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Research Article

Simulation on Gamma Ray Shielding Properties of Polyboron, Paraffin WAX and Ordinary Concrete Using Phits

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Abstract

This current research presents gamma-ray shielding properties of polyboron, paraffin wax and ordinary concrete which have been used as potential radiation shielding materials. The study was carried out using particle and heavy ion transport code system (PHITS) which is a software arrangement, a combination of tools which can be used to simulate the particle transportation accurately through matter. Simulation measurements were conducted by NaI (Tl) scintillation detector and Cs-137 gamma source. Linear attenuation coefficients (μ) and mass attenuation coefficients (μ_m) values were calculated in the photon energies of 0.03 to 20 MeV.

Relaxation lengths (λ) have been also calculated from obtaining linear attenuation coefficients. The calculated values of μ, μ_m and λ strongly depend on the photon energy, chemical composition and density of the studied shielding materials. The obtained results show mass attenuation coefficients, linear attenuation coefficients and relaxation length of the shielding materials on the photon energy. As results, the values of μ_m of polyboron had a little greater than those of paraffin wax at low photon energy range but at beyond the lower energy, the values of μ_m of polyboron and paraffin wax had approximately the same. Regarding with ordinary concrete shielding materials, the values of μ_m had much greater than those of polyboron and paraffin wax at the low energy photon range (0.03 to 0.1 MeV) but at above 0.1 MeV, the values of μ_m for all shielding materials had approximately the same. It could also be noticed that the relaxation length (λ) values of polyboron and paraffin wax had approximately the same over the entire photon energy range but the values of the ordinary concrete had much less than those of polyboron and paraffin wax. The relaxation length values of all sample materials increased over the entire photon energy range in relation with the less the values of λ, the more the values of λ. The results were compared with the database of X-Com taking photon energy range 0.03 to 20 MeV. It was concluded that the values of μ_m of all sample shielding materials had been found less than the error of 10% in comparison with the X-Com values. Therefore, the results of this study can be utilized to comprehend the shielding effectiveness of these materials.

Key Words: Attenuation Coefficients, Gamma Ray, Phits, Photon Energy, Shielding Materials

Introduction

Polymer-based on boron has a lack of typical specific preparation method. Therefore, it has become essential to introduce innovative, rational, selective, high-yield reaction pathways. Different pathways have been reported for the synthesis of various boron-based polymers Formation of certain compounds like halopolyboranes which act as important precursor materials for the development of functionalized polyboranes and carboranes [1]. Decaborane alkyne-hydroboration reactions accelerated via a metal catalyst provides higher yield and efficient route to mono- and dialkenyldecaboranes. Alkenylborane transformations to important molecular, polymeric and solid-state materials supported and accelerated through the catalyst, i.e., with help of transition metal or an ionic liquid. Various methods like selective synthesis and functionalization method of metal latricarbadecaboranyl complexes are developed for biomedical and electronic application [2].

Paraffin waxes are defined as the materials consisting of saturated carbon hydrogen chains integrated with branched, straight and ring-like (aromatics) structures that are relatively complex by nature. This chemical configuration endows the amorphous characteristics and inertness to paraffin waxes, resulting in inactive functional groups where the external chemical reactions become impossible. Based on this stance, paraffin waxes are supposed to be the green thermal reservoirs, lying within the sustainable targets of the current era. Therefore, the applications of paraffin waxes ranging from biomedical to thermal storage/

release are declared relatively safe and environmental-friendly [3-6].

Ordinary concrete is a relatively low-cost material and it can be handling easily as it can be poured into various, complex shapes. More studies were conducted on the use of cement and other materials in radiation shielding. Shielding is considered in the important ways which dependence on radiation protection as well as distance and time, mostly the lead used in shielding against gamma ray and X-ray and concrete is used in nuclear power, X ray rooms, nuclear medical and uses in Nuclear Power plants, Nuclear Power research, laboratories, and hot cells. The choice of shielding materials selection is dependent upon exposure rate reduction, kind of source, and final cost-effective analysis. In general, there are different materials used to protect against radiation in different applications, for example, polyethylene, glass, epoxy, lead and concrete were used to shield neutrons and gamma rays [4].

Use of nuclear technology with time in research, agriculture, health sector and nuclear energy production are increasing day after day. One of the main concerns of dealing with nuclear technology is the radiation which can be exposed to the outside environment and human beings and it can cause severe incidents. So, the radiation must be absorbed enough so that the personnel can be protected from the effects caused by radiation. In reactor environments, industry, and nuclear medicine, gamma radiation shielding is essential. Conventional materials including water, concrete, and lead are frequently utilized. However, other shielding materials have drawn interest because of health, economic, and environmental issues. For designing and choosing an appropriate material for shielding, it is essential to study the characteristics of materials that are exposed to radiation. The parameters related to radiation shielding which are studied in case of designing a shield are total mass and linear attenuation coefficient, for gamma rays and relaxation length [5].

The principle of radiation shielding is to reduce the intensity of external radiation to an acceptable level. A good x-ray/ gamma ray shielding material should have a high value of photon attenuation coefficients and the irradiation effects on its mechanical properties should be small. Many types of photon shielding have been produced, using different material compositions. These have ranged from classic ones such as concrete to more advanced materials such as custom-made shielding constructed from heavy metals dispersed inside organic polymers. Shielding has also been produced using alkali minerals, the radiation-shielding properties of which have been compared with those of concretes [6].

Particle and Heavy Ions Transport Code System (PHITS) is a programming language based on the Monte Carlo method that can be used to calculate particle transport. PHITS was developed by JAEA (Japan Atomic Energy Agency), RIST Information System and Technologies, and KEK High Energy Accelerator Research Organization). The use of the PHITS code aims to support research in the fields of accelerators, radiotherapy, space radiation and in other fields related to the transport phenomena of particles (neutrons, protons, electrons, photons) and heavy ions This code has widely used in many studies in the fields of accelerator and detector design, particle therapy, and cosmic radiation, etc. With the various nuclear reaction models and atomic data libraries, PHITS code makes it possible to simulate photon interactions in polypropylene material with accurate results [7].

The aim of the present study is to simulate gamma-ray shielding properties of polyboron, paraffin wax and ordinary concrete using PHITS.

Theoretical Background

In this study, the mass attenuation coefficient for polyboron, paraffin wax and ordinary concrete were analytically determined and results were compared using the Win X-Com code, Windows version of the X-Com database, at photon energies between 0.03 MeV and 20 MeV.

Calculation of Linear and Mass Attenuation Coefficient

The linear attenuation coefficient and mass attenuation coefficient of polyboron, paraffin wax and ordinary concrete were calculated from PHITS simulation outputs. When a gamma-ray beam traverses an absorber, the intensity of the beam will be attenuated according to the Beer-Lambert's law by the equation [8].

$$I = I_o\, e^{-\mu t} \qquad (1)$$

Where I_0 and I are the attenuated and attenuated gamma ray beam intensities, μ (cm^{-1}) is the linear attenuation coefficient; t (cm) is the linear thickness, Rearranging equation (1) and taking the logarithm of both sides results in the expression

$$\mu = \frac{\ln\left(\frac{I_0}{I}\right)}{t} \qquad (2)$$

By dividing the linear absorption coefficient by the material density (g/cm^3), which is known as the mass absorption coefficient (μ_m), the relationship between radiation and material density is made clear [8].

$$\frac{\mu}{\rho} = \frac{\ln\left(\frac{I_0}{I}\right)}{\rho t} \qquad (3)$$

Calculation of Relaxation length (λ)

Relaxation length (λ)is defined as the mean displacement between two successive collisions or interactions. This length is defined by the equation,

$$\lambda = 1/\mu \qquad (4)$$

where m is the linear attenuation coefficient and x is the absorber thickness [9].

PHITS Monte Carlo Simulation

The calculation of deposited energy for photon transport through material specimen was realized by PHITS code. PHITS is developed for numerical experiments by Monte Carlo techniques for dosimetry, radiation damage, radiation therapy and other actual applications of these particles. For the photon history, following it from scattering to scattering using corresponding inverse distribution between collision, types of target, types of collisions, types of secondary, their energy and scattering angles generates the trajectory. Photon interactions are coherent scattering, incoherent scattering, photoelectric absorption and pair production [10].

Materials and Models

The total mass attenuation coefficient for three shielding materials are polyboron, paraffin and ordinary concrete which has been analytically calculated using equations (2 and 3) at gamma energy range of 0.03 to 20 MeV. The calculation of the mass attenuation coefficients of these samples has been done by PHITS simulation for the mentioned energies range. The analytical results obtained from the PHITS calculation were compared with X-Com values, Linear and mass attenuation coefficients have been calculated for the same gamma radiation sources. Percentages of atomic compositions of the studied samples have been shown in table ---.

Elements	Polyboron (%) (ρ = 0.971 g/cm^3)	Paraffin Wax (%) (ρ = 0.93 g/cm^3)	Ordinary Concrete (%) (ρ = 2.35 g/cm^3)
H	12.38	14.86	0.94
B	4.89		
C	59.88	85.14	0.09
O	22.85		53.66
Na			0.46
Mg			0.12
Al			.1.32
Si			36.74
S			0.08
K			0.31
Ca			5.65
Fe			0.63

Table 1: Percentages of Atomic Compositions of the Studied Samples [9-11]

PHITS Simulation Model of Studied Shielding Properties

Narrow beam transmission geometry was simulated to investigate photon attenuation coefficients of proposed polypropylene. A schematic diagram of PHITS simulation geometry was shown in figure (1). An example of a block sample with thickness of 20 cm × 20 cm × 20 cm in the energy range of 0.03 to 20 MeV was used as a shield and placed between source and detector. Gamma source is defined as disk source with 2.54 cm in diameter and the detector used in this simulation is a NaI (Tl) scintillation detector with 2.54 cm in diameter. In PHITS simulation, "t-track" tally was used to obtain photon fluence in the detector cell determined by the sum of the track length per source divided by the volume of the cell [12]. Figure 1 showed PHITS simulation model of source, polypropylene and detector.

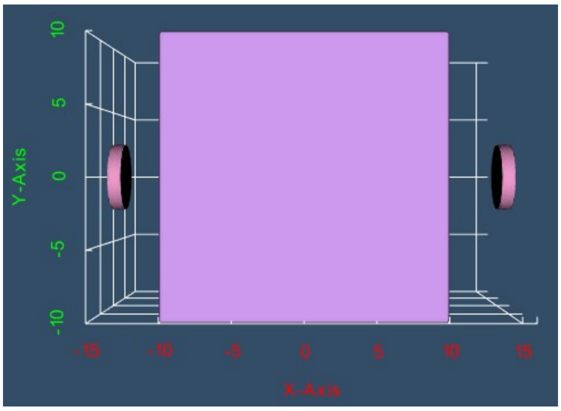

Figure 1: PHITS Simulation Model of source, shielding material and detector designed by PHITS code

Results and Discussion

Calculated values of linear attenuation coefficient (μ) and mass attenuation coefficient (μ_m) of the Studied Materials

The comparison for calculated mass attenuation coefficient values and X-Com values of polyboron, paraffin wax and ordinary concrete are presented by fig.----. Gamma-ray mass attenuation depends on the incident photon energy, material density and chemical composition of the materials. It was found that mass attenuation graph decreases with increasing incident photon energy over the energy range from 0.03 to 20 MeV. Mass attenuation coefficient values were calculated by dividing of linear attenuation coefficient values with material density. The results revealed that the differences between the calculated mass attenuation coefficient values and X-Com values were less than 10%. Comparisons for mass attenuation coefficient values of X-Com as well as polyboron, paraffin wax and ordinary concrete were shown in tables --- to ----. The variation graphs of these materials were illustrated in figure --- to ---.

Photon Energy (MeV)	X-Com	Polyboron
0.03	0.294	0.285
0.04	0.235	0.215
0.05	0.210	0.203
0.06	0.1967	0.176
0.08	0.1802	0.168
0.1	0.1693	0.155
0.15	0.1506	0.133
0.2	0.1375	0.123
0.3	0.1193	0.107
0.4	0.1068	0.0953
0.5	0.0974	0.0883
0.6	0.09014	0.0829
0.8	0.07916	0.0702
1	0.07117	0.0659
1.25	0.06364	0.0591
1.5	0.05791	0.0529
2	0.04966	0.0453
3	0.03973	0.0368
4	0.03389	0.0303
5	0.03	0.0272
6	0.02728	0.0247
8	0.02366	0.0218
10	0.02056	0.0182
15	0.01831	0.01639
20	0.01681	0.01533

Table 2: Comparison for mass attenuation coefficient values of X-Com and Polyboron

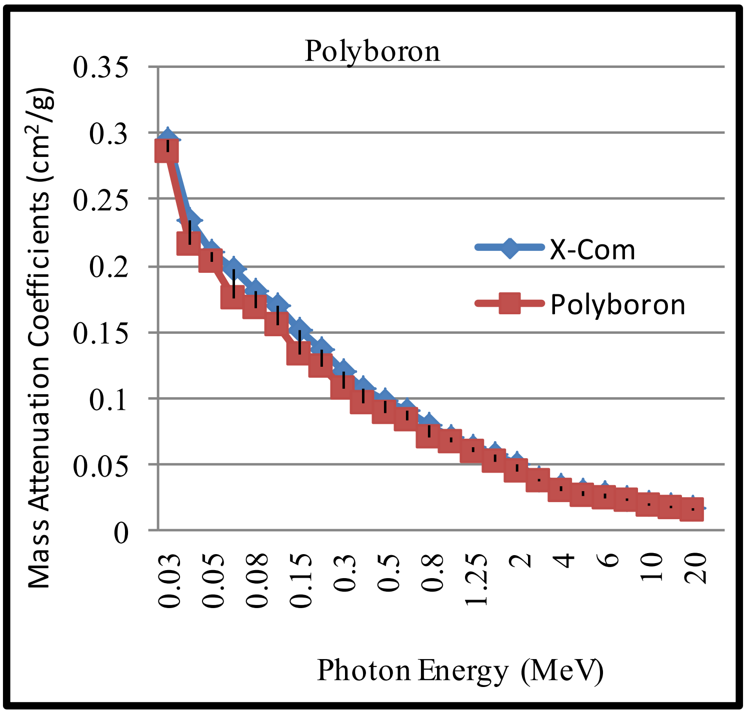

Figure 2: Comparison for mass attenuation coefficients values of X-Com and Polyboron

Photon Energy (MeV)	X-Com	Paraffin Wax
0.03	0.2712	0.243322826
0.04	0.2282	0.205142026
0.05	0.2091	0.186668912
0.06	0.1977	0.18610912
0.08	0.183	0.162919331
0.1	0.1726	0.160596915
0.15	0.1541	0.140554785
0.2	0.1408	0.12687207
0.3	0.1222	0.108980367
0.4	0.1094	0.099089179
0.5	0.09989	0.089547744
0.6	0.09237	0.082950332
0.8	0.08112	0.072912934
1	0.07293	0.067232335
1.25	0.06522	0.060858394
1.5	0.05935	0.054221001
2	0.05086	0.048301562
3	0.04062	0.036596227
4	0.03457	0.031336428
5	0.03056	0.028802123
6	0.0277	0.024773772
8	0.02391	0.021728476
10	0.02152	0.019502152
15	0.01823	0.016756205
20	0.01661	0.015326813

Table 3: Comparison for mass attenuation coefficient values of X-Com and Paraffin Wax

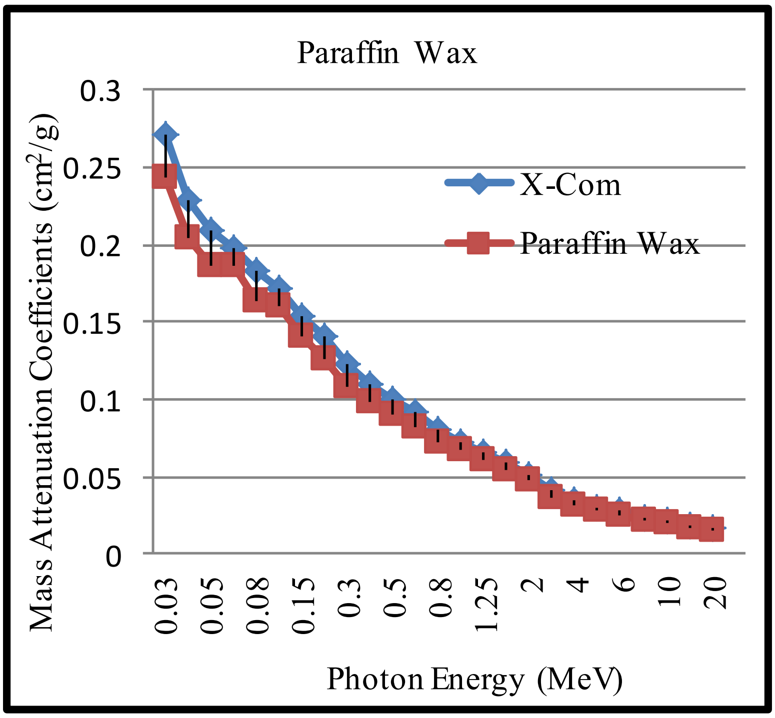

Figure 3: Comparison for mass attenuation coefficients values of X-Com and Paraffin Wax

Photon Energy (MeV)	X-Com	Ordinary Concrete
0.03	1.040	0.95312
0.04	0.541	0.480
0.05	0.358	0.32164
0.06	0.275	0.24765
0.08	0.204	0.1903
0.1	0.1745	0.156533437
0.15	0.1428	0.127897174
0.2	0.1271	0.114587504
0.3	0.1086	0.096843601
0.4	0.09677	0.087140249
0.5	0.08816	0.079435902
0.6	0.08144	0.073000609
0.8	0.07145	0.065170967
1	0.0642	0.057465382
1.25	0.05741	0.051109718
1.5	0.05228	0.047468654
2	0.04507	0.040138482
3	0.03667	0.032853354
4	0.03196	0.028730019
5	0.02895	0.025781767
6	0.02691	0.024024463
8	0.02436	0.022137017
10	0.02291	0.020722243
15	0.02122	0.019354409
20	0.02066	0.018568934

Table 4: Comparison for mass attenuation coefficient values of X-Com and Ordinary Concrete

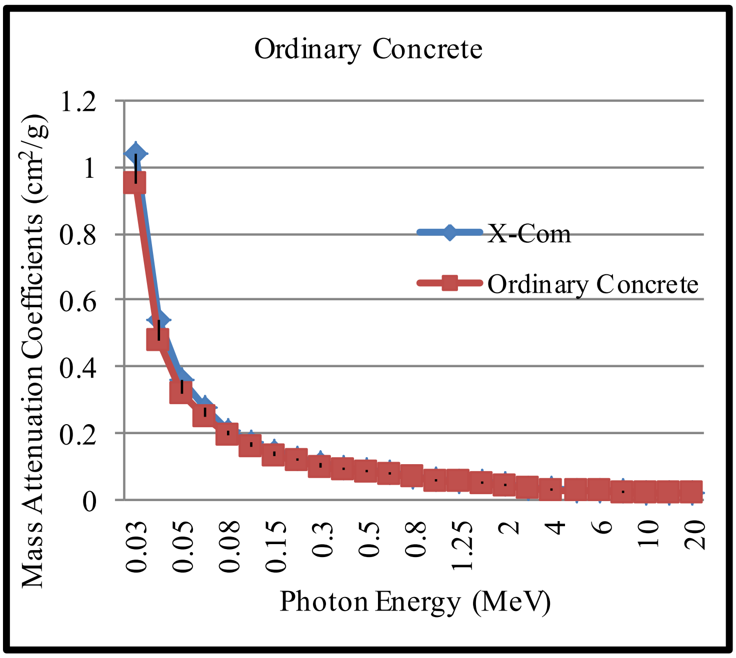

Figure 4: Comparison for mass attenuation coefficients values of X-Com and Ordinary Concrete

Comparison for Mass Attenuation Coefficients of the Shielding Materials

The variations graph of the mass attenuation coefficient and the X-Com values for the studied shielding materials are presented in Figure 3. It can be seen that the derived values from PHITS and X-Com values of mass attenuation coefficients are in fine compatibility.

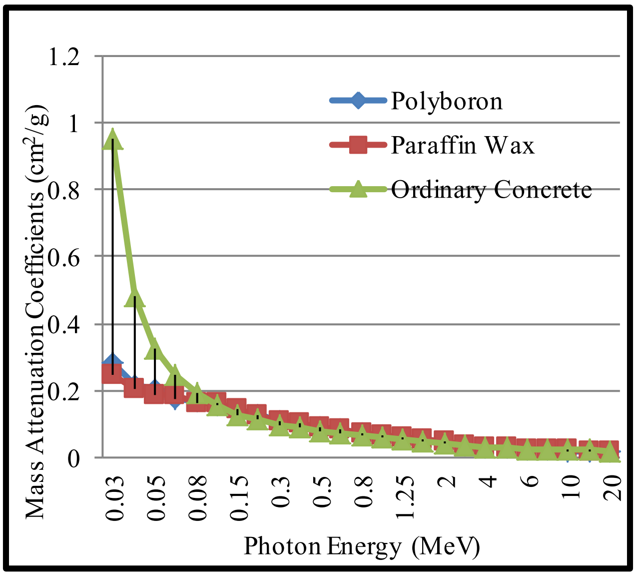

Figure 3: Mass attenuation coefficient of the shielding materials varies as a function of photon energ

Figure 3 makes it clear that mass attenuation coefficient depends on incident gamma ray energy as well as it depends on the composition of material of the shielding materials and decreases if incident photon energy is increased. Figure 3 illustrates the relation between the mass attenuation coefficient and photon energy. Observation indicates that the highest mass attenuation coefficient over an energy range 0.03 to 0.1 MeV has ordinary concrete. From this figure, it is evident that the mass attenuation coefficient of ordinary concrete reduces with increasing photon energy. Materials which have the high atomic number are more effective for gamma-ray shielding. In comparison, ordinary concrete shows the highest mass attenuation coefficient and paraffin wax shows the lowest mass attenuation coefficient due to the highest density of ordinary concrete and the lowest density of paraffin wax among all the sample materials. The materials, ranked in order of decreasing mass attenuation coefficient within the specified energy range, are as follows:

ordinary concrete > polyboron > paraffin from this figure, it shows that increase in the photon energy leads to the mass attenuation coefficient decreases and when the energy of a photon goes over 0.1 MeV, the mass attenuation coefficient of all the shielding materials possess approximately the same values over a particular energy range.

Comparison for Linear Attenuation Coefficients of the Shielding Materials

Figure 4 demonstrates dependency on energy of the linear attenuation coefficient. The nature of the graph for each material remains approximately the same.

From this figure, it is apparent that the highest linear attenuation coefficient across the entire photon energy range is for ordinary concrete which is due to its high density and the availability of high atomic numbered elements. The linear attenuation coefficient of polyboron is a little greater than that of paraffin at the low photon energy but less than that of ordinary concrete over the entire photon energy range.

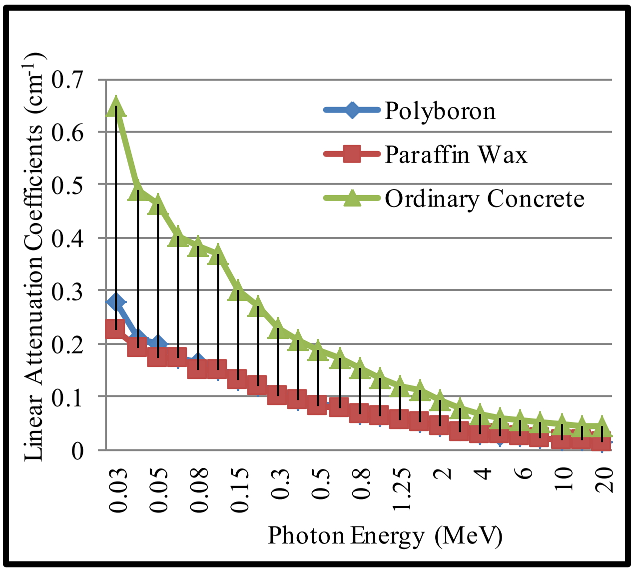

Figure 4: Linear attenuation coefficient of the shielding materials varies as a function of photon energy

Comparison for Relaxation Length (λ)

The relaxation length is computed from by Eq. (---) of the three sample materials changing energy of photon from 0.03 to 20 MeV and its dependency on photon energy has been presented in Fig. ---. Since the relaxation length (l) 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 possesses. The shielding effectiveness improves as the relaxation length decreases. Mathematically this parameter is the same as the inverse of linear attenuation coefficient. It is also seen from this figure that the relaxation length of polyboron and paraffin is approximately the same but higher than that of ordinary concrete over the entire photon energy range. The ordinary concrete has the smallest relaxation length so that it is more efficient than other materials relatively in shielding. Relaxation length values of polyboron, paraffin wax and ordinary concrete wae shown in tible ---. The variation graph of these materials was illustrated.

Photon Energy (MeV)	Polyboron	Paraffin Wax	Ordinary Concrete
0.03	3.613565	4.419104	1.537687372
0.04	4.790075	5.241582	2.038329772
0.05	5.073232	5.760299	2.158822173
0.06	5.851512	5.777626	2.490005119
0.08	6.130155	6.600008	2.608576792
0.1	6.644298	6.695451	2.718472959
0.15	7.743354	7.650176	3.327140884
0.2	8.372895	8.475221	3.713597891
0.3	9.624917	9.866629	4.394011707
0.4	10.80657	10.85153	4.883299295
0.5	11.66326	12.00777	5.356921826
0.6	12.42299	12.9628	5.829155701
0.8	14.67046	14.7473	6.529470634
1	15.62771	15.99333	7.405013233
1.25	17.42582	17.66837	8.325851347
1.5	19.46817	19.83122	8.964482444
2	22.73435	22.26157	10.60159452
3	27.98549	29.38196	12.95246476
4	33.98898	34.3137	14.81140413
5	37.86272	37.33297	16.50514912
6	41.69498	43.40352	17.71244241
8	47.24157	49.48662	19.22264024
10	56.58605	55.1359	20.53503173
15	62.83503	64.17138	21.98630341
20	67.17979	70.15606	22.91633525

Table 5: Relaxation Length Values of Polyboron, Paraffin Wax and Ordinary Concrete

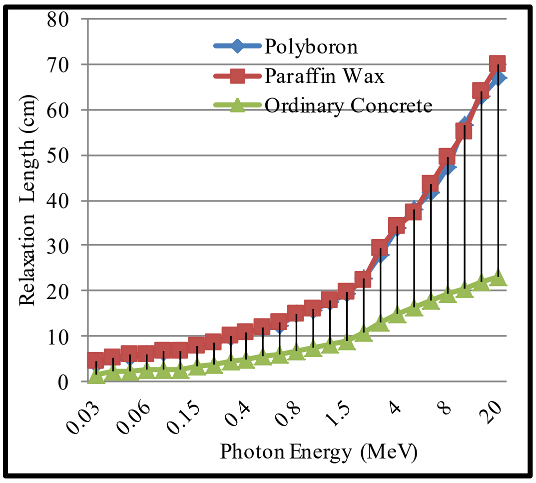

Figure 5: Relaxation Length of the shielding materials as a function of Photon energy

Linear and Mass Attenuation Coefficient Graphs at 0.662 MeV

For comparison purposes, linear attenuation coefficient (μ) and mass attenuation coefficient (μ_m) for different shielding materials at 0.662 MeV is shown in Fig. --- and ---- using PHITS and X-Com. From this figure, one can easily calculate the linear attenuation coefficient and can be used for any shielding design using Cs-137 source (0.662 MeV). The results are reasonably good agreement between PHITS and X-Com.

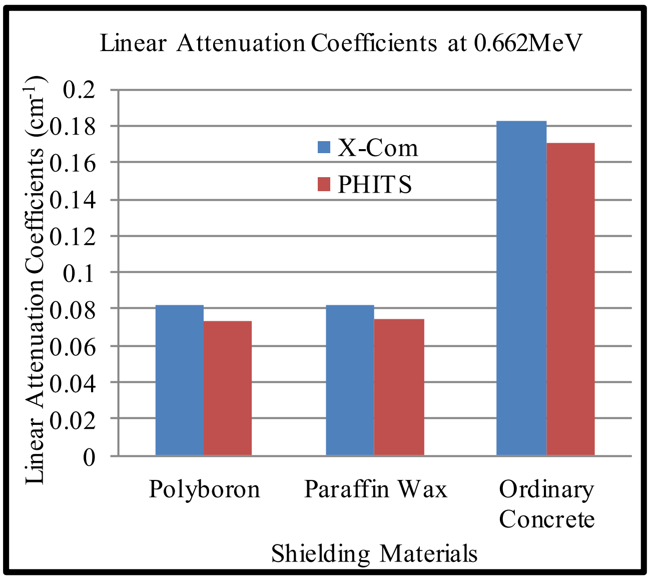

Figure 6: Linear attenuation coefficient at 0.662 MeV for different shielding materials

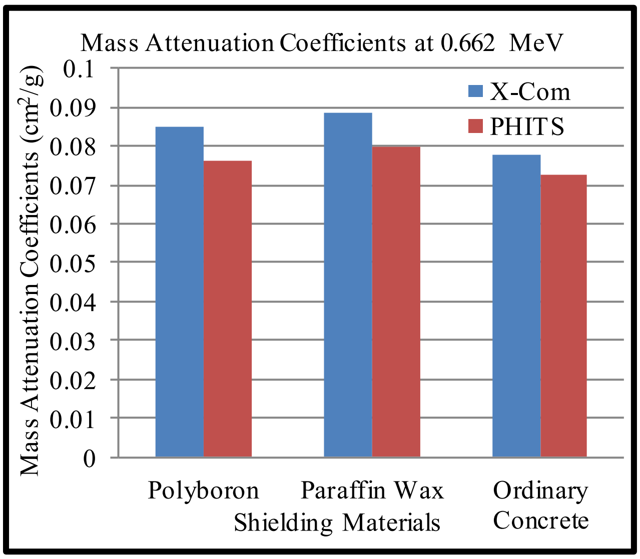

Figure 7: Mass attenuation coefficient at 0.662 MeV for different shielding materials

Conclusion

In this study, the investigated shielding samples has been simulated by PHITS code at incident photon energy range of 0.03 to 20 MeV and the mass attenuation coefficient (μ_m) and linear attenuation coefficient (μ) of these samples have been calculated by the attenuation equations. 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, it is identified that ordinary concrete possesses better gamma-ray attenuation characteristics among the sample materials because of high atomic number and high density. This study can further use for improving these shielding conditions. In addition to, PHITS can be recommended for studying the changes of attenuation properties of other sample materials with the changes of concentrations of high and low atomic numbered elements present in those in contrast, the simulation method by the PHITS code has been observed appropriate method to study attenuation coefficients of other shielding materials and .to develop a simplified virtual model for gamma and neutron transport calculations.

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