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Theoretical Ionizing Radiation Shielding Parameters of Thulium Doped Zinc Borotellurite Glass

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Abstract. Ionizing radiation is considered hazardous to human health but it is very crucial for many applications such as nuclear fuel processing and medical radiography. Glass has played a huge role as a shielding material for ionizing radiation in the application that requires line of sight. Nowadays, lead glass is commonly used in industry due to its properties of high density. However, lead toxicity can give harmful effects on humans' health and the environment. As for concrete, it takes a lot of space, blocks the line of sight and the density of concrete may reduce due to prolonged exposure to radiation. To cater these problems, this study proposed a glass composition that is thulium doped zinc borotellurite glass. Thulium is used due to its potential such as resistance to corrosion and oxidation, good ductility and does not pose any environmental threat. In this study, Phy-X and WinXCom software is used. The main goal of this research is to study the theoretical radiation shielding parameters of thulium doped zinc borotellurite glass. Based on the results, it is found that the best glass sample is the sample composition with 5% thulium oxide whereby it has the highest value for mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), atomic cross section (ACS), electronic cross section (ECS) and effective atomic number (Z_{eff}). The best glass sample with 5% thulium oxide also yields the results of the lowest half-value layer (HVL) and mean free path (MFP). Comparing the results of Phy-X and WinXCom, it is found that the deviation between the software is less than 5%. Also, when the results for each radiation shielding parameter of 5% thulium oxide are compared with other radiation shielding materials, significant results are found where the proposed glass sample provides better shielding against gamma radiation.

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1 Introduction

Ionizing radiation causes hazardous risks to humans. It has high penetration strength as it can pass through barriers such as skin and clothing [1]. Several inches thick of shielding material such as lead and concrete were required to block the radiation of gamma rays. Without shielding material, gamma rays may penetrate through the human body causing ionization that may destroy organic material such as tissue and DNA [1]. Thus, the application of shielding material against gamma rays is very crucial. Shielding material such as concrete and lead is currently used in industry as radiation shielding from gamma radiation. However, there are drawbacks of using these materials. One of the properties of concrete that causes inconvenience is opaque where it becomes inconvenient when line of sight is needed in application [2], [3]. Concrete also requires a large area for installation due to the fact that concrete shielding is dependent on thickness and density [2]–[4].

Moreover, the density of concrete may reduce over time due to prolonged exposure to radiation [2], [3]. Prolonged exposure to radiation also may cause concrete to reduce in mechanical strength which makes it increasingly susceptible to crack. High evaporation rate in concrete which leads to shrinkage is also one of the reasons that causing concrete to has high affinity to crack [5]. On the other hand, usage of lead as alternative radiation shielding causes health impact on humans and environment due to lead toxicity [3], [6]. Lead poisoning is commonly caused by ingesting of lead contaminated food or water [7]. After ingestion, lead can readily be absorbed into the bloodstream causing negative effects on organ systems such as the immune system, kidney, central nervous system and cardiovascular system. In adults, the major source of lead poisoning is due to occupational exposure [7]. According to the World Health Organization [8], the safe blood lead concentration level is still unknown where concentrations as low as 5 µg/dL could lower children’s intelligence, causing difficulties in behavioral and learning problems. It is known that when lead exposure increases, the severity of effect also increases. Lead also had been identified as one of ten substances of major public health concern where measures shall be taken to ensure the safety of workers, children and women of reproductive age [8]. Thus, this study will focus on the usage of alternative elements to replace concrete and lead.

As a replacement of concrete and lead, this study proposed a glass composition that is thulium doped zinc borotellurite glass based on the empirical formula $\{[(TeO_2)_{0.7}(B_2O_3)_{0.3}]_{0.7}[ZnO]_{0.3}\}_{1-x}\{Tm_2O_3\}_x$ where x varied from 0.00 to 0.05. In this study, tellurium dioxide (TeO_2) which is a conditional glass former has been used. The features of tellurite glasses such as low phonon frequency, large transparency window, high solubility (able to mix with almost all elements causing of variation composite with diverse function and properties), low melting temperature, high malleability, high refractive index, high hardness and high chemical durability makes tellurite glass as favorable material for radiation shielding [9], [10]. Besides, density also plays a huge role in choosing radiation shielding material. The properties of tellurite glass that has high density that is 5.67 g/cm^3 resulting in high potential of tellurite glass as shielding material [9]. Furthermore, borate glass made of boron oxide (B_2O_3) are inorganic glass that form non-bridging oxygen (NBO) bond when modifying oxides are incorporated into the glass structure. Combination of binary, ternary and quaternary network forms when modifying oxide incorporated with boron oxide where radiation protection properties have been discovered in this network [11]. Boron oxide have the properties of low price, forms glass at low melting point, good transparency, good thermal stability, high bonding strength with oxygen and a great host for incorporation with different elements [12]–[14]. To enhance thermal stability and chemical durability of borotellurite glass (TeO_2-B_2O_3), zinc oxide (ZnO) was inserted into the glass network. ZnO is an inorganic compound that has the properties of non-toxic and economical [15]. Glass with addition of ZnO shows enhanced properties as zinc oxide acts as modifier and network former. Plus,

addition of ZnO into borotellurite glass composition also shows unique properties such as enhancement in linear attenuation coefficient (LAC) and density [13], [16]. Nowadays, doping glass with materials other than lead grabs researchers' attention to cater the problem of harmful effects involving lead. Thulium specifically is a suitable candidate for alternative elements. The potential of thulium (Tm) to be used as gamma radiation shielding can be seen in a study by Halimah et al. [17]. The density of Tm doped glass increased as dose of gamma radiation increased until 20 kGy. The increasing density was due to radiation-induced densification that is the result of rapid cooling that follows after irradiation. Other than that, thulium also has corrosion resistance, oxidation resistance and good ductility. Most importantly, Tm does not possess any environmental threats to animals and plants [18]. Besides, there is still a lack of study on radiation shielding glass doped by thulium oxide.
Consequently, this study was done to determine the theoretical radiation shielding parameters of thulium doped zinc borotellurite glass and to study the effect of different energies of gamma rays to radiation shielding properties of thulium doped zinc borotellurite glass. In this theoretical study, two software had been used which are Phy-X and WinXCom. Using the results obtained from both software, the radiation shielding parameters of thulium doped zinc borotellurite glass was also compared. This study can significantly contribute to more research on radiation shielding glass doped by thulium oxide.

2 Experiment

2.1 Chemicals and Instrumentation

In this study, two software that were used are Phy-X and WinXCom to determine some shielding parameters of thulium doped zinc borotellurite glass based on the empirical formula $\{[(TeO_2)_{0.7}(B_2O_3)_{0.3}]_{0.7}[ZnO]_{0.3}\}_{1-x}\{Tm_2O_3\}_x$, where x varied from 0.00 to 0.05 mol.

2.2 Procedure

2.2.1 Phy-X Software

Phy-X software was developed by Erdem et al. [19] with the objective to perform calculations on parameters that are relevant to radiation shielding and dosimetry. In addition, the software also includes certain well-known radioactive sources (^{22}Na, ^{55}Fe, ^{60}Co, ^{109}Cd, ^{131}I, ^{133}Ba, ^{137}Cs, ^{152}Eu, and ^{241}Am) as well as some distinctive (K-shell) X-ray energies of Cu, Rb, Mo, Ag, Ba, and Tb elements that may be selected by the users. In the continuous energy range that is from 1 keV-100 GeV, the programme creates data on shielding parameters. The parameters that being calculated by the software are linear attenuation coefficients (LAC), mass attenuation coefficients (MAC), half value layer (HVL), tenth value layers (TVL), mean free path (MFP), effective atomic number (Z_{eff}), effective electron density (N_{eff}), effective conductivity (C_{eff}), energy absorption build up factors (EABF) and exposure build up factors (EBF). Plus, this software may also compute another important shielding metric, the fast neutron removal cross section (FNRCS), in mixture or compound. Phy-X is an online software that can be accessed directly through the website via link https://phy-x.net/module/physics/shielding/. After a user had accessed the Phy-X website, user prompted to enter the chemical composition of the compounds and the density of the compound used in g/cm^3. Then, the energy range of Standard Grid with an energy range of 10^{-3} to 10^5 will be chosen. Besides, for this selection the radioactive isotopes Cs-137 and Co-60 will be chosen as radiation sources. When selection had been made, another pop-up appeared on screen to prompt the user to select the parameter of interest. Then, calculations of radiation shielding parameters was started on the software. Lastly, when the calculations were done, a Microsoft Excel file containing the data of radiation shielding parameters can be downloaded.

2.2.2 WinXCom Software

The WinXCom program was developed by Gerward et al. [20]. This software is the continuation from the WinXCom program that was created by Berger and Hubbell in 1987/1999. It functions to calculate mass attenuation coefficients for any element, compound, or combination at energies ranging from 1 keV to 100 GeV. WinXCom could compute attenuation coefficients for a standard energy grid or a user-specified grid. Compared with the older version which is XCom, the table of cross-sectional or mass-attenuation data in WinXCom may be exported to a specified Microsoft Excel template while this cannot be done using XCom. Thus, this feature is more user friendly as it makes graphical presentation and additional data processing become simpler. WinXCom software can be accessed online via the official website of National Institute of Standard Energy (NIST) via the link https://physics.nist.gov/PhysRefData/WinXCom/html/WinXCom1.html. Then, a page appeared where the user shall click on the type of material whether element, compound and mixture. Users also needed to click on a method of entering additional energies. In this study, the selection 'Mixture' and 'Enter energy addition by hand' was selected. After clicking 'Submit Information', a page that was in the form sheet appeared. In the form, users were asked to enter the formula and relative weight for each compound used in the sample mixture. Also, the user was asked to select graph options and enter the energy range as well as additional energies if applicable. In the graph options, the option 'None' was clicked as only data is needed and the graph can be formed using Microsoft Excel. Furthermore, the energy range that was selected in this study is Standard Grid that is from 0.001 MeV to 10 0000 MeV. After all the information was filled in the form, 'Submit information' button was clicked to generate the data of radiation shielding parameters. The data obtained in the web page was copied and pasted in Microsoft Excel to generate the graphs.

2.2.3 Shielding Parameters Calculation

The shielding parameter such as the linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half-value layer (HVL), tenth-value layer (TVL), mean free path (MFP), atomic cross section (ACS), electronic cross section (ECS), effective atomic number (Z_{eff}) and effective electron density (N_{eff}) can be obtained directly by running the software Phy-X. However, WinXCom software only provides the value of mass attenuation coefficient (MAC). Then, this MAC value are use to calculate linear attenuation coefficient (LAC) using following equation [21]: -

$$LAC = MAC \cdot \rho \tag{1}$$

Where ρ was the density of a glass sample. In present work, the density of all the samples was obtained from a previous study by Hasnimulyati (2017) as shown in Table 1.

Table 1. Tm_2O_3 amounts, glass composition and density of glass samples

Tm_2O_3 (mol)	**Glass Composition**	**Density (g/cm^3)**
0.00	$[(TeO_2)_{0.7}\,(B_2O_3)_{0.3}]_{0.7}\,[ZnO]_{0.3}$	3.69
0.01	$\{[(TeO_2)_{0.7}\,(B_2O_3)_{0.3}]_{0.7}\,[ZnO]_{0.3}\}_{0.99}\,\{Tm_2O_3\}_{0.01}$	4.62
0.02	$\{[(TeO_2)_{0.7}\,(B_2O_3)_{0.3}]_{0.7}\,[ZnO]_{0.3}\}_{0.98}\,\{Tm_2O_3\}_{0.02}$	4.71
0.03	$\{[(TeO_2)_{0.7}\,(B_2O_3)_{0.3}]_{0.7}\,[ZnO]_{0.3}\}_{0.97}\,\{Tm_2O_3\}_{0.03}$	4.80
0.04	$\{[(TeO_2)_{0.7}\,(B_2O_3)_{0.3}]_{0.7}\,[ZnO]_{0.3}\}_{0.96}\,\{Tm_2O_3\}_{0.04}$	4.90

0.05	$\{[(TeO_2)_{0.7} (B_2O_3)_{0.3}]_{0.7} [ZnO]_{0.3}\}_{0.95} \{Tm_2O_3\}_{0.05}$	4.99

Source: Hasnimulyati 2017 [22]

Using the value of LAC, HVL can be determined with the following equation [21]: -

$$HVL = \frac{In\,(2)}{LAC} = \frac{0.693}{LAC} \qquad (2)$$

The value of TVL can be simply obtain by multiplying the value of HVL by 3.32. One TVL is greater or equal to $\log_2 10$ which is 3.32 HVLs approximately. Then, the MFP value can be calculated by the equation below [13].

$$MFP = \frac{1}{LAC} \qquad (3)$$

Using Avogadro's number, N_A, atomic weight of constituent element, A, weight fraction of element, w and MAC value, one can find the ACS value with the equation as follows [23].

$$ACS = \frac{MAC}{N_A \sum \frac{w}{A}} \qquad (4)$$

Here, the weight fraction of element, w can be found by [24]: -

$$w = \frac{n \cdot A}{\sum n \cdot A} \qquad (5)$$

In Equation 5, n refers to the number of formula units. Furthermore, the ECS can be found by [24]: -

$$ECS = \frac{1}{N_A}\left(\sum \frac{f \cdot A}{Z} \cdot (MAC)\right) = \frac{ACS}{Z_{eff}} \qquad (6)$$

Where f, Z, Z_{eff} are the fraction of abundance of element, atomic number of element and effective atomic number respectively. The parameter of Z_{eff} can be found using the relation of ACS and ECS [24].

$$Z_{eff} = \frac{ACS}{ECS} \qquad (7)$$

Lastly, the N_{eff} can be determined using MAC and ECS values as shown in formula below [13].

$$N_{eff} = \frac{MAC}{ECS} \qquad (8)$$

The percentage difference of shielding parameter for the samples obtained between Phy-X and WinXCom was calculated using the equation below [25], [26]:-

$$diff\ (\%) = \frac{[Result_{PHYX} - Result_{XCOM}]}{Result_{PHYX}} \times 100\% \qquad (9)$$

3 Results and Discussion

3.1 Mass Attenuation Coefficient

Table 2 and Table 3 shows that the MAC increases as the amount of Tm_2O_3 increases for photon energy 0.01 MeV to 100 000 MeV. However, at 0.001 MeV, the MAC decreases as the amount of Tm_2O_3 increases. This shows that the glass samples are more suitable to be used to shield radiation with energy higher than 0.01 MeV. This finding indicates that dopant Tm_2O_3 in glass samples is suitable to shield gamma radiation as gamma ray photons in general usually have energy greater than 0.1 MeV [27].

Table 2. Mass attenuation coefficient of Tm-doped zinc borotellurite glass calculated WinXCom

Energy (MeV)	**Mass Attenuation Coefficient (cm^2/g)**					
	0% Tm_2O_3	**1% Tm_2O_3**	**2% Tm_2O_3**	**3% Tm_2O_3**	**4% Tm_2O_3**	**5% Tm_2O_3**
0.001	5140	5120	5100	5080	5060	5040
0.01	115	117	118	119	121	122
0.1	0.828	0.852	0.875	0.899	0.923	0.946
1	0.0583	0.0590	0.0590	0.0590	0.0591	0.0591
10	0.0302	0.0304	0.0305	0.0306	0.0307	0.0309
100	0.0443	0.0446	0.0450	0.0453	0.0456	0.0459
1 000	0.0543	0.0547	0.0551	0.0555	0.0559	0.0563
10 000	0.0565	0.0569	0.0573	0.0577	0.0581	0.0585
100 000	0.0568	0.0572	0.0577	0.0581	0.0585	0.0589

Table 3. Mass attenuation coefficient of Tm-doped zinc borotellurite glass calculated Phy-X

Energy (MeV)	**Mass Attenuation Coefficient (cm^2/g)**					
	0% Tm_2O_3	**1% Tm_2O_3**	**2% Tm_2O_3**	**3% Tm_2O_3**	**4% Tm_2O_3**	**5% Tm_2O_3**
0.001	6001	5908	5819	5734	5652	5574
0.01	120.7	124.8	128.7	132.5	136.1	139.5
0.1	1.090	1.162	1.230	1.296	1.360	1.420
1	0.05906	0.05922	0.05937	0.05952	0.05966	0.05979
10	0.03202	0.03238	0.03271	0.03304	0.03335	0.03364
100	0.04928	0.05016	0.05099	0.05179	0.05256	0.05329
1 000	0.06049	0.06157	0.06260	0.06358	0.06453	0.06544
10 000	0.06294	0.06405	0.06512	0.06615	0.06713	0.06807
100 000	0.06332	0.06444	0.06552	0.06655	0.06753	0.06848

To study the influence of energy with MAC, the graph of Mass Attenuation Coefficient versus Photon Energy for WinXCom and Phy-X was plotted as shown in Figure 1 and Figure 2 respectively. According to the graphs, there are three interactions which are photoelectric effect, Compton scattering and pair production. In Figure 1, the MAC decreases rapidly at energy range from 0.001 MeV to 0.004341 MeV meanwhile in Figure 2 rapid decrease of MAC is observed at energy range between 0.001 MeV and 0.004 MeV. This rapid decrease is due to photoelectric effect interaction where the interaction is dependent on the atomic number of sample and energy [28]. During sharp decrease of MAC values, a few sudden and distinguished increases at 0.00116MeV, 0.00194MeV and 0.0011689 MeV were observed. This phenomenon was related to the K-absorption edge of thulium (atomic number, Z = 69) in the prepared glass samples [29]. However, there is no observation of K-absorption in software Phy-X in Figure 2. In the intermediate energy region that is from 0.004341 MeV to 0.02 MeV in Figure 4.1 and from 0.004 MeV to 0.02 MeV in Figure 2, MAC decreases gradually. The continuation of decline but in slower pace is due to the dominancy of Compton scattering interaction [11]. Differ from the photoelectric effect, Compton scattering is almost independent of the atomic number of materials causing it to partially decrease as photon energy increases. At energy more than 0.02 MeV in both Figure 1 and Figure 2, the MAC was almost constant because pair production become dominant

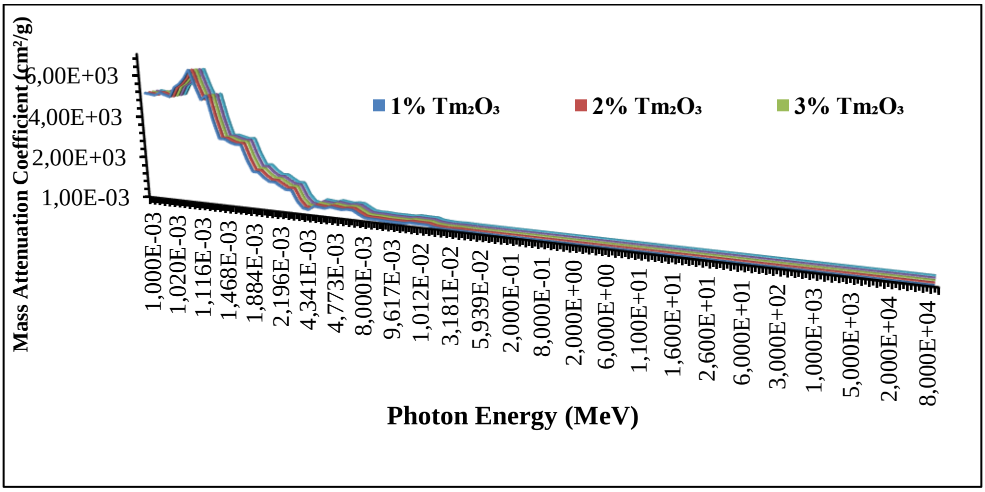

Fig. 1. Graph of photon energy versus mass attenuation coefficient for WinXCom

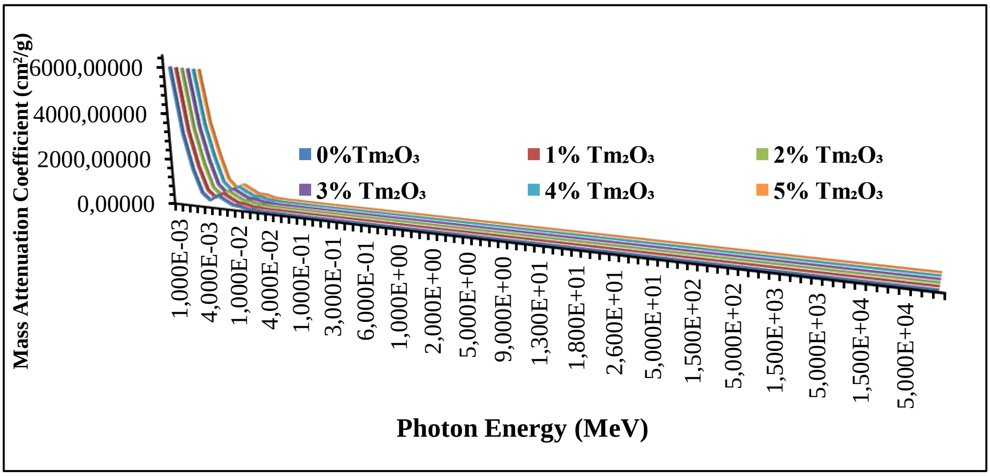

Fig. 2. Graph of photon energy versus mass attenuation coefficient for Phy-X

The MAC result from the gamma rays with energy 1.173 MeV, 1.332 MeV and 0.662 MeV was tabulated in the **Table 4** and **Table 5** below. These three gamma energies were chosen since it is usually used in industry such as medicine (radiotherapy) , industry (sterilization and disinfection) and nuclear industry [30]. Based on Table 4 and Table 5, the mass attenuation coefficient increases as the percentage of Tm_2O_3 increases in both software Phy-X and WinXCom. This can be attributed to the increasing value of rare earth Thulium (Tm) that has a high atomic number compared to other elements. It is also found that the best sample is the composition with 5% Tm_2O_3 as it has the highest MAC compared to other samples. Thus, we can infer that Thulium does enhance the radiation shielding properties of glass.

Table 4. Mass attenuation coefficient of Tm-doped zinc borotellurite glass calculated using WinXCom

Gamma rays energy (MeV)	**Mass Attenuation Coefficient (cm^2/g)**					
	0% Tm_2O_3	**1% Tm_2O_3**	**2% Tm_2O_3**	**3% Tm_2O_3**	**4% Tm_2O_3**	**5% Tm_2O_3**
1.173	0.05419	0.05421	0.05422	0.05424	0.05425	0.05427
1.332	0.05075	0.05076	0.05077	0.05078	0.05079	0.05080
0.662	0.07333	0.07345	0.07358	0.07370	0.07383	0.07395

Table 5. Mass attenuation coefficient of Tm-doped zinc borotellurite glass calculated using Phy-X

Gamma rays energy (MeV)	**Mass Attenuation Coefficient (cm^2/g)**					
	0% Tm_2O_3	**1% Tm_2O_3**	**2% Tm_2O_3**	**3% Tm_2O_3**	**4% Tm_2O_3**	**5% Tm_2O_3**
1.173	0.05406	0.05416	0.05425	0.05434	0.05443	0.05452
1.332	0.05049	0.05056	0.05063	0.05070	0.05076	0.05083
0.662	0.07492	0.07541	0.07587	0.07632	0.07675	0.07716

3.2 Half Value Layer

Half value layer (HVL) is the value for sample thickness that would reduce photon intensity to half of its initial value [31]. Smaller HVL value would provide better gamma ray protection capability [23]. The data of HVL was obtained directly from software Phy-X. Meanwhile, HVL for WinXCom was calculated from LAC using Equation 2. The results obtained from Phy-X and WinXCom were analysed in the form of graphs as shown in Figure 3 and Figure 4. At a low energy level which is at 0.001 MeV to 0.04 MeV for Phy-X and 0.001 MeV to 0.015 MeV for WinXCom, the HVL value is almost zero. Then, rapid increment of HVL is observed at 0.008 MeV to 5.0 MeV for Phy-X and 0.015MeV to 6.0 MeV. Also, it is observed that on the significantly steep increase there is discontinuation on the graph which indicates the K-absorption edge of heavy elements in the sample that is Tm, Te and B [32]. Furthermore, the HVL value starts to decrease and then remains almost constant at 5.0 MeV to 60 000 MeV for Phy-X and 6.0 MeV to 60 000 MeV for WinXCom. In addition, HVL of these samples varies in order as 0% Tm_2O_3 >1% Tm_2O_3 > 2% Tm_2O_3 > 3% Tm_2O_3 > 4% Tm_2O_3 > 5% Tm_2O_3. The reasoning behind this is because of the percentage of Tm_2O_3. When 1% to 5% of TeO_2, B_2O_3 and ZnO compound is replaced with Tm_2O_3, the density of sample will increase. The higher the percentage of replacement, the higher the density of sample. As density increase, HVL will reduces [32]. From Figure 3 and Figure 4, one can conclude that the best sample with lowest HVL is the sample with 5% Tm_2O_3.

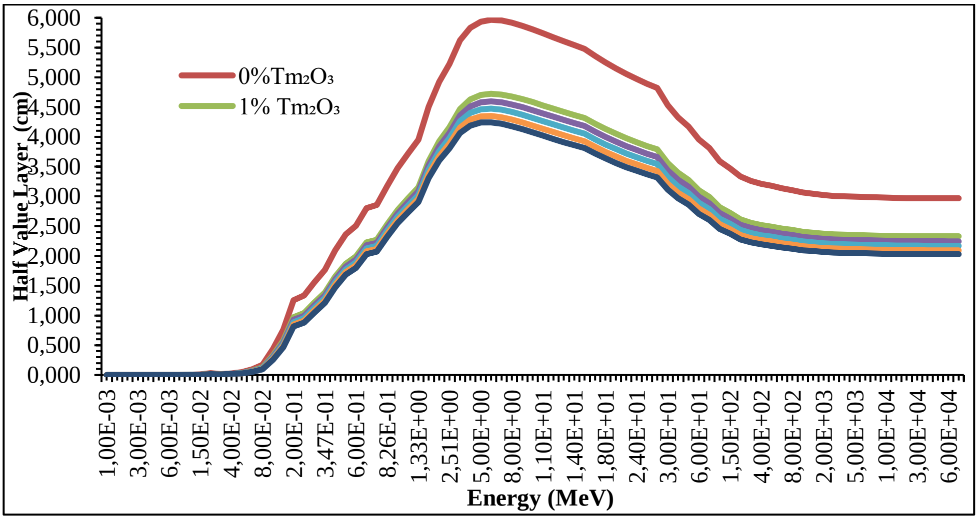

Fig. 3. Graph of half value layer versus energy obtained from Phy-X

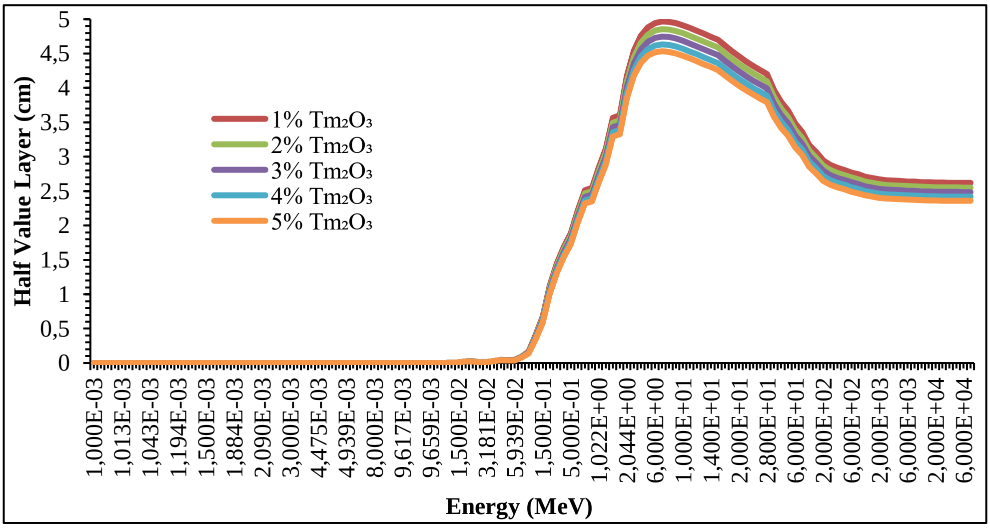

Fig. 4. Graph of half value layer versus energy obtained from WinXCom

3.3 Mean Free Path

MFP can be described as the average distance of two photons interactions [19]. The factor that may affect MFP is density, number of molecules, radius of molecule, pressure and temperature. Figure 5 and Figure 6 show the bar graph of MFP for different percentages of rare-earth Tm_2O_3 at gamma energy of 0.662 MeV, 1.173 MeV and 1.332 MeV. It has been found that the MFP value increases as gamma energy value increases for all compositions in both software Phy-X and WinXCom. It is also found that when the percentage of Tm_2O_3 increases, the MFP decreases. According to Dwaikat et al. [12], the density of sample affects the MFP. When density increases, the arrangement of molecules are closer to each other, causing increment in number of collision and thus, decreasing the MFP.

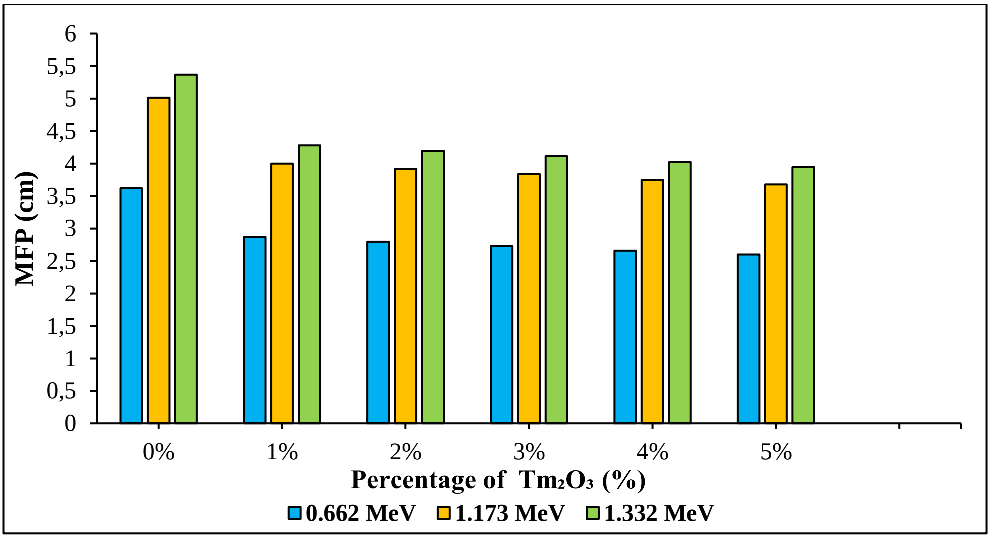

Fig. 5. Graph of mean free path versus percentage of Tm_2O_3 obtained from Phy-X

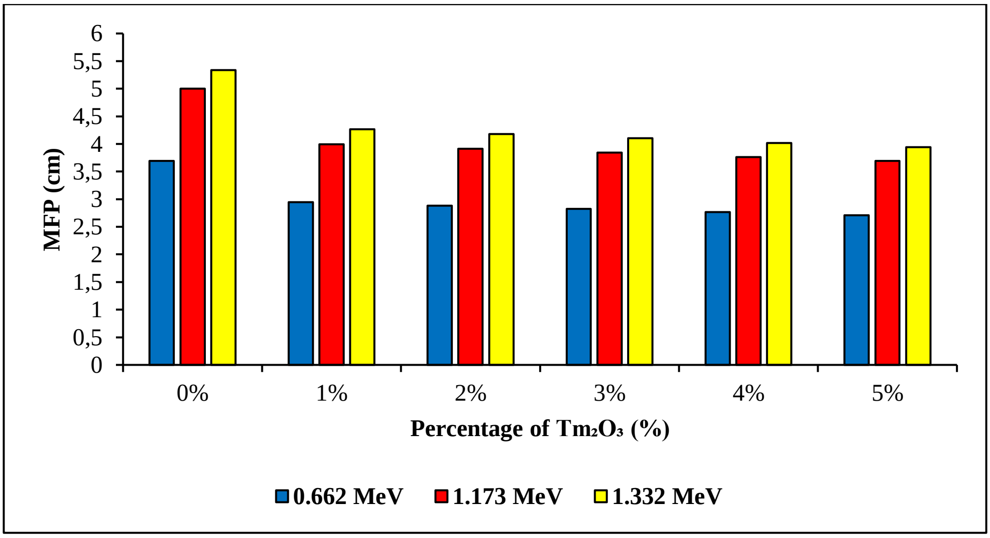

Fig. 6. Graph of mean free path versus percentage of Tm_2O_3 obtained from WinXCom

3.4 Effective Atomic Number (Z_{eff})

Z_{eff} is one of the indispensable parameters in gamma shielding studies whereby it describes the gamma attenuation ability of radiation shielding material as absorber medium [33]. For practical application, Z_{eff} of proposed radiation shielding glass which is thulium doped zinc borotellurite glass should be high. Photons are greatly attenuated in materials with high Z_{eff} values because the material has become the preferred target for photons and causing these photons to collide more frequently [33]. In this study, the highest Z_{eff} is found at 5% Tm_2O_3 making it as the best composition of the proposed glass as shown in Table 6 and Table 7. Other than that, it is found that as the gamma energy increase the Z_{eff} decrease. At high gamma energy, photons are not easily absorbed by the target material leading to low Z_{eff}.

Moreover, density also affect the value of Z_{eff}. It is evident that if the density is high, the Z_{eff} value also will be high because there is high atomic number in the material [34].

Table 6. Calculated effective atomic number of Tm-doped zinc borotellurite glass using Phy-X

Gamma rays energy (MeV)	**Effective Atomic Number (Z_{eff})**					
	0% Tm_2O_3	**1% Tm_2O_3**	**2% Tm_2O_3**	**3% Tm_2O_3**	**4% Tm_2O_3**	**5% Tm_2O_3**
1.173	17.04	17.34	17.64	17.93	18.22	18.51
1.332	17.01	17.31	17.60	17.89	18.17	18.45
0.662	17.65	18.02	18.39	18.75	19.10	19.45

Table 7. Calculated effective atomic number of Tm-doped zinc borotellurite glass using WinXCom

Gamma rays energy (MeV)	**Effective Atomic Number (Z_{eff})**					
	0% Tm_2O_3	**1% Tm_2O_3**	**2% Tm_2O_3**	**3% Tm_2O_3**	**4% Tm_2O_3**	**5% Tm_2O_3**
1.173	17.8048	18.0941	18.3812	18.6645	18.9404	19.2179
1.332	17.8083	18.0933	18.3838	18.6625	18.9411	19.2193
0.662	17.8080	18.0958	18.3800	18.6617	18.9435	19.2152

3.5 Percentage of Deviation Between Phy-X and WinXCom

The percentage difference in MAC for all composition obtained from Phy-X and WinXCom was calculated using Equation 8 and the result was tabulated in Table 8. Based on Table 8, it was found that the difference between Phy-X and WinXCom was less than 5% that is very low. This indicates the results from Phy-X and WinXCom are correlated and can be accepted [16].

Table 8. Percentage deviation of mass attenuation coefficient calculated from Phy-X and WinXCom

Gamma rays energy (MeV)	**Percentage deviation of Mass Attenuation Coefficient (%)**					
	0% Tm_2O_3	**1% Tm_2O_3**	**2% Tm_2O_3**	**3% Tm_2O_3**	**4% Tm_2O_3**	**5% Tm_2O_3**
1.173	0.2399	0.0922	0.0553	0.1844	0.3318	0.4607
1.332	0.5123	0.3940	0.2758	0.1575	0.0591	0.0591
0.662	2.1683	2.6685	3.1123	3.5550	3.9550	4.3408

3.6 Comparison Between Other Radiation Shielding Material with Sample Containing 5% Tm_2O_3

Table 9 shows the comparison of MAC between 5% Tm_2O_3 and other studies proposed glass samples. It is observed that the glass sample with 5% Tm_2O_3 yields better MAC than the glass sample than borotellurite glass [35], and commercial barite concrete [36]. Borotellurite glass has lower MAC than the glass sample of 5 % thulium doped zinc borotellurite glass due to lower density of borotellurite glass. When comparing 5 % thulium doped zinc borotellurite glass with commercial barite concrete, barite concrete has lower MAC. This indicates that 5 % thulium doped zinc borotellurite glass may be used commercially as the replacement of barite concrete for radiation shielding from gamma rays. However, the MAC of 5 % thulium doped zinc borotellurite glass is lower than lead [37] and lead sodium lithium borosilicate [38] glass due to the high-density lead. However, lead toxicity can give harmful effects on humans' health and the environment. Moreover, lead is opaque and cannot be used in application that requires line of sight. Thus, 5 % thulium doped zinc borotellurite glass without lead is a better choice as gamma radiation shielding.

Table 9. Comparison of mass attenuation coefficient between 5% Tm_2O_3 and other samples

Radiation Shielding Material	**Density (g/cm^3)**	**Gamma rays energy (MeV)**		
		1.173	**1.332**	**0.662**
Lead [37]	11.43	0.06180	0.05620	-
Lead sodium lithium borosilicate glass [38]	-	-	0.05300	0.08200
Borotellurite glass [35]	4.26	0.05329	0.05080	0.07625
Commercial Barite Concrete [39]	-	0.05190	0.04900	0.08570
5% Tm_2O_3 Calculated from Phy-X (Present Work)	4.99	0.05452	0.05083	0.07716
5% Tm_2O_3 Calculated from WinXCom (Present Work)	4.99	0.05427	0.05080	0.07395

Table 10 reveals the comparison of the result of sample with 5% Tm_2O_3 obtained from Phy-X and WinXCom with other known radiation shielding material at gamma energy 0.662 MeV, 1.173 MeV and 1.332 MeV. It is observed that the proposed sample with 5% Tm_2O_3 has the lowest HVL compared to lead zinc borate glass [40], borotellurite glass [35] and commercial barite concrete [41]. This is due to the proposed sample with 5% Tm_2O_3 has higher density.

Table 10. Comparison between the values of the half value layers of the prepared glass samples and other known shielding materials

Gamma Energy (MeV)	**Half Value Layer (cm)**				
	5% Tm_2O_3 Phy-X (Present Work)	**5% Tm_2O_3 WinXCom** (Present Work)	**Lead Zinc Borate glass (20% lead)** [40]	**Borotellurite glass** [35]	**Commercial Barite Concrete** [41]
0.662	1.800	1.878	2.256	2.134	3.026
1.173	2.548	2.569	3.207	3.053	4.442
1.332	2.733	2.734	3.382	3.203	4.714

The MFP of proposed best glass that contains 5% Tm_2O_3 was compared with other radiation shielding materials at three photon energy which is 0.662 MeV, 1.173 MeV and 1.332 MeV as shown in Table 11. The MFP of the sample with 5% Tm_2O_3 is the lowest when compared with other glass samples due to its highest density. This indicates a promising shielding feature of the glass.

To study the parameter of Z_{eff} further, Z_{eff} comparison had been done as shown in Table 12. The best sample which is 5% Tm_2O_3 when compared with other radiation shielding material seems to have higher value of Z_{eff}. This also signifies the potential of proposed glass with 5% Tm_2O_3 to be used as radiation shielding.

Table 11. Comparison of mean free path between other composition of radiation shielding material and 5% Tm_2O_3

Radiation Shielding Material	**Density (g/cm^3)**	**Mean Free Path (cm)**		
		1.173 MeV	**1.332 MeV**	**0.662 MeV**
Lead Zinc Borate glass (20% lead) [40]	3.675	4.630	4.878	3.257
Borotellurite glass [35]	4.260	4.405	4.630	3.077
Commercial Barite Concrete [41]	2.720	6.410	6.803	4.367
5% Tm_2O_3 Using Phy-X (Present Work)	4.990	3.676	3.943	2.597
5% Tm_2O_3 Using WinXCom (Present Work)	4.990	3.693	3.945	2.710

Table 12. Comparison between the values of the effective atomic number of the proposed glass samples and other known shielding materials

Radiation Shielding Material	**Effective Atomic Number (Z_{eff})**		
	1.173 MeV	**1.332 MeV**	**0.662 MeV**
Barium–Magnesium–Sodium-Alumina- Borate [26]	11.57	11.56	12.06
TeO_2–Na_2O-$NdCl_3$-Sm_2O_3 [21]	-	17.52	-
5% Tm_2O_3 Using Phy-X (Present Work)	18.51	18.45	19.45
5% Tm_2O_3 Using WinXCom (Present Work)	19.2179	19.2193	19.2152

4 Conclusion

Six series glass samples with chemical composition $\{[(TeO_2)_{0.7}(B_2O_3)_{0.3}]_{0.7}[ZnO]_{0.3}\}_{1-x}\{Tm_2O_3\}_x$ where x varied from 0.00 to 0.05 has been studied theoretically using the Phy-X and WinXCom programs. The shielding parameters of MAC, LAC, HVL, MFP, ACS, ECS and Z_{eff} had been determined. Based on MAC results, the proposed glass samples are found to be suitable to shield gamma radiation that is higher than 0.01 MeV. Then, using the results of MAC, the energy range for photons interactions which are photoelectric effect, Compton scattering and pair production had been studied. At different gamma energy, the MAC increase as the percentage of Tm_2O_3 increases in both software Phy-X and WinXCom due to high atomic number of Tm which increase the density of the glass. The same increasing trend is also observed in Z_{eff}. However, a decreasing trend is observed in HVL and MFP values. As the percentage of Tm_2O_3 increases, HVL and MFP decreases. Smaller HVL value would provide better gamma ray protection capability since the value for sample thickness would reduce photon intensity to half of its initial value. As for MFP, when the density increases, the arrangement of molecules are closer to each other, causing increment in number of collisions and thus, decreasing the MFP. Based on overall results, the best glass sample is the glass with 5% Tm_2O_3 which has the highest MAC and Z_{eff}. This glass also has the lowest

HVL and MFP. When the result for all of the parameters with 5% Tm_2O_3 glass sample was compared with previous radiation shielding material found in other studies, it is observed that the glass sample yields better gamma radiation properties in terms of the parameter observed. Comparing the results obtained from Phy-X and WinXCom, it is found that the deviation is less than 5%.

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