

RESEARCH ARTICLE

Radiation Shielding and Optical Features of Tellurite-Based Glasses Modified with RO (R=Ba, Mg, Sr) Oxides

Khalid I. Hussein^{1,2}, Mohammed S. Alqahtani^{1,2}, Iwona Grelowska³, Manuela Reben³

ABSTRACT: The development of effective radiation shielding materials is essential due to the toxicity, cost, and weight associated with conventional lead-based shields. This study computationally investigates four tellurite-based glass systems containing different metal oxides across an energy range of 0.015–15 MeV. The studied compositions incorporate Er₂O₃, MgO, BaO, and SrO as modifying oxides. Key shielding parameters, including mass and linear attenuation coefficients, half-value layer, mean free path, effective atomic number, effective electron density, and transmission factor, were evaluated using WinXCom and Phy-X/PSD software. The results demonstrate that the BaO-containing glass exhibits marginally superior shielding performance compared with the other investigated compositions, attributed to the higher atomic number and density contribution of barium. Comparative analysis indicates considerable attenuation effectiveness across the studied energy range, with performance exceeding several conventional shielding materials at specific energies. These findings highlight tellurite-based metal-oxide glasses as promising radiation shielding materials for medical and other radiation protection applications.

Keywords: Radiation Shielding, Tellurite Glasses, Attenuation Coefficients, Half-Value Layer, Effective Atomic Number, Metal Oxide Modification

Received: 24 December 2025; Revised: 04 February 2026; Accepted: 14 March 2026; Published Online: 02 May 2026

1. INTRODUCTION

Ionizing radiation technologies have become indispensable across numerous beneficial applications, particularly in the fields of medical imaging and cancer therapy [1-3]. The continuous advancement of diagnostic and therapeutic techniques has led to increased utilization of x-rays, gamma rays, and other forms of ionizing radiation, bringing

substantial benefits to patient care while simultaneously introducing inherent risks that must be carefully managed. The fundamental principles of radiation protection center on three primary factors: minimizing exposure time, maximizing distance from radiation sources, and implementing effective shielding strategies. Despite the undeniable advantages of these technologies, there exists a well-documented association between ionizing radiation exposure and potential harmful biological effects, which has prompted extensive investigation into the relative contributions of medical exposures to population dose burdens [4-8].

Radiation shielding constitutes one of the most critical components in comprehensive radiation protection programs, serving to attenuate radiation beams and reduce the dose received by both patients and healthcare workers to levels that are considered safe for human health. The effectiveness of any shielding material depends on multiple interrelated

¹ Central Labs, King Khalid University, AlQura,a, Abha, P. O. Box 906, Saudi Arabia.

² Department of Radiological Sciences, College of Applied Medical Sciences, King Khalid University, Abha 61421, Saudi Arabia.

³ Faculty of Materials Science and Ceramics, AGH – University of Science and Technology, al. Mickiewicza 30, 30-059 Cracow, Poland.

* Author to whom correspondence should be addressed:
kirahim@kku.edu.sa (Khalid I. Hussein)

factors, including the energy of incident photons, the type and intensity of radiation emission, and the intrinsic physical characteristics of the shielding material itself. Generally, materials possessing high atomic numbers and high densities demonstrate superior shielding effectiveness due to their increased probability of photon interactions through photoelectric absorption and Compton scattering processes. Historically, lead, tungsten, and various concrete formulations have served as the primary materials for x-ray and gamma-ray shielding applications, with lead being particularly favored due to its combination of high atomic number ($Z=82$), substantial density, and relatively low cost compared to other heavy metals [9-12].

However, the widespread use of lead in radiation shielding presents several significant drawbacks that have motivated researchers to seek viable alternatives. Lead is highly toxic and poses serious health risks during manufacturing, installation, and disposal processes, requiring stringent safety protocols to prevent occupational exposure [10]. Additionally, lead shielding materials are remarkably heavy and bulky, making them impractical for many applications where mobility or space constraints are considerations. The poor mechanical strength and relatively low melting point of lead further limit its applicability in certain environments. These limitations have driven substantial research efforts toward developing alternative shielding materials that can match or exceed the attenuation properties of lead while eliminating its disadvantages [11-12].

Among the most promising candidates for next-generation radiation shielding materials are phosphate, tellurite, and germanate-tellurite glass systems doped with various metal oxides [13-32]. These glass materials offer a remarkable combination of properties that make them particularly attractive for radiation protection applications, including excellent thermal stability, good optical transparency that allows for visual monitoring of equipment, high shielding efficiency across a broad energy spectrum, and the ability to be fabricated into complex shapes using established glass-forming techniques. The incorporation of metal oxides such as sodium oxide (Na_2O), barium oxide (BaO), erbium oxide (Er_2O_3), and zinc oxide (ZnO) into the glass matrix allows for systematic modification of the material's physical and shielding properties through careful compositional tuning.

Considerable research attention has been directed toward understanding the relationships between glass composition, physical properties, and radiation shielding parameters. Kaur and colleagues [18] conducted a comprehensive investigation of the bismuth borate glass system modified with barium oxide (Bi_2O_3 - BaO - B_2O_3) across a wide energy range spanning from 1 keV to 100 GeV, demonstrating that the addition of barium effectively increases the effective atomic number while simultaneously decreasing the tenth-value layer and mean free path, thereby enhancing shielding performance. Vania and coworkers [19] examined the structural, optical, thermal, and gamma-ray shielding characteristics of fluoro-tellurite glasses doped with barium and zinc, concluding that glass systems

incorporating heavy elements such as barium exhibit strengthened shielding properties and represent viable substitutes for conventional concrete and lead-based glasses. Grelowska and associates [20] investigated the influence of barium oxide on the optical and thermal properties of TeO_2 - BaO - Na_2O and TeO_2 - BaO - WO_3 glass systems, finding that barium-containing glasses demonstrate higher refractive indices, greater network polymerization, and enhanced crystallization tendencies compared to glasses containing other heavy elements.

The novelty of the present work lies in the comprehensive evaluation of four novel tellurite-based glass compositions that have not been previously investigated for their combined optical and radiation attenuation properties. Specifically, we have designed and analyzed glass systems incorporating magnesium oxide, barium oxide, and strontium oxide as modifiers within the same base glass framework, enabling direct comparison of the effects of these different alkaline earth oxides on shielding performance. While individual studies have examined some of these components separately, the systematic comparison of RO oxides (where R represents Ba, Mg, or Sr) within identical tellurite glass matrices provides unique insights into the relative contributions of each modifier to the overall shielding effectiveness.

Furthermore, the present investigation extends beyond simple attenuation coefficient calculations to encompass comprehensive shielding parameters including total atomic cross-sections, electronic cross-sections, effective atomic numbers, effective electron densities, equivalent atomic numbers, and exposure buildup factors, thereby providing a thorough characterization of these materials for radiation protection applications.

In this paper, we report the synthesis and comprehensive evaluation of four novel tellurite-based glass systems with compositions of 75TeO_2 - $10\text{P}_2\text{O}_5$ - 10ZnO - 5PbF_2 - $0.24\text{Er}_2\text{O}_3$, 70TeO_2 - $10\text{P}_2\text{O}_5$ - 10ZnO - 5PbF_2 - 5MgO - $0.24\text{Er}_2\text{O}_3$, 70TeO_2 - $10\text{P}_2\text{O}_5$ - 10ZnO - 5PbF_2 - 5BaO - $0.24\text{Er}_2\text{O}_3$, and 70TeO_2 - $10\text{P}_2\text{O}_5$ - 10ZnO - 5PbF_2 - 5SrO .

The radiation shielding parameters including mass and linear attenuation coefficients, half-value layers, mean free paths, atomic and electronic cross-sections, effective atomic numbers, effective electron densities, equivalent atomic numbers, and exposure buildup factors have been systematically calculated across a wide energy spectrum ranging from 0.015 to 15 MeV using the WinXcom program and the Phy-X/PSD online software platform. Additionally, the optical properties including dispersion energy, single oscillator energy, refractive indices, and nonlinear optical susceptibilities have been evaluated to establish comprehensive structure-property relationships. The shielding effectiveness of the proposed glass systems is compared with commercially available radiation shielding materials including RS-253 G18, RS-520, and RS-369 glass formulations as well as chromite and ferrite concretes, demonstrating the considerable potential of these novel glass compositions for practical radiation protection applications in medical diagnostic and therapeutic settings.

2. EXPERIMENTAL DETAILS

2.1 Experimental Procedure

The Er^{3+} ions doped glass systems with a composition of We developed tellurite glass systems with different compositions: $75\text{TeO}_2 - 10\text{P}_2\text{O}_5 - 10\text{ZnO} - 5\text{PbF}_2 - 0.24\text{Er}_2\text{O}_3$ (Sample A), $70\text{TeO}_2 - 10\text{P}_2\text{O}_5 - 10\text{ZnO} - 5\text{PbF}_2 - 5\text{MgO} - 0.24\text{Er}_2\text{O}_3$ (Sample B), $70\text{TeO}_2 - 10\text{P}_2\text{O}_5 - 10\text{ZnO} - 5\text{PbF}_2 - 5\text{BaO} - 0.24\text{Er}_2\text{O}_3$ (Sample C) and $70\text{TeO}_2 - 10\text{P}_2\text{O}_5 - 10\text{ZnO} - 5\text{PbF}_2 - 5\text{SrO}$ (Sample D). We prepared the samples with a melting technique. We put the raw material in Pt crucible in the heating furnace at a temperature of 850°C for 30 min, the melt was stirred, when the viscous of it was high consequently the melt cast in the brass mold. The prepared sample was put in the annealing furnace for 2h at 320°C and after that switch off. The prepared samples A, B, C, and D after annealing were homogeneous by our research group [33] and were shown in Figure 1. Table 1 shows the weights of prepared samples with the mole fractions of their component elements (Te, O, P, Zn, Pb, F, Mg, Ba, Sr, Er). The densities of these glasses are in the range between 5.126 to 5.267 g/cm^3 . The shielding parameters of the proposed glasses system were computed using the program WinXcom [34] and the online developed software (Phy-X/PSD) [35]. The results of shielding properties were compared with other

commercial shielding materials commonly used in photon and neutron applications.

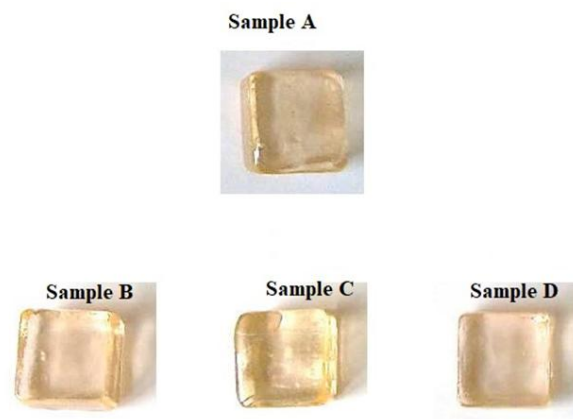


Fig. 1. Photographs for the prepared glassy samples as quenching after annealing by the same authors [33].

The probability for the interaction of photons with the material could be achieved by the total atom cross-section (σ_a) and total electronic cross-section (σ_e) using the following relations [32]:

Table 1. Summary of the chemical compositions, densities, and weight fractions of the elements utilized for the proposed sample A, B, C, and D.

Sample ID	Composition in mol%	Density ρ (g/cm^3)	The weight fraction of elements in percentage									
			Te	O	P	Zn	Pb	F	Mg	Ba	Sr	Er
Sample A	$75\text{TeO}_2 - 10\text{P}_2\text{O}_5 - 10\text{ZnO} - 5\text{PbF}_2 - 0.24\text{Er}_2\text{O}_3$	5.267	0.6166	0.2172	0.0399	0.0421	0.0667	0.0122	-----	-----	-----	0.0052
Sample B	$70\text{TeO}_2 - 10\text{P}_2\text{O}_5 - 10\text{ZnO} - 5\text{PbF}_2 - 5\text{MgO} - 0.24\text{Er}_2\text{O}_3$	5.126	0.5985	0.2205	0.0415	0.0438	0.0694	0.0127	0.0081	-----	-----	0.0054
Sample C	$70\text{TeO}_2 - 10\text{P}_2\text{O}_5 - 10\text{ZnO} - 5\text{PbF}_2 - 5\text{BaO} - 0.24\text{Er}_2\text{O}_3$	5.262	0.5876	0.2119	0.0380	0.0401	0.0636	0.0117	-----	0.0422	-----	0.0049
Sample D	$70\text{TeO}_2 - 10\text{P}_2\text{O}_5 - 10\text{ZnO} - 5\text{PbF}_2 - 5\text{SrO}$	5.208	0.6001	0.2157	0.0388	0.0410	0.0650	0.0119	-----	-----	0.0275	-----

$$\sigma_a = \frac{1}{N_A} \sum_i f_i A_i \left(\frac{\mu}{\rho}\right)_i \quad (2)$$

$$\sigma_e = \frac{1}{N_A} \sum_j f_j \frac{A_j}{Z_j} \left(\frac{\mu}{\rho}\right)_j \quad (3)$$

Where f_i is the fraction by mole of the i^{th} atomic element, A_i is the atomic weight of the i^{th} atomic element, Z_j is atomic number and N_A is Avogadro constant. The effective atomic number is a basic parameter, which can be used to characterize the properties of a radiation shielding composition. The effective atomic number which varies with energies can be calculated from the ratio of atomic and electronic cross-sections by the following relation:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \quad (4)$$

The electron density which represents the number of electrons per unit mass of the shielding material can be computed as follow [32]:

$$N_e = \frac{N_A}{A} Z_{eff} \quad (5)$$

Where A represents the mean atomic mass, which is equal to $\sum_i f_i A_i$; f_i is the fraction by mole of the i^{th} atomic element, A_i is the atomic weight of the i^{th} atomic element. The mean free path (MFP) and the half-value layer (HVL) are also play a prime role in characterizing the effects of the ionizing radiation shielding materials. The HVL is the thickness that reduced the intensity of the mono-energetic beam to half of its value. The average distance between two successive interactions represented as the MFP. These parameters can define by the following relations:

$$HVL = \frac{0.693}{\mu} \quad (6)$$

$$MFP = \frac{1}{\mu} \quad (7)$$

Where μ is the linear attenuation coefficient. The equivalent atomic number (Z_{eq}) for the proposed shielding composition can be computed through matching the mass attenuation coefficients' ratio of the compton component to the total mass attenuation coefficients at selected energies with the ratio of an element within the same range of the selected ionizing radiation energies. If the ratio lies between two elements, the equivalent atomic number (Z_{eq}) is calculated using the following interpolation procedure [29, 30]:

$$Z_{eq} = \frac{(Z_1 \log R_2 - \log R) + (\log R - \log R_1)}{\log R_2 - \log R_1} \quad (8)$$

Where Z_1 and Z_2 are atomic numbers of two elements in relation to the ratio R_1 and R_2 , R is the ratio of the proposed shielding material. In estimating the physical properties of the proposed shielding material using Lambert-Beer Law, the thin absorbing material is considered which is not the general condition, for the general condition an additional correction

factor needs to be introduced which account for the photon buildup in the material of intersect. The buildup factor is the proportion of the overall radiation quantity at any spot to the quantity value of the uncollided ionizing photons reaching the same spot. Two types of buildup factors are of interest: The exposure buildup factor (EBF) and the energy absorption buildup factor (EABF) [35]. These factors depend upon the atomic number of the shielding composition, photon energy, and the mean free path of mono-energetic beam. The buildup factors can be computed utilizing the geometric-progression (G-P) developed by Harima et.al [35, 36]. The G-P fitting parameters for the proposed materials can be computed using the following formula:

$$C = \frac{(C_1 \log Z_2 - \log Z_{eq}) + (\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1} \quad (9)$$

Where C_1 and C_2 are the values of the G-P fitting parameters, which correspond to the atomic numbers Z_1 and Z_2 , respectively. Using the G-P fitting parameters at selected range of energies, the Buildup factors can be estimated from the following equations [31]:

$$B(E, X) = 1 + \frac{b-1}{K-1} (K^x - 1) \quad \text{for } K \neq 1 \quad (10)$$

$$B(E, X) = 1 + (b-1)X \quad \text{for } K = 1 \quad (11)$$

$$K(E, X) = CX^a + d \frac{\tanh\left(\frac{x}{X_K} - 2\right) - \tanh(-2)}{1 - \tanh(-2)} \quad \text{for } x \leq 40 \text{ mf} \quad (12)$$

Where x represents the source -detector distance (SDD), in MFP units. E represents the energy of the incident photons, (X_K , b , a , and d) expresses the G-P fitting parameters, and $K(E, x)$ represents the dose multiplicative factor.

3. RESULTS AND DISCUSSION

Optical parameters such as; dispersion energy, E_d , single oscillator energy, E_s , electronic with magnetic oscillator strength, linear refractive indices, n , non-linear refractive indices, n_2 , and third-order susceptibility $\chi^{(3)}$ are important to use in the process of fabricating optical devices. These parameters strongly depended on the chemical composition of prepared glasses. By utilizing the single oscillator model estimated by wimple and DiDomenico, the results of E_d and E_s were evaluated by using the following relation:

$$[n^2 - 1]^{-1} = \frac{E_s^2 - E^2}{E_d E_s} \quad (13)$$

Where $E = \frac{hw}{2\pi}$, Figure (1) shows a plot of $[n^2 - 1]^{-1}$ versus, E^2 , for prepared samples A, B, C, and D were investigated. From the linear regression, we can determine the values of, E_s , and, E_d , for prepared glasses, which E_s and E_d are in two different ranges between 7.13 and 7.48, and from 20.33 to

21.28 eV, respectively.

Based on the above model, the single oscillator parameters, E_s and E_d are related to the imaginary component, ε_i , of the complex dielectric constant and the -1 and -3 moments of the, ε_i , the optical spectrum can be derived from them;

$$E_s^2 = \frac{M_{-1}}{M_{-3}} \quad (14)$$

$$E_d^2 = \frac{M_{-1}^3}{M_{-3}} \quad (15)$$

hence,

$$M_{-1} = \frac{E_d}{E_s}, \quad M_{-3} = \frac{E_d^3}{E_s^3} \quad (16)$$

Moreover, sample B has the highest value of both E_d and E_s in eV otherwise sample D has the lowest value. This value depends directly on the single bond strength B_{M-O} in kJ/mol of the modifier in the glasses sample where it is of MgO= 155kJ/mol, BaO= 138 kJ/mol and of SrO= 134 kJ/mol), otherwise the value of M_{-3} indirect sequences with B_{M-O} in kJ/mol. The third-order nonlinear optical susceptibility, $\chi^{(3)}$, could be determined through utilizing linear optical susceptibility, $\chi^{(1)}$, by:

$$\chi^{(3)} = 1.7 \cdot [\chi^{(1)}]^4 \times 10^{-10} \quad \text{esu} \quad (17)$$

Where, $\chi^{(1)} = (1/12.56) \times (n^2 - 1)$. The $\chi^{(3)}$, and, n_2 , values at 1700 nm of prototyped glasses are listed in Table 1. They increase from 4.78 to 5.47×10^{-13} esu and from 2.28 to

2.6×10^{-12} esu with increasing TeO_2 in the glasses matrix. Depend heavily on the polarizability of the Te^{2+} ions within the glass network, because the third equatorial position of the ions of Te^{4+} is occupied by a lone pair of electrons phase of TeO_4 which has a greater polarizability relative to TeO_3 and TeO_{3+1} phases. Moreover, sample B has the highest value of both E_d and E_s in eV otherwise sample D has the lowest value. This value depends on the single bond strength B_{M-O} in kJ/mol where it is equal of MgO= 155kJ/mol, BaO= 138 kJ/mol and of SrO= 134 kJ/mol). This behavior will result in increasing the value of the $\chi^{(3)}$ and n_2 . The molar refraction, R_m ,

$$R_M = \frac{M \cdot [n^2 - 1]}{\rho \cdot [n^2 + 2]} \quad (18)$$

and molar polarizability, α_M , equal;

$$\alpha_M = \frac{3R_M}{4\pi N_A} \quad (19)$$

Where N_A represents Avogadro's number and M expresses the molecular weight of prepared glasses. The R_M , and α_M values at 1700nm are decreased from 14.63 to 14.21 in $\text{cm}^3 \cdot \text{mol}^{-1}$ and from 5.8 to 5.64 in $\text{\AA}^3$, respectively. Sample A has the highest value of the linear refractive index and also has the highest molar polarizability. Nevertheless, sample B (MgO) has the lowest value of both R_M , and, α_M at 1700 nm, which occurred in the sequence BaO, SrO, MgO which is directly proportional to the increasing cation polarizability of metals of modifiers as follows: $\text{Ba}^{2+} (1.595 \text{ \AA}^3) > \text{Sr}^{2+} (0.861 \text{ \AA}^3) > \text{Mg}^{2+} (0.094 \text{ \AA}^3)$.

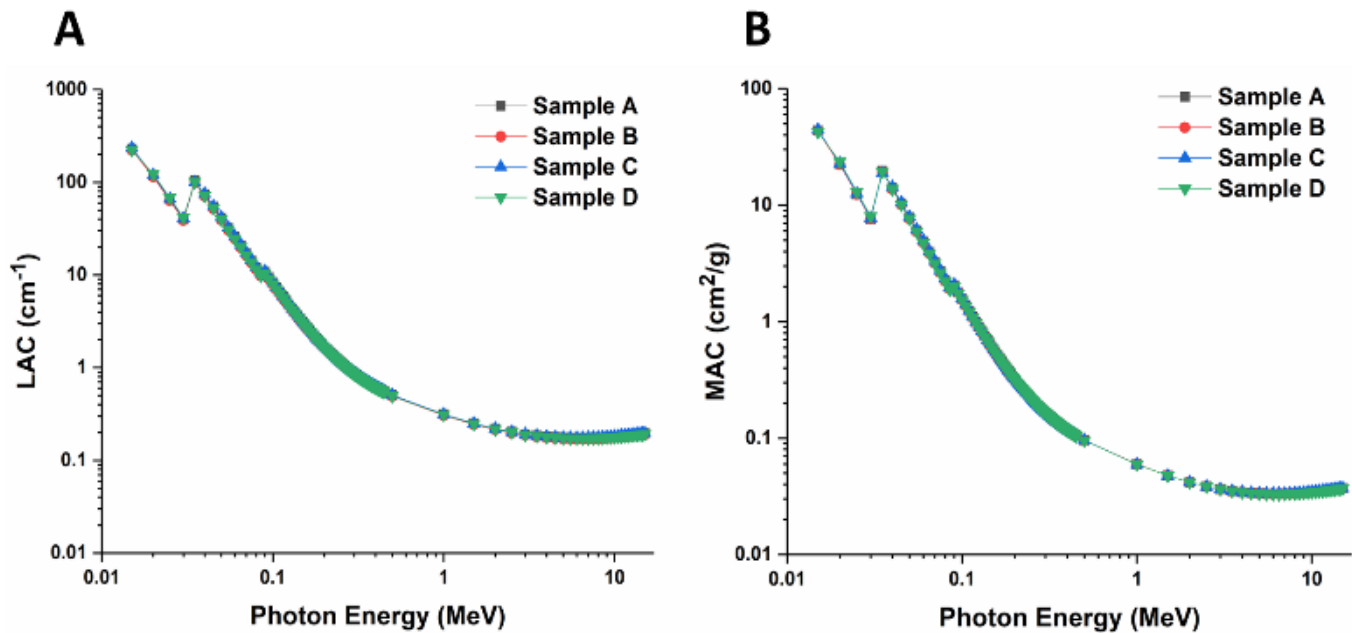


Fig. 1. The linear attenuation coefficient (A) and the mass attenuation coefficient (B) for the four prepared glass samples (Sample A, B, C, and D).

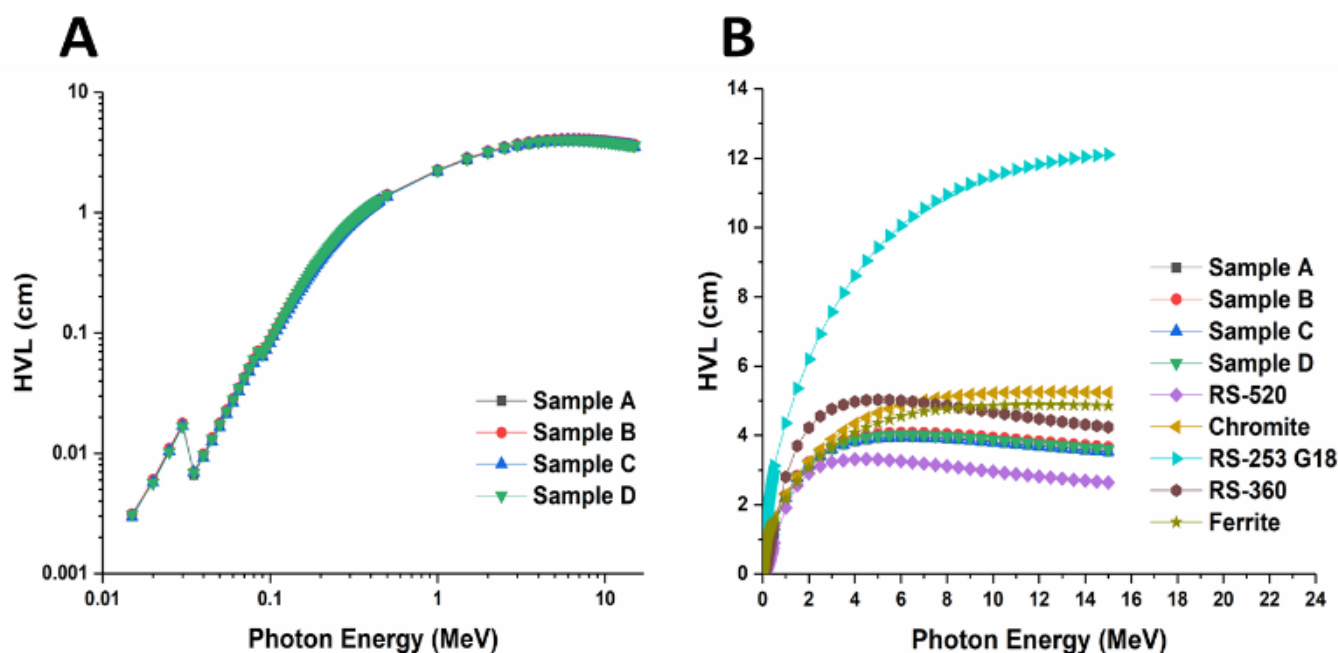


Fig. 2. (A) The reported half-value layer (HVL) values for the proposed shielding materials (Samples A, B, C, and D); and (B) Comparison of the reported HVL values with other HVLs for a variety of ionizing radiation shielding materials.

Herein we determine metallization criterion, M_c , of the prototyped samples A, B, C and D at a varied wavelengths by following the relation:

$$M_c = \frac{3}{n^2 + 2} \quad (20)$$

The value M_c , reported in the range from 0.501 to 0.507 at 1700nm which strongly depended on optical basicity [$\Lambda(n)$] of modifier MgO, BaO and SrO. It is occurred in the sequence as follow $MgO > SrO > BaO$ increasing direct with $\Lambda(n)$ of metal modifier ($MgO = 0.69$, $SrO = 1.10$, $BaO = 1.21$).

Figure 1 (A, B) show the computed linear and mass attenuation coefficients (LAC, MAC) of the four proposed samples namely, $75TeO_2 - 10PbO_5 - 10ZnO - 5PbF_2 - 0.24Er_2O_3$, $70TeO_2 - 10PbO_5 - 10ZnO - 5PbF_2 - 5MgO - 0.24Er_2O_3$, $70TeO_2 - 10PbO_5 - 10ZnO - 5PbF_2 - 5BaO - 0.24Er_2O_3$ and $70TeO_2 - 10PbO_5 - 10ZnO - 5PbF_2 - 5SrO$ in a wide energy spectrum ranging from 0.015 to 15 MeV. As seen in Figure 1 (A, B), the photon attenuation for the four samples depends on the doped oxide materials as well as on the x-ray photon energy. For instant, sample C which contains Barium oxide (BaO) recorded slightly higher linear attenuation and mass attenuation coefficients compared with the other samples under. These results agree with other findings [18-20]. The decrease of attenuation coefficients with the increased photon energy as shown in Figure 1 (A, B) is due to the contribution of the photoelectric effect and Compton scattering which are the most predominant interaction in the diagnostic energies range. For example, the value of the linear attenuation coefficient recorded for sample C was $3.14cm^{-1}$ compared to 3.09, 2.99, and $3.01cm^{-1}$ at 0.15MeV,

with percentage differences of 1.33%, 4.6%, and 4.2% for sample A, B, and D respectively. Similar behaviour was recorded for the mass attenuation coefficients.

The half value layer (HVL) is one of the prime shielding factors to study the effectiveness of shielding materials in terms of the required thickness that need to reduce the intensity of radiation beam to its half value. HVL is commonly used to estimate the required shielding thickness for the specific energy range. Figure 2(A) shows the computed half-value layers of the proposed sample materials in a wide energy spectrum ranging from 0.015 to 15 MeV. As shown in Figure 2(A), the reported values for sample C are slightly lower than that of the other samples under investigation, which is expected due to the higher linear attenuation recorded for sample C compared with other samples. The high attenuation recorded is due to the high atomic number and density of the doped materials as discussed before, which increases the possibility of photon interaction within the material and decreases the possibility of the transmission of a photon through it. For example, the computed HVL value of sample C was found 0.22cm compared to 0.223, 0.2314, and 0.2304cm at 0.15 MeV, with percentage differences of 1.33%, 4.6%, and 4.2% for sample A, B, and D respectively. The superior behavior of sample C is mainly due to the contribution of the photoelectric effect and Compton scattering which are the most predominant interaction in the diagnostic energies range. The lower values of HVL of sample C is an evidence of the fact that doping the glass shielding material with oxide materials that have a high atomic number and high weight will improve the effectiveness of the shielding material. These findings agree with other findings [27-30]. Furthermore, the half-value layer (HVL) of common commercial and recently

investigated shielding materials [17-22] were used for comparison with computed values for the proposed glass materials.

Figure 2(B) show the comparison of the HVLS of the proposed glasses systems with the most common commercial shielding glass materials developed by Schott Co. (RS-253 G18, RS-520 (71 mole% of PbO) and RS-369(45 mole% of PbO)) [38] and common concrete materials Chromite and Ferrite [18]. The proposed samples materials show lower values of HVL compared to the common commercial shielding materials RS-253 G18, Ferrite, and Chromite at all energies, which indicates that the proposed samples have better shielding characteristics compared to them. In addition to that, the proposed samples were recorded lower values of HVL in high energy above 0.4 MeV compared with that of RS-369. For example, the computed HVL values at 0.5MeV of sample C, RS-360, Chromite, and RS-253 G18 were 1.369, 0.89, 1.65, and 3.12cm respectively, with percentage differences of 17%, 2%, and 56%. Nevertheless, RS-520 shielding materials have better performance than the proposed shielding materials at all energies, this is due to the presence of high weighted lead oxide contain RS-520 (89.59%).

The mean free path (MFP) is also an important parameter used to evaluate the capability of a radiation shielding material, which determine the average distance between two successive interaction. The lower the value of MFP the better the effectiveness of the shielding materials. Figure 3(A) illustrated the mean free path (MFP) as a function of photon energy (keV) of the proposed four samples. Sample C recorded the lowest value of MFP among the other samples under investigation, this agrees with findings recorded for the HVL, in which both are strongly

dependent on the attenuation coefficients and the physical density of samples under investigation. Furthermore, the mean free path of proposed samples was compared with other shielding material (RS-253 G18, RS-520, RS-369, Chromite, and Ferrite) as shown in Figure 3(B). Similar findings to the half-value layer were noticed. The higher the density and photon attenuation of shielding material the lowest the recorded mean free path.

Figure 4 shows the values of the total atom cross-section (σ_a) and total electronic cross-section (σ_e) as a function of photon energy for the prototyped glass system. These values define the probability of photon interaction with the material. The higher the values of atomic and electronic cross-sections the more effective the shielding material. Sample C recorded the higher values of atomic and electronic cross-sections compared with other samples under investigation. These results are consistent with the findings discussed before for linear and mass attenuations.

The density of the material is highly dependent on the atomic number and the number of electrons available in the elements, the higher the atomic number and number of electrons the greater the density of the element. For a compound or mixture, the atomic number and number of electrons are defined as effective atomic number (Z_{eff}) and effective electron numbers (N_{eff}), which can be computed from the mass attenuation coefficients of the compound elements. Effective atomic number and effective electron numbers are also prime factors for investigating the effectiveness of the prototyped shielding materials. Figure 5 (A, B) illustrates the effective atomic number (Z_{eff}) and effective electron numbers (N_{eff}) as a function of photon energy (keV) of the proposed samples.

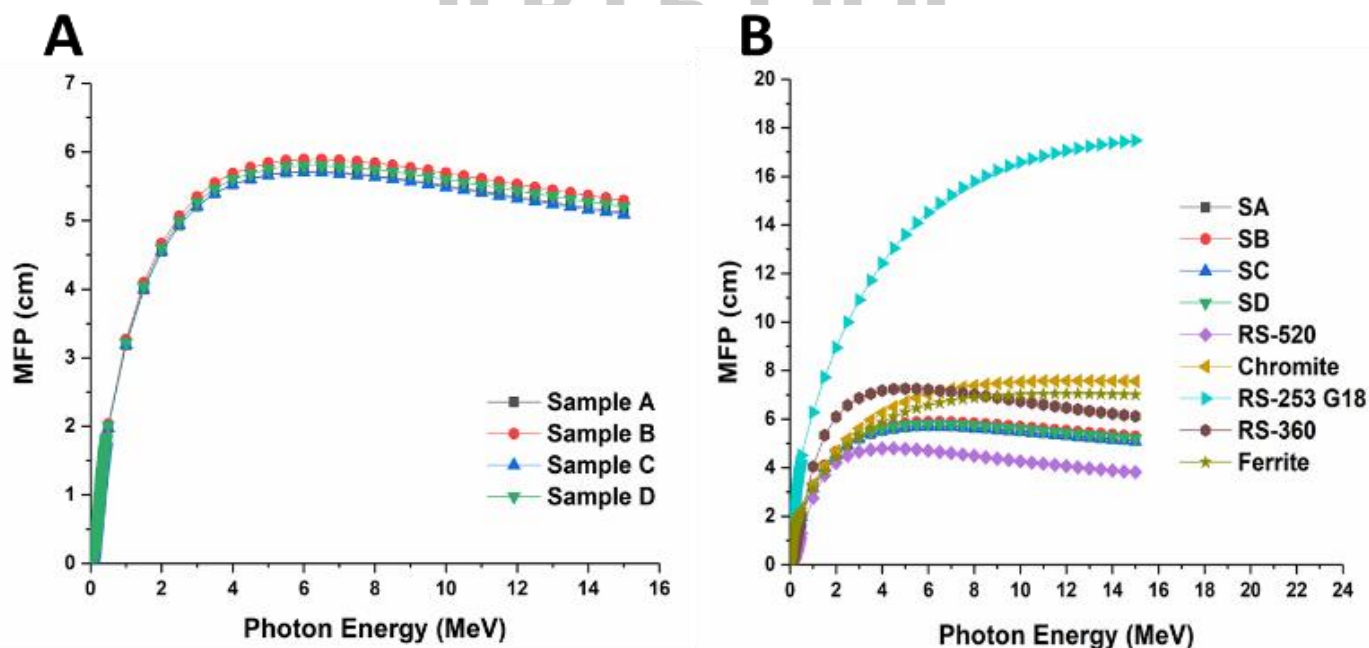


Fig. 3. (A) Recorded mean free path (MFP) values for the proposed materials, i.e. Samples A, B, C, and D; (B) Comparison of the reported MFP values with other MFPs for a variety of ionizing radiation shielding materials.

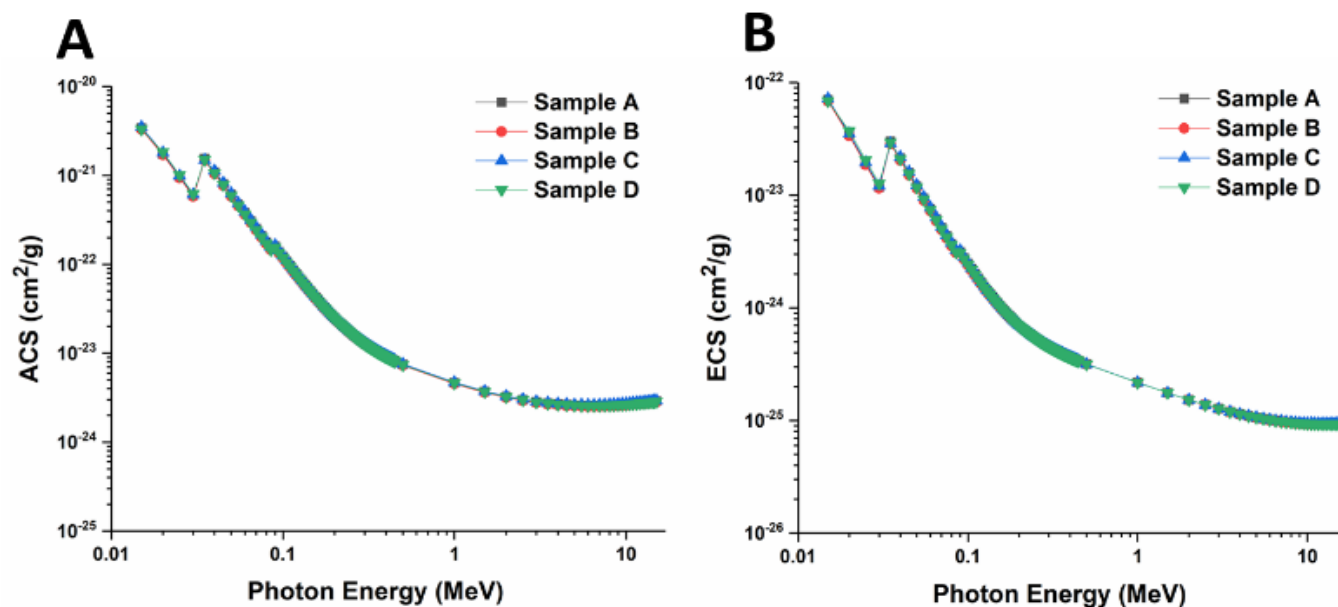


Fig. 4. Line graphs showing the total atom cross-section (σ_a) (A) and total electronic cross-section (σ_a) (B) as a function of photon energy for the prototyped shielding samples.

Sample C recorded the highest effective atomic number (Z_{eff}) and effective electron numbers, which consistent with previous findings for the linear attenuation coefficient and the other shielding parameters. The effective electron numbers (N_{eff}) is directly proportional to the effective atomic number and inversely proportional to the mean atomic mass of the proposed shielding material. Sample C has the highest mean atomic mass among other samples, this results in slightly lower values of effective electron numbers (N_{eff}) compared with the other samples.

The equivalent atomic number (Z_{eq}) of the proposed shielding materials also evaluated against a wide energy spectrum ranging between 0.015 and 15 MeV. Figure 6 shows the values of Z_{eq} for the proposed shielding materials. As Z_{eq} was estimated from the ratio of ratio mass attenuation coefficients of the Compton component to the total mass attenuation coefficients, sample C recorded the highest values among the other samples. The highest values of the equivalent atomic number were recorded at intermediate energies as a result of the effect of the Compton scatter process which the most predominant process in this region.

Figure 7(A-D) illustrates the exposure build-up factors (EBFs) for the proposed samples as a function of penetration depth at energies 15keV, 500keV, 2MeV, and 15MeV. As shown in Figure 5 at low energy (15keV) the exposure build-up factors for all samples increase as penetration depth increases up to the certain depth and then curve become flatter, this is because at low energy the photoelectric absorption is the predominate interaction process, in which all photons are completely absorbed. At intermediate and higher photon energies, the exposure build-up factors for all samples increase gradually as penetration depth increases due to the contribution of the more energetic Compton

scattering photons and the production of the annihilation gamma photons. In low energy photon, it can be seen obviously that the EBFs increase as the equivalent atomic number (Z_{eq}) increases, while at intermediate and high energies the values of EBFs become independent of the Z_{eq} due to the contribution of Compton scatter. These results agree with other findings [39, 40].

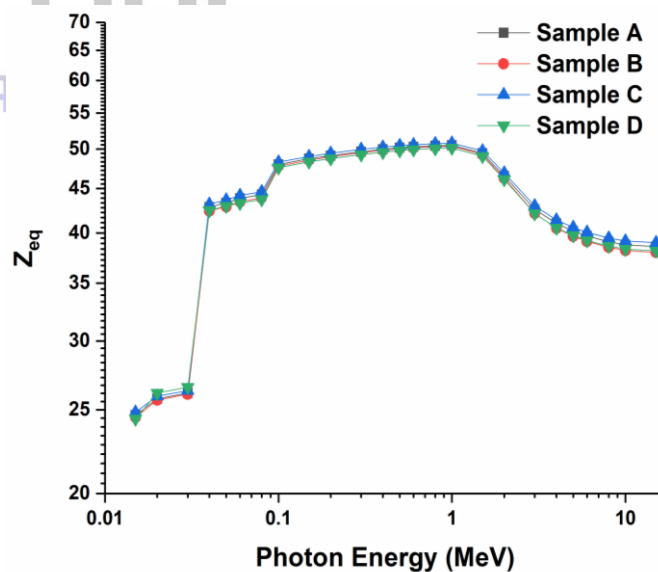


Fig. 6. The equivalent atomic number (Z_{eq}) of the proposed samples as a function of ionizing incident photons' energy. Sample C recorded the higher values of Z_{eq} in comparison to other proposed samples.

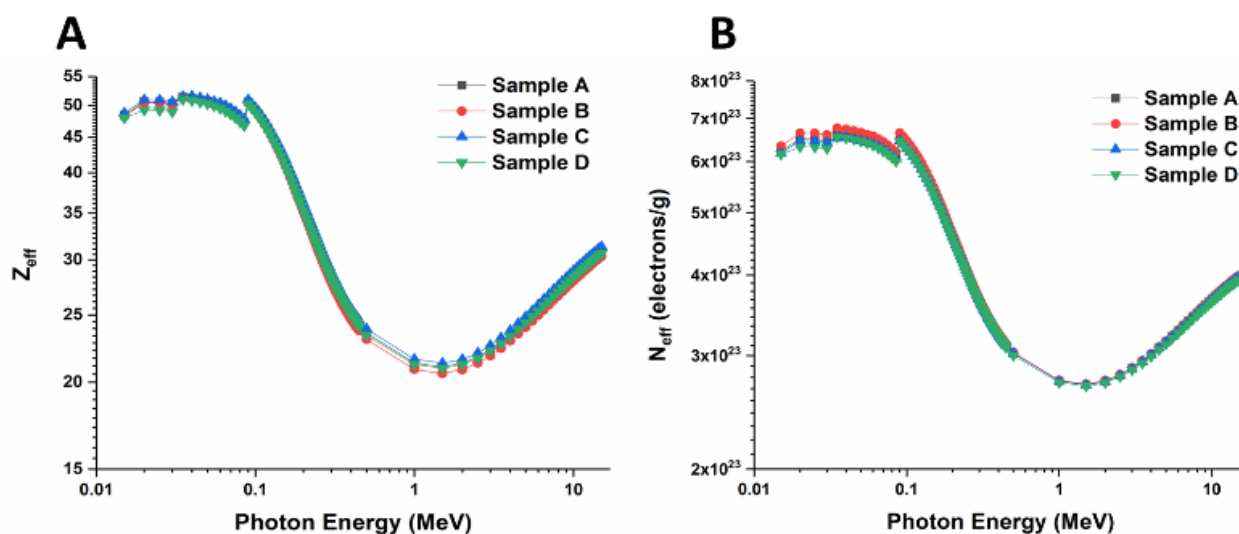


Fig. 5. Line graphs showing the changes in effective atomic number (A) and effective electron density (B) as a function of incident photons' energy.

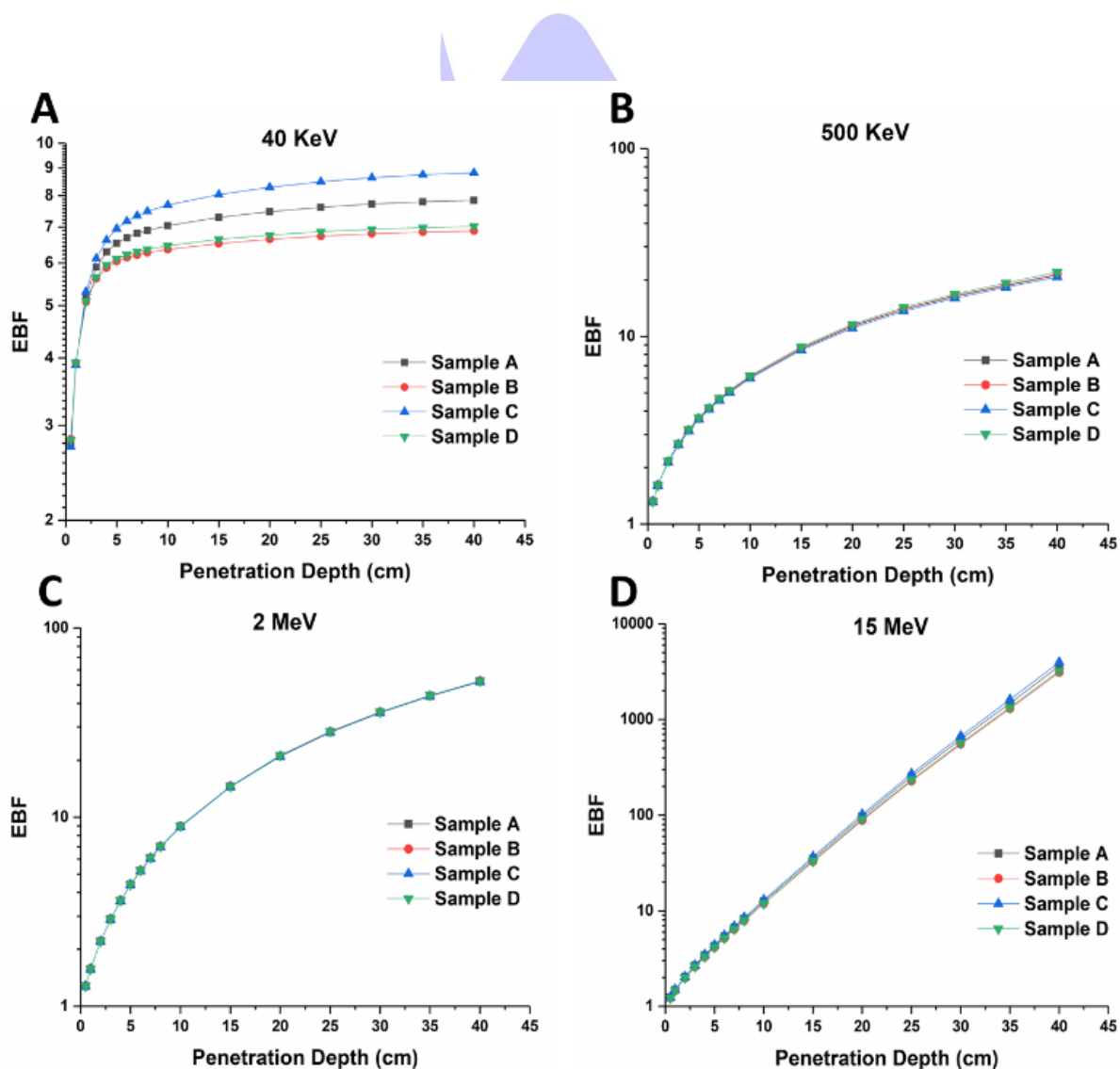


Fig. 7. Line graphs illustrating the exposure build-up factors (EBFs) for the proposed shielding materials as function of penetration depth at energies 15keV (A), 500keV (B), 2MeV (C) and 15 MeV(D).

4. CONCLUSION

The development of new shielding materials for medical applications is a matter of interest for radiation protection purposes. The effectiveness of a material as a shielding material depends on its physical properties and the shielding parameters including density, linear and mass attenuation coefficients, HVL, MFP, Z_{eff} , N_{eff} , and the transmission factor. The study aimed to investigate the photon shielding parameters for four glasses sample materials doped with several oxide namely, 75TeO₂ -10P₂O₅ -10ZnO-5PbF₂ -0.24Er₂O₃, 70TeO₂ -10P₂O₅ -10ZnO-5PbF₂ -5MgO -0.24Er₂O₃, 70TeO₂ -10P₂O₅ -10ZnO-5PbF₂ -5BaO-0.24Er₂O₃ and 70TeO₂ -10P₂O₅ -10ZnO-5PbF₂ -5SrO) in a wide energy spectrum ranging between 0.015 and 15 MeV. The shielding parameters have been calculated the program WinXcom [33, 34] the online developed software (Phy-X/PSD). Sample C which contains Barium oxide (BaO) recorded the highest linear attenuation and mass attenuation coefficients compared with the other samples. Furthermore, sample C show superior shielding performance to that of the other samples under investigation in terms of the lowest recorded Half-value layer (HVL), Transmission factor and Mean free path (MFP) and it possesses the higher recorded values of Z_{eff} . Comparing the effectiveness of proposed samples under investigation with some commercial shielding materials (RS-520, RS-369, RS-253 G18, Chromite, and Ferrite), the proposed samples materials show better shielding effectiveness compared with the commercial shielding materials; RS-253 G18, Chromite, and Ferrite at all energies and superior to that of RS-369 at energies above 0.4 MeV. These results indicate that the proposed samples have good characteristics as radiation shielding materials, which can be used in various diagnostic and therapy applications.

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.

Funding

Not applicable

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

Khalid I. Hussein: Formal Analysis, Data Curation, interpretation of results and Original draft preparation; Mohammed S. Alqahtani: Sample preparation, Experimental Work, Data collection, and interpretation of results. Iwona Grelowska: Data Curation, Write and Review. Manuela Reben: Data Curation, Write and Review.

REFERENCES

- [1] Grelowska, I., **2018**. *Investigation of novel fluorotellurite glass doped with rare earth ions* (Doctoral dissertation).
- [2] Parker, H.M.D. and Joyce, M.J., **2015**. The use of ionising radiation to image nuclear fuel: A review. *Progress in Nuclear Energy*, 85, pp.297-318. <https://doi.org/10.1016/j.pnucene.2015.06.006>
- [3] Vreysen, M.J. and Robinson, A.S., **2011**. Ionising radiation and area-wide management of insect pests to promote sustainable agriculture. In *Sustainable Agriculture Volume 2* (pp. 671-692). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-0394-0_29
- [4] Smith-Bindman, R., Miglioretti, D.L. and Larson, E.B., **2008**. Rising use of diagnostic medical imaging in a large integrated health system. *Health affairs*, 27(6), pp.1491-1502. <https://doi.org/10.1377/hlthaff.27.6.1491>
- [5] Meulepas, J.M., Ronckers, C.M., Smets, A.M., Nievelstein, R.A., Gradowska, P., Lee, C., Jahnen, A., van Straten, M., de Wit, M.C.Y., Zonnenberg, B. and Klein, W.M., **2019**. Radiation exposure from pediatric CT scans and subsequent cancer risk in the Netherlands. *JNCI: Journal of the National Cancer Institute*, 111(3), pp.256-263. <https://doi.org/10.1093/jnci/djy104>
- [6] Mathews, J.D., Forsythe, A.V., Brady, Z., Butler, M.W., Goergen, S.K., Byrnes, G.B., Giles, G.G., Wallace, A.B., Anderson, P.R., Guiver, T.A. and McGale, P., **2013**. Cancer risk in 680 000 people exposed to computed tomography scans in childhood or

- adolescence: <https://doi.org/10.1136/bmj.f2360> data linkage study of 11 million Australians. *Bmj*, 346. <https://doi.org/10.1136/bmj.f2360>
- [7] Linet, M.S., Slovis, T.L., Miller, D.L., Kleinerman, R., Lee, C., Rajaraman, P. and Berrington de Gonzalez, A., **2012**. Cancer risks associated with external radiation from diagnostic imaging procedures. *CA: a cancer journal for clinicians*, 62(2), pp.75-100. <https://doi.org/10.3322/caac.21132>
- [8] Hall, E.J. and Brenner, D.J., **2012**. Cancer risks from diagnostic radiology: the impact of new epidemiological data. *The British journal of radiology*, 85(1020), pp.e1316-e1317. <https://doi.org/10.1259/bjr/13739950>
- [9] Phase, B.V., **2006**. Health risks from exposure to low levels of ionizing radiation. *Washington, DC: The British Institute of Radiology*, 23.
- [10] Shoag, J.M., Michael Burns, K., Kahlon, S.S., Parsons, P.J., Bijur, P.E., Taragin, B.H. and Markowitz, M., **2020**. Lead poisoning risk assessment of radiology workers using lead shields. *Archives of environmental & occupational health*, 75(1), pp.60-64. <https://doi.org/10.1080/19338244.2018.1553843>
- [11] Burns, K.M., Shoag, J.M., Kahlon, S.S., Parsons, P.J., Bijur, P.E., Taragin, B.H. and Markowitz, M., **2017**. Lead aprons are a lead exposure hazard. *Journal of the American College of Radiology*, 14(5), pp.641-647. <https://doi.org/10.1016/j.jacr.2016.10.024>
- [12] McCaffrey, J.P., Shen, H., Downton, B. and Mainegra-Hing, E., **2007**. Radiation attenuation by lead and nonlead materials used in radiation shielding garments. *Medical physics*, 34(2), pp.530-537. <https://doi.org/10.1118/1.2426404>
- [13] Schueler, B.A., **2010**. Operator shielding: how and why. *Techniques in vascular and interventional radiology*, 13(3), pp.167-171. <https://doi.org/10.1053/j.tvir.2010.03.005>
- [14] Kaewkhao, J. and Limsuwan, P., **2010**. Mass attenuation coefficients and effective atomic numbers in phosphate glass containing Bi₂O₃, PbO and BaO at 662 keV. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 619(1-3), pp.295-297. <https://doi.org/10.1016/j.nima.2009.11.033>
- [15] Zhang, Y., Lu, C., Feng, Y., Sun, L., Ni, Y. and Xu, Z., **2011**. Effects of GeO₂ on the thermal stability and optical properties of Er³⁺/Yb³⁺-codoped oxyfluoride tellurite glasses. *Materials Chemistry and Physics*, 126(3), pp.786-790. <https://doi.org/10.1016/j.matchemphys.2010.12.043>
- [16] Gedikoğlu, N., Ersundu, A.E., Aydin, S. and Ersundu, M.Ç., **2018**. Crystallization behavior of WO₃-MoO₃-TeO₂ glasses. *Journal of Non-Crystalline Solids*, 501, pp.93-100. <https://doi.org/10.1016/j.jnoncrysol.2017.11.030>
- [17] Hong, K.S., Kim, M., Ha, M.G., Kim, J.P., Yoon, J.H., Kim, J.H., Yang, H.S. and Kim, H.G., **2019**. Red-emission properties and crystallization behavior in Eu₂O₃-TeO₂ glasses. *Journal of Non-Crystalline Solids*, 505, pp.400-405. <https://doi.org/10.1016/j.jnoncrysol.2018.10.030>
- [18] Ghribi, N., Dutreilh-Colas, M., Duclère, J.R., Hayakawa, T., Carreaud, J., Karray, R., Kabadou, A. and Thomas, P., **2015**. Thermal, optical and structural properties of glasses within the TeO₂TiO₂ZnO system. *Journal of Alloys and Compounds*, 622, pp.333-340. <https://doi.org/10.1016/j.jallcom.2014.10.063>
- [19] Kaur, P., Singh, K.J., Thakur, S., Singh, P. and Bajwa, B.S., **2019**. Investigation of bismuth borate glass system modified with barium for structural and gamma-ray shielding properties. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 206, pp.367-377. <https://doi.org/10.1016/j.saa.2018.08.038>
- [20] Vani, P., Vinitha, G., Sayyed, M.I., Elbashir, B.O. and Manikandan, N., **2019**. Investigation on structural, optical, thermal and gamma photon shielding properties of zinc and barium doped fluorotellurite glasses. *Journal of Non-Crystalline Solids*, 511, pp.194-200. <https://doi.org/10.1016/j.jnoncrysol.2019.02.005>
- [21] Grelowska, I., Reben, M., Burtan, B., Sitarz, M., Cisowski, J., Yousef, E.S., Knapik, A. and Dudek, M., **2016**. Structural and optical study of tellurite-barium glasses. *Journal of Molecular structure*, 1126, pp.219-225. <https://doi.org/10.1016/j.molstruc.2016.01.034>
- [22] Ticha, H., Schwarz, J. and Tichy, L., **2019**. Raman spectra and optical band gap in some PbO-ZnO-TeO₂ glasses. *Materials Chemistry and Physics*, 237, p.121834. <https://doi.org/10.1016/j.matchemphys.2019.121834>
- [23] Sayyed, M.I., Kaky, K.M., Gaikwad, D.K., Agar, O., Gawai, U.P. and Baki, S.O., **2019**. Physical, structural, optical and gamma radiation shielding properties of borate glasses containing heavy metals (Bi₂O₃/MoO₃). *Journal of Non-Crystalline Solids*, 507,

- pp.30-37.
<https://doi.org/10.1016/j.jnoncrysol.2018.12.010>
- [24] Bashter, I.I., **1997**. Calculation of radiation attenuation coefficients for shielding concretes. *Annals of nuclear Energy*, 24(17), pp.1389-1401.
[https://doi.org/10.1016/S0306-4549\(97\)00003-0](https://doi.org/10.1016/S0306-4549(97)00003-0)
- [25] Singh, K., Singh, H., Sharma, G., Gerward, L., Khanna, A., Kumar, R., Nathuram, R. and Sahota, H.S., **2005**. Gamma-ray shielding properties of CaO–SrO–B₂O₃ glasses. *Radiation Physics and Chemistry*, 72(2-3), pp.225-228.
<https://doi.org/10.1016/j.radphyschem.2003.11.010>
- [26] Singh, N., Singh, K.J., Singh, K. and Singh, H., **2006**. Gamma-ray attenuation studies of PbO–BaO–B₂O₃ glass system. *Radiation measurements*, 41(1), pp.84-88.
<https://doi.org/10.1016/j.radmeas.2004.09.009>
- [27] Kurudirek, M., Özdemir, Y., Şimşek, Ö. and Durak, R., **2010**. Comparison of some lead and non-lead based glass systems, standard shielding concretes and commercial window glasses in terms of shielding parameters in the energy region of 1 keV–100 GeV: a comparative study. *Journal of nuclear materials*, 407(2), pp.110-115.
<https://doi.org/10.1016/j.jnucmat.2010.10.007>
- [28] Singh, S., Kumar, A., Singh, D., Thind, K.S. and Mudahar, G.S., **2008**. Barium–borate–flyash glasses: as radiation shielding materials. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 266(1), pp.140-146. <https://doi.org/10.1016/j.nimb.2007.10.018>
- [29] Sayyed, M.I., **2016**. Bismuth modified shielding properties of zinc boro-tellurite glasses. *Journal of alloys and compounds*, 688, pp.111-117.
<https://doi.org/10.1016/j.jallcom.2016.07.153>
- [30] Saudi, H.A., Gomaa, H.M., Sayyed, M.I. and Kityk, I.V., **2019**. Investigation of bismuth silicate glass system modified by vanadium and copper cations for structural and gamma-ray shielding properties: HA Saudi et al. *SN Applied Sciences*, 1(3), p.218.
<https://doi.org/10.1007/s42452-019-0197-x>
- [31] Al-Hadeethi, Y., Sayyed, M.I., Mohammed, H. and Rimondini, L., **2020**. X-ray photons attenuation characteristics for two tellurite based glass systems at dental diagnostic energies. *Ceramics International*, 46(1), pp.251-257.
<https://doi.org/10.1016/j.ceramint.2019.08.258>
- [32] Almatari, M., Agar, O., Altunsoy, E.E., Kilicoglu, O., Sayyed, M.I. and Tekin, H.O., **2019**. Photon and neutron shielding characteristics of samarium doped lead alumino borate glasses containing barium, lithium and zinc oxides determined at medical diagnostic energies. *Results in Physics*, 12, pp.2123-2128.
<https://doi.org/10.1016/j.rinp.2019.01.094>
- [33] Tekin, H.O., Altunsoy, E.E., Kavaz, E., Sayyed, M.I., Agar, O. and Kamislioglu, M., **2019**. Photon and neutron shielding performance of boron phosphate glasses for diagnostic radiology facilities. *Results in Physics*, 12, pp.1457-1464.
<https://doi.org/10.1016/j.rinp.2019.01.060>
- [34] Hussein, K.I., Alqahtani, M.S., Grelowska, I., Reben, M., Afifi, H., Zahran, H., Yaha, I.S. and Yousef, E.S., **2021**. Optically transparent glass modified with metal oxides for X-rays and gamma rays shielding material. *Journal of X-Ray Science and Technology*, 29(2), pp.331-345.
<https://doi.org/10.3233/XST-200780>
- [35] Bagheri, R., Moghaddam, A.K. and Yousefnia, H., **2017**. Gamma ray shielding study of barium–bismuth–borosilicate glasses as transparent shielding materials using MCNP-4C code, XCOM program, and available experimental data. *Nuclear Engineering and Technology*, 49(1), pp.216-223.
<https://doi.org/10.1016/j.net.2016.08.013>
- [36] Şakar, E., Özpolat, Ö.F., Alım, B., Sayyed, M.I. and Kurudirek, M., **2020**. Phy-X/PSD: development of a user friendly online software for calculation of parameters relevant to radiation shielding and dosimetry. *Radiation Physics and Chemistry*, 166, p.108496.
<https://doi.org/10.1016/j.radphyschem.2019.108496>
- [37] Harima, Y., Kurosawa, N. and Sakamoto, Y., **2014**. Parameter search of geometric-progression formula for gamma-ray isotropic point source buildup factors up to depths of 100 mfp, including contribution of secondary radiations. *Progress in Nuclear Science and Technology*, 4, pp.548-552.
<https://doi.org/10.15669/pnst.4.548>
- [38] Sharaf, J.M. and Saleh, H., **2015**. Gamma-ray energy buildup factor calculations and shielding effects of some Jordanian building structures. *Radiation Physics and Chemistry*, 110, pp.87-95.
<https://doi.org/10.1016/j.radphyschem.2015.01.031>
- [39] Alqahtani, M.S., Hussein, K.I., Afifi, H., Reben, M., Grelowska, I., Zahran, H.Y., Yahia, I.S. and Yousef, E.S., **2022**. Optical and radiation shielding characteristics of tellurite glass doped with different rare-earth oxides. *Journal of X-Ray Science and*

Technology, 30(2), pp.293-305.

<https://doi.org/10.3233/XST-211017>

- [40] Singh, V.P. and Badiger, N., **2013**. A Comprehensive Study on Gamma-Ray Exposure Build-Up Factors and

Fast Neutron Removal Cross Sections of Fly-Ash Bricks. *Journal of Ceramics*, 2013(1), p.967264.

<https://doi.org/10.1155/2013/967264>

