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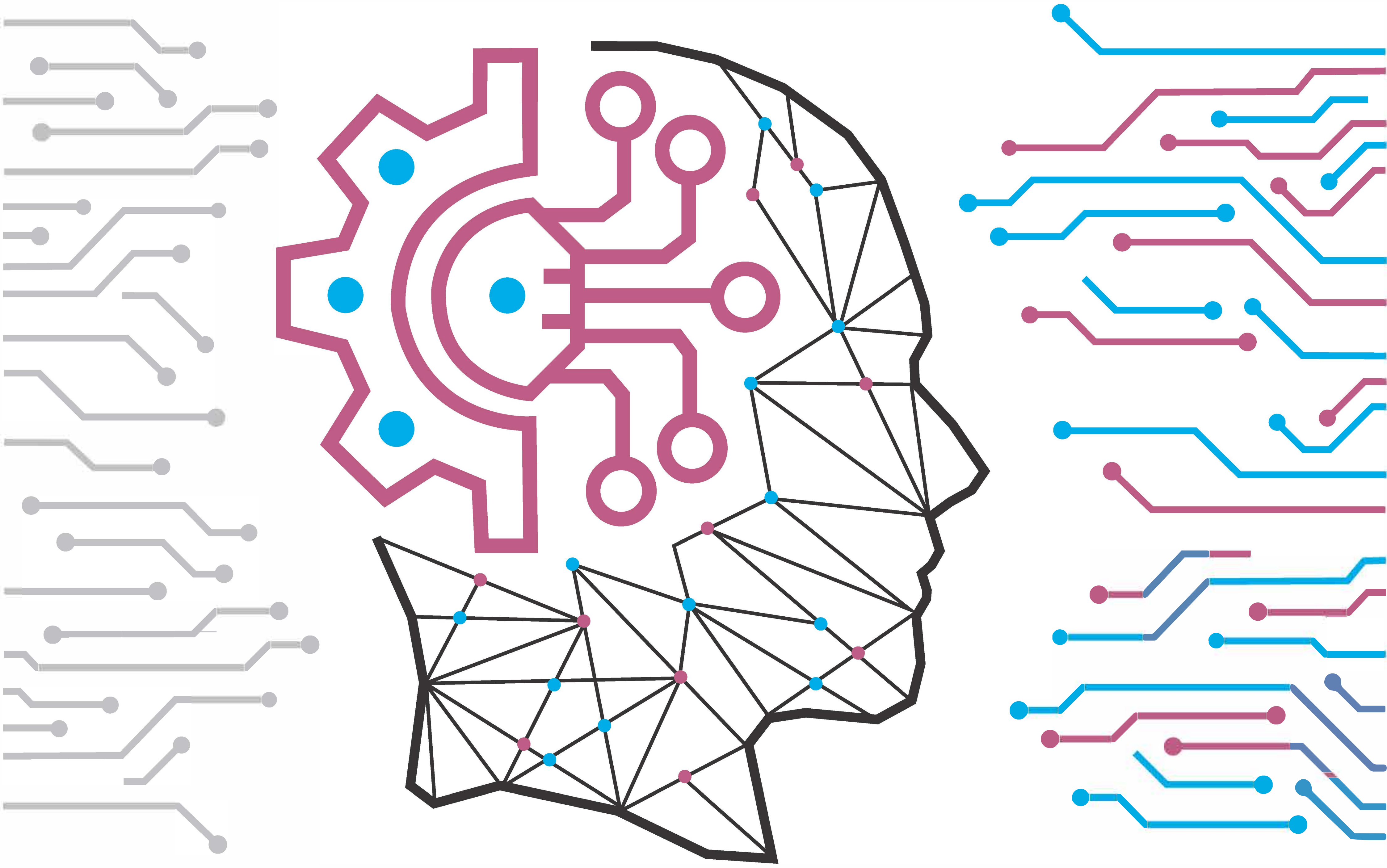

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EXTENDED ABSTRACTS

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TUNGSTEN TELLURITE DOPED GLASS AS RADIATION SHIELDING MATERIAL

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ABSTRACT

In this investigation, a glass system $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ where $x = 0, 3, 5, 7, 9$ mol% was synthesized using the melt–quenching technique to evaluate the impact of WO_3 on radiation shielding properties. Employing XCOM software, important parameters such as mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), and mean free path (MFP) in the energy range of 0.015 – 15 MeV. The glass with the highest WO_3 content demonstrated superior MAC and LAC values while HVL and MFP decreased with increasing WO_3. Notably, the composition $20K_2O$-$9WO_3$-$69TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ exhibited optimal photon shielding properties.

Keyword: tungsten; tellurite glass; XCOM; radiation shielding; mass attenuation coefficient

1. INTRODUCTION

Ionizing radiation application is an essential technology in various fields, including medicine, energy production, safety measures, diagnostics, and resource exploration. Nevertheless, the utilization of this technology comes with the potential for radiation exposure, which is not entirely devoid of risks. Even exposure to minimal amounts of radiation carries the potential for adverse effects, leading to immediate harm like radiation sickness or burns and an increased long-term risk of developing cancer [1]. The primary objective of radiation shielding is to decrease or weaken the energy of radiation to a safe level that would not cause harm to humans or the environment. Lead (Pb) and its derivatives have long been regarded as an excellent choice for a wide range of shielding purposes because of their affordability, durability, hardness, and remarkable capability to effectively block ionizing radiation [2], [3]. However, in recent times, the use of Pb-based materials in shielding applications has been prohibited due to the toxicity of lead and its detrimental impacts on both human health and the environment [4], [5]. This development has sparked significant interest in the search for a viable alternative solution. Consequently, many materials, including concrete, alloys, rocks, polymers, and glasses, have been frequently proposed by scientists as potential alternatives to provide effective protection against harmful radiation [6]–[9].

Among the materials proposed, glasses have drawn attention for their intriguing attributes such as being non-toxic, dense, and transparent to visible light where these distinctive characteristics of glass systems have made them a focal point of interest for researchers in the field of radiation shielding [10–12]. M.I. Sayyed et al., studied that within the selected range of tellurite with different oxide compositions (B_2O_3, BaO, V_2O_5, WO_3 and ZnO) glasses, TeO_2-WO_3 stands out as the most effective gamma ray shielding glass attributed to its superior mass attenuation coefficient (MAC) [6]. Other than that, for (80-x)TeO_2-20PbO-$x$$WO_3$ (x = 0, 5, 10, 15 and 20 mol%) glass system showed that the incorporation of WO3 has a positive impact on the density of the glass, consequently enhancing its ability to shield against gamma and beta radiation and this influence is notably more pronounced when it comes to shielding against gamma radiation [13]. Moreover, glasses that incorporate heavy metal oxides (HMOs) like WO_3, Bi_2O_3, and PbO exhibit high density and a substantial effective atomic number attributed to their elevated molecular mass, making them more efficient for shielding against gamma rays [14]. In general, the scattering and absorption of high-energy photons are directly related to the density (ρ) and atomic number (Z) of the shielding material, which makes these heavy metal oxide-containing glasses particularly effective for gamma-ray shielding. Consequently, our research aims to investigate the impact of adding WO_3 on radiation attenuation and the interactions that take place within the $20K_2O$-$x$$WO_3$-(78-$x$)$TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ (x = 0, 3, 5, 7, 9 mol%) glass system.

2. METHODOLOGY

2.1 Sample preparation

The $20K_2O$-$x$$WO_3$-(78-$x$)$TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ (x = 0, 3, 5, 7, 9 mol%) glass system was prepared using a melt-quenching technique. Firstly, mixed high purity (99.99%) powders of potassium carbonate (K_2CO_3), tungsten(IV) oxide (WO_3), tellurium(IV) oxide (TeO_2), erbium(III) oxide (Er_2O_3) and ytterbium(III) oxide (Yb_2O_3) were appropriately weighed and used. Next, the powder-form mixtures were ground in an agate mortar for approximately 1 hour or until mixtures become homogeneous then placed into a ceramic crucible. The homogeneous mixed powders were melted in a furnace (Carbolite CWF1200) at 950 °C for 1 hour. The molten mixture was then swiftly quenched into a stainless-steel mold placed in another furnace (Carbolite CWF1200) and annealed at 350 °C for 3 hours. Lastly, the annealed glassy samples were polished or ground ahead of analysis.

2.2 Sample characterization

The mass attenuation coefficient (μ/ρ) stands as a crucial parameter widely employed in radiation research to describe gamma-ray interactions within the glass medium. The gamma radiation shielding properties are assessed by employing XCOM software encompassing photon energies ranging from 0.015 to 15 MeV.

The determination of mass attenuation coefficients for glass containing different concentrations of WO3 across various photon energy levels was carried out by assessing the intensity of incident and transmitted gamma rays at a specific energy level in accordance with the Beer-Lambert law, as outlined in Eq. 1 [15]:

$$I = I_0 exp^{-\mu x} \tag{1}$$

In this equation, I represent the transmitted intensity of the radiation or energy, I0 signifies the initial intensity, t stands for the sample thickness, and (μ/ρ) denotes the mass attenuation coefficient (MAC). The MAC is a measure of a material's ability to attenuate radiation, where a higher value indicates a more effective shielding capacity [16].

The MAC was employed to characterize the penetration and interaction of photons with the materials, and this can be calculated using Eq. 2 as follows [17]:

$$MAC = \frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \tag{2}$$

where (μ/ρ)i represents the mass attenuation coefficient of each constituent element, while w_i denotes the weight fraction of these constituent elements within the glass sample.

Linear Attenuation Coefficient (LAC) value is the product of the MAC values with the density of glass samples as shown in Eq. 3:

$$\left(\frac{\mu}{\rho}\right) \times \rho = \mu \tag{3}$$

Half Value Layer (HVL) signifies the thickness of a material required to reduce the incoming radiation intensity by half. Therefore, a decreased HVL value indicates superior shielding capabilities. The HVL values for the glass in this investigation have been calculated since they play a vital role in assessing a material's radiation shielding effectiveness, as depicted by Eq. 4:

$$HVL = 0.693/LAC \tag{4}$$

The mean free path (MFP) refers to the average distance a moving particle, like a photon, travels between successive collisions. A smaller MFP indicates that the particle travels shorter distances due to an increased number of collisions with the surrounding materials. As a result, having a smaller MFP is advisable. You can calculate it using the provided equation in Eq. 5:

$$MFP = 1/\mu \tag{5}$$

3. FINDINGS

3.1 Mass Attenuation Coefficient (MAC)

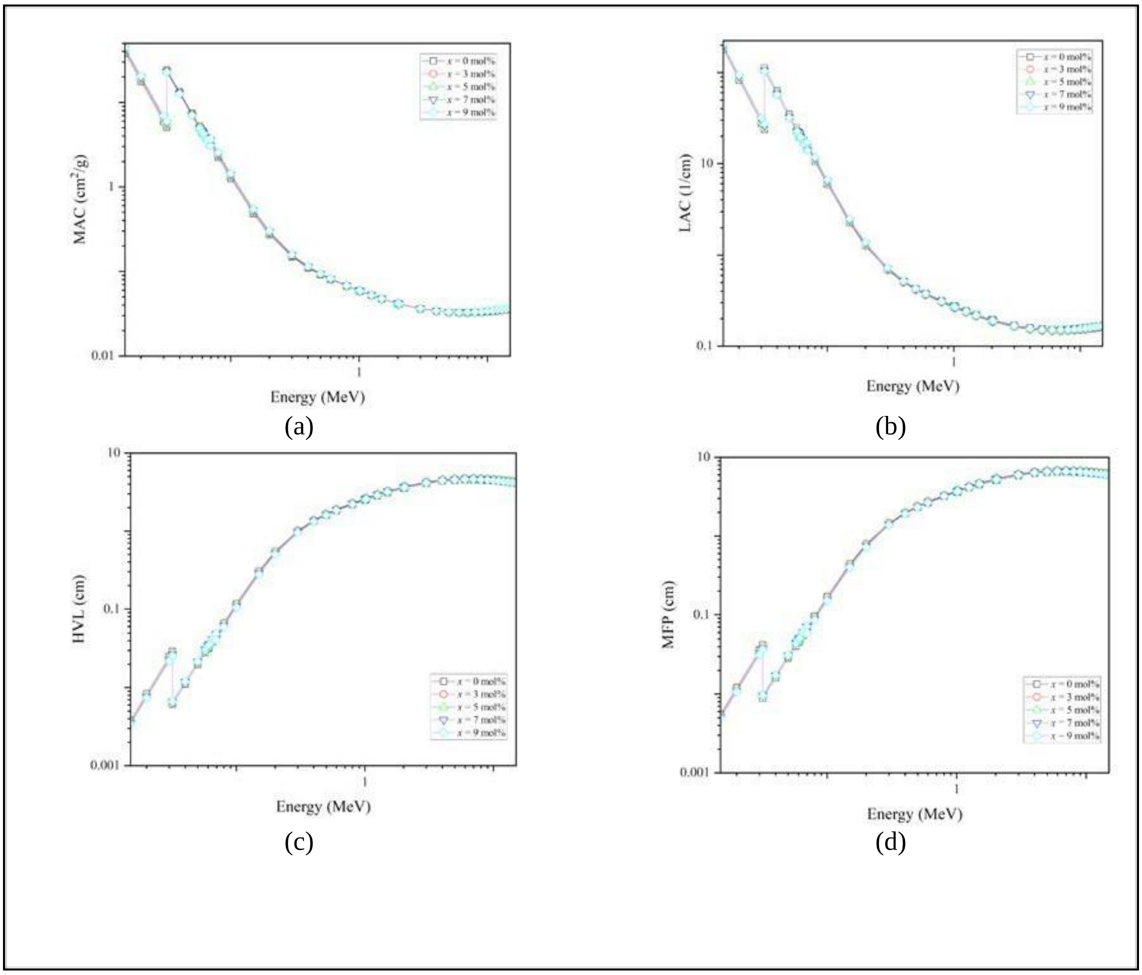
Fig. 1(a). showcases the Mass Attenuation Coefficient (MAC), represented as μ/ρ, which is the LAC divided by the material density, for the $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ (x = 0, 3, 5, 7, 9 mol%) glass composition. The highest MAC values were recorded at the lowest energy level examined, which was 0.015 MeV, and these values were 38.19 cm²/g for 0 mol% WO_3, 40.27 cm²/g for 3 mol% WO_3, 41.67 cm²/g for 5 mol% WO_3, 43.06 cm²/g for 7 mol% WO_3 and 44.45 cm²/g for 9 mol% WO_3. The MAC values decrease at all energy levels with a peak noted at 0.03 MeV for all glass samples due to the K-absorption edge for Te (tellurium) element [18]. At higher energies, the MAC values for the samples are very low. This trend can be attributed to the Compton scattering interaction which exhibits little dependence on the atomic number of the materials [19]. The behaviour of the glass samples in terms of MAC indicates their effectiveness in attenuating low-energy radiation but they are less effective when exposed to comparatively high-energy radiation [20]. The mass attenuation coefficient quantifies the rate at which a photon beam loses energy as it traverses through a medium and is not contingent on the density of that medium [1]. Notably, the glass sample with x = 9 mol% exhibits the highest MAC value, making it the top choice for gamma-ray shielding in both lower and higher photon energy regions.

3.2 Linear Attenuation Coefficient (LAC)

Fig. 1(b). depicts the correlation between the linear attenuation coefficient (LAC) and energy for the glass composition $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ (x = 0, 3, 5, 7, 9 mol%). The LAC measures the glass sample's ability to absorb photons, with higher values indicating superior shielding. The highest LAC values were observed at the lowest energy level examined, 0.015 MeV, with specific values as follows: 180.257 cm^{-1} for 0 mol% WO_3, 184.604 cm^{-1} for 3 mol% WO_3, 187.932 cm^{-1} for 5 mol% WO_3, 195.492 cm^{-1} for 7 mol% WO_3, and 203.137 cm-1 for 9 mol% WO_3. These values decrease across all energies with a peak at 0.03 MeV due to the K-absorption edge [18]. At higher energies, the LAC for all samples drops significantly and the differences between values become marginal. For instance, at 0.5 MeV, the LAC for all samples is around 0.433 cm^{-1} ± 0.1. This trend is attributed to Compton scattering interaction which has a weak dependence on material atomic numbers [19]. Moreover, it is noted that LAC values remain relatively stable as WO_3 concentration increases. This behavior suggests that the prepared glass samples effectively shield low-energy radiation but are less efficient against higher-energy radiation. Among the samples, the composition of $20K_2O$-$9WO_3$-$69TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ emerges as the most effective attenuator, indicating its excellent photon shielding capability.

3.3 Half-Value Layer (HVL)

HVL is an indicator of the ability of a glass to reduce incoming radiation intensity by half. Smaller HVL values denote more effective shielding [21]. In Fig. 1(c), the correlation between HVL and photon energy is presented for the $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ glass system with x ranging from 0 to 9 mol%. The figure displays HVL values across an energy spectrum spanning from 0.015 to 15 MeV. The obtained HVL values demonstrated an escalation with the increase in energy then eventually stabilizing in the higher energy range (E > 5 MeV). This pattern signifies a diminishing efficacy of the glass system. Overall, it implies that a thicker glass is necessary to reduce the intensity of incoming higher-energy radiation by half to maintain the shielding efficiency of the glass [20]. Regarding the WO_3 content, glass samples with 9 mol% WO_3 exhibit the lowest HVL while those with 0 mol% WO_3 content show the highest HVL at each radiation energy level. This indicates that for a given energy level, the $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ glass with 9 mol% WO_3 requires an narrow thickness compared to a glass with 0 mol% WO_3 to reduce incoming radiation intensity by 50%. Therefore, a higher concentration of WO_3 significantly enhances the radiation shielding capacity of the glass.



(a)

(b)

(c)

(d)

Fig. 1. (a) Mass Attenuation Coefficient (MAC), (b) Linear Attenuation Coefficient (LAC), (c) Half-Value Layer (HVL), and (d) Mean Free Path (MFP) for $20K_2O$-$x$$WO_3$-(78-$x$)$TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ (x = 0, 3, 5, 7, 9 mol%) glass system.

3.4 Mean Free Path (MFP)

MFP was also computed to assess the effectiveness of the glass system in stopping gamma rays. Glass samples with a shorter MFP correspond to higher LAC values (MFP = 1/LAC), indicating stronger attenuation. In Fig. 1(d), you can observe the MFP values for the glass samples. The findings demonstrate that the inclusion of WO_3 leads to a reduction in MFP signifying more effective attenuation and shielding [22]. Furthermore, the energy of radiation plays a role in determining the MFP for these prepared samples. The lowest MFP values for all samples were observed at 0.015 MeV where the values are as follows: 0.00557 cm for 0 mol% WO_3, 0.00555 cm for 3 mol% WO_3, 0.00532 cm for 5 mol% WO_3, 0.00512 cm for 7 mol% WO_3, and 0.00492 cm for 9 mol% WO_3. Conversely, at 6.0 MeV, the samples exhibited the highest MFP among all energy levels, indicating they attenuated radiation less effectively at higher energy levels. This implies a positive correlation between increasing energy and MFP suggesting that for specific applications, a thicker $20K_2O$-$x$$WO_3$-(78-$x$)$TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ glass is preferable. The density of these glasses increases with higher WO_3 concentrations due to volume reduction which subsequently leads to an increase in LAC. The elevated LAC values contribute to the lower HVL and MFP values. Among all the glass samples, the glass with $x = 9$ mol% exhibited the shortest MFP making it the most effective sample for radiation shielding.

4. CONCLUSION

This study investigates the radiation shielding capabilities of $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ glasses produced using traditional melt-quench techniques. The effect of WO_3 on the radiation shielding properties of these glasses with various compositions of $x = 0$, 3, 5, 7, and 9 mol%, was evaluated by XCOM software. In general, glass samples containing 9 mol% WO_3 $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ glass systems exhibited the most effective radiation shielding performance. It was demonstrated based on the lowest MFP and HVL values, as well as the highest LAC and MAC values when being compared to the samples with 0, 3, 5, and 7 mol% WO_3. This indicates that the $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ glass system with 9 mol% WO_3 possesses the most robust radiation shielding ability against photon radiation. The MAC values suggested that the glass with a higher WO_3 content (and lower TeO2 content) is more effective for shielding purposes. Furthermore, the HVL results indicated that the use of 9 mol% WO_3 in practical shielding applications can reduce the thickness of the glass which is advantageous in space-constrained conditions. The lowest MFP value, which indicates superior gamma shielding properties, was associated with the sample containing 9 mol% WO_3 and the lowest concentration of TeO_2. In conclusion, the addition of tungsten in the $20K_2O$-xWO_3-$(78-x)TeO_2$-$1Er_2O_3$-$1Yb_2O_3$ glass system significantly enhances its radiation shieldingproperties.

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