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Energy Absorption Buildup factor for some Oxide Glasses: Penetration Depth, Photon Energy and Effective Atomic Number Dependence

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***Abstract*-**In present investigation, the study of gamma ray Energy absorption buildup factors (EABF) for three oxide glasses, viz. $CaO\text{-}Al_2O_3$, $Na_2O\text{-}SiO_2$, and $Na_2O\text{-}Al_2O_3\text{-}SiO_2$. The computations were done by ANSI/ANS-6.4.3 library and interpolation method using the Geometric Progression fitting formula for the energy range from 0.015 to 15 MeV, up to penetration depths 40 mfp (mean free path). The buildup factors have been studied as functions of penetration depth, incident photon energy and effective atomic number (Z_{eff}) and presented in the forms of graphs.

***Index Terms*-** Buildup factor, Effective atomic number (Z_{eff}), Gamma radiation, G-P fitting formula, Radiation shielding.

I. INTRODUCTION

DUE to increasing harmful effects of radiations the need to develop materials arises which can act as good radiation shield under the environment of high nuclear radiation exposure [1]. In this regard, glasses are promising materials because of their range of composition and homogeneity. Typical applications of radiation shielding glasses are in airport security X-ray screens, for dental clinic, X-ray and radiation protection spectacles, hospital X-ray rooms, laboratories, nuclear facilities, space technology for protecting human being. Brar *et al*. [2] has given a brief discription of types of buildup factor. Exposure build up factor and energy absorption buildup factor are the main two types of buildup factors. Build up factor in which the energy response function is that of absorption in air and the quantity of interest is exposure is called as exposure buildup factor and the buildup factor in which energy response function is that of absorption in the material and the quantity of interest is the absorbed or deposited energy in the shielding medium is known as energy absorption buildup factor. Detailed review on applications of buildup factor and various calculations have been given by Harima [3]. The ANSI/ANS-6.4.3-1991 [4] standard reference data gives buildup factor data for various elements. But this data lacks information for various mixture and compounds with exceptions of water, air and concrete etc. Manohara *et al*. [5] studied the energy absorption geometric progression fitting parameters and corresponding buildup factors for human organs and tissues for for the energy range (0.015–15.0 MeV) up to the penetration depth of 40 mean free path. Singh *et al*. [6] investigated the dependence of energy absorption buildup factor of flyash on incident photon energy and penetration depth. Manohara *et al.* [7] studied the heavy metal oxide glasses are better shields to gamma- radiations and may be used as transparent radiation shielding materials. The chosen oxide glasses has been obtained from literature of J-E Shelby [8]. There are successful contributions which are based on the buildup factor studies in different types of glasses available in the literature. For example, Manohara *et al.* [9] studied the variation of exposure buildup factors for heavy metal oxide glass with photon energy and penetration depth. Kaewkhao *et al*. [10] studied the mass attenuation coefficients and shielding parameters of borate glass matrices containing with Bi_2O_3 and BaO have been investigated at 662 keV, and compare with PbO in same glass structure. Kaundal *et al.* [11] has been investigate the structural properties of lead strontium borate glasses for gamma-ray shielding applications. K.S.Maan *et al*. [12] studied the inverse relationship between values of buildup factors and equivalent atomic numbers of some low atomic number (*Z*) silicates for the wide energy range (0.015–15.0 MeV) up to the penetration depth of 40 mean free path. Recently, Van Kirk *et al*. [13] and Ford *et al*. [14] studied the bismuth based glasses have received attention due to its many potential applications.

In the present work, the EABF were computed using the geometric Progression (G-P) fitting formula for oxide glasses systems, viz. $CaO\text{-}Al_2O_3$, $Na_2O\text{-}SiO_2$, and $Na_2O\text{-}Al_2O_3\text{-}SiO_2$ glasses in the energy range 0.015 – 15 MeV up to penetration depths of 40 mfp (mean free path). The EABF data so generated has been studied as a function of penetration depth, incident energy, and effective atomic number (Z_{eff}). Buildup factors of these glasses are useful for practical calculations in gamma ray shield designs.

Table I: Equivalent Atomic Numbers (Z_{eq}) and Energy Absorption G-P Fitting Parameters for $65CaO\text{-}35Al_2O_3$ in the Energy Range 0.015-15.0 MeV

Energy [MeV]	Zeq	a	b	c	d	Xk

.0150	15.14	1.0177	.3830	.2250	11.9164	-.1329
.0200	15.29	1.0407	.3790	.2148	18.0424	-.2182
.0300	15.45	1.1291	.3886	.2172	13.8792	-.1195
.0400	15.50	1.2936	.4217	.2037	14.7057	-.1156
.0500	15.56	1.5179	.4994	.1685	14.9390	-.0923
.0600	15.64	1.8215	.5628	.1473	14.6970	-.0789
.0800	15.66	2.6082	.6740	.1160	13.2731	-.0764
.1000	15.90	3.2037	.8491	.0577	13.6087	-.0524
.1500	15.99	3.8361	1.1659	-.0232	12.9490	-.0106
.2000	14.96	3.7097	1.4137	-.0697	16.0999	.0129
.3000	14.50	3.1212	1.5545	-.0954	14.3025	.0261
.4000	14.50	2.7932	1.5486	-.0959	14.9057	.0275
.5000	14.50	2.5802	1.5222	-.0934	15.0887	.0277
.6000	14.50	2.4381	1.4858	-.0890	14.9744	.0270
.8000	14.50	2.2435	1.4169	-.0795	15.1461	.0254
1.000	14.50	2.1194	1.3580	-.0710	14.9953	.0242
1.500	14.50	1.9420	1.2374	-.0500	14.6903	.0177
2.000	12.88	1.8349	1.1606	-.0500	14.8355	.0110
3.000	13.59	1.6970	1.0542	-.0092	11.2431	-.0028
4.000	13.58	1.5997	.9955	.0060	12.7753	-.0102
5.000	13.23	1.5318	.9457	.0210	14.2765	-.0231
6.000	13.51	1.4598	.9402	.0230	15.1227	-.0281
8.000	13.63	1.3695	.9092	.0342	12.7483	-.0293
10.00	13.82	1.3695	.9139	.0335	13.5159	-.0298
15.00	13.63	1.2114	.8841	.0468	14.2702	-.0442

Table II: Equivalent Atomic Numbers (Z_{eq}) and energy absorption G-P fitting parameters for $20Na_2O$-$80SiO_2$ in the energy Range 0.015-15.0 MeV

Energy [MeV]	Zeq	a	b	c	d	Xk
.0150	11.34	1.0461	.4062	.2019	12.1012	-.1060
.0200	11.38	1.1077	.4162	.1954	14.5305	-.1044
.0300	11.44	1.3528	.4598	.1850	14.4962	-.0973
.0400	11.46	1.7525	.5951	.1272	15.7651	-.0666
.0500	11.47	2.3816	.6822	.1082	14.3164	-.0658
.0600	11.51	2.9663	.8480	.0559	13.7389	-.0417
.0800	11.49	3.9732	1.1389	-.0195	13.0074	-.0043
.1000	10.56	4.3669	1.3533	-.0619	12.9377	.0158
.1500	10.92	4.0422	1.7389	-.1251	13.5499	.0496
.2000	10.50	3.5776	1.8340	-.1373	13.8092	.0534
.3000	10.50	3.0060	1.7989	-.1341	13.9036	.0499
.4000	10.50	2.7106	1.7230	-.1341	14.1412	.0459
.5000	10.50	2.5294	1.6512	-.1166	14.2544	.0427
.6000	10.50	2.3969	1.5817	-.1063	14.5235	.0382
.8000	10.50	2.2251	1.4763	-.0915	14.7899	.0337
1.000	10.50	2.1108	1.3928	-.0783	14.7550	.0291
1.500	10.50	1.9370	1.2542	-.0543	14.2844	.0208
2.000	9.757	1.8427	1.1589	-.0351	14.7010	.0132
3.000	10.33	1.7068	1.0504	-.0094	11.3661	-.0006
4.000	10.66	1.6147	.9833	.0087	13.1413	-.0115
5.000	10.57	1.5438	.9455	.0189	12.7464	-.0147
6.000	10.86	1.4801	.9281	.0242	15.9342	-.0271
8.000	10.81	1.3893	.9026	.0329	12.2827	-.0229
10.00	10.57	1.3280	.8906	.0366	13.9262	-.0284
15.00	10.73	1.2277	.8886	.0388	14.7223	-.0330

Table III: Equivalent Atomic Numbers (Z_{eq}) and energy absorption G-P fitting parameters for $20Na_2O$-$5Al_2O_3$-$75SiO_2$ in the energy Range 0.015-15.0 MeV

Energy [MeV]	Zeq	a	b	c	d	Xk
.0150	11.31	1.0465	.4064	.2015	12.0437	-.1047
.0200	11.35	1.1088	.4158	.1959	14.5320	-.1049
.0300	11.40	1.3571	.4609	.1845	14.5135	-.0970
.0400	11.44	1.7566	.5965	.1266	15.7824	-.0663
.0500	11.44	2.3912	.6856	.1069	14.3580	-.0656
.0600	11.46	2.9860	.8551	.0537	13.8015	-.0406
.0800	11.51	3.9653	1.1356	-.0187	13.0611	-.0047
.1000	11.56	4.3669	1.3533	-.0619	12.9377	.0158
.1500	10.92	4.0422	1.7389	-.1251	13.5499	.0496
.2000	12.93	3.6872	1.5917	-.1011	14.1283	.0322
.3000	12.50	3.0790	1.6693	-.1144	14.2159	.0385
.4000	12.50	2.7714	1.6204	-.1079	14.6375	.0341
.5000	12.50	2.5811	1.5618	-.0999	14.9653	.0306
.6000	12.50	2.4221	1.5323	-.0980	14.6871	.0332
.8000	12.50	2.2375	1.4439	-.0850	14.7486	.0291
1.000	12.50	2.1170	1.3729	-.0740	15.0945	.0262
1.500	12.50	1.9400	1.2470	-.0525	14.6171	.0199
2.000	9.772	1.8428	1.1588	-.0351	14.7017	.0132
3.000	10.35	1.7068	1.0504	-.0094	11.3434	-.0006
4.000	10.66	1.6147	.9833	.0087	13.1413	-.0115
5.000	10.57	1.5438	.9455	.0189	12.7464	-.0147
6.000	10.86	1.4801	.9281	.0242	15.9342	-.0271
8.000	10.62	1.3905	.9022	.0328	12.2855	-.0226
10.00	10.57	1.3280	.8906	.0366	13.9262	-.0284
15.00	10.73	1.2277	.8886	.0388	14.7223	-.0330

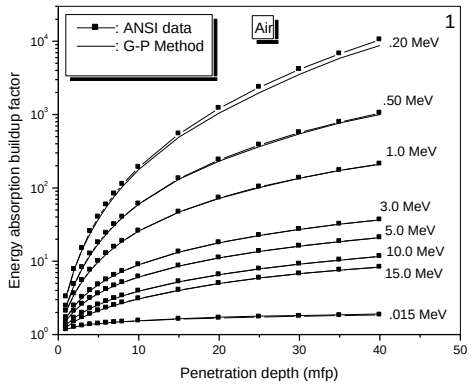


Figure 1. EABF of air obtained in the present work (G-P method) compared with those of the ANSI/ANS-6.4.3 standard [4] at selected incident photon energies (in MeV)

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:

A. Calculation of the equivalent atomic number Z_{eq}
B. Calculation of geometric progression (G-P fitting parameters)
C. Calculation of energy absorption buildup factors.

A. Calculation of Z_{eq}

Firstly the values of the Compton partial attenuation coefficient ($\mu_{compton}$) and the total attenuation coefficients (μ_{total}) in cm^2g^{-1} were obtained for the elements from Z = 4 to 40 and for the chosen oxide glasses systems in the energy range 0.015 to 15.0 MeV, using the XCOM computer programme [15]. Further,

by using a simple computer program the ratio ($\mu_{compton}$ /μ_{Total}) was obtained for all the elements and the chosen oxide glasses systems.

The value of Z_{eq} for the oxide glasses system was calculated by matching the ratio ($\mu_{compton}$ /μ_{Total}) of a particular oxide glasses system at a selected energy with the corresponding ratio of an element at the same energy. For those cases where the ratio value lies between two ratios for known elements, the value Z_{eq} was interpolated using the following formula [16], [17]:

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

Here, Z_1 and Z_2 are the elemental atomic numbers corresponding to the ratio (μ_{comp}/μ_{total}) R_1 and R_2 respectively and R is the ratio for the chosen oxide glasses system at a particular energy. R_1 and R_2 are the two ratios of elements between which lies the ratio (μ_{comp}/μ_{total}), the ratio R of the oxide slass system. The value of z_{eq} for the different oxide glasses systems so obtained are given in Table I, II, and III.

B. Calculations of Geometric Progression (GP) Fitting Parameters

By using the following interpolation formula[16], [17], GP fiting parameters (*a, b, c, d, and* X_k) for energy absorption buildup factors were calculated from the Z_{eq} values obtained from step (A) above.

$$P = \frac{P_1(\log Z_2 - \log Z_{eq}) + P_2(\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1} \qquad \mathbf{(2)}$$

where Z_1 and Z_2 are the atomic numbers of elements and the equivalent atomic number (Z_{eq}) of a given oxide glasses system lies between them and corresponding to the atomic numbers Z_1 and Z_2 at a given energy, P_1 and P_2 are the values of G-P fitting parameters respectively. For the pure elements, G-P fitting parameters were obtained from the standard reference ANSI/ANS-6.4.3-1991 [4]. Table I, II, and III gives the resulting energy absorption G-P fitting parameters for oxide glasses systems

C. Calculation of energy absorption build-up factors

The G-P fitting parameters were then used to generate energy absorption buildup factor data for these materials using the following geometric Progression fitting given by Harima et al. [18]:

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

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

Where

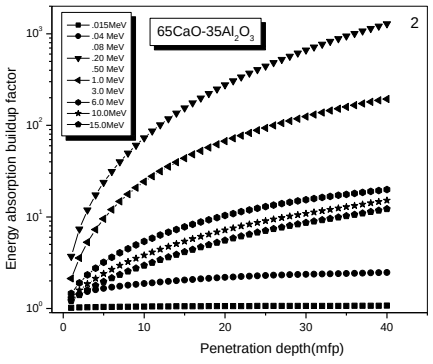
$$K(E,x) = cx^a + d\,\frac{\tanh(x/X_k - 2) - \tanh(-2)}{1 - \tanh(-2)} \text{ for } \quad x \le 40mfp \qquad (5)$$

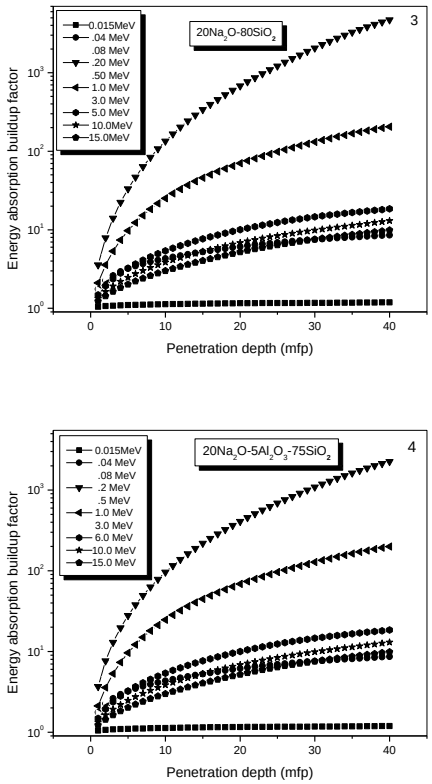
Here x= source-detector distance of the medium in mfp, b is the buildup factor value at 1 mfp and is an important parameter with physical meaning. When photons emitted from an initial monoenergetic source arrive at 1 mfp from the source, the uncollided and scattered photons that compose the shape of the energy spectrum reflects the characteristics of the materials and the source energy. The energy distribution at 1 mfp represents a source spectrum with continuous energies for further deep penetration. The fitting parameters a, b, c, d, and X_k depend on the attenuating medium and source energy. The term K (E, x) is the dose multiplication factor. Equation (5) shows the dependence of K on x.

III Result and Discussion

A. Standardization of the procedure:-

In order to check the reliability of present method, EABF values for air are compared with EABF values given by ANSI/ANS-6.4.3 data [4] for some selected energies ranges from 0.015 MeV-15 MeV, and up to penetration depths of 40 mfp. From fig. 1 it can be analyzed that our calculated EABF values of air by the present method are in excellent agreement with standard data. This gives confidence in our results for the glass materials.





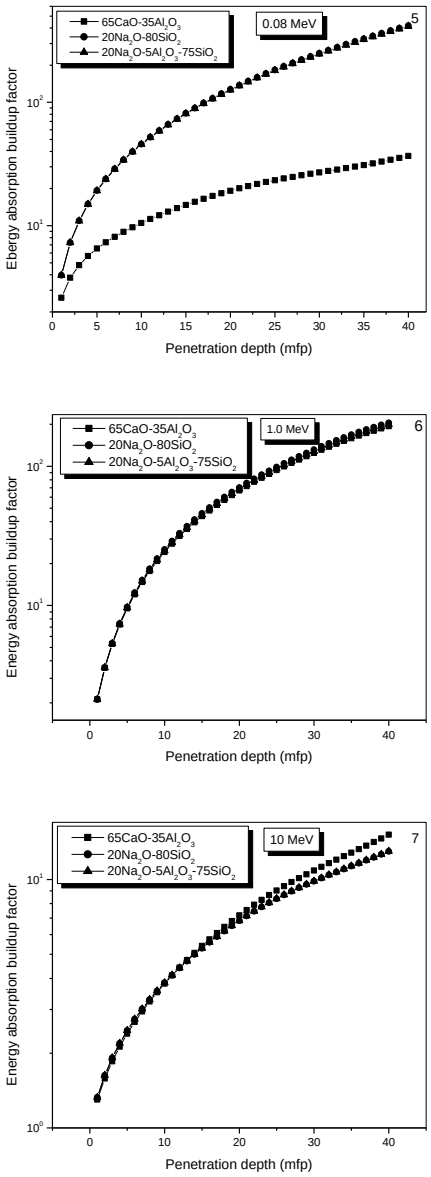
Figures: 2-4. Variation of the EABF with penetration depth (in units of mfp) for some selected photon energies (in MeV): (2) 65CaO-$35Al_2O_3$, (3) $20Na_2O$-$80SiO_2$, and (4) 20 Na_2O-$5Al_2O_3$-$75SiO_2$.

B. Buildup factors of oxide glasses

As table I, II, and III shows the computed energy absorption GP fitting parameters, so to generate energy absorption buildup factors those values were used. In the paragraphs below, we discuss how the buildup factors vary with penetration depths, incident photon energy, and effective atomic number (Z_{eff}).

1. EABF as a Function of Penetration Depth

Figs. 2-4 shows the variation of EABF as a function of penetration depth for some selected photon energies in the energy range 0.015- 15 MeV. The values of EABF more or less remain constant ($\cong$ unity) and low for all penetration depth at the lowest energy 0.015 MeV due to dominance of photoelectric effect. But at energies i.e. 0.20 MeV and 0.50 MeV the values of EABF are much higher and increases with increase in penetration depth for all glass materials, due to more multiple scattered photons are generated at large penetration depth i.e. increasing the buildup factor, also it can be seen that at higher energies i.e. 3 to 15 MeV EABF values are in between lower and higher values due to predominance of pair- production.



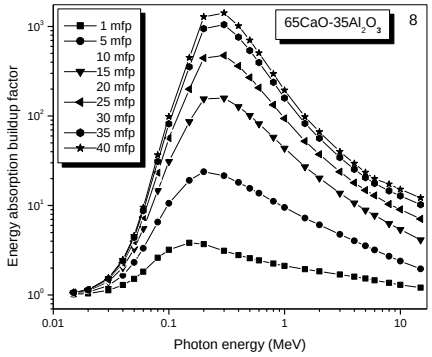
Figures: 5-7. Comparison of EABF up to 40 mfp for chosen oxide glasses at photon energy: (5) 0.08 MeV, (6) 1.0 MeV, and (7) 10 MeV

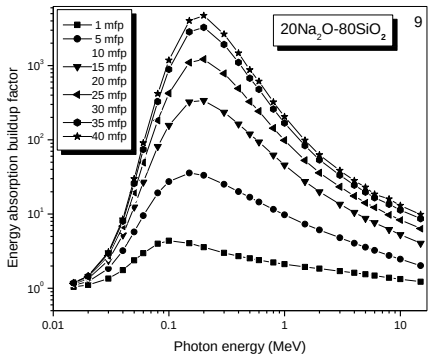
In figs. 5-7 shows that at energy 0.08 MeV EABF value of 65CaO-$35Al_2O_3$ is lower as compared to other two glasses, but at higher energies like 1 MeV and 10 MeV EABF of all glasses are more or less equal.

2. EABF as a Function of Incident Photon Energy

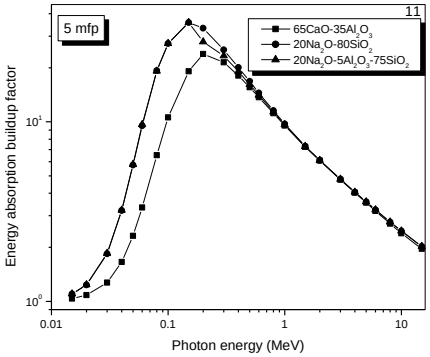
From Figs. 8-13 it has been observed that EABF values of all oxide glasses start increasing with increase in photon energy up to a maximum at intermediate energies and then further start decreasing with increase in energy of gamma ray. Here the low value of buildup factor around 0.015 MeV is due to predominance 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

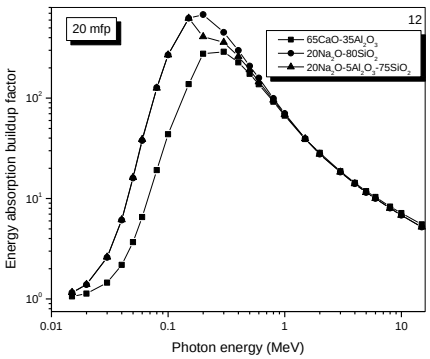
Compton effect, Which only helps in the degradation of photon energy and fails to remove a photon completely. Because of multiple scattering of photons they exist for longer time in material which leads to a higher value of buildup factor. Here it is also observed that at gamma ray energy around 0.2 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 with incident photon energy seems to be independent of chemical composition of above materials beyond 2.0 MeV respectively.

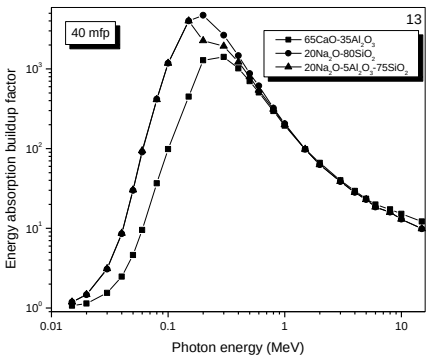




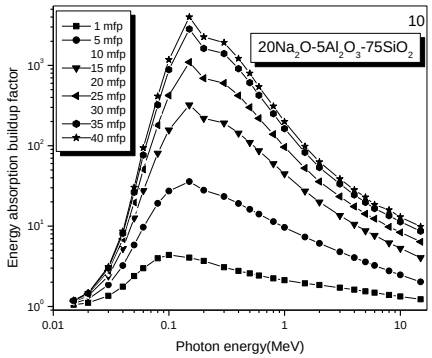
Figures: 8-10. Variation of the EABF with incident photon energy (in MeV) for some selected penetration depths (in mfp): (8) $65CaO\text{-}35Al_2O_3$, (9) $20Na_2O\text{-}80SiO_2$, and (10) $20\ Na_2O\text{-}5Al_2O_3\text{-}75SiO_2$.

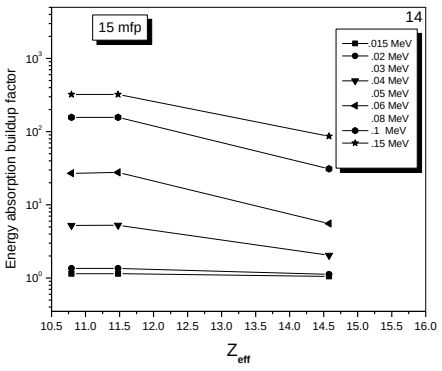


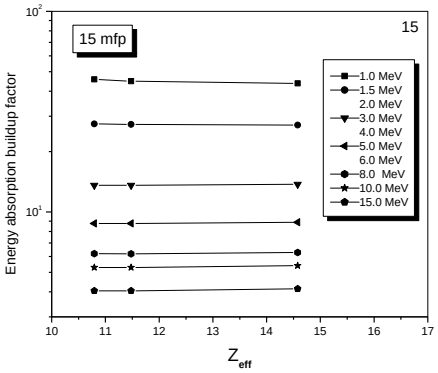




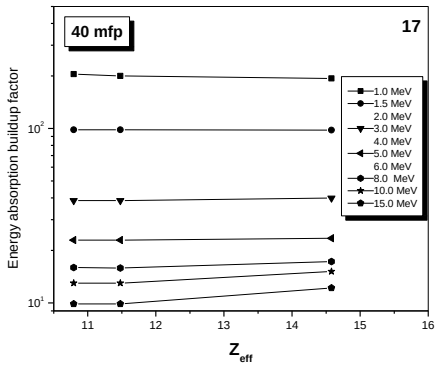
Figures: 11-13. Comparison of EABF up to 15 MeV for chosen oxide glasses at penetration depth: (11) 5 mfp, (12) 20 mfp, and (13) 40 mfp.







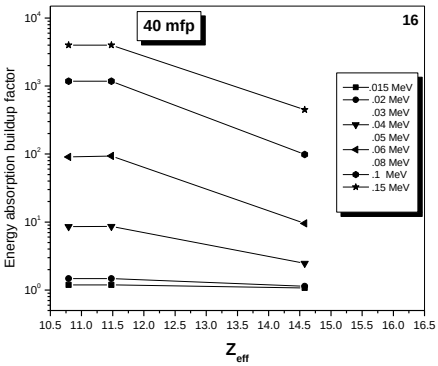
Figures: 14, 15. The EABF as a function of the effective atomic number (Z_{eff}) at 15 mfp for energy range: (14) 0.015 – 0.15 MeV, and (15) 1.0 – 15 MeV.



Figures: 16, 17. The EABF as a function of the effective atomic number (Z_{eff}) at 40 mfp for energy range: (16) 0.015 – 0.15 MeV, and (17) 1.0 – 15 MeV.

3. EABF as a Function of Effective Atomic Number (Z_{eff})

In the present investigation the Z_{eq} at various photon energies (Table I, II, and III) of each chosen glasses is averaged over the incident photon energies and the calculated values is treated as the effective atomic number (Z_{eff}) of that sample, i.e. $\left[Z_{eff} = \frac{\sum_{B=0.015}^{15.0} Z_{eq}}{25} \right]$. This is helpful in assigning a particular atomic number to each glass irrespective of incident photon energy. Fig. 14 shows that at energy 0.015 MeV and 0.02 MeV EABF tends to remain constant as Z_{eff} increases. From 0.03-0.15MeV the EABF is slowly decrease with increasing Z_{eff}. This behavior is due to the fact that photoelectric absorption is dominant process in low energy region. So for a given value of incident photon energy, as one moves from the lower to higher Z_{eff} side, the photons are more readily absorbed by photoelectric interaction, so their life time in the materials is small which lower the value of buildup factor. However, at E > 1 MeV (fig. 15) there is practically no change in EABF. So EABF is seen to be independent of Z_{eff}. So we can say that at higher photon energies, the attenuation properties are not affected by the chemical composition of materials.



At the higher penetration depth of 40 mfp (Figs. 16, 17) EABF values show a similar trend to that of 15 mfp penetration, but E > 6 MeV EABF values slightly increases with increased Z_{eff}. Also, the value of EABF at 40 mfp is comparatively higher at all incident energies this is because the probability of multiple scattering increases with increase in penetration depth creating more photons in the material which results in increasing the EABF value.

IV. Conclusion

The G-P fitting formula has been successfully applied for the computation of the energy absorption buildup factor of three oxide glasses. The generated EABF has been studied as a function of penetration depth, photon energy, and effective atomic number (Zeff).

The values of EABF remains constant and low for all penetration at 0.015 MeV, but at energies i.e 0.2 and 0.5 MeV EABF values are much higher and increases with increase in penetration depth. However at higher energies EABF values are in between lower and higher values.

Significant increase in EABF has been observed for three oxide glass systems in energy region of 0.2 MeV approximately, where Compton scattering predominates. The variation of EABF with incident photon energy seem to be

independent of chemical composition of above materials beyond 2.0 MeV.

At 15 mfp EABF remain constant at energy 0.015 MeV and 0.02 MeV but it slowly decreases in the energy region 0.03- 0.15 MeV. However at higher energies, there is practically no change with increased Z_{eff}. At 40 mfp EABF values show a similar trend to that of 15 mfp penetration.

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