

Study of Photon Interaction Parameters for Some Oxide Glasses as Gamma Ray Shielding Materials

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ABSTRACT: Gamma ray shielding properties of three oxide glasses, viz. $65\text{CaO}-35\text{Al}_2\text{O}_3$ (OG1), $20\text{Na}_2\text{O}-80\text{SiO}_2$ (OG2) and $20\text{Na}_2\text{O}-5\text{Al}_2\text{O}_3-75\text{SiO}_2$ (OG3) have been evaluated in terms of exposure buildup factor, equivalent atomic number parameters. Gamma ray exposure buildup factor for chosen oxide glasses has been computed using five parametric geometric progression energy range of 15 keV – 15 MeV, up to the penetration of 40 mfp. The buildup factors have been studied as functions of incident photon energy and also studied equivalent atomic number (Z_{eq}) as a function of incident photon energy. The results are presented in the forms of graphs. This change results from the dominance of different interaction process in different energy regions. Also here we conclude that glass samples of high Z_{eq} and low EBF show as good shielding nature.

KEYWORDS: Oxide glasses, Buildup factor, Equivalent atomic number (Z_{eq}), G-P fitting formula.

I. INTRODUCTION

Radiological protection, is the science and practice of protecting people and the environment from the harmful effects of ionizing radiation. Ionizing radiation is widely used in industry and medicine, and can present a significant health hazard. It causes microscopic damage to living tissue, which can result in skin burns and radiation sickness high exposures known as "tissue effects", and statistically elevated risks of cancer at low exposures known as "stochastic effects". Different types of ionizing radiation interact in different ways with shielding material. The effectiveness of shielding is dependent on the stopping power of radiation particles, which varies with the type and energy of radiation and the shielding material used.

so we required materials which are used as shielding from gamma radiation. Oxide glasses are the good systems which are used as shielding materials. 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. Apart from good shielding property, the selection of a suitable shielding material is based on availability, effectiveness, application constraints and economic considerations. In easy words, shielding, or the attenuation of gamma radiation, occurs through the interaction of the gamma radiation with matter. The degree to which gamma radiation is attenuated is dependent upon the energy of the incident gamma radiation, the atomic number and density of the elements in the shielding material, and the thickness of the shielding. Composite materials may offer additional benefits in chemical resistance, physical durability, and portability.

II. THEORETICAL BACKGROUNDS

The concept of buildup factor is introduced by White [1]; Further Fano [2] recognized the importance of buildup factor in attenuation studies. Eisenhour and Simmons [3], using the moments method, calculated the point isotropic buildup factors in concrete up to a penetration depth of 40 mfp for energy range 15 keV to 15 MeV.

The exposure buildup factor (EBF) in which the quantity of interest is the exposure and the detector response function is that of absorption in air. Due to the abundance of oxide glasses, an attempt has been made to check the feasibility of

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using these materials to make shields for protection from the ionizing radiations. Different methods such as G-P fitting method [4], invariant embedding method [5]. American National Standards ANSI/ANS 6.4.3 [6] has used point kernel Geometric Progression (G-P) fitting method and provided buildup factor data for 23 elements, one compound (water) and two mixtures (air and concrete) at 25 standard energies in the energy range 0.015- 15.0 MeV up to the penetration depth of 40 mean free path (mfp).

Recently, shielding effectiveness of different materials have been investigated by various researchers, namely, Kumar et al.[7], Kurudirek and Topcuoglu [8], Nil kucuket al.[9], V.P. Singh et al.[10] and Tejbir Singh et al. [11]. Chemical composition of oxide glasses (for 100 gm. of glass) are taken from book of J-E Shelby [12]. In the present work, an attempt has been made to verify shielding effectiveness of selected low cost, light weight and low-Z, oxide glasses in the selected energy range by computing equivalent atomic number (Z_{eq}) and exposure buildup factor (EBF) in the energy region 15 keV-15.0 MeV up to penetration depths of 40 mfp.

III. COMPUTATIONAL WORK

Calculation of mass attenuation coefficient

A narrow beam of mono-energetic photons having an initial intensity I_0 is attenuated to an intensity 'I' after passing through a layer of material with mass-per-unit-area 'x', according to the exponential law: $I = I_0 e^{-\mu/\rho \cdot x}$, where μ/ρ is the mass attenuation coefficient. That equation can be rewritten as:

$$\frac{\mu}{\rho} = \frac{\ln\left(\frac{I_0}{I}\right)}{x}$$

Therefore, mass attenuation coefficient ($\mu_m = \mu/\rho$) can be calculated by substituting the measured values of I_0 , I and x in above equation.

Calculation of buildup factor

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

A. Calculation of Z_{eq}

Firstly the values of the Compton partial attenuation coefficient ($\mu_{compton}$) and the total attenuation coefficients (μ_{total}) in $cm^2 g^{-1}$ were obtained for the elements from $Z = 4$ to 40 and for the chosen oxide glasses systems in the energy range 15 keV to 15.0 MeV, using the XCOM computer programme [13]. The value of Z_{eq} for the oxide glasses system was calculated by matching the ratio ($\mu_{compton} / \mu_{Total}$) 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 [14-15]:

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

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. Which lies between ratios R_1 and R_2 . The value of Z_{eq} for the different oxide glasses systems so obtained are given in Table II, III, and IV.

B. Calculations of Geometric Progression (GP) Fitting Parameters

The Z_{eq} values obtained from step (A) above were used to calculate GP fitting parameters (a , b , c , d , and X_k) for exposure buildup factors using the following interpolation formula[14-15]

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

where Z_1 and Z_2 are the atomic numbers of elements between which the equivalent atomic number (Z_{eq}) of a given oxide glasses system lies and P_1 and P_2 are the values of G-P fitting parameters corresponding to the atomic numbers Z_1 and Z_2 respectively at a given energy. G-P fitting parameters for the pure elements were taken from the standard reference ANSI/ANS-6.4.3-1991 [6]. The resulting energy absorption G-P fitting parameters for oxide glasses systems are given in Table II, III, and IV.

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Table I: Chemical composition of oxide glasses (for 100 gm. of glass) [12].

Chosen Samples	CaO (gm.)	Al ₂ O ₃ (gm.)	Na ₂ O (gm.)	SiO ₂ (gm.)
65CaO-35Al ₂ O ₃ (OG1)	50.5	49.5	-----	-----
20Na ₂ O-80SiO ₂ (OG2)	-----	-----	20.5	79.5
20Na ₂ O-5Al ₂ O ₃ -75SiO ₂ (OG3)	-----	8.15	19.8	72.0

Table II: Z_{eq} and Energy Absorption G-P Fitting Parameters for (OG1) in the Energy Range 0.015-15.0 MeV

Energy [MeV]	Z _{eq}	a	b	c	d	X _k
.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 III: Z_{eq} and energy absorption G-P fitting parameters for (OG2) in the energy Range 0.015-15.0 MeV

Energy [MeV]	Z _{eq}	a	b	c	d	X _k
.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 IV: Z_{eq} and energy absorption G-P fitting parameters for (OG3) in the energy Range 0.015-15.0 MeV

Energy [MeV]	Z _{eq}	a	b	c	d	X _k
.0150	11.31	1.0465	.406	.2015	12.0437	-.1047
.0200	11.35	1.1088	4	.1959	14.5320	-.1049
.0300	11.40	1.3571	.4158	.1845	14.5135	-.0970
.0400	11.44	1.7566	.4609	.1266	15.7824	-.0663
.0500	11.44	2.3912	.5965	.1069	14.3580	-.0656
.0600	11.46	2.9860	.6856	.0537	13.8015	-.0406
.0800	11.51	3.9653	.8551	-.0187	13.0611	-.0047
.1000	11.56	4.3669	1.1356	-.0619	12.9377	.0158
.1500	10.92	4.0422	1.3533	-.1251	13.5499	.0496
.2000	12.93	3.6872	1.7389	-.1011	14.1283	.0322
.3000	12.50	3.0790	1.5917	-.1144	14.2159	.0385
.4000	12.50	2.7714	1.6693	-.1079	14.6375	.0341
.5000	12.50	2.5811	1.6204	-.0999	14.9653	.0306
.6000	12.50	2.4221	1.5618	-.0980	14.6871	.0332
.8000	12.50	2.2375	1.5323	-.0850	14.7486	.0291
1.000	12.50	2.1170	1.4439	-.0740	15.0945	.0262
1.500	12.50	1.9400	1.3729	-.0525	14.6171	.0199
2.000	9.772	1.8428	1.2470	-.0351	14.7017	.0132
3.000	10.35	1.7068	1.1588	-.0094	11.3434	-.0006
4.000	10.66	1.6147	1.0504	.0087	13.1413	-.0115
5.000	10.57	1.5438	.9833	.0189	12.7464	-.0147
6.000	10.86	1.4801	.9455	.0242	15.9342	-.0271
8.000	10.62	1.3905	.9281	.0328	12.2855	-.0226
10.00	10.57	1.3280	.9022	.0366	13.9262	-.0284
15.00	10.73	1.2277	.8906	.0388	14.7223	-.0330

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C. Calculation of exposure build-up factors

The G-P fitting parameters were then used to generate exposure buildup factor data for these materials using the following geometric Progression fitting given by Harima et al. [16]:

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

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

Where

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

IV. RESULT AND DISCUSSION

The exposure buildup factor data has been generated by interpolation method using the G. P. fitting formula for the various gamma ray interaction parameters such as equivalent atomic numbers and buildup factors and have been studied as a function of incident photon energy.

Effect of Incident Photon Energy on Exposure buildup factor of chosen samples:-

The variation of generated exposure buildup factor with incident photon energy at fixed penetration depths for chosen samples is shown in figs. 1-3.

It is observed that exposure buildup factor values of chosen materials start increasing with increase in incident photon energy up to a maximum value at intermediate energies and then further start decreasing with increase in incident photon energy.

It is observed that generated exposure buildup factor values are low in the incident photon energy range 10KeV to 100 KeV. It is due to predominance of photo electric effect in this energy region, which results in fast removal of low energy photons there by not allowing these photons to buildup.

It is further observed that in the energy range 100 KeV to 500 KeV the generated values of exposure buildup factor values are high for a given penetration depth. It is 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. It is also observed that the generated exposure buildup factor value is very high at incident photon energy around 200 KeV, because of exclusive dominance of compton effect.

Furthermore it is observed that for incident photon energies greater than 1.0 MeV, the dominance of pair production phenomenon over compton effect increases, so values of generated exposure buildup factor decreases.

It is also observed that the generated exposure buildup factors increases with increase in penetration depth for chosen material. This is because of the reason that with increase in penetration depth the probability of multiple scattering increases which results in the increase of multiple scattered photons of low energy, hence in the increased value of generated exposure buildup factor.

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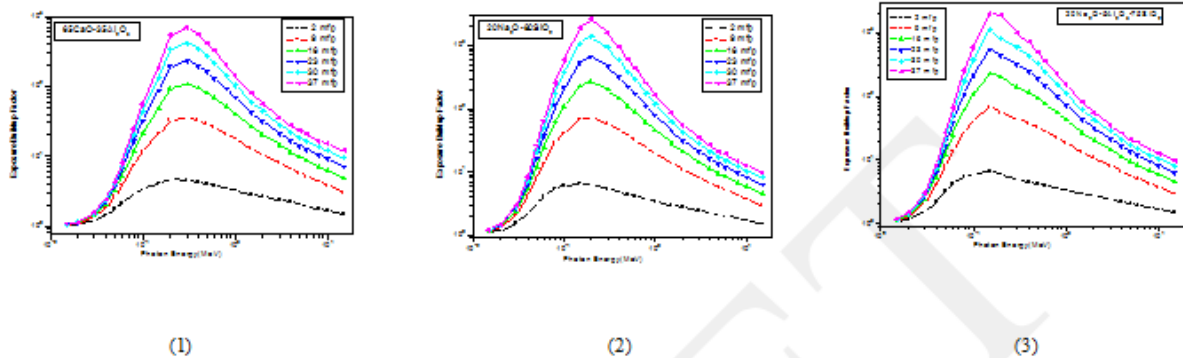


Fig. 1-3 Variation of the Exposure Buildup factor of oxide glasses with incident photon energy (MeV) for some selected penetration depth (in mfp)

Comparison of EBF of chosen oxide glasses with respect to Lead glass EBF calculated by PALLAS code

Fig. 4 to 6 shows the variation of ratio of EBF of oxide glasses to EBF of lead glass calculated by PALLAS code [17]. At incident photon energy 0.15 MeV, ratio is increasing with penetration depth, also the increasing rate of OG2 and OG3 is rapid and it becomes 1000 times at 40 mfp as compared to OG1 for which ratio increases only 100 times. But at 1.5 MeV all ratios show similar trends and slightly increase and at 40 mfp it becomes only 4 times for all glasses. At 15 MeV ratio which is less than 1, decreases with increase in penetration depth and at 40 mfp its value are approx. 0.011, 0.008 and 0.008 for the three glasses. So we conclude that at lower energies up to 1.5 MeV EBF of samples is greater than lead glass and at 15 MeV it is lower which further interprets that at higher energy all chosen samples shows good shielding effectiveness than lead but at lower energies lead glass show good shielding nature than all samples.

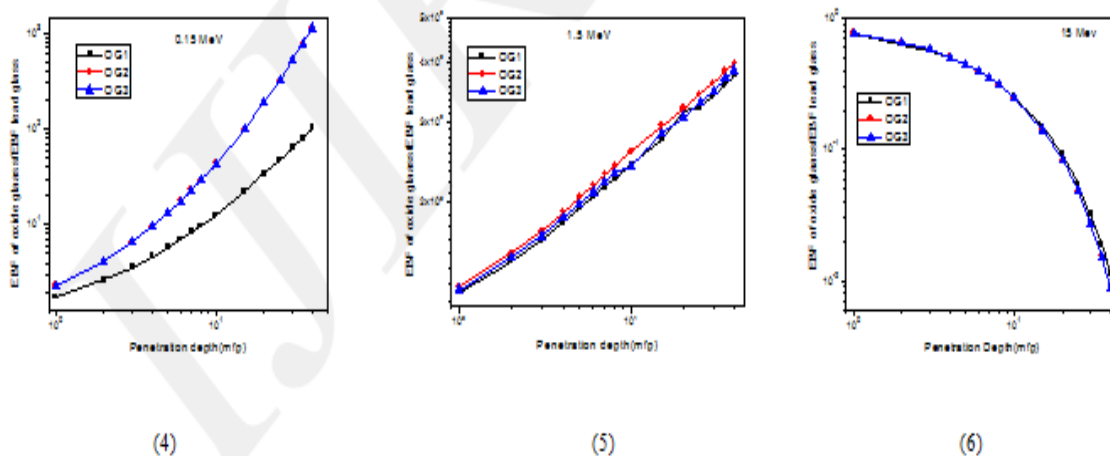


Fig. 4-6 Variation of ratio of EBF of oxide glasses calculated by interpolation method and EBF of lead glass calculated by PALLAS with penetration depth (in mfp) at some incident photon energies (in MeV)

Comparison of Mass attenuation of coefficient of chosen samples with mass att. coeff. of lead glass calculated by PALLAS Code

Fig 7 shows the variation of ratio of mass attenuation coeff. of all samples with respect to mass attenuation coefficient of lead glass calculated by PALLAS code [17]. For the lower energy region i.e. from 0.01 MeV to 0.1 MeV it shows the mixed behavior but after 0.1 MeV it increases up to 1.5 MeV and then decrease with increase in incident photon energy. From 0.8 to 4 MeV the ratio is more than one otherwise ratio is less than 1. So we conclude that all samples show better shielding effectiveness than lead glass in the energy range where ratio is greater than 1.

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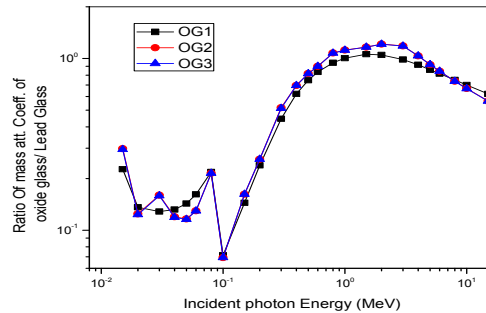


Fig. 7 Variation of ratio of mass attenuation coeff. of oxide glasses calculated by interpolation method and of lead glass calculated by PALLAS with incident photon energies(in MeV)

Comparison of Equivalent atomic number of chosen samples with equivalent atomic number of concrete[17]

Fig 8 shows the comparison of Z_{eq} of oxide glasses and equivalent atomic number of concrete which conclude that all samples whether oxide glasses or concrete show the almost same values of Z_{eq} with little variation. We know that concrete is low cost and easily available and by this comparison it can also be concluded that it has a good shielding effect as that of oxide glasses.

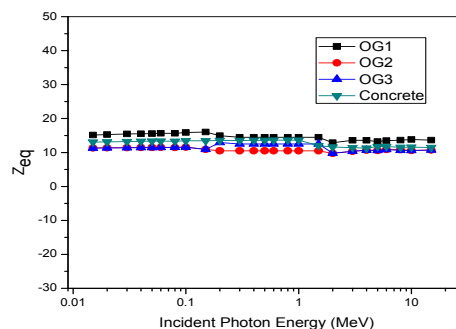


Fig. 8 Variation of Equivalent atomic number of oxide glasses and concrete with incident photon energies(in MeV)

V. CONCLUSION

- ❖ In the present study, it is concluded that the radiation energy exposure parameters are useful for deciding of the shielding effectiveness of oxide glasses used for specific constructions. During interaction of gamma ray photon with matter, the values of these parameters are dependent on the physical and chemical environments of the material.
- ❖ The G-P fitting formula has been successfully applied for the computation of the exposure buildup factor of three oxide glasses. The generated EBF has been studied as a function of penetration depth, photon energy.
- ❖ Significant increase in EBF has been observed for three oxide glass systems in energy region of 0.2 MeV approximately, where Compton scattering predominates. The variation of EBF with incident photon energy seem to be independent of chemical composition of above materials beyond 2.0 MeV.
- ❖ By comparing the variation of ratio of EBF of oxide glasses to EBF of lead glass calculated by PALLAS code, it is concluded that at higher energy all chosen samples shows good shielding effectiveness than lead glass but at lower energies lead glass show good shielding nature than all samples.
- ❖ By comparing the variation of ratio of mass attenuation coeff. of all samples with respect to mass attenuation coefficient of lead glass calculated by PALLAS code, we conclude that From 0.8 to 4 MeV all samples show better shielding effectiveness than lead glass.
- ❖ All samples whether oxide glasses or concrete show the almost same values of Z_{eq} with little variation.

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