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A Comprehensive Study of Gamma Ray Interaction Parameters in Dana's Minerals

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ABSTRACT: To check the feasibility of the use of Dana's minerals such as Analcime (M1), Chabazite (M2), Heulandites (M3), Pyrophyllite (M4), Scapolite (M5), Stilbite (M6) and Serpentine (M7) as gamma ray shielding materials, some parameters of dosimetric interest has been investigated at incident photon energies from 15 keV to 15 MeV and penetration depth upto 40 mfp.The photon interaction with minerals has been discussed mainly in terms of Mass attenuation coefficient (μ_m), Equivalent atomic number($Z_{eq.}$) and exposure buildup factors (EBF). The results have been shown graphically with more useful conclusions. From the present investigations, it has been concluded that among the selected minerals, M2 and M5are the best gamma ray shielding material, due to its higher values of mass attenuation coefficient and least values for exposure buildup factor in the selected energy range.

KEYWORDS: Dana's minerals, Mass attenuation coefficient, Equivalent atomic number and ExposureBuildup factor.

I. INTRODUCTION

Although gamma radiation has hazardous effects on human health, developing technologies bring lots of its uses in fields like medicine, nuclear power plants, etc. In every case protection from undesirable radiation is necessity for human health [**1**].That's why we need effective ways of protecting ourselves from this bombardment. With the extensive use of gamma-active isotopes in medicine, industry and agriculture, the study ofabsorption of gamma rays in the composite materials has become an interesting and exciting field of research. In the study of design of the gamma radiations shielding materials, the knowledge of shielding effectiveness of the material is a useful parameter. In experiments to estimate the absorption dose of gamma rays, there is an undesired situation faced by radiation physists, resulting from the secondary radiations that occur due to build-up of photons from the collided part of the incident beam. For this reason, it is of importance to determine the build-up factors to make corrections for effective energy deposition in different shielding materials [**2**]. The photon mass attenuation coefficient, equivalent atomic number and exposure buildup factor are the basic parametrs required in determining the penetration of X-rays and gamma photons in matter. The mass attenuation coefficient (μ/ρ) is a measure of probability of interaction that occurs between incident photons and matter per unit mass per unit area.

Buildup factors are the shielding materials and geometry dependent parameters which correct the simple attenuation calculations so that they include the contribution of the radiation field produced by the collided part of beam. As far as application of buildup factors in practical shielding problems is concerned, these have been incorporated into a number of point kernel methods of dose calculations in the case of a variety of radiation sources. The concept of buildup factor was mutually introduced by White [3] and Fano [4] who recognized its importance in attenuation studies. There are two type of buildup factor (a) the energy absorption buildupfactor that is the buildup factor in which the quantity of interest

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is the absorbed or deposited energy in the interacting material and the detector response function is that of absorption in the interacting material. (b) the exposure buildup factor is the buildup factor in which the quantity of interest is the exposure and the detector response function is that of absorption in the air[5].There are different available methods to calculate the buildup factor such as G.P fitting method [6] and invariant embedding method [7]-[9]. American National standards ANSI/ANS-6.4.3[10] has provided buildup factor data for 23 elements, one compound and two mixtures (i.e. air and water) and concrete at energies in the range 0.015-15 MeV up to penetration depths of 40 mfp by using the G.P method. Harima has made the excessive historical review and an assessment for the status of buildup factor calculations and applications [11].Berger and Hubble [12] have developed computer program, XCOM, which calculates photon cross-sections and attenuation coefficients for pure elements and mixtures in the energy range of 1keV to 100 GeV.

Many researchers have studied linear and mass attenuation coefficients [13-16] for different energies and our research group [17-20]have studied interaction parameters for various low-Z composite materials. Also various researcher have studied gamma ray buildup factors of different types of materials such as amino acids, fatty acids and carbohydrates (21), polymers (22), Heavy metal oxide glass (23), which showed that the GP fitting is a very useful method for estimation of exposure and energy absorption build-up factors.

Presently, we have studied theoretically gamma-ray exposure build-up factor (EBF) for seven types of Dana's minerals by GP fitting in the photon energy range from 15 keV to 15 MeV up to penetration depth of 40 mfp. Mass attenuation coefficient and equivalent atomic number are also determined for gamma ray interaction. It should be noted that this study is valuable in shielding analysis and estimation of first hand emergency dose.

Dana's minerals are a group of rock-forming framework alumina silicates common in a wide variety of igneous and metamorphic rocks. These are proved to be useful materials for shielding effectiveness from gamma rays. According to [24], zeolites are formed in various conditions and geological systems. This is also supported by Ljima [25], who reported that zeolites were formed in various sediments or rocks in varying physical and chemical environment for protection from shielding [26].

Materials

The molecular formula's of the chosen minerals are obtained from Handbook of "Dana's minerals and how to study them" by "Cornelius S. Hurlbul and W.Edwin Sharp (27). The Molecular formula's of the selected minerals has been given in Table 1.

Table 1.Molecular formula'sof Dana's Minerals

Sr. No.	Name of chosen minerals	Molecular formula	Density (gm/cc)
1	Analcime (M1)	$Na_2Al_2Si_4O_{12}.2H_2O$	2.27
2	Chabazite (M2)	$CaAl_2Si_4O_{12}.6H_2O$	2.10
3	Heulandites (M3)	$CaAl_2Si_7O_{18}.6H_2O$	2.20
4	Pyrophyllite (M4)	$Al2Si_4O_{10}(OH)_2$	2.81
5	Scapolite (M5)	$(Na,Ca)_4(Al_2Si_2O8)_3(Cl,CO_3)$	2.65
6	Stilbite (M6)	$NaCa_2Al_5Si_{13}O_{36}.14H_2O$	2.15
7	Serpentine (M7)	$Mg_6Si_4O_{10}(OH)_8$	2.60

II. THEORETICAL COMPUTATION METHOD

Calculation of Mass Attenuation Coefficient

The absorption coefficient of Dana's minerals is dependent on its content and gamma - ray energy. This work describes a study of content dependence on measurements of attenuation of gamma - radiation at gamma-ray energy of selected minerals .The attenuation of gamma rays are expressed as:

$I= I_o e^{-\mu x}$(1)

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Where Io is the number of particles of radiation counted during a certain time duration without any absorber, I is the number counted during the same time with a thickness x of absorber between the source of radiation and the detector, and μ is the linear absorption coefficient. This equation may be cast into the linear form,

$\log I = \log I_o - \mu x$

i.e. $\mu x = \log (I_o / I)$

$\mu = (1/x) \log (I_o/I)$ (2)

The mass absorption coefficient of selected minerals, μ_m is defined as

$\mu_m = \mu/\rho$ (3)

Where, μ_m is the mass attenuation coefficient and ρ is the density of selected minerals. The unit of μ is cm^{-1} and that of μ_m is cm^2/gm.

Exposure Buildup Factor

The computational work of exposure buildup factor has been divided into three parts. The first part concern with the computation of equivalent atomic number (Z_{eq}) for the selected minerals. The second part deals with the computation of G.P. fitting parameters and finally in the third part, exposure buildup factor values have been computed.

Computation of equivalent atomic number

The equivalent atomic number is a parameter describing the properties of the composite materials in terms of equivalent elements, hence it is similar to the atomic number of elements. However, the interaction of gamma rays with materials is based on, domination of different partial photon interaction processes in different energy regions, thus Z_{eq} is an energy dependent parameter. Since the buildup factor mainly arises from multiple scattering events, Z_{eq} is derived from the contribution of the Compton scattering process. So firstly the values of Compton partial attenuation coefficient (μ_{comp}) and total attenuation coefficients ($\mu_{tot.}$) in cm^2/g were obtained for elements from Z = 1 to 25 and

Table 2 Equivalent atomic numbers (Z_{eq}) of different Dana's minerals in the energy range of 15 keV - 15.0 MeV

E(MeV)	M1	M2	M3	M4	M5	M6	M7
0.015	11.04	11.85	11.77	11.27	13.35	11.66	10.76
0.02	11.08	11.96	11.87	11.33	13.46	11.74	10.83
0.03	11.12	12.11	12.01	11.37	13.56	11.86	10.86
0.04	11.17	12.17	12.05	11.4	13.65	11.94	10.91
0.05	11.24	12.24	12.12	11.45	13.72	11.96	10.98
0.06	11.23	12.31	12.18	11.44	13.79	12.01	10.93
0.08	11.24	12.27	12.2	11.47	13.77	12.1	10.96
0.1	11.34	12.33	12.35	11.55	13.84	12.14	11.09
0.15	10.9	11.82	11.85	10.9	14.01	11.85	10.88
0.2	12.92	12.87	12.89	12.92	14.49	12.89	10.5
0.3	12.5	12.5	12.5	12.5	14.5	12.5	10.5
0.4	12.5	12.5	12.5	12.5	14.5	12.5	10.5
0.5	12.5	12.5	12.5	12.5	14.5	12.5	10.5
0.6	12.5	12.5	12.5	12.5	14.5	12.5	10.5
0.8	12.5	12.5	12.5	12.5	14.5	12.5	10.5
1	12.5	12.5	12.5	12.5	14.5	12.5	10.5
1.5	12.5	12.5	12.5	12.5	14.5	12.5	10.5
2	9.711	8.663	9.622	9.711	12.9	9.608	9.637
3	10.3	10.18	10.21	10.3	12.62	10.58	9.745
4	10.28	10.43	10.14	10.6	11.99	10.14	9.769
5	10.18	10.27	10.31	10.49	12.28	10.31	9.788
6	10.17	10.51	10.57	10.46	11.92	10.57	10.06
8	10.09	10.49	10.55	10.29	12.16	10.36	9.973
10	10.21	10.3	10.51	10.5	12.14	10.37	9.931
15	10.26	10.43	10.43	10.51	12.01	10.31	10.05

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chosen samples in the energy of 15 keV-15.0 MeV, using the state-of-the-art and convenient computer program XCOM and WinXCom (28-29).Further, by using a simple computer program, the ratio R ($^{\mu}$cmop/$^{\mu}$tot) was obtained for selected minerals. Then the value of equivalent atomic number (Z_{eq}) for these samples was calculated by matching the ratio R ($^{\mu}$cmop/$^{\mu}$tot) of particular sample at a given energy with corresponding ratios of elements at the same energy. For the case the ratio lies in between the two ratios of known elements. The value of Z_{eq} was interpolated by using the following formula of interpolation (11) given in the following equation

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1}$$

Where Z_1 and Z_2 are the atomic numbers of elements corresponding to the ($^{\mu}$cmop/$^{\mu}$tot.) ratios, R_1 and R_2, respectively, and R ($^{\mu}$cmop/$^{\mu}$tot.) is the ratio for the selected minerals at a particular energy which lies between ratios R_1 and R_2.The calculatedZ_{eq} of the chosen minerals are given in Table 2.

Computation of G.P. fitting parameters

To calculate the G-P fitting parameters a similar interpolation procedure was adopted as in the case of the equivalent atomic number. American National Standard has provided the energy absorption G.P. fitting parameters of 23 elements (Be, B, C, N, O, Na, Mg, Al,Si, P, S, Ar, K, Ca, Fe, Cu, Mo, Sn, La, Gd, W, Pb and U), one compound(water) and two mixtures (air and concrete) in the energy range of 15 keV -15.0 MeV and upto a penetration depth of 40 mfp (10).

Using the interpolation formula, five G.P. fitting parameters (b, c, a, X_k and d) for selected samples were computed at the different incident photon energies using equivalent atomic number (Z_{eq}), in the chosen energy range (15 keV -15.0 MeV) andupto penetration depth of 40 mfp. The formula used for the purpose of interpolation (21) is as follows:

$$C = \frac{C_1\left(\log Z_2 - \log Z_{eq}\right) + C_2\left(\log Z_{eq} - \log Z_1\right)}{\log Z_2 - \log Z_1}$$

Here C_1 and C_2 are the values of G.P. fitting parameters corresponding to the atomic numbers Z_1 and Z_2 respectively at a fixed energy, whereas Z is the equivalent atomic number of the chosen sample at the same energy. Z_1 and Z_2 are the elemental atomic numbers between which the equivalent atomic number Z of the chosen samples lies.

Computation of Exposure Buildup Factor

The computed G.P. fitting parameters were then used to compute the exposure buildup factors for the selected samples at some standard incident photon energies up to a penetration depth of 40 mean free paths, with the help of G.P. fitting formula, as given by following equations (11)

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

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

Where

$$K(E,x) = cx^a + d\,\frac{\tanh(x/X_k - 2) - \tanh(-2)}{1 - \tanh(-2)}$$

$$\text{for } x \leq 40mfp \qquad (5)$$

where a, b, c, d and X_k are the G-P fitting parameters and x is source to detector distance in the medium (mfp). The parameter K (E, x) represents photon dose multiplication and change in the shape of the spectrum.

III. RESULT AND DISCUSSION

The exposure buildupfactors has been shown in graphical form at fixed penetration depths (fig. 1-4) as well as at fixed energy values (fig. 7-10). Fig. 5-6 shows the significant variation in EBF with incident photon energy at high energy range with fixed penetration depth. Fig. 11-13 shows the variations of mass attenuation coeff. (μ_m) and equivalent atomic number (Z_{eq}) with photon energy for selected minerals (Table 2). Detailed study of graphical representation is as below.

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Exposure Buildup factor

Energy dependence

Fig. 1-4 showsthe variation of EBF with energy seems to be similar forall chosen minerals. Initially, the EBF values start increasing with increasing in photon energy up to a maximum value at intermediate energies, thenit starts decreasing with further the increase in incident photon energy. This is because, at lower energies, the dominant photon interaction processes is photoelectric absorption, for which the atomic cross-section is proportional to ($Z^{4.5}$ / $E^{3.5}$). Further, maximum valueof EBF were observed at intermediate energy range (0.08-0.2 MeV) where Compton scattering dominates. In Compton scattering process, photons are not completely removed but only degradation of photon energy occurs . It is due to multiple scattering of photons, due to whichphotons exist for longer time in material which leads to a higher value of buildup factor. It is indicated that the value of EBF is minimum for sample M5 in this energy region. Further, at higher energies, the pair production absorption process starts dominating, but there is no significance variation in the EBF with equivalent atomic number. Since the cross-section of pair protection is proportional to Z^2. At higher energies the cross section increasing slowly with incident photon energy between the 1022 keV to about 4 MeV. For further higher energies it is proportional to log E resulting in lower value of EBF. Thus to conclude, one should especially note that in the continuous energy region, since the radiation interaction with matter differs in the different partial photon interaction processes, the absorption process lower the values of EBF and the scattering process increasing the values of EBF [30].

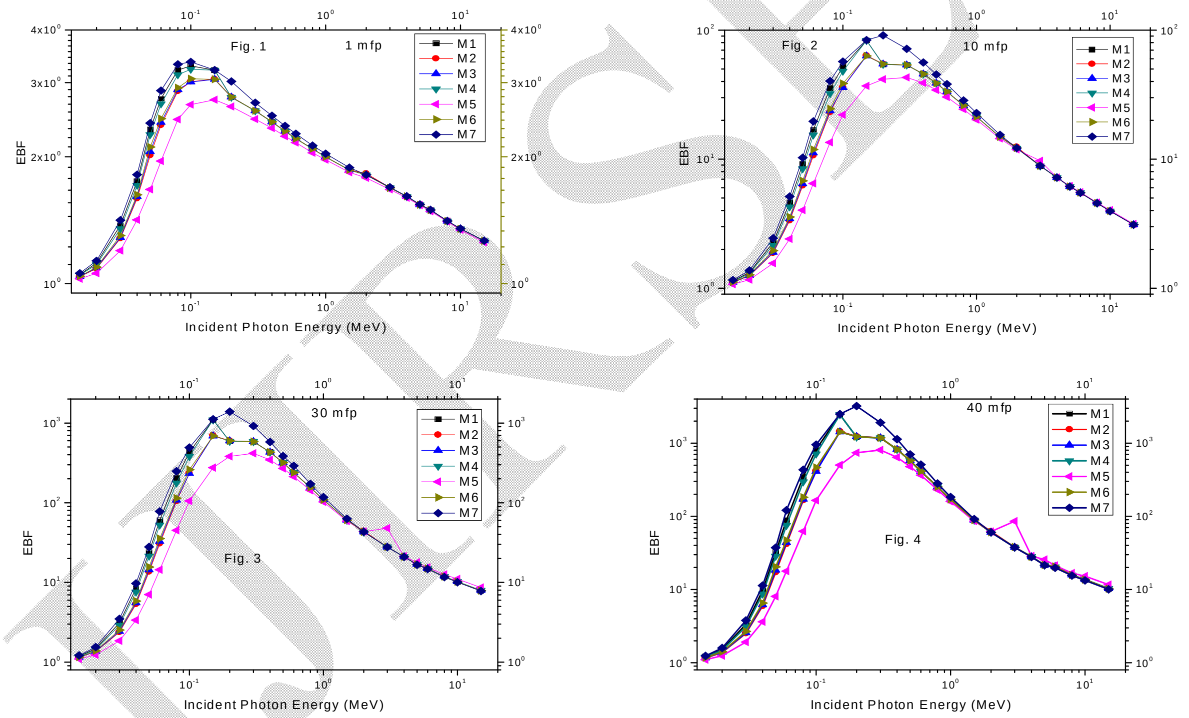
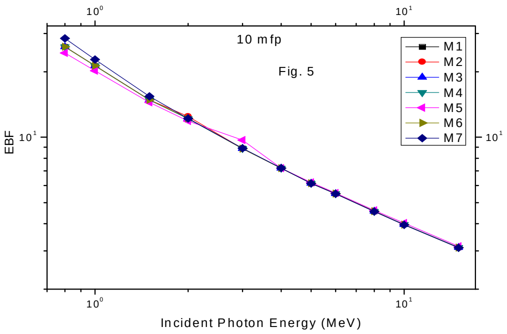


Fig. 1-4 Variation of Exposure buildup factor of selected minerals with incident photon energy(0.015-15MeV) at 1mfp,10 mfp, 30 mfp and 40 mfp

Fig. 5-6 shows that the expandedhigher energy part of plots which depicts the reverse trend of EBF values of M5 in the higher energy region. The energy distribution to the electron-positron pair depends on the energy of incident photon. Further these particles (electron and positron) required to undergo number of collisions with the atoms/molecules of the interacting material to lose their energy and come to rest, which needs sufficient penetration depth of interacting material. After coming to rest, annihilation process takes place, which result in emission of pair of gamma photons of 511 keV each in the opposite direction.

For small penetration depth (10 mfp), the electron–positron pair created as the result of pair-production does not find sufficient thickness for losing its energy separately, which is required for the annihilation process to occur. Hence there is only absorption of photons which results in decreasing buildup factor values.

However, for higher penetration depth of 40 mfp, the electron – positron pair created as the result of pair-production find sufficient thickness for losing its energy separately and undergoes annihilation process. Hence, there is not only absorption of photons due to the pair-production process but also the creation of two gamma rays as a result of annihilation process, which results in increasing buildup factor values.



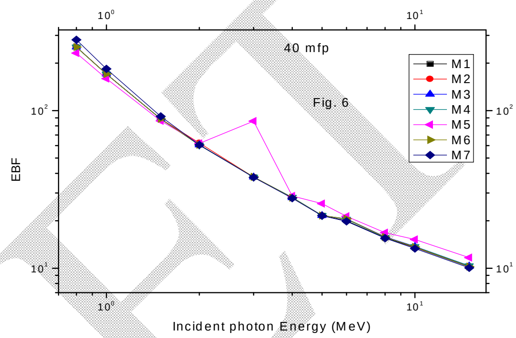
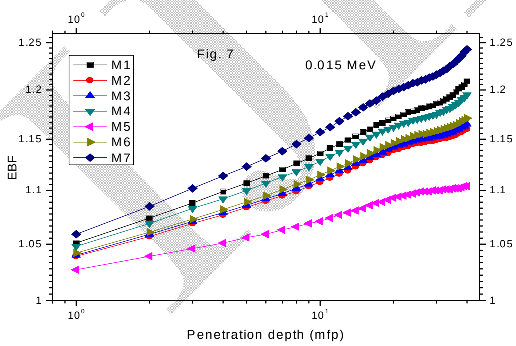
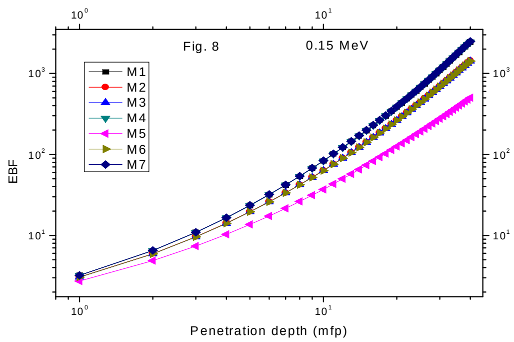


Fig. 5-6 Variation of Exposure buildup factor of selected minerals with incident photon energy(0.8-15MeV) at 10 mfp, and 40 mfp

Penetration depth

Figures 7-10 show the variation of exposurebuildup factor with penetration depth for the chosen shielding materials at fixed incident photon energies 0.015, 0.15, 1.5 and 15.0 MeV respectively. It can be seen that at all energy range, there is an increase in the values of EBF with increase in penetration depth for all the materials due to an increase in the number of multiple scattered photons.For the given materials at 0.15 MeV (fig. 8), the maximum values of EBF at 1, 10, 30, 40 mfp are between 2.732-3.214, 36.99-83.8, 275.9-1113, 501.3-2491, respectively. The M7 mainly dominates for the maximum values of EBF, the M5 material mainly have lower values of EBF. From Figure 8 it is noted that the dependence of buildup factor on the nature of materials reduces at the incident photon energy 0.15 MeV. From Fig. 9.it is also observed that the exposurebuildup factor values are practically the same for different selected materials at the energy value of 1.5 MeV. Thus, the buildup factor values become almost independent of the chemical composition of the given materials at this energy region, where Compton scattering process dominates. From Fig. 10, it is further noted that at penetration depth greater than 10 mfp, the trend of dependence of exposure buildup factor on nature of materials has also been reversed at the incident photon energy of 15.0 MeV.





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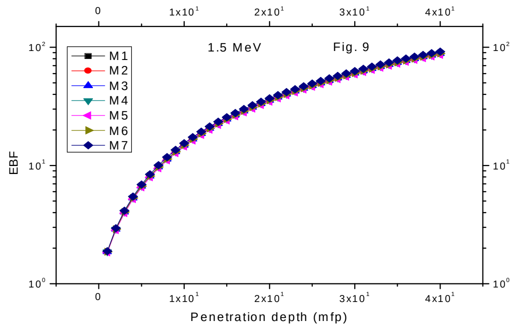


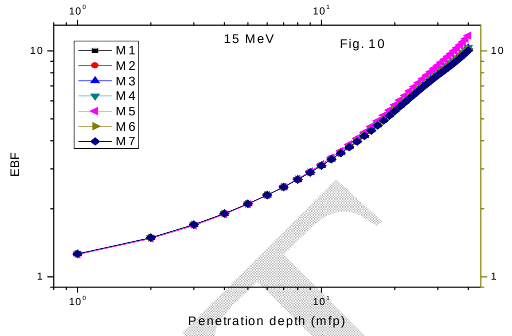


Fig. 7-10 Variation of Exposure buildup factor of selected samples with penetration depth up to 40 mfp at 0.015MeV, 0.15 MeV, 1.5 MeV and 15MeV

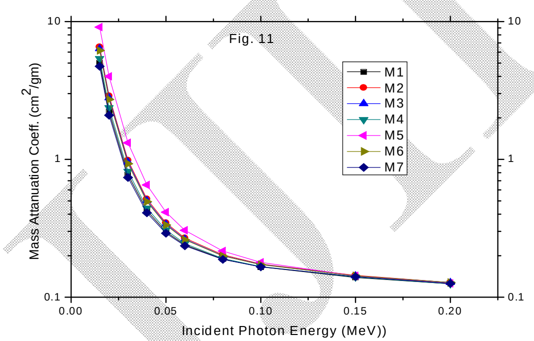
Dependence of shielding effectiveness of Dana's minerals on energy absorption parameter

Mass attenuation coefficient

The mass attenuation coefficient is a measure of the relative dominance of the partial interaction process (photoelectric effect, Compton scattering effect and pair production) of gamma rays with the samples. Fig. 11-12 clearly explain the photon energy dependence of mass attenuation coefficients of all Dana's minerals. It is concluded that the values of mass attenuation coefficients for samples M2 and M5 are higher than that of other minerals. The shielding effectiveness of a sample is directly related to the mass attenuation coefficients of the samples.

Effective atomic number(Z_{eq})

It is concluded from Fig. 13 thatinitially the Z_{eq} values slightly increases with increasing in photon energy upto 100 keVand in the energy region (0.3-1.5 MeV)Z_{eq}becomes maximum and constant values, then Z_{eq}starts decreasing with further increase in incident photon energy. It is also observed that M5 and M2 minerals shows high values of Z_{eq} then all other selected minerals. Moreover, mineral M2 shows a sharp click at energy 2 MeV. Fig. 13 again support the fact that M5 and M2 possesses good shielding effectiveness from the selected minerals in the selected continuous energy range.



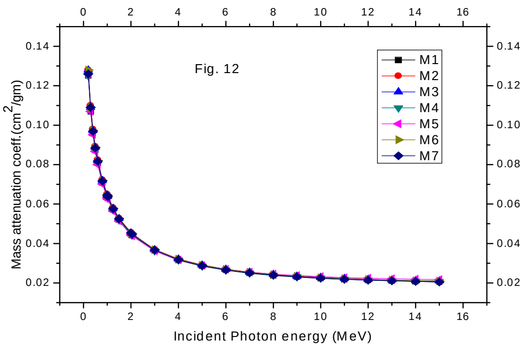


Fig. 11-12 Variation of mass attenuation coefficients with incident photon energy range of 0.015-0.20 MeV and 0.2-15 MeV

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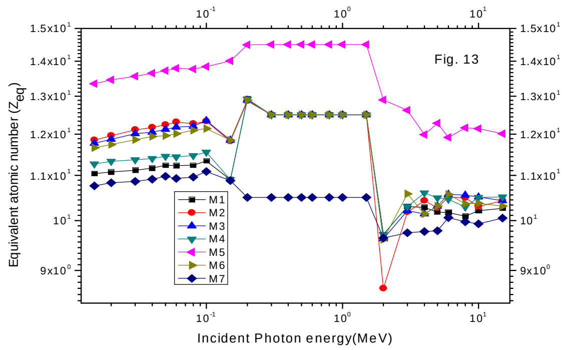

Fig. 13 Variation of equivalent atomic numbers with incident photon energy range of 0.015-15 MeV

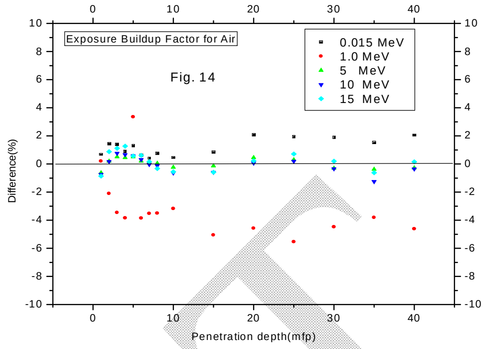

Fig. 14 Difference(%) between ANSI data and our work with respect to the calculated values of EBF for air at some energy levels upto 40 mfp

The validity of our interpolation method

To check the validity of our interpolation method, exposurebuildup factor for air is calculated by our method and then it is compared with available ANSI/ANS (1991) data.Fig. 14 shows that (%) difference between exposure buildup factor for air calculated by our method and available standard base ANSI/ANS(1991) data is varying between 5.54% to 3.35% at some selected energy level up to penetration depth 40 mfp.Hence, weconclude that the exposurebuildup factors generated by our computational procedure are in good agreement with those given by ANSI/ANS (1991) database for air.

IV. SUMMARY OF THE PRESENT WORK

In the present work, it is concluded that the radiation energy absorption parameters are useful for deciding of the shielding effectiveness of dana's minerals used for specific construction. During interaction of gamma ray photon with matter, the values of these parameters are dependent on the physical and chemical environment of the minerals. The results of the present study will be helpful to understand how energy absorption parameters values change with the incident photon energy of some dana's minerals.

- From the present investigations, we have found that among the selected samples, M2 and M5 acts as best gamma ray shielding material, due to its higher values for mass attenuation coefficient and least values for exposure buildup factor in the selected energy range.
- M5 acts as good shielding material at deep penetration in the energy region of 4-15 MeV.
- The shielding effectiveness of the dana's minerals is directly proportional to Z_{eq}.
- The computed data G.P. fitting parameters and exposure buildup factors for selected seven low-Z shielding materials (25 energies and 40 penetration depths) may be useful in the future study of variety of shielding configurations.

So finally, it is evident from the above discussion that dana's minerals can be used for low-cost shielding purpose as they are abundantly available on earth.

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