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Calculation of gamma-ray attenuation parameters for locally developed shielding material: Polyboron

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ABSTRACT

In the present study, the mass attenuation coefficient (μ_m) has been calculated analytically for a locally developed shielding material, polyboron, and compared with the values obtained from the WinXCom code, a Windows version of the XCOM database at the photon energy range 0.001 MeV–20 MeV. A good agreement has been observed between these two values. The linear attenuation coefficients (μ) and relaxation lengths (λ) have also been calculated from the obtained μ_m values and their variations with photon energy have been plotted. For comparison, other four shielding materials- ordinary concrete, pure polyethylene, borated polyethylene and water have also been studied. The obtained result shows that μ_m, μ and λ strongly depends on the photon energy, chemical composition and density of the shielding materials. The values of μ_m and μ of polyboron have been found greater than those of pure polyethylene and borated polyethylene but less than those of ordinary concrete and water at low photon energy range; and at the intermediate photon energy range (0.125 MeV–6 MeV), all the sample materials have approximately the same μ_m values. It has also been noticed that polyboron has the medial relaxation length (λ) over the entire photon energy range. The total mass attenuation coefficient (μ_m) and linear attenuation coefficient (μ), Half Value Layer (HVL) and Tenth Value Layer (TVL) of the five sample materials for some common gamma sources have been worked out and the transmission curves have been plotted. The curves exhibit that the transmission factor of the sample materials decreases with the increase in shielding thickness. The results of this study can be utilized to comprehend the shielding effectiveness of this locally developed material.

1. Introduction

Due to the development of nuclear technology with time, various beneficial applications of different types of radiations in medicine, industry, agriculture and research as well as for nuclear power generation are increasing day by day. But a drawback to these peaceful uses of radiation is that if it is exposed to the personnel including other human beings, who

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are in vicinity of it beyond its permissible dose limit, a deleterious effect may be observed in them. When radiation is exposed to organs or tissues, it loses some its energy through different kinds of interactions and this loss of energy may ionize the atoms of the cell, destroying the normal chemical equilibrium of the cell and eventually can bring death to the cell. Therefore, the radiation must be attenuated enough to protect the personnel from the harmful effects caused by it and also enable them to work by using an apposite shielding material. The shielding used for this purpose is generally known as biological shielding.

To design and choose an appropriate biological shielding, it is necessary to have known its nuclear, structural and physical properties and also the characteristics of radiation impinging on it. The nuclear parameters that must be known to design and choose a shielding material are total mass attenuation coefficient (μ_m), linear attenuation coefficient (μ) for gamma rays which is related to Half Value Layer (HVL), Tenth Value Layer (TVL) and mean free path (λ). Many research workers have determined the values of different shielding parameters in various ways (Akkurt, Akyıldırım, Mavi, Kilincarslan, & Basyigit, 2010; El-Khayatt, 2010; El-Khayatt & Akkurt, 2013; Elmahroug, Tellili, & Souga, 2013; Kucuk, Cakir, & Isitman, 2012; Madhusudhan Rao, Narender, Gopal Kishan Rao, Krishna, & Murthy, 2013; Md. Fakarudin, IqbalSaripan, Nor Pa'iza, & Ismail, 2011; Singh & Badiger, 2014; Yılmaz et al., 2011) to know the shielding effectiveness of the shielding materials developed with time.

It is widely known that hydrogenous materials are used as neutron shielding for their effectiveness of neutron moderation. When boron is added to these hydrogenous materials, it promotes the absorption of neutron and reduces secondary gamma radiation. On the basis of this, a neutron shielding material, termed "polyboron" was locally developed. The compositions of this material are polyethylene, boron ester and paraffin wax at a ratio of 16.5 : 37.5 : 46 by weight percentage. The density of this material is 0.971 g/cm^3 which is somewhat less than water density (1.0 g/cm^3). Some of the shielding properties of this locally developed material have been studied experimentally (Ahmed, Bhuiyan, Mollah, & Rahman, 1992; Huda, Bhuiyan, Ahmed, Mollah, & Mondal, 1998). But almost no reports have been carried out on the μ_m, μ, λ, HVL, TVL for different photon energies. The main objectives of the present study are to determine the values of above parameters and to represent a comparison of shielding effectiveness of the sample materials used in the present work at different photon energy.

2. Theoretical background

2.1. Calculation of total mass attenuation coefficient and linear attenuation coefficient

When a gamma-ray beam traverses an absorber, the intensity of the beam will be attenuated according to the Beer–Lambert's law (Elmahroug et al., 2013):

$$I = I_o e^{-\mu t} = I_o e^{-(\mu/\rho) t_d} = I_o\ e^{-\mu_m t_d} \tag{1}$$

where I_0 and I are the unattenuated and attenuated gamma ray beam intensities, μ (cm^{-1}) is the linear attenuation coefficient, t (cm) is the linear thickness, $\mu_m = \mu/\rho$ (cm^2/g) is the mass attenuation coefficient and t_d (g/cm^2) is the density thickness of the absorber sample. If the absorber density is ρ (g/cm^3), then the relationship between t and t_d is given by,

$$t_d = \rho \times t \tag{2}$$

and the relationship between μ and μ_m is given by the following equation (Herman et al., 2009):

$$\mu = \mu_m \times \rho \tag{3}$$

The total mass attenuation coefficient, $(\mu/\rho)_{\text{compound or mixture}}$ for any chemical compound or mixture of elements is given by mixture rule (Elmahroug et al., 2013):

$$(\mu/\rho)_{\text{compound}} = \Sigma_i(\mu/\rho)_i w_i \tag{4}$$

where w_i and $(\mu/\rho)_i$ are the weight fraction and mass attenuation coefficient of the ith constituent element, respectively. For a chemical compound, the fraction by weight (w_i) is given by,

$$w_i = \frac{n_i A_i}{\sum_j n_j A_j} \tag{5}$$

where A_i is the atomic weight of the ith element and n_i is the number of formula units and $\Sigma_i\ w_i = 1$.

The total linear attenuation coefficient, $\mu_{\text{compound or mixture}}$ of the compound or mixture can then be simply found by multiplying the total mass attenuation coefficient, $(\mu/\rho)_{\text{compound}}$ with its density, ρ. Thus,

$$\mu_{\text{compound}} = \left(\frac{\mu}{\rho}\right)_{\text{compound}} \times \rho \tag{6}$$

2.2. Calculation of HVL, TVL and relaxation length (λ)

Half Value Layer (HVL) is the thickness of a shield or an absorber that reduces the radiation level by a factor of 2 that is to half the initial level and is calculated by the following equation:

$$\text{HVL} = \frac{\ln 2}{\mu} = \frac{0.693}{\mu} \tag{7}$$

where μ (cm^{-1}) is the linear attenuation coefficient of the absorber.

Similarly, Tenth Value Layer (TVL) is defined as the thickness of a shield required for attenuating a radiation beam to 10% of its radiation level and is computed by,

$$\text{TVL} = \frac{\ln 10}{\mu} = \frac{2.3026}{\mu} \tag{8}$$

2.3. Calculation of relaxation length (λ)

The average distance between two successive interactions is called the relaxation length (λ). It is also called the photon mean free path which is determined by the equation:

$$\lambda = \frac{\int_0^\infty x\exp(-\mu x)dx}{\int_0^\infty \exp(-\mu x)dx} = \frac{1}{\mu} \tag{9}$$

Table 1 – Elemental composition of polyboron.

Element	Partial or Elemental density, ρ_i (g/cm^3)	Total density, ρ (g/cm^3)	Fraction by weight, ρ_i/ρ	%Weight fraction
H	0.1202	0.971	0.1238	12.38
O	0.2219		0.2285	22.85
C	0.5814		0.5988	59.88
B	0.0475		0.0489	4.89

where μ is the linear attenuation coefficient and x is the absorber thickness.

3. Method of calculation

In the present work, the mass attenuation coefficient, μ/ρ (cm^2/g) for different chemical elements has been taken from Hubbell and Seltzer (1995) and the total mass attenuation coefficient and linear attenuation coefficient for five shielding materials – polyboron, ordinary concrete, pure polyethylene, borated polyethylene and water have been calculated analytically using Eqs. (4–6) at the photon energy of range from 0.001 MeV to 20 MeV. The computation of the mass attenuation coefficients of the above five sample materials has been carried out by the mixture rule by using the WinX-com software for the mentioned energy range to present a comparison between the calculated and X-com values. The μ_m, μ, HVL and TVL values have also been calculated at the photon energy of some common gamma sources for the sample materials. The locally developed polyboron whose attenuation properties are studied in this work has been taken from Ahmed et al. (1992) and ordinary concrete from Herman et. al. (2009); pure polyethylene and borated polyethylene from Elmahroug et al. (2013) (see Table 1 and 2).

4. Results and discussion

4.1. Total mass attenuation coefficient (μ_m)

The theoretically calculated values of mass attenuation coefficient, μ_m (cm^2/g) using Eq. (4) and the X-com values of the five shielding materials for gamma rays of energy range from 0.001 MeV to 20 MeV have been shown in Table 3. From this table, it is seen that the calculated and X-com values of μ_m are in good agreement. The variation of mass attenuation coefficient ($\mu_{m)}$ with incident photon energy of the five sample materials are represented by Fig. 2. From Fig. 2, it is clear that gamma-ray mass attenuation depends on the incident photon energy and chemical composition of the materials and decreases with increasing incident photon energy.

Fig. 2 shows the mass attenuation coefficient as a function of photon energy. It is observed that ordinary concrete has the highest mass attenuation coefficient over an approximate energy range 0.001 MeV to 0.125 MeV except at very low energy range (about 0.001 MeV to 0.0015 MeV). From this figure, it is seen that the mass attenuation coefficient of ordinary concrete rises abruptly to a maximum value at the approximate photon energy 0.0015 MeV and then decreases with the increase in photon energy (i.e. a peak is observed at about 0.0015 MeV). The highest mass attenuation coefficient of ordinary concrete is due to its containment of high atomic numbered elements which are more effective for gamma-ray attenuation. This can be explained by the three interactions of gamma rays with materials-photoelectric effect, pair production and Compton effect by which the incident photon dissipates its energy. Among the three interactions, photoelectric effect is favored by low energy photons and high atomic numbered absorbers and hence the ordinary concrete has the highest mass attenuation coefficient over that low energy range because photoelectric effect predominates at this range. When the incident photon energy is equal to the ionization or binding energy of an electron of the absorber atom, then the probability of ejection of that electron (i.e.

Table 2 – Percentage of atomic composition of the samples.

Element	Sample types				
	Polyboron ($\rho = 0.971$ g/cm^3)	Polythene ($\rho = 0.92$ g/cm^3)	Borated polyethylene ($\rho = 1.19$ g/cm^3)	Water ($\rho = 1.0$ g/cm^3)	Ordinary concrete ($\rho = 2.35$ g/cm^3)
H	12.38	14.37	8.76	11.9	0.56
B	4.89	85.63	30.00		
C	59.88		60.60		
O	22.85		0.02	88.1	49.56
Na					1.71
Mg					0.24
Al					4.56
Si			0.04		31.35
S					0.12
K					1.92
Ca					8.26
Fe			0.04		1.22

Table 3 – The theoretical and X-Com values (with coherent scattering) of mass attenuation coefficients, μ_m (cm^2/g) for different shielding materials.

Photon energy (MeV)	Polyboron		Ordinary concrete		Pure polyethylene		Borated polyethylene		Water	
	Theoretical value	X-Com value	Theoretical value	X-Com value	Theoretical value	X-Com value	Theoretical value	X-Com value	Theoretical value	X-Com value
1.00E-03	2.434E+03	2.434E+03	3.428E+03	3.445E+03	1.894E+03	1.894E+03	1.714E+03	1.723E+03	4.077E+03	4.077E+03
1.50E-03	7.919E+02	7.920E+02	1.229E+03	1.235E+03	5.999E+02	6.001E+02	5.394E+02	5.425E+02	1.376E+03	1.376E+03
2.00E-03	3.479E+02	3.479E+02	1.448E+03	1.455E+03	2.593E+02	2.592E+02	2.333E+02	2.345E+02	6.172E+02	6.173E+02
3.00E-03	1.061E+02	1.060E+02	4.952E+02	4.977E+02	7.743E+01	7.743E+01	6.945E+01	6.982E+01	1.929E+02	1.928E+02
4.00E-03	4.491E+01	4.491E+01	2.409E+02	2.421E+02	3.242E+01	3.242E+01	2.902E+01	2.918E+01	8.277E+01	8.277E+01
5.00E-03	2.292E+01	2.292E+01	1.737E+02	1.745E+02	1.643E+01	1.643E+01	1.469E+01	1.477E+01	4.259E+01	4.259E+01
6.00E-03	1.321E+01	1.320E+01	1.048E+02	1.053E+02	9.435E+00	9.431E+00	8.431E+00	8.474E+00	2.464E+01	2.464E+01
8.00E-03	5.561E+00	5.561E+00	4.987E+01	5.013E+01	3.975E+00	3.975E+00	3.662E+00	3.682E+00	1.037E+01	1.037E+01
1.00E-02	2.890E+00	2.890E+00	2.646E+01	2.659E+01	2.087E+00	2.087E+00	1.931E+00	1.942E+00	5.329E+00	5.330E+00
1.50E-02	9.730E-01	9.732E-01	8.268E+00	8.308E+00	7.452E-01	7.455E-01	6.942E-01	6.982E-01	1.673E+00	1.672E+00
2.00E-02	5.228E-01	5.229E-01	3.639E+00	3.657E+00	4.316E-01	4.316E-01	4.029E-01	4.050E-01	8.096E-01	8.098E-01
3.00E-02	2.940E-01	2.940E-01	1.210E+00	1.216E+00	2.707E-01	2.707E-01	2.523E-01	2.537E-01	3.755E-01	3.756E-01
4.00E-02	2.350E-01	2.350E-01	6.100E-01	6.130E-01	2.275E-01	2.275E-01	2.117E-01	2.129E-01	2.683E-01	2.683E-01
5.00E-02	2.104E-01	2.104E-01	3.928E-01	3.948E-01	2.084E-01	2.084E-01	1.937E-01	1.948E-01	2.269E-01	2.269E-01
6.00E-02	1.966E-01	1.967E-01	2.945E-01	2.959E-01	1.970E-01	1.970E-01	1.829E-01	1.840E-01	2.058E-01	2.059E-01
8.00E-02	1.802E-01	1.802E-01	2.115E-01	2.126E-01	1.823E-01	1.823E-01	1.692E-01	1.701E-01	1.836E-01	1.837E-01
1.00E-01	1.693E-01	1.693E-01	1.774E-01	1.784E-01	1.719E-01	1.719E-01	1.595E-01	1.604E-01	1.707E-01	1.707E-01
1.50E-01	1.507E-01	1.506E-01	1.427E-01	1.434E-01	1.534E-01	1.534E-01	1.423E-01	1.431E-01	1.505E-01	1.505E-01
2.00E-01	1.375E-01	1.375E-01	1.264E-01	1.270E-01	1.401E-01	1.402E-01	1.300E-01	1.307E-01	1.370E-01	1.370E-01
3.00E-01	1.192E-01	1.193E-01	1.077E-01	1.082E-01	1.216E-01	1.217E-01	1.128E-01	1.134E-01	1.187E-01	1.186E-01
4.00E-01	1.068E-01	1.068E-01	9.580E-02	9.628E-02	1.089E-01	1.089E-01	1.010E-01	1.016E-01	1.061E-01	1.061E-01
5.00E-01	9.748E-02	9.748E-02	8.724E-02	8.768E-02	9.947E-02	9.947E-02	9.224E-02	9.274E-02	9.687E-02	9.687E-02
6.00E-01	9.013E-02	9.014E-02	8.057E-02	8.098E-02	9.198E-02	9.198E-02	8.530E-02	8.576E-02	8.956E-02	8.956E-02
8.00E-01	7.916E-02	7.915E-02	7.068E-02	7.103E-02	8.078E-02	8.078E-02	7.490E-02	7.531E-02	7.866E-02	7.866E-02
1.00E+00	7.117E-02	7.117E-02	6.350E-02	6.382E-02	7.262E-02	7.262E-02	6.734E-02	6.772E-02	7.072E-02	7.072E-02
1.25E+00	6.364E-02	6.364E-02	5.678E-02	5.706E-02	6.495E-02	6.495E-02	6.022E-02	6.056E-02	6.323E-02	6.323E-02
1.50E+00	5.792E-02	5.791E-02	5.171E-02	5.197E-02	5.911E-02	5.910E-02	5.480E-02	5.510E-02	5.754E-02	5.754E-02
2.00E+00	4.965E-02	4.966E-02	4.460E-02	4.483E-02	5.064E-02	5.064E-02	4.697E-02	4.723E-02	4.941E-02	4.942E-02
3.00E+00	3.972E-02	3.972E-02	3.636E-02	3.654E-02	4.045E-02	4.045E-02	3.754E-02	3.774E-02	3.969E-02	3.969E-02
4.00E+00	3.388E-02	3.389E-02	3.174E-02	3.190E-02	3.443E-02	3.444E-02	3.198E-02	3.215E-02	3.403E-02	3.403E-02
5.00E+00	3.002E-02	3.002E-02	2.881E-02	2.895E-02	3.044E-02	3.045E-02	2.829E-02	2.845E-02	3.031E-02	3.031E-02
6.00E+00	2.728E-02	2.728E-02	2.683E-02	2.696E-02	2.761E-02	2.760E-02	2.567E-02	2.581E-02	2.770E-02	2.770E-02
8.00E+00	2.366E-02	2.366E-02	2.438E-02	2.450E-02	2.383E-02	2.383E-02	2.220E-02	2.232E-02	2.429E-02	2.429E-02
1.00E+01	2.139E-02	2.139E-02	2.300E-02	2.311E-02	2.145E-02	2.145E-02	2.001E-02	2.012E-02	2.219E-02	2.219E-02
1.50E+01	1.831E-02	1.831E-02	2.143E-02	2.154E-02	1.819E-02	1.819E-02	1.702E-02	1.712E-02	1.941E-02	1.941E-02
2.00E+01	1.681E-02	1.681E-02	2.095E-02	2.105E-02	1.658E-02	1.658E-02	1.556E-02	1.565E-02	1.813E-02	1.813E-02

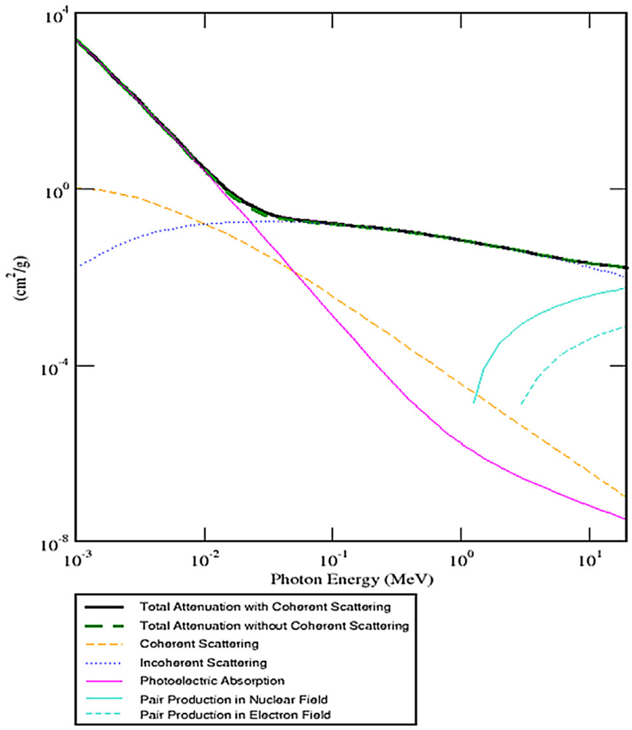

Fig. 1 – Mass attenuation coefficient, μ_m (cm^2/g) versus incident photon energy of polyboron for total and partial interactions.

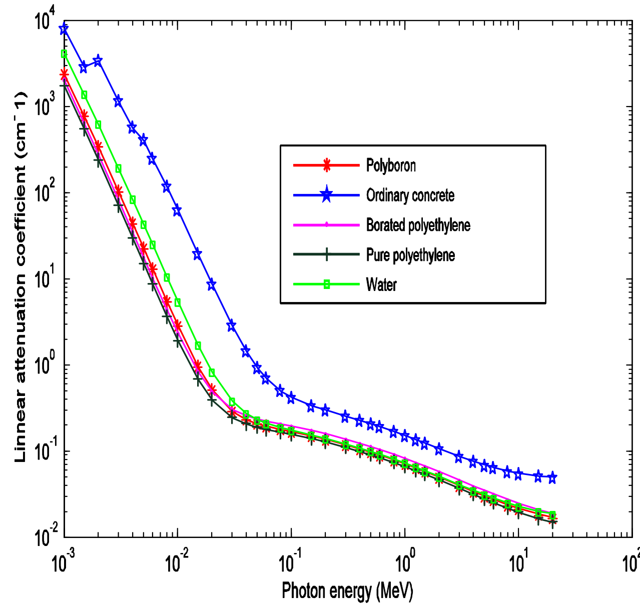

Fig. 3 – Linear attenuation coefficient of the sample materials as a function of photon energy.

photoelectric cross section) becomes the maximum. The peak is an indication of that and denotes the minimum photon energy required to eject the differently bound electrons. Thus the peak is found due to the absorption k-edge of the high Z elements (Na, Mg, Al, Si, K, Ca, S and Fe) that are present in ordinary concrete.

Borated polyethylene which contains the maximum amount of boron (30%) by weight percent has the minimum mass attenuation coefficient. The relative high density ($\rho = 1.19$ g/cm^3) of borated polyethylene which is less than the density of ordinary concrete ($\rho = 2.35$ g/cm^3) but greater than the density of pure polyethylene, polyboron and water is also responsible for this. From Fig. 2, it is also observed that the mass attenuation coefficient of polyboron is slightly less than

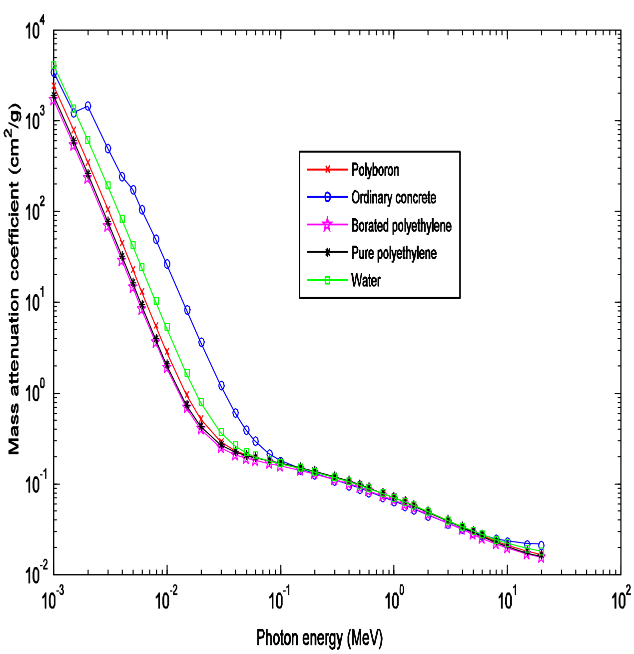

Fig. 2 – Mass attenuation coefficient of the sample materials as a function of photon energy.

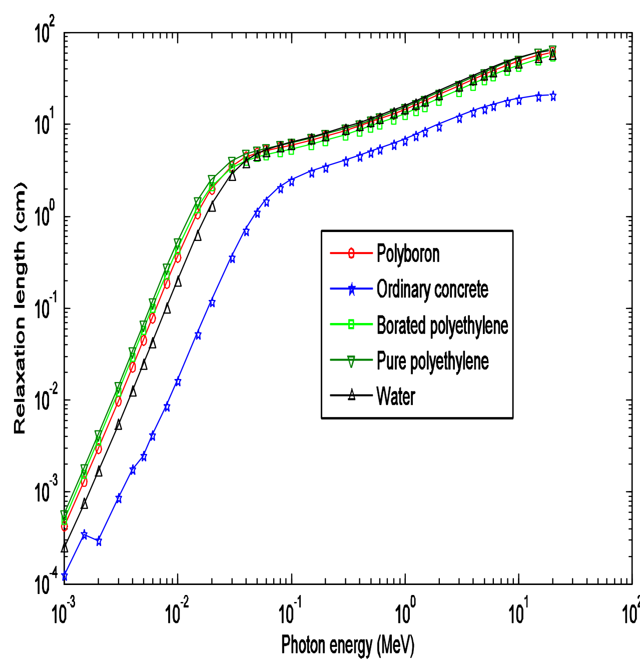

Fig. 4 – Relaxation length of the sample materials as a function of photon energy.

Table 4 – Total mass attenuation coefficient (μ/ρ) and linear attenuation coefficient (μ) of different sample materials for some common gamma sources.

Source Identity	Photon energy (MeV)	Polyboron		Ordinary concrete		Pure polyethylene		Borated polyethylene		Water	
		μ/ρ (cm^2/g)	μ (cm^{-1})	μ/ρ (cm^2/g)	μ (cm^{-1})	μ/ρ (cm^2/g)	μ (cm^{-1})	μ/ρ (cm^2/g)	μ (cm^{-1})	μ/ρ (cm^2/g)	μ (cm^{-1})
^{131}I	0.364	0.11127	0.10804	0.10007	0.23517	0.11351	0.10443	0.10527	0.12527	0.11064	0.11064
^{137}Cs	0.662	0.08673	0.08422	0.07751	0.18214	0.08851	0.08143	0.08208	0.09767	0.08618	0.08618
^{60}Co	1.1732	0.06595	0.06404	0.05884	0.13828	0.06730	0.06192	0.06241	0.07427	0.06553	0.06553
^{60}Co	1.25	0.06364	0.06180	0.05678	0.13342	0.06495	0.05975	0.06023	0.07167	0.06323	0.06323
^{60}Co	1.3325	0.06175	0.05996	0.05510	0.12949	0.06302	0.05798	0.05844	0.06954	0.06135	0.06135
^{24}Na	2.75	0.04221	0.04098	0.03842	0.09028	0.04299	0.03956	0.03990	0.04748	0.04212	0.04212
^{16}N	7.12	0.02525	0.02452	0.02546	0.05982	0.02549	0.02345	0.02373	0.02824	0.02579	0.02579

that of water but greater than that of pure polyethylene over the above photon energy range 0.001 MeV–0.125 MeV. This can be explained by the presence of boron (4.75%) in polyboron while no boron additives are present in water. The order of the materials according to their decrease in mass attenuation coefficient over the mentioned energy range is,

ordinary concrete > water > polyboron > pure polyethylene > borated polyethylene.

As the photon energy increases, from Fig. 2, it is seen that mass attenuation coefficient decreases (and so as the photoelectric effect) and when the photon energy exceeds 0.125 MeV, the mass attenuation coefficient of all the shielding materials approximately possess the same value over a certain energy range. The reason is that at this intermediate energy range, Compton scattering predominates all the way and at this range, the ratio of atomic number to the atomic weight (Z/M) for all elements on which the mass attenuation coefficient depends is approximately equal to ½ except for hydrogen and the heavy elements (John et al., 1967). This means that at those energies where Compton scattering is the dominant process, values of mass attenuation coefficient tend to be roughly the same for all elements and almost all materials have, on a mass basis, about the same gamma ray attenuation properties. When the photon energy exceeds 1.02 MeV, the pair production starts to be dominant for all the samples and increases with the increase of photon energy which is also responsible for the increase in mass attenuation coefficient. For the reasons discussed above, from Fig. 2, it is clear that all the present sample materials possess approximately the same mass attenuation coefficient over an approximate photon energy range 0.125 MeV–6 MeV.

4.2. *Linear attenuation coefficient* (μ)

Fig. 3 presents the linear attenuation coefficient (μ) as a function of photon energy for all the sample materials. The shape of each graph remains the same but each of them changes by a factor according to the density of that material since the linear attenuation coefficient of each mixture is

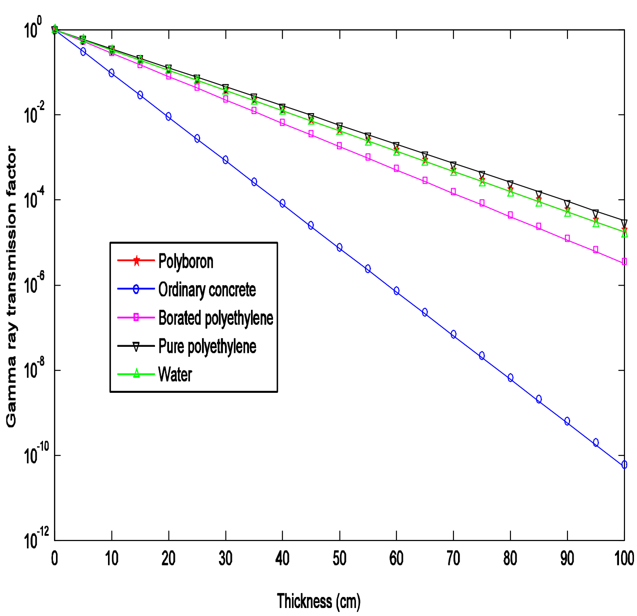

Fig. 5 – Comparison of gamma-ray transmission factor as a function of shielding thickness for ^{131}I (0.364 MeV) source.

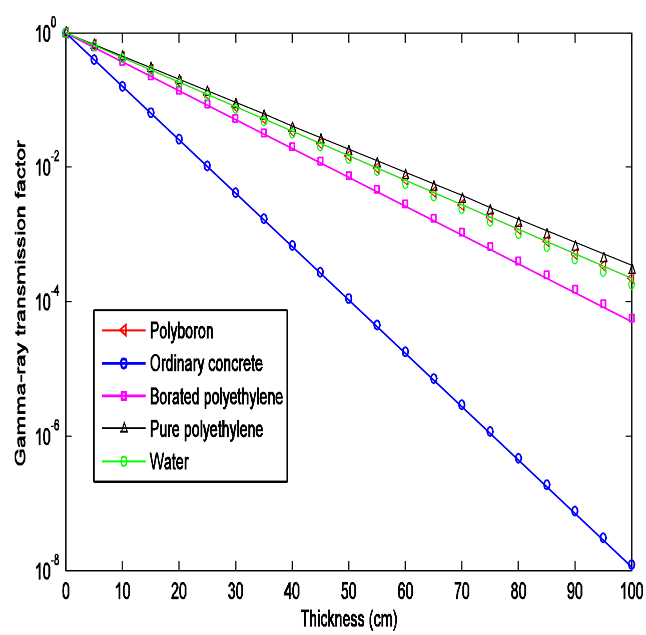

Fig. 6 – Comparison of gamma-ray transmission factor as a function of shielding thickness for ^{137}Cs (0.662 MeV) source.

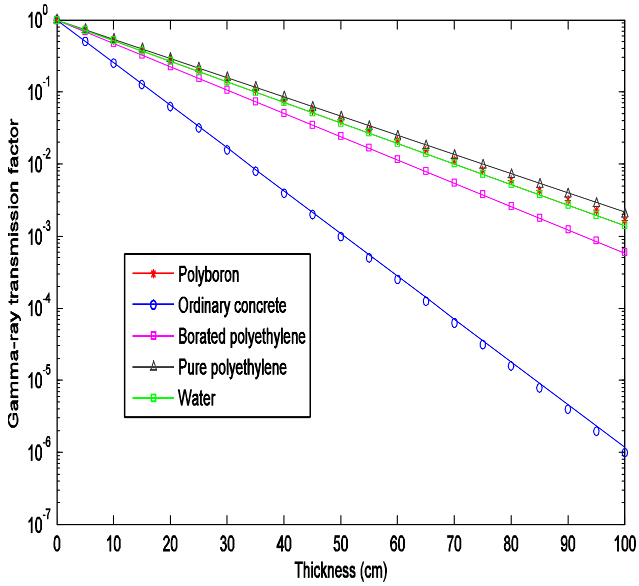

Fig. 7 – Comparison of gamma-ray transmission factor as a function of shielding thickness for ^{60}Co (1.1732 MeV) source.

simply found by multiplying its mass attenuation coefficient with its physical density. From this figure, it is seen that ordinary concrete has the highest linear attenuation coefficient over all the photon energy range due to its high density and the containment of high atomic numbered elements. The linear attenuation coefficient of polyboron is greater than that of borated polyethylene and pure polyethylene but less than that of ordinary concrete and water at the low photon energy range. So at this range, the shielding properties of polyboron for gamma rays are much better than those of pure polyethylene and borated polyethylene.

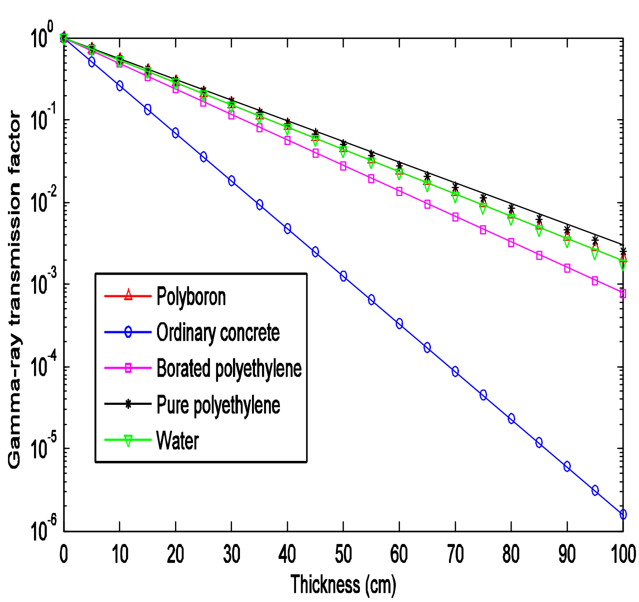

Fig. 8 – Comparison of gamma-ray transmission factor as a function of shielding thickness for ^{60}Co (1.25 MeV) source.

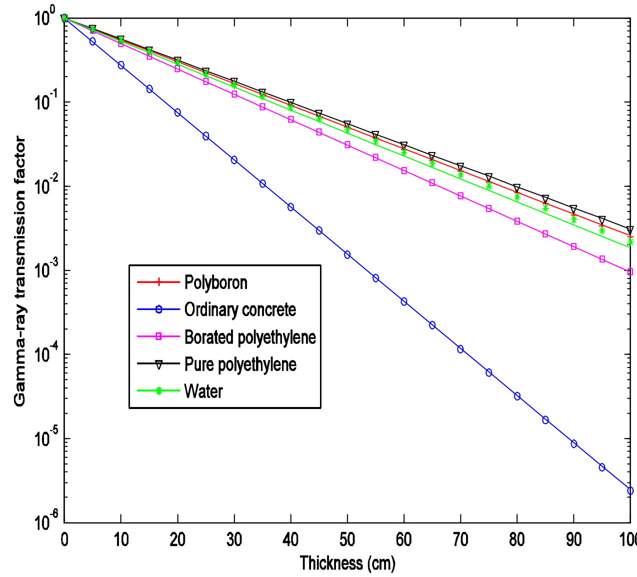

Fig. 9 – Comparison of gamma-ray transmission factor as a function of shielding thickness for ^{60}Co (1.3325 MeV) source.

To clarify the above phenomena, Fig. 1 has been taken from X-com output that represents the variation of mass attenuation coefficient of polyboron with different photon energy for total and partial interactions. It is seen that at very low photon energy range, photoelectric absorption predominates over both the coherent and incoherent (Compton effect) scattering for a certain energy range and after that, Compton effect becomes the dominating interaction till the ending value (20 MeV) of the range. From this figure, it is also noticed that pair production begins at 1.02 MeV.

4.3. *Relaxation length (λ)*

The relaxation length (λ) is calculated from μ by Eq. (9) of the five sample materials at the photon energy range 0.001 MeV–20 MeV and its changes with photon energy has been represented in Fig. 4. Since the relaxation length (λ) of any particular radiation represents the average distance between two successive interactions, the shielding properties of the present materials can be easily compared by studying this parameter for that particular kind of radiation. The less the relaxation length of a material, the better the shielding properties it possess. Mathematically this parameter (λ) is equivalent to the reciprocal of linear attenuation coefficient (μ) and the ordinary concrete hence has the lowest λ over the entire photon energy range. From Fig. 4, it can be concluded that the low energy photons can lose its energy in a short distance while high energy photons need a longer distance to lose their energy. It is also seen from this figure that the relaxation length of polyboron is less than that of pure polyethylene and borated polyethylene but higher than that of ordinary concrete and water at a certain low photon energy range. So polyboron is much better than borated polyethylene (and also than pure polyethylene) for gamma-ray attenuation over this energy range.

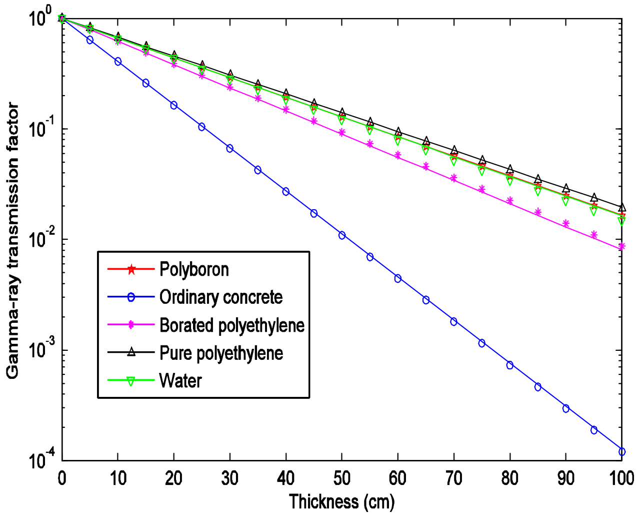

Fig. 10 – Comparison of gamma-ray transmission factor as a function of shielding thickness for ^{24}Na (2.75 MeV) source.

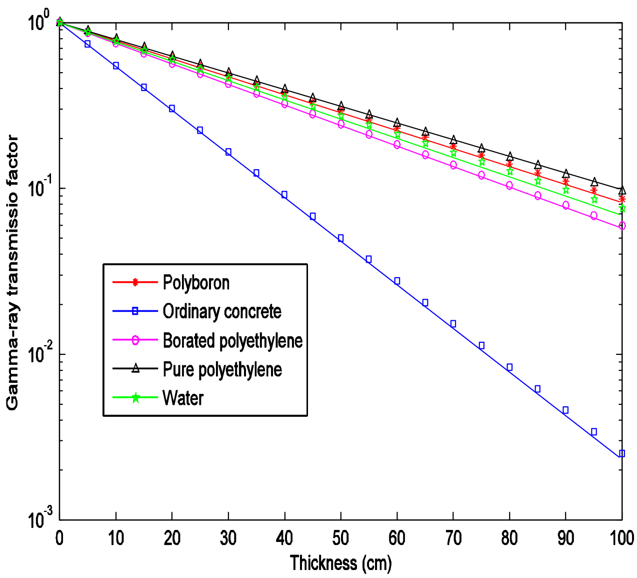

Fig. 11 – Comparison of gamma-ray transmission factor as a function of shielding thickness for ^{16}N (7.12 MeV) source.

4.4. Total mass attenuation coefficient (μ_m), linear attenuation coefficient (μ), half value layer (HVL) and tenth value layer (TVL) for some common gamma sources

In Table 4, the calculated total mass attenuation coefficient (μ_m) and linear attenuation coefficient (μ) of the five sample materials for some common gamma sources – ^{137}Cs (0.662 MeV), ^{60}Co (1.1732 MeV, 1.3325 MeV and the average of these two values, 1.25 MeV), ^{16}N (7.12 MeV), ^{131}I (0.364 MeV) and ^{24}Na (2.75 MeV) that are widely used in various purposes, have been shown and the plotting of variation of gamma-ray transmission factor (I/I_0) with shielding thickness at these source energies are shown in Figs. 5–11. Half value layer (HVL) and tenth value layer (TVL) are two important parameters in designing any radiation shielding since half value layer and tenth value layer indicates the required thickness of an absorber to reduce the radiation level to half and one tenth of its initial value respectively. The calculated HVL and TVL of the sample materials at the mentioned source energy have been shown in Table 5. This study can be useful for selecting the appropriate shielding materials for these gamma sources. From Figs. 5–11, it is seen that for all the gamma sources mentioned above, ordinary concrete has the best shielding properties (since its transmission factor drops rapidly than that of any other of the four shielding materials with the increase in thickness). These figures show that gamma-ray transmission factor for these sources drops according to the following order:

ordinary concrete > borated polyethylene > water > polyboron > pure polyethylene.

So for these gamma sources, ordinary concrete will be the best appropriate shielding while polyboron possess the fourth position on a thickness basis.

5. Conclusion

The present study concludes that the shielding effectiveness of any shielding material depends on its density, the types of chemical composition and the concentration of the elements that it contains. To design and select an appropriate shielding material, all the nuclear parameters associated with it should be studied thoroughly. In the current research, the gamma-

Table 5 – Half value layer (HVL) and Tenth value layer (TVL) of different sample materials for some common gamma sources.

Source Identity	Photon energy (MeV)	Polyboron		Ordinary concrete		Pure polyethylene		Borated polyethylene		Water	
		HVL (cm)	TVL (cm)	HVL (cm)	TVL (cm)	HVL (cm)	TVL (cm)	HVL (cm)	TVL (cm)	HVL (cm)	TVL (cm)
^{131}I	0.364	6.41	21.32	2.95	9.79	6.64	22.05	5.53	18.39	6.26	20.81
^{137}Cs	0.662	8.23	27.35	3.80	12.64	8.51	28.28	7.10	23.58	8.04	26.72
^{60}Co	1.1732	10.82	35.96	5.01	16.65	11.19	37.19	9.33	31.01	10.58	35.14
^{60}Co	1.25	11.21	37.27	5.19	17.26	11.60	38.54	9.67	32.13	10.96	36.42
^{60}Co	1.3325	11.56	38.41	5.35	17.78	11.95	39.72	9.97	33.12	11.30	37.54
^{24}Na	2.75	16.91	56.20	7.68	25.51	17.52	58.22	14.60	48.51	16.45	54.68
^{16}N	7.12	28.26	93.92	11.58	38.50	29.55	98.20	24.54	81.57	26.87	89.31

ray attenuation parameters have been studied for the locally developed shielding material, polyboron, and it has been found that this material possesses medial gamma-ray attenuation characteristics among the sample materials over a certain photon energy range (0.125 MeV–6 MeV) and at this energy range, it can be used as a biological shielding against gamma rays considering the cost, local availability and ease of fabrication. This study can also be utilized for improving the shielding performance of polyboron to make it a universal radiation shielding material and the theoretically computed results of the present study can be taken as a preliminary result and an additional experimental work based on it can be performed in future. In addition to that, it can be recommended to study the changes of attenuation properties of polyboron with the changes of concentrations of high and low atomic numbered elements present in it; and to develop a simplified empirical model for neutron and gamma ray transport calculations.

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