The International Journal of Engineering and Science (IJES)
|| Volume || 7 || Issue || 4 Ver. III || Pages || PP 44-52 || 2018 ||
ISSN (e): 2319 – 1813 ISSN (p): 23-19 – 1805

Buildup Factors ofGamma RayCalculation forpolymeric IlmeniteandMagnetite Composites

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---***ABSTRACT***---

In this study, three composites were investigated in terms of different photon interaction parameters in the energy region of 0.015 – 15.0 MeV. The polymeric composites Epoxy/Ilmenite (EP/Ilm), Polyester/Ilmenite (CUP/Ilm) and Polyester/Magnetite (CUP/Mag) were used for various shielding purposes. The first, as well, was investigated as a restoration/injection mortar for cracks developing in biological shields. The computed parameters of photon interaction; equivalent atomic number Z_{eq}*, energy absorption buildup factor (EABF) and exposure buildup factor (EBF) were studied as afunction of incident photon energy, materials elemental composition and penetration depths up to 40 mean free paths (mfp). Both buildup factors were found to be small at low and high photon energy meanwhile their values are comparatively high in the intermediate energy region.In addition, Kerma relative to air for photon energy from 1 KeV to 20 MeV were computed and found to be dependent upon equivalent atomic numbers.*

In this work it was clear that filled composites offer better shielding capabilities over unfilled formulations and results of all concerned parameters revealed that loaded epoxy and polyester composites exhibited effectiveness for shielding, cracks treatment and design. The obtained data can be useful in estimating the gamma irradiation received by personnel or equipment protected by such shields in many application fields.

KEYWORDS: *radiation shielding, composite, buildup factors, mean free path,kerma*

Date of Submission: 02-04-2018 Date of acceptance: 24-04-2018

I. INTRODUCTION

The interaction parameters of photons with matter are widely used in many application areas such as industry, medical physics and radiation shielding. Nowadays there is a need to create composites with a good mechanical, physical and attenuation properties for many applied radiation fields. In the past decades there wasan interest in the use of mineral filled polymeric composites at different radiation shielding situations. Polymers arehydrocarbonic substances and when filled with crushed minerals of high atomic mass number give an end product that can guarantee both neutron and gamma ray attenuation by different techniques (1,2 and 3). Epoxy/Ilmenite (EP/Ilm), Polyester/Ilmenite (CUP/Ilm) and Polyester/Magnetite (CUP/Mag) composites have a potential as shielding materials in theliterature(4, 5). The first was selected as restoration mortar for cracks developed in biological shields in addition to the use asimproved polymeric composite in various shielding applications. The two other polyester composites have the potential for applications as general-purpose shield castings.

Recent huge nuclear accidents; for example,Fukushima accident in Japan created fears andthe need for precise studies on shielding parameters. The release of multi-energetic photons needs protection utilizing thick shields around radiation source terms. Since gamma ray attenuates and builds up upon interaction with absorbing medii, the well knownLamberts-Beer law for the estimation of photon fields that applies under good geometry conditions won't hold, and transmitted radiation is best dealt with a correction term named "Buildup factor – B" making transmitted intensity $I=B\ I_o\ e^{-\mu t}$. The mentioned law holds for thin shield thicknesses and narrow beam, where the buildup factor B =1. For a shield barrier (as in the concerned composites), scattering events deflect the gamma rays out of the beam and thus away from the detector , in addition, the width of beam plays another role to violate the law, hence, the buildup factor (B) increases to values greater than one(6). The buildup factor B is a dimensionless term which may be considered as a correction factor for the response of an un-collided photon beam (7,8).Buildup factor is classified as energy absorption buildup factor(EABF) and exposure buildup factor (EBF). The first; is a factor in which the considered quantity is the deposited energy in the shield of interest. The second; is a factor in which the quantity of interest is exposure and the energy response function is that of absorption in theair(9).The Factors depend on absorbing medium, photon energy and attenuation coefficient of medium.

A compilation of buildup factors using different codes is presented in the American Nuclear Society (10). The factors data are for 23 elements, one compound and two mixtures over the energy range 0.015 – 15 MeV up to the penetration depth 40 mean free path(mfp). Harima et al. (11) developed the five geometric parameters (GP) fitting formula, which gives factor values in good agreement with the report (10). As well, Harima (12) reviewed and reported current gamma ray buildup factors. Many researchers provided gamma ray buildup factors data for various substances such as different concretes by Kaur et al., (7), gel dosimeters by Singh and Badiger (13), oxide dispersion strengthened steels by Singh et al., (14), basalt rock samples by Karabul et al., (9) and poly methyl methacrylate and kapton by Manjunatha (15).

This work is an attempt to determine the photon parameters; energy absorption buildup factor (EABF) and exposure buildup factor (EBF), made a comparison in terms of equivalent atomic numbers Z_{eq} and study of kerma values. Investigated parameters have been achieved for the previously studied polymeric (Epoxy and polyester) formulas and filled Ilmenite and Magnetite composites at photon energies 0.015 – 15 MeV using methodology presented in the literature.

II. COMPUTATIONALMETHOD

The calculation of EABF and EBF was divided into 3 parts. The first part starts with the calculation of Z_{eq} followed by computation of GPfitting parameters and the last comes to its evaluation.

2.1. a.Computation of equivalent atomic numbers Z_{eq}

The equivalent atomic number is a parameter that resembles an atomic number of elements and it is energy dependent. It is assigned to any compound/mixture and gives proper weight to their compton scattering process.
In order to compute Z_{eq} for a particular polymeric formulation; the ratio $R((\mu/\rho)_{Compton}/(\mu/\rho)_{total})$ for such was to match the corresponding ratio of an element at the same energy.
Thus, firstly $(\mu/\rho)_{Compton}$ and $(\mu/\rho)_{total}$ were obtained for elements of Z= 4 to Z= 40 and for the concerned polymeric formulations at the energy region 0.015 – 15 MeV, using WinXCom program (16). In case of R lies between two ratios for successive known elements, Z_{eq} was interpolated using the following logarithmic interpolationformula(17,18)

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

Where;
Z_1 andZ_2 are the atomic numbers of elements corresponding to the (μ_{comp} / μ_{tot}) ratios R_1 and R_2 respectively.
R $(\mu_{compton}/\mu_{total})$ is the ratio of theselected polymeric formulation at a particular energy, which lies between ratios R_1 and R_2.

2.1.b.Computation of geometric G.P. fitting parameters

And, as a second step in order to calculate G.P. fitting parameters, a similar interpolation procedure was adopted as the case for Z_{eq}.
G.P. fitting parameters for elements were taken from standard (10), which has the database for twenty three elements and two mixtures (air and concrete) at the energy range 0.015 – 15.0MeV and up to a penetration depth of 40 mean free paths. Geometric ParametersG.P.'s for the used formulations were interpolated according to the following formula(17,18)

$$P = \frac{P_1\,(\log Z_2 - \log Zeq) + P_2\,(\log Zeq - \log Z_1)}{\log Z_2 - \log Z_1} \tag{2}$$

Where;
Z_1 and Z_2 are the elemental atomic numbers between which Z of the chosen formula is located. P_1 and P_2 are values of G.P.s corresponding to Z_1 and Z_2 at a given energy, respectively.

2.1.c.Computation of buildup factors

The computation was carried on by the G.P. fitting formula to evaluate EABF and EBF at the energy range (0.015 – 15.0 MeV) and up to 40 (mfp) using the equations given by (10, 11 and 12).

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

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

and;

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

Where, E is the photon energy, x the penetration depth in (mfp); a,b,c,d and X_k are G.P. fitting parameters that depend on the attenuating medium and b is the value of buildup factor at 1 (mfp). The parameter K(E,x) represents photon dose multiplication. For detailed calculation procedures refer to (19).

2.2.Standardization of the calculation method

In order to purport standardization for the current study, a comparison was held for the EBF values in water, using the present G-P fitting method and ANS-6.4.3 - 1991 standard (10) along with the MCNP-5 code (20). Figure1 presents the three relations at different penetration depths 1 - 40 (mfp) over photon energies 0.015 – 15 MeV; where a clear agreement could be realized (12, 21).This comparative tool shows that the G-P fitting method could be effectively used for the computation of buildup factors for the concerned Polymeric samples.

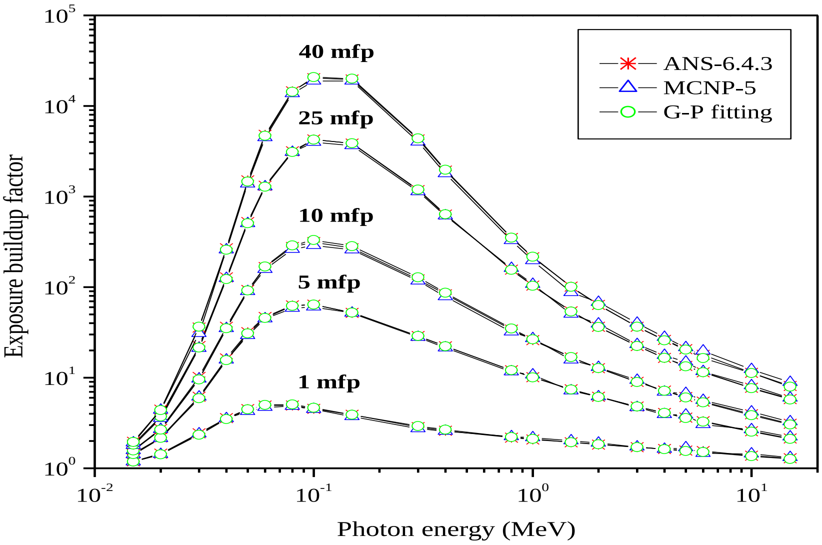


Figure 1: EBF values in water at different penetration depths over the concerned photon energy region (0.015 – 15 MeV) and at penetration depths 1, 5, 10, 25 and 40 (mfp)

2.3.Kerma relative to air

Kerma value has been defined to be the sum of initial kinetic energies produced by liberated secondary charged particles resulting from the photon interaction per unit mass at thepoint of interest(22, 23).The computation ofkerma relative to air is deduced by the following relation,

$$K_a = \frac{K_{Sample}}{K_{Air}} = \frac{(\mu_{en}/\rho)_{Sample}}{(\mu_{en}/\rho)_{Air}} \qquad (6)$$

The massenergy absorption coefficient, μ_{en}/ρ for both sample and air are calculated using compounding rule:

$$\mu_{en}/\rho = \Sigma_i w_i(\mu_{en}/\rho)_i \qquad (7)$$

where, w_i and $(\mu_{en}/\rho)_I$are weight fraction and mass energy absorption coefficient for the ith constituting element, respectively.The μ_{en}/ρ values for elements are taken from the report (24).

III. RESULTSAND DISCUSSION

3.1.Equivalent atomic number Z_{eq}

The equivalent atomic numbers Z_{eq} of the concerned blank formulas and filled composites were computed at the photon energy range 0.015 – 15 MeV and are given in Fig. 2. The values of Z_{eq} describethe properties of the sample in terms of equivalent elements that should each time imitatethe atomic number of a proposed single element. As we know, the interaction process of photons with matter is through the photoabsorption, compton scattering and pair production, which are energy dependent. Since Z_{eq} is calculated on the basis of compton scattering, the slight variation in its value with photon energy can be explained in terms of variation in compton scattering cross-section with energy. It is clear that, the filled composites have higher Z_{eq}values rather than the unfilled blank formulas. In addition, Z_{eq}in both cases individually (either blank formulas or filled composites)is very close and at all the incident photon energies. This behavior returns to the closing of densities, either for blank formulas (CUP, ρ =1.08 g/cm^3 and EP, ρ =1.16 g/cm^3) or for filled composites (EP/Ilm, ρ = 2.516 g/cm^3,CUP/Ilm ρ =2.7 g/cm^{3}CUP/Mag, ρ =2.75 g/cm^3).

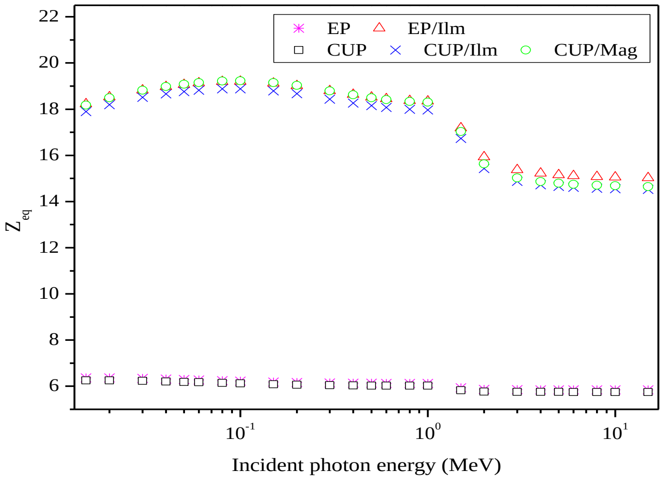


Figure 2: Variation of equivalent atomic number with photon energy for polymeric composites

3.2.Variation of EABF and EBF with incident photon energy

The variation of energy absorption and exposure buildup factors (EABF and EBF) with the photon energywas computed at energy rangefrom 0.015 – 15 MeVand at fixed penetration depths of 1, 5, 10, 25 and 40 mean free paths (mfp).This variation was illustrated forthe concerned shields;Epoxy and polyester blank formulas, as well as, filled ilmenite and magnetite composites and are displayed in Figs. (3-6).

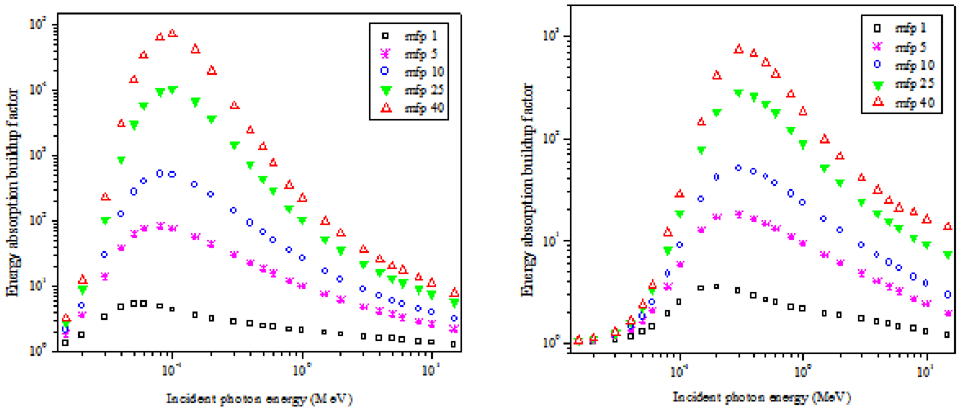

a) b)

Figure 3 (a and b): Change of energy absorption buildup factor for EP and EP/Ilm with incident photon energy

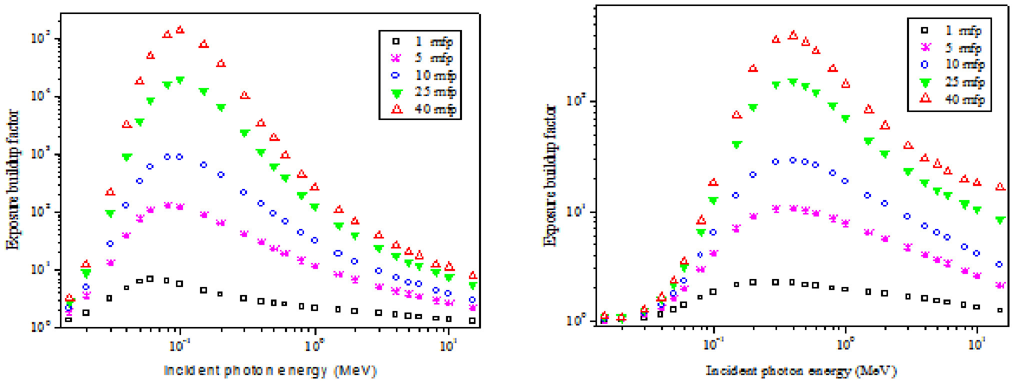
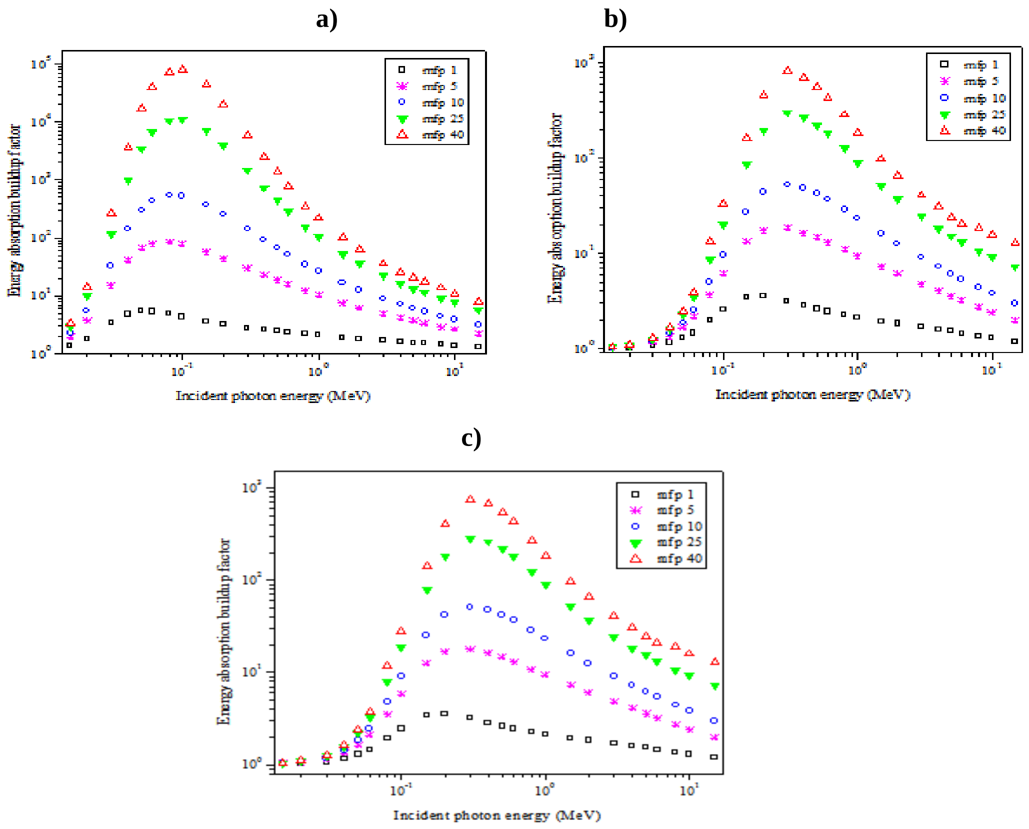
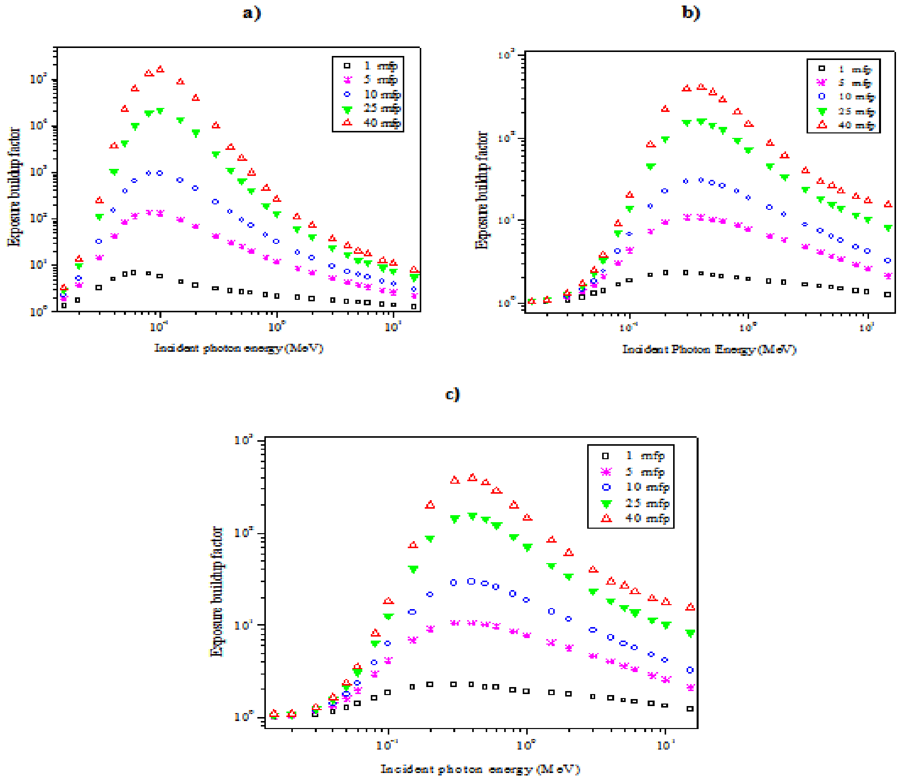

a) b)

Figure 4 (a and b): Change of exposure buildup factor for EP and EP/Ilm with incident photon energy



a) b) c)

Figure 5 (a - c): Change of energy absorption buildup factor for CUP, CUP/Ilm and CUP/Mag with incident photon energy



a) b) c)

Figure 6 (a - c): Change of exposure buildup factor for CUP, CUP/Ilm and CUP/Mag with incident photon energy

It is clear that both buildup factors (EABF and EBF) were almost constant (≈ unity) for all penetration depths at the initial gamma energy value 0.015 MeV for given penetration depths and for all polymeric formulas and filled composites. It is worth to mention that all samples show similar curves; they have the same general shape and variation over the continuous energy region based on domination of various photon interaction processes. Both factors are always greater than one and they increase with the increase in penetration depth showinga clear violation of Lambert-Beer law, and they have almost the similar trend.

Generally; at low energies, photoelectric absorption is the dominant interaction process at which the atomic cross-section is directly proportional to Z^{4-5}/E^{3-4}. The buildup values are minimum; this is because the complete removal of photons makes their lifetime comparatively small. With theincrease in the photon energy, and at an intermediate range, compton multiple scattering dominates linearly with Z making the factors reaching maximum values. Photons are not absorbed but only their energies are degraded. The latter interaction overtakes the photoelectric absorption and gives the maximum factors at energies crossing E_{PC}. This parameter is the energy value at which the photoelectric absorption coefficient matches with compton interaction coefficient. Thereafter; and for higher energies (above 1.02 MeV) pair production reaction, which is considered an (absorbing process), starts dominating and takes over the compton scattering with dependency upon Z^2 and log (E), and this again reduces the factors to a minimum value. For the same figures, the magnitude of both factors increases as “mfp” increases. That maybe explained by the fact that the chance of multiple compton interaction increases with thickness, i.e. increasing of the scattering volume.

For filled composites that are compared to unfilled one as shown in Figs. (3 b, 4 b, 5 (b, c) and 6 (b, c)) and at the penetration depths 25, 40 (mfp), for energies beyond (> 8 MeV); there may be less rapid decrease for both factors. This could be attributed to the fact that particle-antiparticle produced by the latter reaction undergo an annihilation process, which results in the emission of two gamma ray photons of 0.511 MeV. The released photons have energies in the region of compton scattering. That means, they may undergo energy degradation by this process until final absorption. Therefore, the chance of photons to escape through deeper thicknesses increases resulting in higher values for both factors.

Further, in Figs. ((3a, 4a) and (5a, 6a)) and for the unfilled formulas, the (EABF and EBF) reach values in the highest range :($7.19 \times 10^4 - 1.37 \times 10^5$) and ($7.84 \times 10^4 - 1.53 \times 10^5$) respectively. The blank formulas have an equivalent atomic number Z_{eq}, in the range (5.74 - 6.36). On the other hand Figs. ((3b, 4b),(5b, 6b) and (5c, 6c)) and for filled composites, the (EABF, EBF) reach relatively lower values in the range (7.4×10^2–3.92×10^2), ($8.21 \times 10^2 - 4.1 \times 10^2$) and($7.38 \times 10^2$– 3.93×10^2) respectively. The composites have higher equivalent atomic number Z_{eq}, in the range (14.64 – 18.22); hence, the factors vary inversely with Z_{eq}. These phenomena may be explained in terms of (Z and cross-section) dependence for the various photon interaction processes. From the same figures and upon considering the unfilled and filled samples, it is also observed that photon energies corresponding to maxima buildup factors shift to higher values as specific density increases. This maybe explained in correspondence to E_{PC}. The factors give higher locations for energies crossing E_{PC} where compton scattering starts dominating. This value is borderative between the two different reactions. It would be expected in case of low E_{PC}, that the photon energy corresponding to maximum factors would be low and vice versa.

Also, upon comparing the individual curves (separately) for unfilled and filled samples in Figs. (3-6); it can be shown for 10, 25 mean free paths and up a borderative energy value of 2 MeV which divides the figures by two phenomenon:the first, above 2 MeV where factors show proportional variation with Z_{eq}, while the second and below 2 MeV,it can observe and for the same factors reversal variation with Z_{eq}. This maybe explained in terms of pair production reaction dominance in the high energy region.

The maximum values of EABF for EP, EP/Ilm, CUP, CUP/Ilm and CUP/Mag occurs at energies 0.1, 0.3, 0.1, 0.3 and 0.3 MeV, respectively i.e. over the energy range 0.1 – 0.3 MeV.Also, the maximum values of EBF for the same samples occurs at energies 0.1, 0.4, 0.1, 0.4 and 0.4 MeV, respectively i.e. at the energy range 0.1 – 0.4 MeV, at these energy locations compton scattering dominates and both other reactions are of relatively little importance result in high buildup factors.

3.3.Comparison between energy absorption and exposure buildup factors

It is clear that EABF and EBF have similar variation pattern depending on the incident photon energy, penetration depth and elemental composition. However, the difference between the two values exists as samples differ within the concerned energy region 0.015 – 15 MeV. The maximum difference occurs in the intermediate energy region where the compton interaction is dominant(25).The difference was evaluated for the minimum and maximum values of Z_{eq}, i.e. for CUP and CUP/Mag respectively, whereboth samples give the maximum difference of 49.31 % and 105.67 % as shown in Figs. 7(a,b). The difference is a technique to estimate where the maximum radiation occurs; whether inside or at the surface of thematerial. Air is comparable with materials of low Z_{eq} and its value range from (7-8). In the concerned study, CUP is the lightest sample and therefore EBF values can be more than the EABF values. On the other hand, for CUP/Mag more energy deposition occurs inside the sample rather than air and EABF values, are higher than EBF over the intermediate energy region where more photon buildup exists (26).

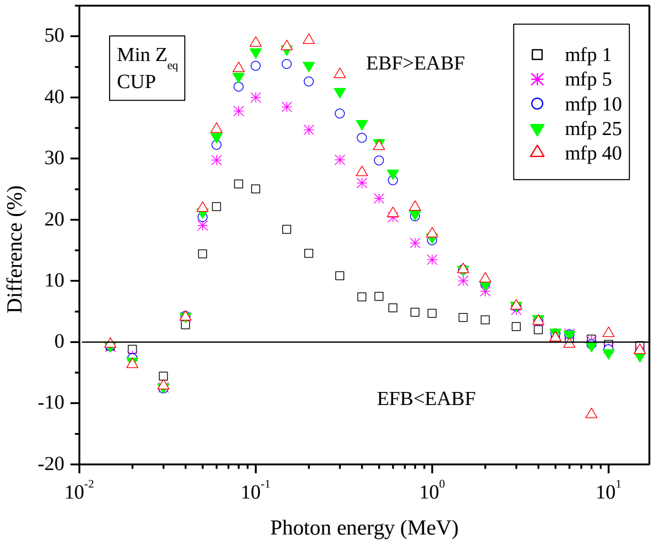


Figure 7 a: Difference (%) for CUP Sample

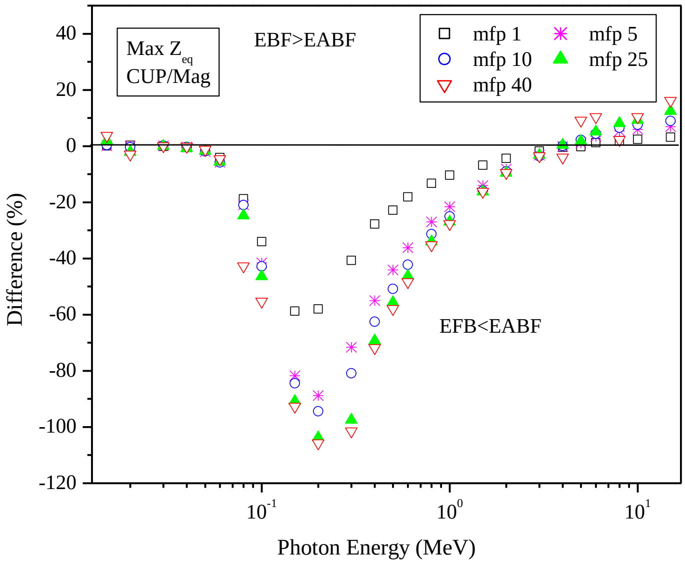


Figure 7 b: Difference (%) for CUP/Mag Sample

3.4. Kerma

The variation of kermarelative to air for the polymeric blank formulas (EP and CUP) and filled composites (EP/Ilm, CUP/Ilm and CUP/Mag) for photons energy (1 KeV – 20 MeV) is shown in Figs. 8(a,b).The K_a variation with photons energy represents the fluctuation in Z_{eq} as partial interaction processes (Photoelectric absorption, Compton scattering, and pair production). The blank formulas K_a values are near unity and the filled composites give a sharp peak at (0.4 MeV). This peak is due to the presence of Fe and other heavy elements in the filled samples; since large photon interaction occurs for high Z elements where the photoelectric cross section is proportional to Z^{4-5}.

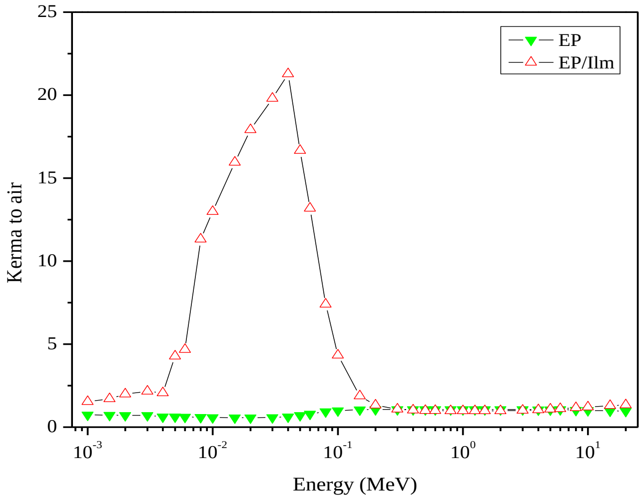


Figure 8 a: Change of kerma relative to air for EP samples vs photon energy

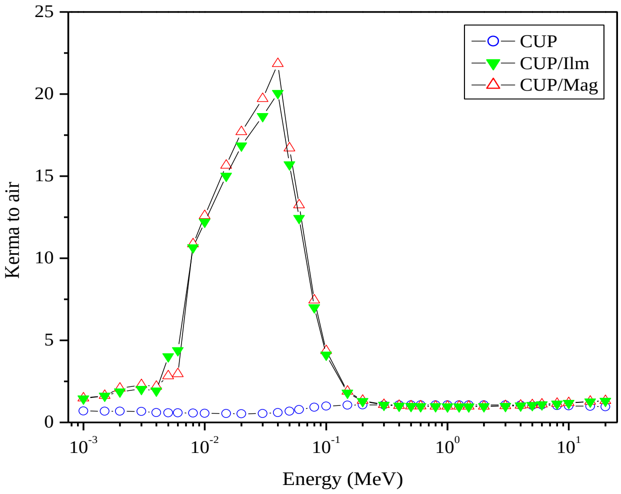


Figure 8 b: Change of kerma relative to air for CUP samples vs photon energy

IV. CONCLUSION

From the present study, it can be concluded that, the equivalent atomic number of investigated materials is directly proportional to the atomic number of its constituent elements with little fluctuation according to compton scattering reaction. Maximum values are for filled composites while minimumare for the blank formulas.

The investigated energy absorption buildup factor EABF and exposure buildup factor EBF in the energy range 0.015 – 15 MeV and up to 40 (mfp) penetration depths show lower values for filled composites rather than blank formulas; however for photon energies more than specific threshold values, both factors show somewhat reversal results making the rely on single component not effective in shielding structure design.

From the study, it is clear that the difference between the factors for lightest sample CUP and heaviest sample CUP/Mag is 49.31 % and 105.67% respectively. Also, the calculated Kerma relative to air values for the investigated materials should be useful in personnel monitoring, radiation and accident dosimetry.

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M. A. El-Sarraf."Buildup Factors Of Gamma Raycalculation forpolymeric Ilmenite and Magnetite Composites. "The International Journal of Engineering and Science (IJES) 7.4 (2018): 44-52