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A Comprehensive Study on Energy Absorption and Exposure Buildup Factors for some Soils and Ceramic Materials

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Abstract: *Study of gamma ray energy absorption (EABF) and exposure buildup factors (EBF) for some essential soils, ceramic materials in the energy region 0.015-15 MeV up to a penetration depth of 40 mfp (mean free path). To calculate both EABF and EBF, five parameter geometric progressions (G-P) fitting approximation has been used. Variation of EABF and EBF with incident photon energy, penetration depth and effective atomic number (Z_{eff}) has been studied and presented in the form of graphs. This change results from the dominance of different interaction process in different energy regions. Significant variations were also observed between EABF and EBF which may due to different chemical composition of given materials.*
Keywords: *Cascade silt loam (CSL), Energy absorption buildup factor, Exposure buildup factor, Kaolinite (KLN), Mica, Sand.*

I. Introduction

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 [1] and Fano [2] recognized its importance in attenuation studies. There are two type of buildup factor (a) the energy absorption buildup factor that is the buildup factor in which the quantity of interest 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[3].There are different available methods to calculate the buildup factor such as G.P fitting method[4] and invariant embedding method[5]-[7]. Recently American National standards ANSI/ANS-6.4.3[8] 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. The developed G-P fitting formula is known to be accurate within a few percent error [4], [9]. Recently, Harima has made the excessive historical review and an assessment for the status of buildup factor calculations and applications [10]. The gamma ray transmission method has been reported as the most accurate and convenient techniques for non destructive measurements of soil parameters like moisture content, density etc. [11]. The composition of soils like sand and cascade silt loam has been taken from literature of Brady N.C. [12] and of ceramic materials like kaolinite and mica has been taken from literature of Bear F.E. [13]. There are successful contributions which are based on the buildup factor studies in some soils and ceramic materials available in the literature. For example, Brar *et al.* [14] have studied the variation of buildup factors of soils with weight fractions of iron and silicon. Sidhu *et al.* [15] have studied the energy and effective atomic number dependence of the exposure buildup factors in biological samples. Manohara *et al.* [16] studied the variation of exposure buildup factors for heavy metal oxide glass with photon energy and penetration depth. Singh *et al.* [17] studied the energy dependence of total photon attenuation coefficients of composite materials. In the present work, we study the EABF and EBF by using the G-P fitting method for some essential soils and ceramic materials in the energy region 0.015-15 MeV up to penetration depth of 40 mfp. The generated EABF and EBF data have been studied as a function of incident energy, penetration depth and effective atomic number (Z_{eff}). Also, the comparison of EABF and EBF has been made and significant variation was noted.

II. Computational work

To calculate the buildup factors, the G-P fitting parameters were obtained by the method of interpolations from the equivalent atomic number (Z_{eq}). Computations are illustrated step by step as follows:

2.1. Calculation of the equivalent atomic number Z_{eq}
2.2. Calculation of geometric progression (G-P fitting parameters)
2.3. Calculation of energy absorption and exposure buildup factors

Table1 Chemical Composition (%) by Weight for Chosen Materials

Composition	Sand	Cascade Silt Loam
SiO_2	91.49	70.40
TiO_2	0.50	1.08
Fe_2O_3	1.75	3.90
Al_2O_3	4.51	13.14
MnO	0.007	0.07
CaO	0.01	1.78
MgO	0.02	0.97
K_2O	0.16	2.11
Na_2O	-	1.98
P_2O_5	0.05	0.16
SO_3	0.05	0.21
Nitrogen	0.02	0.08

Table2 Equivalent Atomic Numbers of Different Soils in the Energy Range 0.015-15.0 MeV

	Soils	
E(MeV)	Sand	Cascade silt loam
.1500E-01	.1267E+02	.1274E+02
.2000E-01	.1278E+02	.1284E+02
.3000E-01	.1291E+02	.1297E+02
.4000E-01	.1300E+02	.1306E+02
.5000E-01	.1309E+02	.1317E+02
.6000E-01	.1313E+02	.1322E+02
.8000E-01	.1311E+02	.1329E+02
.1000E+00	.1336E+02	.1336E+02
.1500E+00	.1344E+02	.1344E+02
.2000E+00	.1292E+02	.1449E+02
.3000E+00	.1250E+02	.1450E+02
.4000E+00	.1250E+02	.1450E+02
.5000E+00	.1250E+02	.1450E+02
.6000E+00	.1250E+02	.1450E+02
.8000E+00	.1250E+02	.1450E+02
.1000E+01	.1250E+02	.1450E+02
.1500E+01	.1250E+02	.1450E+02
.2000E+01	.9741E+01	.9757E+01
.3000E+01	.1159E+02	.1071E+02
.4000E+01	.1096E+02	.1146E+02
.5000E+01	.1117E+02	.1161E+02
.6000E+01	.1127E+02	.1152E+02
.8000E+01	.1144E+02	.1178E+02
.1000E+02	.1136E+02	.1136E+02
.1500E+02	.1149E+02	.1149E+02

Table 3 Chemical Formula of Chosen Ceramic Material

Ceramics	Chemical Formula
Kaolinite	$Si_4Al_4O_{10}(OH)_8$
Mica	$K_2Al_2Si_6Al_4O_{20}(OH)_4$

Table 4 Equivalent Atomic Numbers of Different Ceramic Materials in the Energy Range 0.015-15.0 MeV

	Ceramic materials	
E(MeV)	Mica	Kaolinite
.1500E-01	.1338E+02	.1092E+02
.2000E-01	.1343E+02	.1097E+02
.3000E-01	.1343E+02	.1102E+02
.4000E-01	.1344E+02	.1106E+02
.5000E-01	.1348E+02	.1112E+02
.6000E-01	.1352E+02	.1109E+02
.8000E-01	.1339E+02	.1122E+02
.1000E+00	.1338E+02	.1132E+02
.1500E+00	.1347E+02	.1088E+02
.2000E+00	.1293E+02	.1290E+02
.3000E+00	.1250E+02	.1250E+02
.4000E+00	.1250E+02	.1250E+02
.5000E+00	.1250E+02	.1250E+02
.6000E+00	.1250E+02	.1250E+02
.8000E+00	.1250E+02	.1250E+02
.1000E+01	.1250E+02	.1250E+02
.1500E+01	.1250E+02	.1250E+02
.2000E+01	.1288E+02	.8703E+01
.3000E+01	.1316E+02	.9774E+01
.4000E+01	.1266E+02	.9810E+01
.5000E+01	.1297E+02	.1009E+02
.6000E+01	.1312E+02	.1006E+02
.8000E+01	.1299E+02	.1003E+02
.1000E+02	.1289E+02	.1014E+02
.1500E+02	.1312E+02	.1005E+02

The equivalent atomic number, Z_{eq} is a parameter describing the properties of the composite materials in terms of equivalent elements, hence it is similar to that atomic number of element. Hence 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 Compton scattering process.

At the first step, the equivalent atomic number Z_{eq} for particular material has been calculated by matching the ratio, $(\mu/\rho)_{compton} / (\mu/\rho)_{Total}$, of that material at a specific 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 elements of Z= 4-40 and for the soils and ceramic materials in the energy region 0.015-15 MeV, using the XCOM [18] computer program. 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 formula has been employed [16]:

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

Where Z_1 and Z_2 are the elemental atomic numbers corresponding to the ratios $(\mu/\rho)_{compton}$ /$(\mu/\rho)_{Tot,}$ R_1 and R_2 respectively, and R are the ratio for given soils and ceramic materials at a particular energy. The value of Z_{eq} for the selected soils and ceramic materials so obtained are given in Table 3 and 4.

In the second step, to calculate the G-P fitting parameter a similar interpolation procedure was adopted as in the case of the equivalent atomic number. The G-P fitting parameter for elements were taken from the ANSI/ANS-6.4.3[8] standard reference data base which provides the G-P fitting parameters for elements from beryllium to iron in the energy region 0.015-15 MeV up to 40 mfp. Formula given below is used in interpolation of G-P fitting buildup coefficient of the used materials:

$$C = \frac{C_1\left(\log Z_2 - \log Z_{eq}\right) + C_2\left(\log Z_{eq} - \log Z_1\right)}{\log Z_2 - \log Z_1} \qquad (2)$$

Where C_1 and C_2 are the values of coefficients (G-P fitting parameters) corresponding to the atomic numbers of Z_1 and Z_2 respectively, at a given energy and Z_{eq} is the equivalent atomic number of the given material.

At the final step, The G.P fitting parameters were then used to generate energy absorption and exposure buildup factor data for these materials using the following G.P fitting formula given by Harima *et al.*[4]

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

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

Where

$$K(E,x) = cx^a + d\,\frac{\tanh(x/X_k - 2) - \tanh(-2)}{1 - \tanh(-2)} \quad \text{for } x \le 40mfp \qquad (5)$$

Where E is the incident photon energy, x is the penetration depth in mean free path, a,b,c,d and X_k are the G-P fitting parameters and b is the value of buildup factor at 1 mfp. The parameter K(E,x) is the photon dose multiplication factor and change in the shape of the spectrum. Here the mean free path (mfp) is defined as the average distance that photons of a given energy travel before an two successive interactions in a given medium occur. It is equal to the reciprocal of the attenuation coefficient. The ratio of the total value of a specified radiation quantity at any point to the contribution to that value from radiation reaching the point without having undergone any collision is called "buildup factor".

III. Result and Discussion

The chemical composition of soils is listed in Table 1 and Chemical formulas of ceramic materials are listed in Table 2. Table 3 and 4 shows the obtained equivalent atomic numbers of the material listed above. The EABF and EBF have been shown in graphical form at fixed penetration depth (Figs. 1(a) to 4(a), (b)) as well as at fixed energy values (Figs. 5 to 8). Figs. 9(a, b) and 10(a, b) shows the variation of EABF and EBF with effective atomic number (Z_{eff}) for different energies at penetration depth of 15 mfp. Fig. 11(a) and (b) shows the relative difference between ANSI [8] database and the present work with respect to the calculated values of EABF and EBF for air. In the following subsections, various figures mentioned above are analyzed.

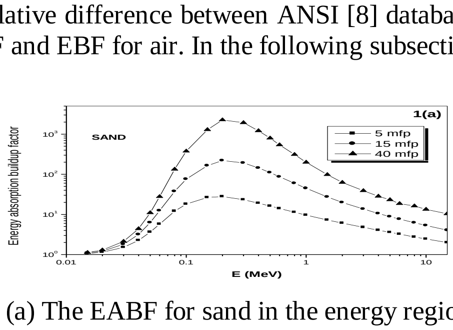

Fig. 1 (a) The EABF for sand in the energy region 0.015-15 MeV at 5, 15, 40 mfp

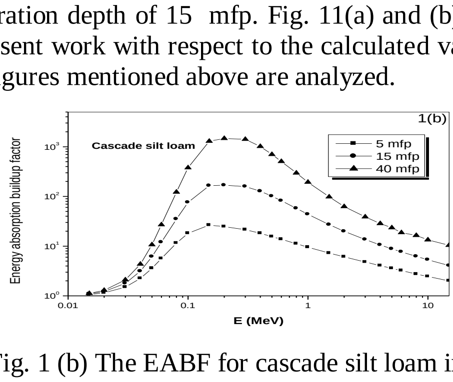

Fig. 1 (b) The EABF for cascade silt loam in the energy region 0.015-15 MeV at 5, 15, 40 mfp

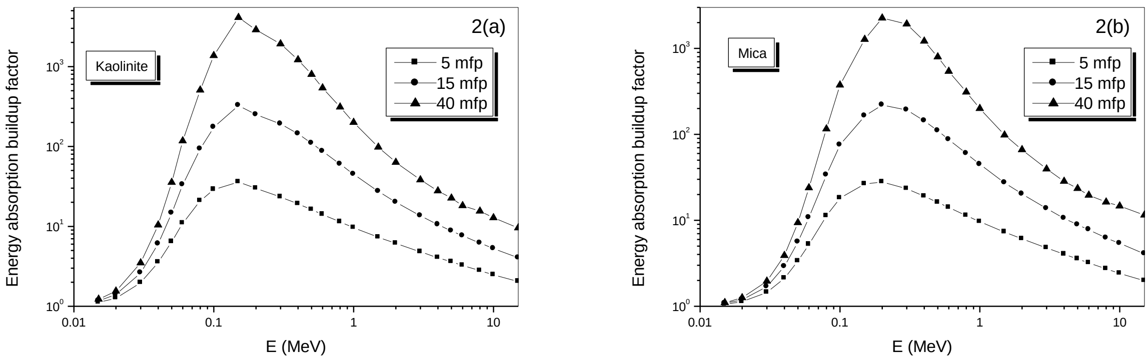

Fig. 2(a), (b) The EABF for Kaolinite and Mica in the energy region 0.015-15 MeV at 5, 15, 40mfp

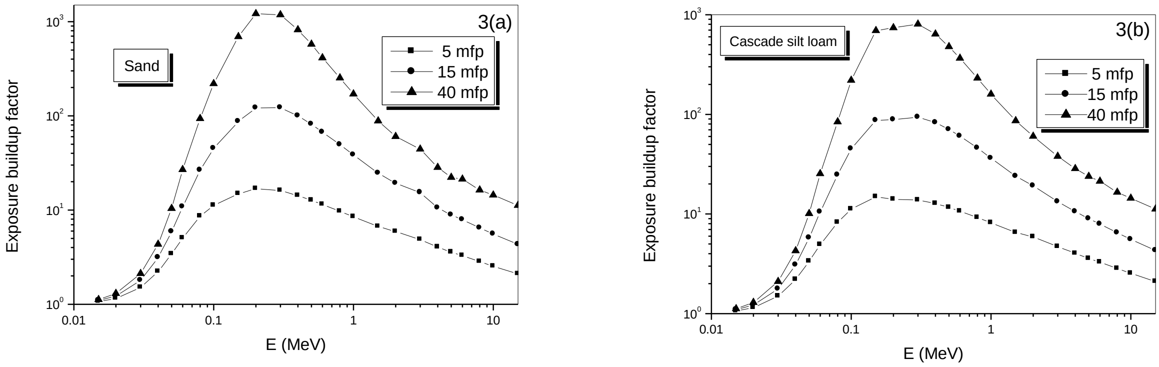

Fig. 3(a, b) The EBF for Sand and Cascade silt loam in energy region 0.015-15 MeV at 5, 15,40 mfp

3.1 EABF and EBF of Soils and Ceramic Materials

3.1.1 Effect of Incident Photon Energy on EABF and EBF

From Figs. 1 to 4(a,b) it has been observed that EABF and EBF values of soils and ceramic materials start increasing with increase in photon energy up to a maximum energy at intermediate energies and then further start decreasing with increase in energy of gamma ray. Here the low value of buildup factor around 0.015 MeV is due to predominance of photo electric effect in this energy region which results in fast removal of low energy photons, thereby not allowing these photons to buildup. It is further observed that in the energy range 0.15 MeV to 0.8 MeV the buildup factor values are high for a given penetration depth due to dominance of Compton effect. Which only helps in the degradation of photon energy and fails to remove a photon completely. Because of multiple scattering of photons they exist for longer time in material which leads to a higher value of buildup factor. Here it is also observed that at gamma ray energy 0.2 MeV, buildup factor value is very high because of exclusive dominance of Compton effect. Furthermore it is also observed that for energies greater than 2.0 MeV, the dominance of pair production phenomenon over Compton effect increases, so values of buildup factor decreases. The variation of EABF and EBF with incident photon energy seem to be independent of chemical composition of above materials beyond 2.0 MeV respectively.

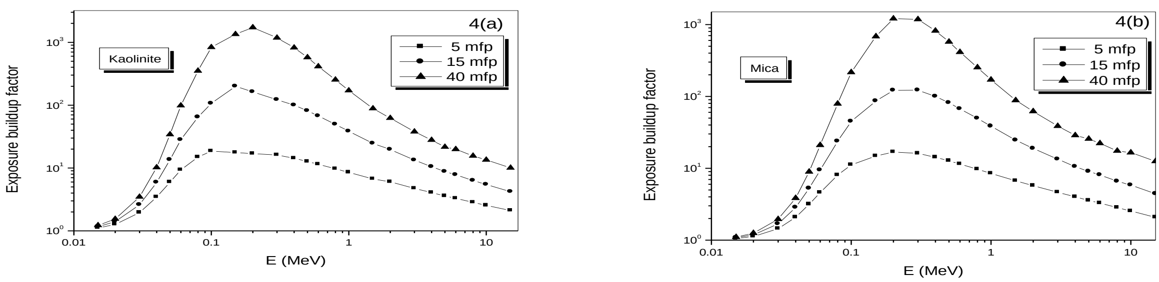

Fig. 4(a), (b) The EBF for Kaolinite and Mica in the energy region 0.015-15 MeV at 5, 15, 40mfp

3.1.2 Effect of Penetration Depth on EABF and EBF

The values of EABF and EBF of soils and ceramic materials increase with the increase in penetration depth. At lowest photon energy 0.015 MeV EABF and EBF values are low because of dominance of photoelectric effect, but at 0.2 MeV photon energy EABF and EBF values are much higher due to dominance of Compton effect. It can also be seen, at photon energy 5 and 15 MeV EABF and EBF values are low due to predominance of pair- production as in figs. 5 to 8.

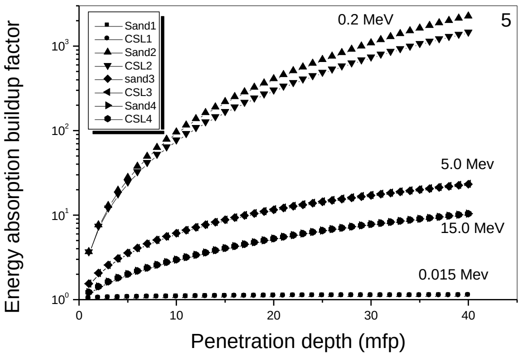

Fig. 5 The EABF for soils upto 40mfp at 0.015, 0.2, 5.0, 15MeV

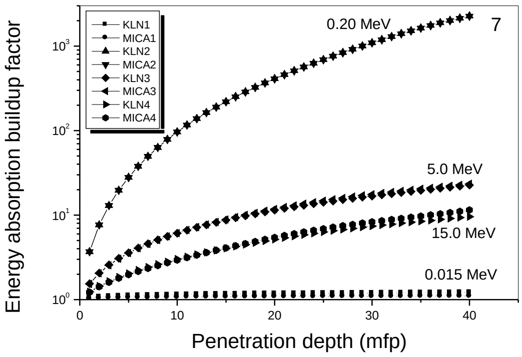

Fig.7 The EABF for ceramic materials up to 40mfp at 0.015, 0.2, 5.0, 15MeV

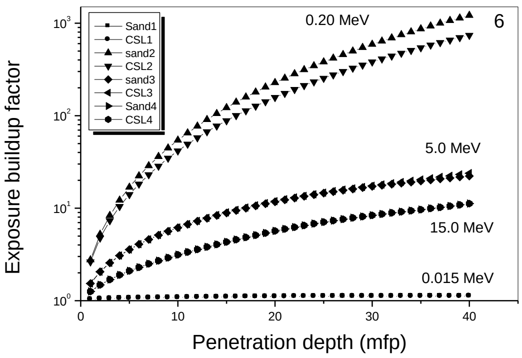

Fig.6 The EBF for soils upto 40mfp at 0.015, 0.2, 5.0, 15MeV

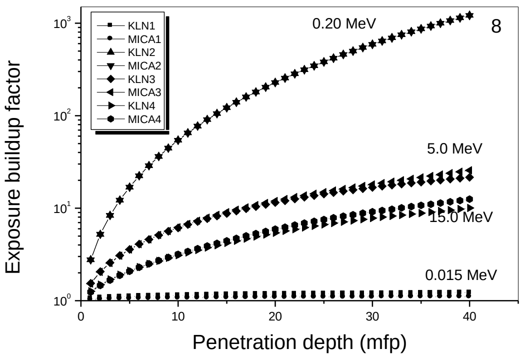

Fig. 8 The EBF for ceramic materials up to 40mfp at 0.015, 0.2, 5.0, 15MeV

From Figs. 5 to 8 we see at the lowest photon energy 0.015 MeV the values of EABF and EBF is slightly more in case of sand than cascade silt loam, but in case of ceramic materials kaolinite with low Z_{eq} value has much higher values of EABF and EBF than mica with higher value of Z_{eq}.

At the photon energy 0.20 MeV EABF and EBF of sand is more than cascade silt loam at penetration depth from 20 to 40 mfp. But EABF and EBF both are approximately same in case of kaolinite and mica as in Figs 7 and 8.. The variation of EABF and EBF of soils with increase in penetration depth is not affected by the chemical composition of material at higher energy range 5-15 MeV, but at that energy range EABF and EBF slightly differ of ceramic materials according to chemical composition .

However, the values of EABF and EBF of ceramic material increases with increase in penetration depth between 15 to 40 mfp at energy range of 5-15 MeV. The reason behind the pair production process starts pre- dominating and results with an electron-positron pair for lower penetration depth, these particles may escape from the material or after multiple collisions with in the material comes to rest and further annihilates. With the increase in penetration depth, these secondary gamma rays (as a result of annihilation) contribute to the rise in intensity of the primary gamma rays [19].

3.1.3 Effect of Effective Atomic Number on EABF and EBF

As in Table 3 and 4 each material have different Z_{eq} at various energy levels, so to assign a particular atomic number to each material, mean of Z_{eq} of each sample at various photon energies is calculated and mean so calculated is treated as the effective atomic number i.e. Z_{eff} of that material

$$\left[Z_{eff} = \frac{\sum_{B=0.015}^{15.0} Z_{eq}}{25} \right].$$

Values of Z_{eff} of kaolinite, sand, cascade silt loam and mica are 11.12108, 12.27724, 12.95068 and 13.0056 respectively. This is very helpful in studying the behavior of buildup factor of different chosen materials at fixed penetration depths and fixed photon energy.

To investigate EABF and EBF as a function of Z_{eff}, one penetration depth has been selected, 15 mfp, for low energy range i.e. from 0.015-0.15 MeV and for higher energy range which is 1.0-15 MeV. From Fig. 9(a) and 10(a) it is analyzed that at 15 mfp and for lower energy range, EABF and EBF shows a decreasing trend as the Z_{eff} increases. This trend is pronounced for lower Z_{eff} in comparison to higher Z_{eff}. Fig. 9(b) and 10(b) informs that for high energy range there is practically no change in value of EABF and EBF which implies that attenuation properties of materials taken at higher incident photon energies is not at all effected by their chemical composition.

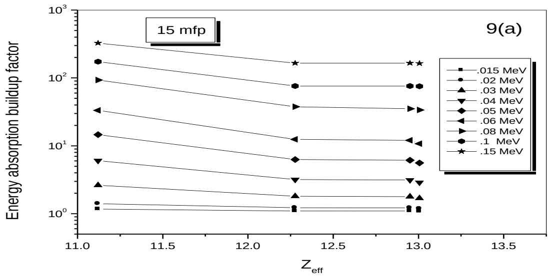

Fig.9 (a) Variation of EABF with effective atomic number(Z_{eff})for energies 0.015-0.15 MeV at 15 mfp.

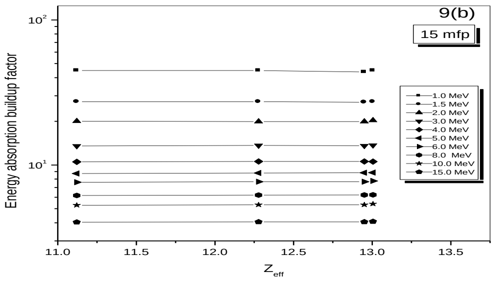

Fig.9 (b) Variation of EABF with effective atomic number(Z_{eff})for energies 1.0-15.0 MeV at 15 mfp.

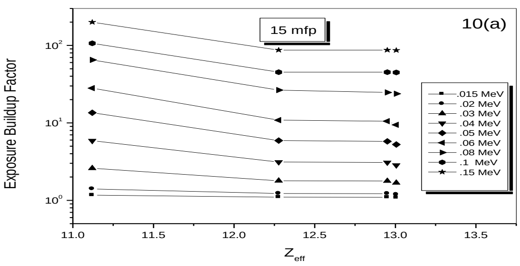

Fig.10 (a) Variation of EBF with effective atomic number(Z_{eff})for energies 0.015-0.15 MeV at 15 mfp.

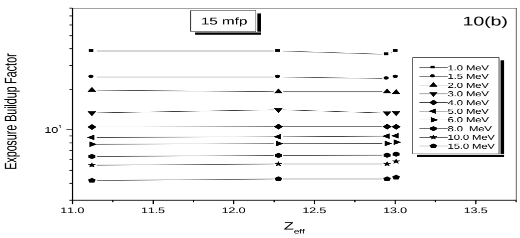

Fig.10 (b) Variation of EBF with effective atomic number(Z_{eff})for energies 1.0-15 MeV at 15 mfp.

IV. Calculation Uncertainty

The calculated values of EABF and EBF for air have been compared with that EABF and EBF for air in ANSI/ANS [8] data base in the energy region 0.015-15.0 MeV and penetration depth up to 40 mfp. From the Fig. 11 (a,b) it can be clearly seen that our calculated values of air agree well with ANSI/ANS[8]database within a few percent uncertainty. Recently, Asano and Sakamoto have evaluate the buildup factors of heavy concrete and various materials for the shielding wall by using the Monte Carlo simulation code, EGS4[20]. They also compared their calculated values by that of concrete in ANSI/ANS-6.4.3**[8]** standard reference database. Both the calculations are in good agreement except for the slight differences which may be due to (a) the development of the low energy photon treatments in EGS4 such as K-X ray, L-X ray and Bremsstrahlung. It was shown by Shimizu *et al.* that the methods based on invariant embedding, G-P fitting and Monte Carlo simulation agree well for 18 low-Z materials within small discrepancies [7], (b) the ANSI/ANS data are based on the calculation result data by using the moments method **[**21**]** with parallel beam source and the Monte Carlo code, EGS4 with emission source. The all materials used in the present study consist of low-Z materials. When compared with other available approximations such as Taylor, Berger, and three exponential, the geometric-progression (G-P) fitting seem to reproduce the buildup factors with better accuracy. Harima *et al.* have shown that the absolute values of maximum deviations of exposure build factors for water in G-P fitting is within 0.5-3%, in Taylor approximation is within 0.4-53.2%, in Berger approach is within 0.9-42.7%, in three-exponential approach is within 0.4-9.3%[22].

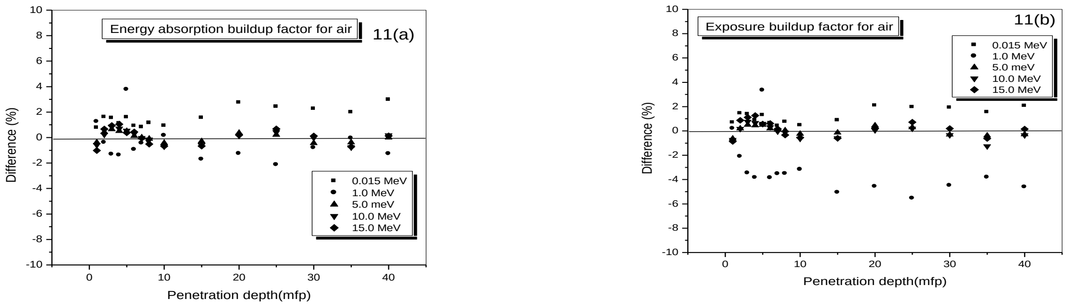

Fig. 11 (a) and (b) Difference (%) between ANSI data base and present work with respect to the calculated values of EABF and EBF for Air at some energy levels upto 40 mfp.

V. Conclusion

What are concluded from the present study are:

Some essential soils and ceramic materials have been investigated in terms of the gamma ray EABF and EBF which are obtained by using the five parameter geometric progression (G-P) fitting formula in the energy region 0.015-15 MeV up to a penetration depth of 40 mfp. Significant increase in EABF and EBF have been observed for soils and ceramic materials in energy region of 0.2 MeV approximately, where Compton scattering predominates. The variation of EABF and EBF with incident photon energy seem to be independent of chemical composition of above materials beyond 2.0 MeV At higher energy range 5-15 MeV chemical composition does not affect the variation of EABF and EBF of soils with increase in penetration depths but this does not happen in case of ceramic materials. At lower energy range 0.015-0.2 MeV values of EABF and EBF show decreasing trend with increase in Z_{eff} but at higher energy range 1.0-15 MeV, the values tends to remain constant.

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