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Research Article

Novel High Strength Economical Shielding Materials

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Abstract

In the present study, gamma-ray shielding performance was investigated using mass attenuation coefficients and exposure buildup factors for tourmaline, datolite, galena, amethyst and hormirad. The mass attenuation coefficients were also calculated using GEANT4 simulation toolkit, compared with XCOM results, a good agreement between XCOM and GEANT4 results was observed. The exposure buildup factors were calculated using GP fitting method for photon energy 0.015 to 15 MeV up to 40 mfp. The hormirad is superior shielding material among than tourmaline, datolite and amethyst whereas galena is the best shielding materials in low photon energy except near to 100 keV. The investigation would be very useful for shielding application of these materials.

Keywords: Novel shielding, galena, XCOM, GEANT4, gamma-ray

Yeni Yüksek Mukavemetli Ekonomik Zırhlama Malzemeleri

Öz

Bu çalışmada, kütle zayıflatma katsayısı ve ekpojur buildup faktörleri kullanılarak tourmaline, datolite, galena, amethyst ve hormirad için gama ışını zırhlaması incelenmiştir. Kütle zayıflama katsayıları GEANT4 simülasyon kodu kullanılarak hesaplandığında,ve XCOM sonuçları ile karşılaştırıldığında, XCOM ve GEANT4 sonuçları arasında iyi bir uyum gözlenmiştir. Ekpojur buildup faktörleri, 0.015 ila 15 MeV arasında 40 mfp'ye kadar olan foton enerjisi için GP fittiing yöntemi kullanılarak hesaplanmıştır. Hormirad; turmalin, datolit ve ametist malzemeleri arasında üstün zırhlama malzemesiyken, galena 100 keV'e yakın düşük foton enerjisi seviyeleri haricinde en iyi koruma malzemesidir. Bu çalışma; ilgili malzemelerin zırhlama uygulamalarında faydalı bir çalışma olabilir.

Keywords: Yeni zırhlam, galena, XCOM, GEANT4, gamma ışını

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Introduction

Radiation protection and shielding requirements have been evolved in utilizations of radiation and nuclear technology. The shielding is found one of the most important aspects of radiation protection to control the personnel exposure right from beginning of nuclear or radiation facility and source control methodology. The shielding materials have been invented of various types based on the requirements for type of radiation, application, facility requirements, etc. Concrete, composed of portland cement, sand, aggregate (stones, gravel, etc.), and water, is one of the most common building materials for construction of commercial buildings. Specific properties make concrete an excellent choice for building material. On the other hand, concrete has been found one of the most desired permanent shielding materials for nuclear facility for construction to stop radiation coming from it and exposure control.

Shielding against radiation is result of radiation interaction process with material, more interaction results in attenuation of more radiation, called as effective shielding. The number of interaction depends upon number of target (nucleolus or atom) of the material, other way it can be said that the density plays a vital role in shielding effectiveness. Therefore, high density materials are unique choice for radiation shielding applications. Various investigations have been reported for high density shielding materials used in various applications [1-2]. In recent days, some investigations on high strength shielding materials have also been reported [3-6], where detailed investigation is very important for selection of these materials for nuclear and radiation facilities. It has encouraged us to investigate the shielding parameters of the high strength shielding materials. This study is very essential as it reflects the shielding efficiency and their ability to stop or decrease the intensity by absorbing the gamma-ray falling on it. The shielding of the gamma-ray requires in-depth knowledge of mass attenuation coefficients, mean free path (mfp) and buildup factors.

The intensity of a gamma-ray beam through a medium follows Lambert's Beer law ($I = I_o * e^{-\mu x}$) under three conditions such as (i) mono-chromatic rays (ii) thin absorbing material, and (iii) narrow beam geometry. In case, any of the above conditions is not being met, this law is no longer applicable. The law can be made applicable by using a correction multiplication factor, called as "buildup factor". The modified equation becomes $I = B * I_o * e^{-\mu x}$, where B is the buildup factor for particular energy at the shield thickness x, I_o is the incident photon intensity, I is attenuated photon intensity, μ is linear attenuation coefficient in cm^{-1} and 'x' is the shield thickness in cm.

The factor B depends on absorbing medium, photon energy, attenuation coefficient for specific energy photons in the medium and absorber thickness. The compilation for buildup factors by various codes is reported by American Nuclear Society in ANS, 1991 [7]. The data in the report covers the energy range 0.015-15 MeV up to a penetration depth of 40 mfps. The buildup factors in the report are for 23 elements (Z=4 to 92). Harima et al. [8] developed a fitting formula, called a Geometric Progression (GP) which gives buildup factors of the good agreement with the report by ANS, 1991. The GP fitting formula is known to be accurate within the estimated uncertainty (<5%). Various researchers investigated gamma-ray buildup factors in different materials; silicate, neutron shielding and concretes [9-11] which shows that the GP fitting is a very useful method and accurate for estimation of the buildup factors.

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The shielding efficiency parameters are very important for progress of next generation nuclear energy program. With the objective of shielding applications, in the present work, mass attenuation coefficients and exposure buildup factors (using GP fitting method) have been computed for high strength materials (given in Table 1). This study should be potential importance for radiation shield design and selection of the shielding materials and reactor design.

Material and Methods

The shielding materials having strength are given in Table 1.

Table 1. *Compositions of Novel Shielding Materials*

Material	Density ($g.cm^{-3}$)	Composition (%)
Tourmaline	3.00-3.25	Si O_2(42.65), Al_2O_3(25.14), Fe_2O_3(13.02), TiO_2 (0.21), CaO (0.89), MgO (0.51), NaO_2 (2.04), K_2O (1.07), SO_3 (0.05), P_2O_5(0.59), B_2O_3 (11.08)
Datolite	2.80-3.00	CaO (35), B_2O_3 (21.8), SiO_2 (37.6) H_2O (5.6)
Galena	7.00-7.50	Pb (86.59),S (13.40)
Amethyst Ore	2.65-2.66	B (6.1003), F (0.3541), Cr (0.0213), Mn (0.2220), Na(0.2141), Mg (0.2187), Al (1.384), Si (89.8957), P (0.0486), S (0.0647), Cl (0.0706), K (0.3889), Ca (0.2008), Ti (0.0434), Fe (0.7050), Ni (0.0101), Zn (0.0053), Br (0.0007), Sr (0.0026), Yt (0.0027), Ga (0.0071), As (0.0119), U (0.0053)
Hormirad	3.44-4.10	Fe (60.8), O (31.26), Ca (4.36), Si (1.87), H (0.44), Mg (0.39), P (0.29), Ti (0.19), Al (0.17), K (0.06), Mn (0.06), V (0.05), C (0.04), S (0.01), N (0.003)

Mass attenuation coefficients

The μ/ρ values of the selected materials were calculated by using mixture rule ($(\mu/\rho)_{alloy} = \sum_i^n w_i(\mu/\rho)_i$) where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of the i^{th} element by using WinXcom [12]. The mass attenuation coefficients of the selected materials have been reported using theoretical method [13]. The use of the Monte Carlo method became widespread with different codes especially on radiation attenuation studies [14-16]. One of the well-known Monte Carlo code is GEANT4 [17]. The physics of GEANT4 simulation depends on narrow beam geometry with the various photon energies. The experimental set-up of the simulation consists of a mono-energetic photon beam impinging on a slab of the shielding material. The mass attenuation coefficients of investigated materials were determined by the transmission method according to Lambert-Beer's law ($I = I_0 e^{-\mu_m t}$), where I_0 and I are the incident and attenuated photon intensity, respectively, μ_m ($cm^2.g^{-1}$) is the mass attenuation coefficient and t is the mass thickness of the slab. The thickness of the slab is optimized according to the energy of the incident beam, to avoid that all the photons are absorbed in the slab or traverse the slab without interacting. The primary photons emerging unperturbed from the slab are counted. The energy range of incident photons varied between 1 keV and 100 GeV. Attenuation of photons is calculated by simulating all relevant physical processes and interactions before and after inserting the samples under the investigation. Photon interactions include photoelectric effect, Compton scattering, pair production, Rayleigh scattering, and electrons interactions include Bremsstrahlung, multiple scattering and ionization. Atomic effects after photoelectric effect, as X-rays emission and Auger effect are included. So it is possible to have a vertex from photoelectric effect [20]. A good agreement between GEANT4 model for electromagnetic processes and National Institute of Standards and Technologies (NIST) reference data has been reported recently [20]. This statistical analysis estimated quantitatively the compatibility of Geant4 electromagnetic models with reference data and highlighted the respective strengths.

Exposure buildup factors

The exposure buildup factor (EBF) and GP fitting parameters are calculated by the method of logarithmic interpolation using Z_{eq} of a composite or compound material. The computational work of these parameters is done in three steps as;

a) Calculation of equivalent atomic number
b) Calculation of GP fitting parameters
c) Calculation of buildup factors

Z_{eq}, is a parameter which describes the composite material properties in terms of equivalent elements similar to atomic number for a single element. The photoelectric absorption and pair production are the photon removal processes. Therefore the buildup of photons in a medium is mainly due to multiple scattering events in Compton scattering region, so that Z_{eq} is derived from the Compton scattering interaction process.

The Z_{eq}, for a composite or compound material is estimated by matching the ratio of $(\mu/\rho)_{Compton}$ / $(\mu/\rho)_{Total}$, at a particular energy with the corresponding ratio of an element at the same energy. Thus, firstly the Compton partial mass attenuation coefficient, $(\mu/\rho)_{Compton}$ and the total mass attenuation coefficients, $(\mu/\rho)_{Total}$, were obtained for the material in the energy region 0.015 to 15 MeV using WinXCom computer program (Gerward, et al., 2004). For the interpolation of Z_{eq} for which the ratio $(\mu/\rho)_{Compton}/(\mu/\rho)_{Total}$ lies between two successive ratios of elements, the following formulae were employed [18-19]:

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1}, \qquad \text{...}(1)$$

where Z_1 and Z_2 are the atomic numbers of elements corresponding to the ratios R_1 and R_2 respectively, R is the ratio for the chosen ODS steel alloys at a specific energy. In the second step, the GP fitting parameters were calculated in a similar fashion of interpolation procedure for Z_{eq}. Third and final step is buildup factors estimation by GP fitting parameters (b, c, a, X_k and d) in the photon energy range of 0.015-15 MeV up to a 40 mfp by equations as [18-19]:

$$B(E,x) = 1 + \frac{(b-1)(K^x - 1)}{K-1} \quad \text{for} \quad K \neq 1 \qquad \text{...}(3)$$

$$B(E,x) = 1 + (b-1)x \quad \text{for} \quad K = 1, \qquad \text{...}(4)$$

where,

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$$K(E,x) = cx^a + d\,\frac{\tanh(x/X_K - 2) - \tanh(-2)}{1 - \tanh(-2)}, \quad \text{for penetration depth } (X) \le 40 \text{ mfp}$$

... (5)

where x is the source-detector distance for the medium in terms of mfp and b, the value of the exposure buildup factor at 1 mfp, K (E, X) is the dose multiplicative factor, and b, c, a, X_K and d are computed GP fitting parameters which depends on the attenuating medium and source energy.

Results and discussion

The mass attenuation coefficients and exposure buildup factors of the novel high strength shielding materials are shown in Fig. 1 and Fig 2 (a-e), respectively. The mass attenuation coefficients at particular energies were also simulated using GEANT4 toolkit and given in Table 2 with comparison of the XCOM results. The results of these parameters are explained in brief in next sections.

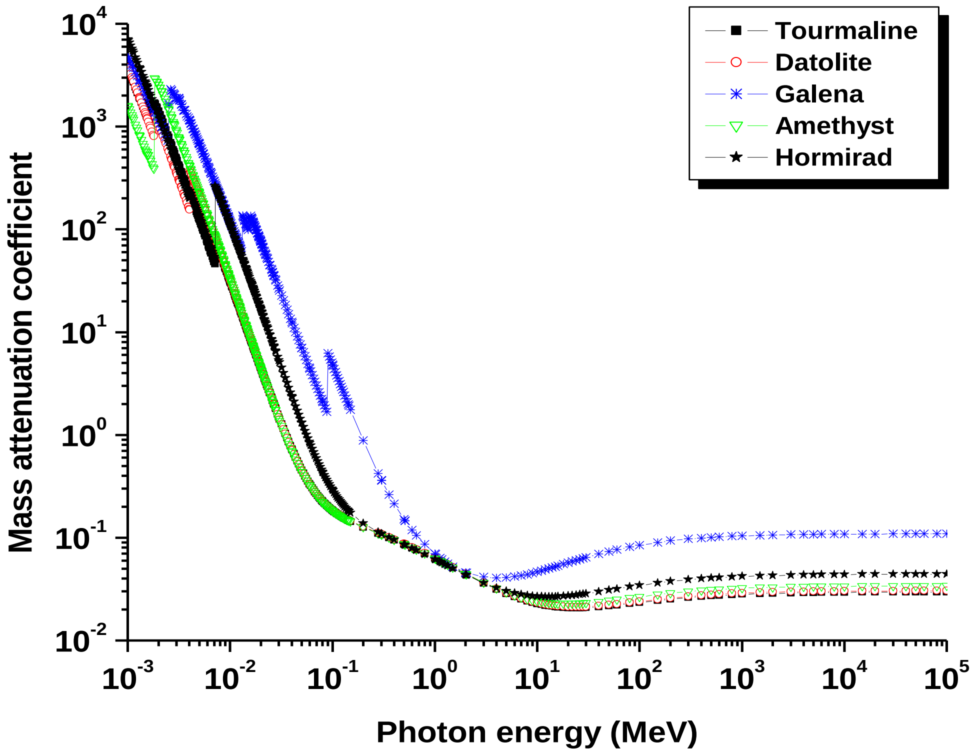

Fig.1. *Mass attenuation coefficients of shielding materials*

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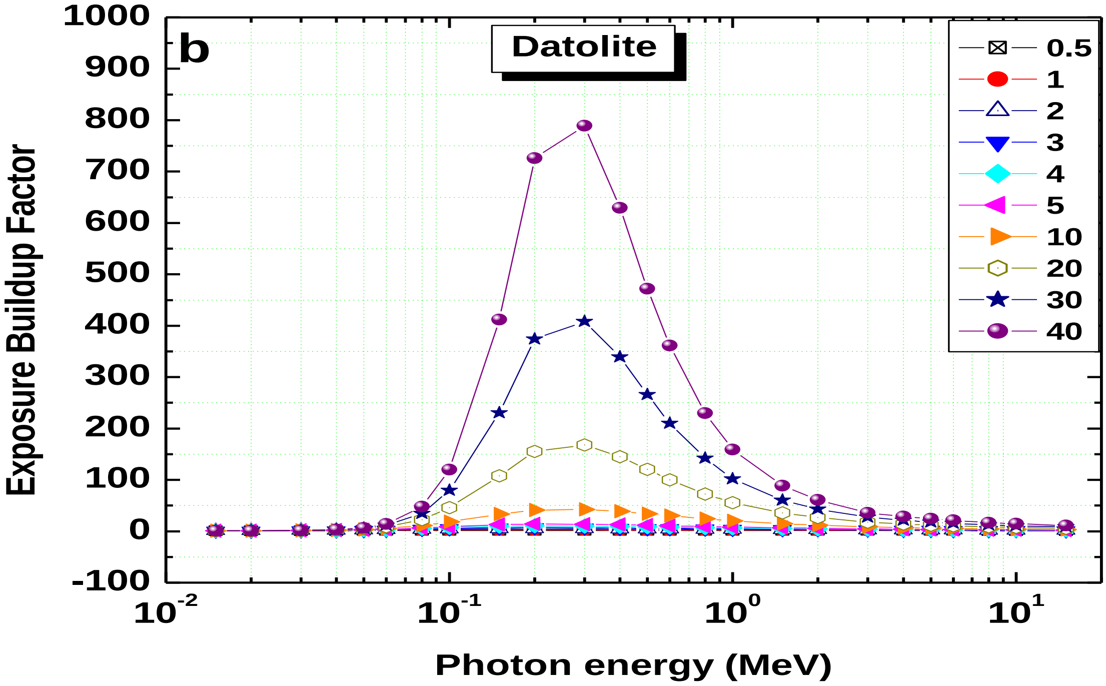

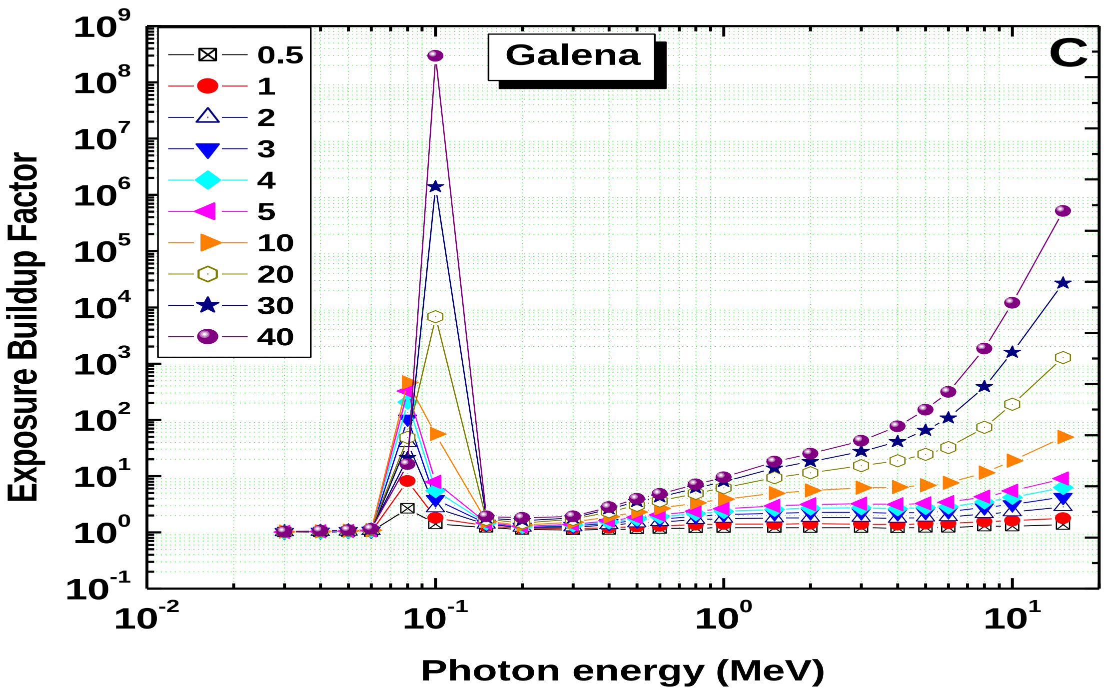

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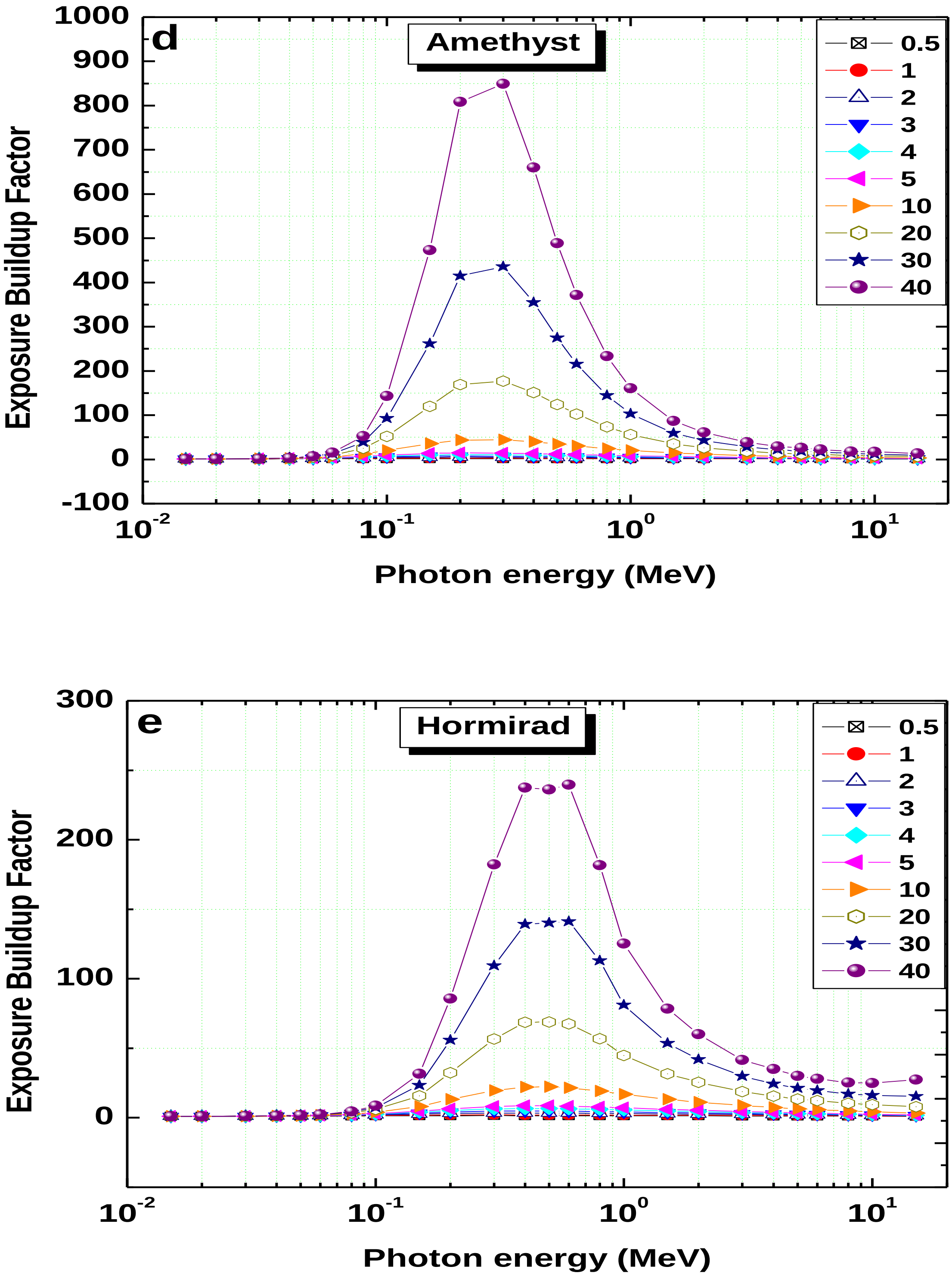

Fig.2. *Exposure buildup factors of shielding materials*

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Table 2: *Comparison of mass attenuation coefficients of novel shielding materials using GEANT4 and XCOM*

Energy (MeV)	Tourmaline			Datolite			Galena			Amethyst			Hormirad		
	GEANT4	XCOM	% Dev.	GEANT4	XCOM	% Dev.	GEANT4	XCOM	% Dev.	GEANT4	XCOM	% Dev.	GEANT4	XCOM	% Dev.
0.276	0.1082	0.1100	1.64	0.1141	0.1120	-1.87	0.4313	0.4310	-0.07	0.1091	0.1110	1.71	0.1104	0.1140	3.16
0.303	0.1043	0.1060	1.60	0.1102	0.1080	-2.04	0.3566	0.3570	0.11	0.1053	0.1070	1.59	0.1056	0.1090	3.12
0.356	0.0979	0.0996	1.75	0.1036	0.1010	-2.57	0.2624	0.2620	-0.15	0.0990	0.1000	0.98	0.0982	0.1010	2.79
0.383	0.0950	0.0966	1.64	0.1007	0.0981	-2.65	0.2305	0.2310	0.22	0.0962	0.0973	1.11	0.0951	0.0971	2.10
0.663	0.0753	0.0762	1.21	0.0800	0.0774	-3.29	0.1056	0.1060	0.38	0.0764	0.0768	0.47	0.0745	0.0752	0.89
1.25	0.0556	0.0562	1.14	0.0591	0.0570	-3.60	0.0585	0.0585	-0.02	0.0565	0.0565	0.07	0.0549	0.0551	0.38
2	0.0437	0.0441	0.86	0.0463	0.0448	-3.44	0.0459	0.0459	-0.04	0.0445	0.0445	0.02	0.0435	0.0436	0.14
6	0.0266	0.0266	0.11	0.0273	0.0271	-0.63	0.0419	0.0419	0.07	0.0275	0.0275	-0.04	0.0290	0.0290	0.17
10	0.0229	0.0228	-0.44	0.0229	0.0233	1.67	0.0465	0.0465	-0.06	0.0241	0.0242	0.25	0.0269	0.0269	0.04

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Mass attenuation coefficients

In Fig. 1, the mass attenuation coefficients of the novel high strength shielding materials for photon energy 1 keV to 100 GeV are shown. From Fig. 1, it is found that the mass attenuation coefficients of all the materials initially reduce very sharply, then slowly and finally again increase to become constant. Therefore, this variation has been divided in three parts as low-, medium-and high-energy regions and explained using partial photon interaction processes.

In the low energy region (E<100 keV), the attenuation coefficient values reduces very sharply due to photoelectric effect. Since the photoelectric interaction cross section is dependent upon $Z^{4-5}/E^{3.5}$, results in dominance of atomic number of elements as well as reduction with increase of photon energy. In medium energy region (100 keV<E<2 MeV), μ_m values varies slowly because photon goes under Compton scattering process where incoherent scattering is linearly dependent upon Z. In the high energy region, μ_m values increase, where the pair production is significant cross section is proportional to Z^2.

In photon energy region (E<100 keV), various sharp edges are observed in Fig 1.These sharp edges are due to absorption edges of K, L, M…… shell electrons of various elements of the materials. Mass attenuation coefficients of Datolite are found to be lowest values (except some energy in photoelectric absorption region) whereas Galena shows the largest values. The largest values of mass attenuation coefficient signify that the removal of photon from the materials is highest. Therefore, Galena provides superior X/gamma-ray shielding effectiveness.

The mass attenuation coefficients of selected novel shielding materials were also investigated for some photon energies using GEANT4 simulation toolkit to compare theoretical and simulation results. From Table 1, it is found that the mass attenuation coefficients simulated using GEANT4 of the selected shielding materials are in very good agreement with the theoretical estimation by XCOM.

Exposure buildup factors

The exposure buildup factor (EBF) of selected novel shielding materials is shown in Fig. 2 (a-e) for photon energy 0.015 to 15 MeV up to 40 mfp. It was observed that the EBF of all the shielding materials containing low-atomic numbers (tourmaline, datolite, amethyst and hormirad) were very small of order of unity in low- and high-energy regions, whereas very high in intermediate energy region. The EBF values of hormirad were found lesser than tourmaline, datolite and amethyst. The EBF for galena showed a different behavior with respect to energy from these materials, very high peak was shown up to 100 keV and large EBF value in high energy region. It is observed that the EBF values of all the shielding materials increases with mean free path or thickness due to multiple interaction and photon buildup.

The variation of EBF of selected shielding materials is possible to explain using photon interaction process with the materials. The photon interaction processes are photoelectric effect, Compton scattering and pair production, mainly dependent upon photon energy and atomic number of elements of material. In photoelectric effect, the interaction cross section is dependent upon proportional to $Z^{4-5}/E^{7/2}$ i.e. photoelectric effect is dominant for high atomic number in low photon energy region. In Compton scattering, the interaction cross section is dependent upon proportional to Z/E i.e. Compton scattering

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decreases with increase in photon energy. However, in pair production the interaction cross section is dependent upon proportional to Z^2 i.e. the pair production increases with atomic number of elements. The compound or composite materials are represented by single value called as effective atomic number (Z_{eff}) similar to single element, where Z_{eff} is photon energy dependent. The effective atomic number of a compound or composite material can be derived by considering all the interaction process one time or separately (called as equivalent atomic number) based on the requirement.

During computation of the EBF of the selected materials (see above), the equivalent atomic numbers (Z_{eq}) were derived using Compton scattering process only because of dominant interaction process for photon buildup. The EBF values in low- and high- photon energy are found to be small because of dominant interaction processes of photoelectric effect and pair production. In photoelectric effect, the photon is completely removed by transferring it's complete energy to the interacting material. In case of pair production process, a photon generates electron and positron. The positron annihilates with electron at rest and re-generates two photons of 511 keV energy. These two photon buildup due to multiple scattering in the materials because of their energy lies in Compton scattering dominant interaction process.

The effect of multiple scattering of photon after pair production and annihilation is less significant for materials low atomic number elements (tourmaline, datolite, amethyst and hormirad), whereas this effect plays vital role for material

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containing high atomic number (galena). Large EBF values in pair production region for galena for large penetration depth are because of fundamental pair production interaction property of dependency of interaction on atomic number as Z^2. Galena is also showing a large peak of EBF at around 100 keV, which is due to absorption of photon at K-edge of lead (88 keV).

It can be seen that the hormirad is superior shielding material among than tourmaline, datolite and amethyst whereas galena is the best shielding materials in low photon energy except near to 100 keV.

Conclusion

In present study, mass attenuation coefficients and exposure buildup factors of novel shielding materials tourmaline datolite, galena. amethyst and hormirad were investigated. The mass attenuation coefficients of shielding materials were calculated theoretically using XCOM program and compared with GENAT4. Good agreement between XCOM and GEANT4 was observed. The exposure buildup factors were calculated using GP fitting method to assess the effectiveness of shielding performance. The investigation would be very useful for shielding application of these materials.

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