectional area per atom for photon interaction and provides insight into the microscopic attenuation behavior of the glass. As shown in Figure 9, the ACS decreases strongly with photon energy, apart from the discontinuities in the low-energy region, reaches a minimum at approximately 6–10 MeV, and increases slightly toward 15 MeV. At 0.015 MeV, the ACS values are 5.35×10^{-21} , 6.19×10^{-21} , and 6.62×10^{-21} cm²/g for S1, S2, and S3, respectively. At 15 MeV, the values decrease to 4.15×10^{-24} , 4.45×10^{-24} , and 4.55×10^{-24} cm²/g, respectively. S3 generally exhibits the highest ACS values across the energy range, consistent with its higher effective atomic number and greater photoelectric absorption capability.

The electronic cross-section (ECS) also decreases with increasing photon energy and becomes nearly constant in the high-energy region, as shown in Figure 10. At 0.015 MeV, the ECS values are 9.43×10^{-23} , 1.02×10^{-22} , and 1.04×10^{-22} cm²/g for S1, S2, and S3, respectively. At 15 MeV, the values are 1.07×10^{-25} , 1.08×10^{-25} , and 1.08×10^{-25} cm²/g, respectively. The compositional separation is smaller for

ECS than for ACS, especially at higher energies, because the ECS is normalized by the number of electrons rather than the number of atoms, and the electron density varies less among the three glasses than the atomic number.

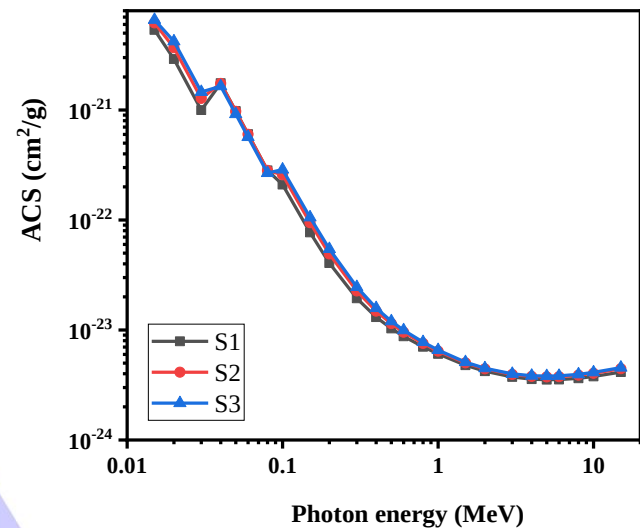


Fig. 9. Atomic cross-section of S1, S2, and S3 as a function of photon energy.

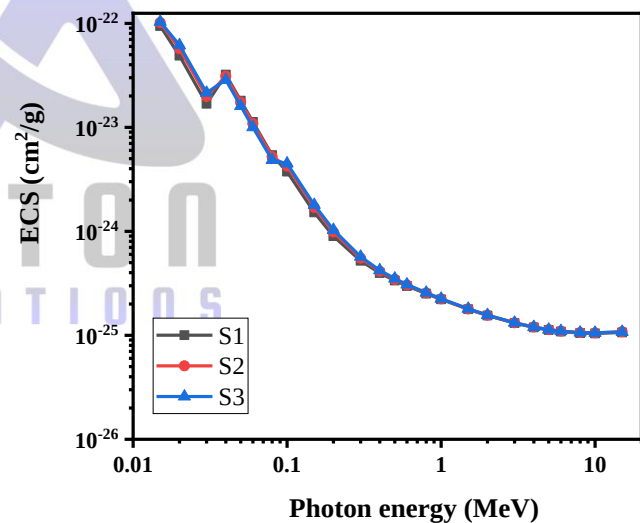


Fig. 10. Electronic cross-section of S1, S2, and S3 as a function of photon energy.

3.5. Fast-neutron removal cross-section

The fast-neutron removal cross-section (FNRCs) is a key parameter for assessing the effectiveness of a material in attenuating fast neutrons. The calculated FNRCs values are 0.095 cm⁻¹ for S1, 0.094 cm⁻¹ for S2, and 0.107 cm⁻¹ for S3. Thus, the three glasses follow the order S1 $\approx$ S2 < S3, with S3 exhibiting the largest fast-neutron removal cross-section

among the investigated compositions. This result can be attributed to the higher density and higher bismuth content of S3, since bismuth has a relatively large neutron removal cross-section compared with barium and tellurium.

Figure 11 compares the FNRCs values of the investigated glasses with those of commercial shielding glasses and selected concrete materials. S3 exceeds RS-253-G18, RS-360, and RS-520, while RS-360 exhibits the lowest FNRCs among the materials included in the comparison. Chromite, ferrite, and magnetite show higher FNRCs values than the investigated glasses, whereas barite exhibits values close to those of the glass samples. Therefore, S3 shows a larger calculated FNRCs than the listed commercial glasses, although its value remains below those of chromite-, ferrite-, and magnetite-based concretes [6]. These results suggest that S3 is a promising candidate for combined photon and fast-neutron shielding applications, particularly where the superior photon attenuation of the glass is advantageous.

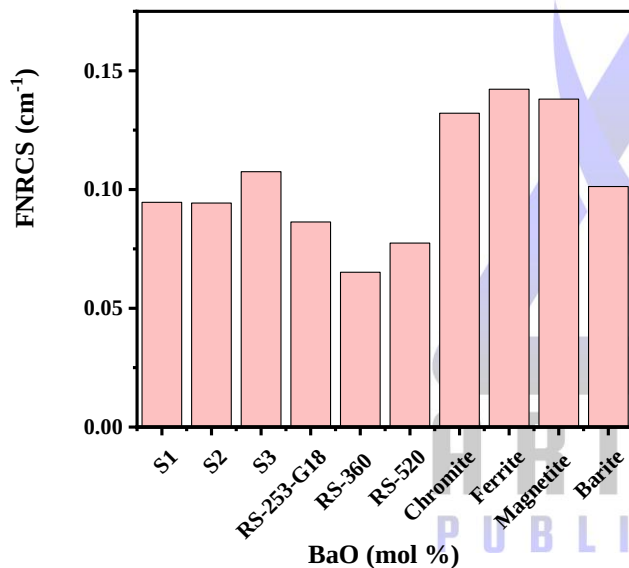


Fig. 11. Fast-neutron removal cross-sections of S1, S2, and S3 compared with commercial shielding glasses and concretes.

3.6. Exposure and energy absorption buildup factors

The exposure buildup factor (EBF) and energy absorption buildup factor (EABF) account for the contribution of scattered photons that accumulate within finite shielding thicknesses and can significantly alter the effective dose behind a shield. These parameters depend strongly on photon energy and penetration depth, as illustrated in Figures 12–17 for the three glasses.

For S1, the EBF and EABF increase with penetration depth from 0.5 to 40 mfp, as shown in Figures 12 and 13. At 0.015 MeV, both factors remain close to unity over the

examined penetration-depth range, indicating that scattered photons make a negligible contribution to the total dose at this energy. A sharp maximum occurs at 0.04 MeV, where the EBF and EABF values at 40 mfp reach 2.91×10^5 and 2.07×10^5 , respectively. This maximum coincides with the K-shell absorption edge of tellurium and reflects the abrupt increase in photoelectric absorption followed by increased scattering. The buildup factors decrease at intermediate energies before increasing toward the upper end of the energy range, where pair production and Compton scattering produce additional scattered photons.

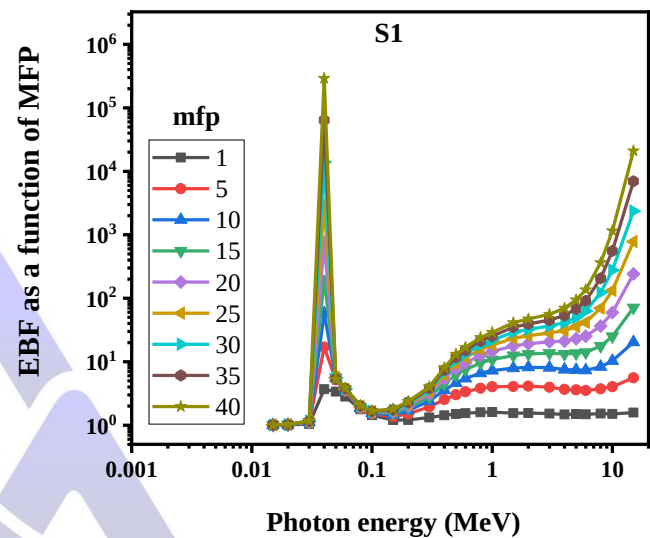


Fig. 12. Exposure buildup factor of S1 as a function of photon energy at penetration depths of 0.5–40 mfp.

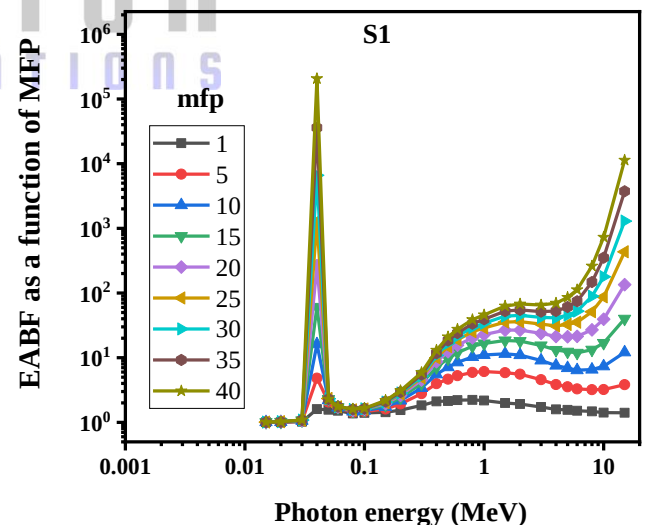


Fig. 13. Energy absorption buildup factor of S1 as a function of photon energy at penetration depths of 0.5–40 mfp.

For S2, the EBF values at 0.015 MeV remain close to unity

at all penetration depths, as shown in Figure 14. At 0.02 MeV, however, the EBF increases from 1.19 at 0.5 mfp to 9.13×10^{21} at 40 mfp. A secondary maximum is observed at 0.04 MeV, where the EBF increases from 2.42 at 0.5 mfp to 3.30×10^4 at 40 mfp. At photon energies above approximately 0.05 MeV, the EBF values decrease sharply from these low-energy maxima and remain comparatively low at moderate penetration depths.

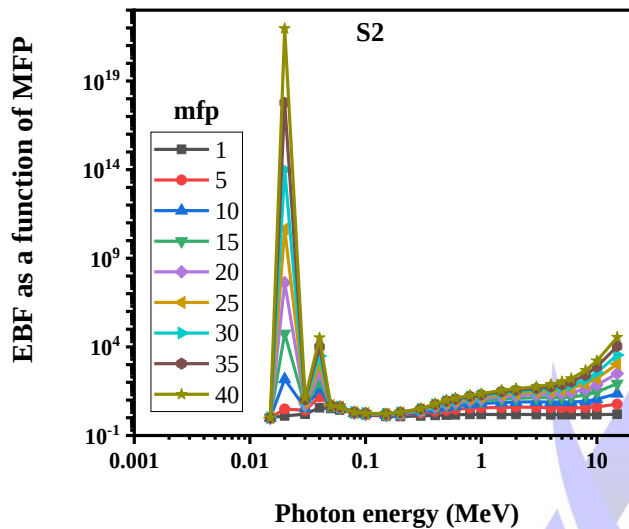


Fig. 14. Exposure buildup factor of S2 as a function of photon energy at penetration depths of 0.5–40 mfp.

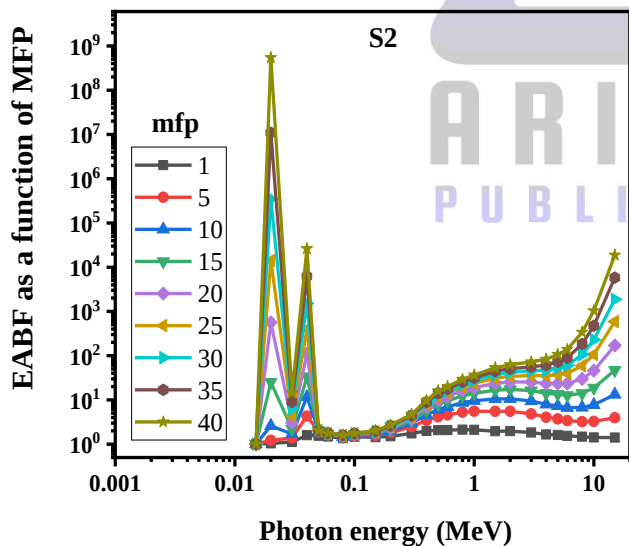


Fig. 15. Energy absorption buildup factor of S2 as a function of photon energy at penetration depths of 0.5–40 mfp.

At higher energies, the EBF again increases with penetration depth, particularly above approximately 0.3 MeV. The corresponding EABF results for S2 are presented in Figure 15. The EABF curves show the same overall dependence on photon energy and penetration depth, but their magnitudes

differ from those of EBF. At 0.02 MeV, the EABF increases from 1.03 at 0.5 mfp to 5.44×10^8 at 40 mfp. At 0.04 MeV, the EABF increases from 1.31 at 0.5 mfp to 2.63×10^4 at 40 mfp. The EABF values are therefore lower than the corresponding EBF values at 0.02 MeV, although both quantities show pronounced maxima at the same low-energy position.

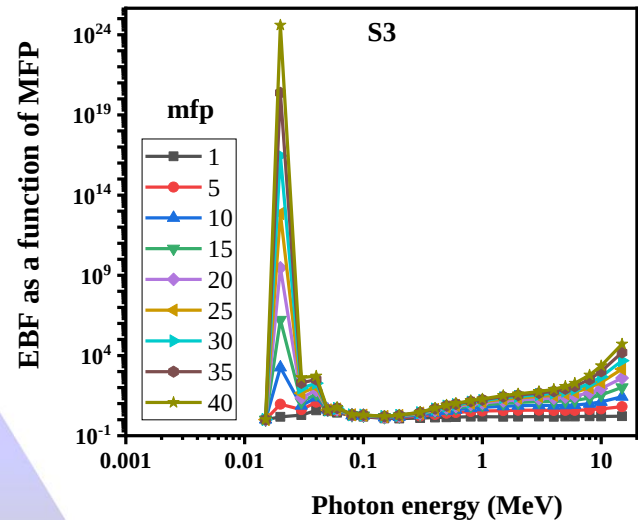


Fig. 16. Exposure buildup factor of S3 as a function of photon energy at penetration depths of 0.5–40 mfp.

For S3, the EBF values at 0.015 MeV remain close to unity for all depths, as observed for S1 and S2, as shown in Figure 16. At 0.02 MeV, the calculated EBF increases from 1.29 at 0.5 mfp to 4.00×10^{24} at 40 mfp. This value exceeds the corresponding maximum for S2. The secondary EBF maximum at 0.04 MeV is also evident, although it is considerably smaller than the peak at 0.02 MeV; the EBF rises from 2.49 at 0.5 mfp to 5.27×10^2 at 40 mfp. Beyond the low-energy maxima, the curves decrease sharply and then increase again toward the high-energy end of the investigated range as the penetration depth increases. Figure 17 shows the EABF of S3. At 0.02 MeV, the EABF increases from 1.04 at 0.5 mfp to 3.51×10^{12} at 40 mfp. At 0.04 MeV, the EABF increases from 1.31 at 0.5 mfp to 4.25×10^2 at 40 mfp. As in S2, the EABF of S3 retains the same locations of the principal and secondary low-energy maxima as the EBF, while the corresponding numerical magnitudes differ.

The sharp maxima in Figures 14–17 occur at photon energies where Z_{eq} and the G–P fitting coefficients change abruptly. For S2, Z_{eq} increases from 28.33 at 0.015 MeV to 30.97 at 0.02 MeV and 31.44 at 0.03 MeV before increasing to 46.81 at 0.04 MeV. For S3, Z_{eq} increases from 29.03 at 0.015 MeV to 32.54 at 0.02 MeV and 33.02 at 0.03 MeV before reaching 45.87 at 0.04 MeV. The large buildup values coincide with the energy points at which the G–P parameter sets differ most strongly between adjacent photon energies. Therefore, the low-energy maxima should be reported as calculated G–P buildup-factor results and interpreted

cautiously. Outside the narrow maxima near 0.02 and 0.04 MeV, the calculated EBF and EABF values are substantially lower over the intermediate-energy interval of 0.1–1 MeV. For example, at 1 MeV and 40 mfp, the EBF values are 22.9 for S2 and 19.6 for S3, whereas the EABF values are 36.4 for S2 and 30.9 for S3. These values are many orders of magnitude lower than the corresponding low-energy maxima at 0.02 MeV. The comparison demonstrates that buildup behavior depends strongly on photon energy and penetration depth and cannot be represented by a single composition-dependent ranking over the entire energy range.

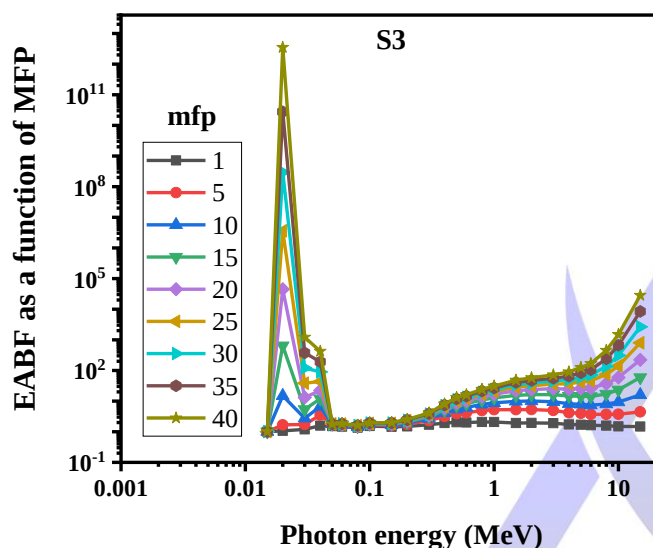


Fig. 17. Energy absorption buildup factor of S3 as a function of photon energy at penetration depths of 0.5–40 mfp.

The results presented in this section demonstrate that the BaO–Bi₂O₃–TeO₂ glasses, particularly S3, exhibit promising photon and fast-neutron shielding characteristics. The systematic variation of composition and density across the S1–S3 series leads to consistent trends in all calculated parameters, with S3 consistently showing the most favorable combination of high attenuation coefficients, high effective atomic number and electron density, low half-value layer and mean free path, and high fast-neutron removal cross-section. These findings provide a basis for further experimental investigation and potential application of these glasses in radiation shielding.

4. CONCLUSION

Three BaO–Bi₂O₃–TeO₂ glasses, S1, S2 and S3, with measured densities of 5.427, 5.546 and 6.371 g/cm³, respectively, were assessed using Phy-X/PSD software over the photon-energy range 0.015–15 MeV. The calculated photon-shielding parameters included μ_m , μ , HVL, TVL, MFP, Z_{eff} , N_{eff} , Z_{eq} , ACS, ECS, EBF and EABF. Fast-neutron removal cross-sections were also calculated. The mass

attenuation coefficients decreased with increasing photon energy to a broad minimum in the few-MeV region and rose slightly at high energies. The linear attenuation coefficient followed the order S3 > S2 > S1 throughout the evaluated energy range. Consequently, S3 showed the smallest HVL, TVL and MFP values. At 15 MeV, the HVL, TVL and MFP of S3 were 2.508, 8.331 and 3.618 cm, respectively, compared with 3.111, 10.335 and 4.489 cm for S1. S3 also exhibited the largest values of Z_{eff} , N_{eff} and Z_{eq} . The calculated FNRCs values were 0.095, 0.094 and 0.107 cm⁻¹ for S1, S2 and S3, respectively. S3 exceeded the selected commercial shielding glasses in the FNRCs comparison, whereas chromite, ferrite and magnetite remained higher than the present glass compositions. The EBF and EABF increased with penetration depth and showed pronounced maxima at low energies, particularly at 0.02 MeV for S2 and S3. Away from these low-energy peaks, the buildup factors were substantially lower over the intermediate energy range of 0.1–1 MeV. Among the three investigated compositions, S3 provided the most favourable set of calculated photon-attenuation and fast-neutron-removal parameters.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

Abdulaziz A. Asiri: Formal Analysis, Data Curation, interpretation of results and original draft preparation; Ahmed Y. A. Mohamed: Sample preparation, Experimental

Work, Data collection, and interpretation of results. Ahmed Y. A. Mohamed: Data Curation, Write and Review.

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