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Feasibility of Pb-Zn Binary Alloys as Gamma Rays Shielding Materials

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***Abstract*—An attempt has been made to visualize the feasibility of using different compositions of PbxZn100-x(where x=20%, 40%, 60%, 80%) binary alloys as gamma rays shielding material. Gamma rays shielding effectiveness of the binary alloys has been analysed in terms of parameters viz. effective atomic number (Z_{eff}), mean free path (mfp), half value layer (HVL) and Tenth value layer (TVL). WinXCom: mass attenuation coefficient database (2001) has been used to evaluate molecular, atomic and electronic cross-section values in the wide energy range 1 keV to 100 GeV. The effective atomic numbers for the binary alloys have been computed using atomic to electronic cross-section ratio method. The experimentally measured density values for the prepared binary alloy samples have been used in evaluating linear attenuation coefficient, which is further used to calculate mean free path, half value layer and tenth value layer. Further, the variation of effective atomic number, mean free path, HVL and TVL with incident photon energy for the selected binary alloys has been investigated.**

***Index Terms*—Binary alloys, effective atomic number, half value layer, tenth value layer, mean free path.**

I. Introduction

THE future demand is to produce more and more energy from conventional and non-conventional sources. To fulfill this desire of energy in different countries, the use of nuclear energy is in concern. For this purpose, nuclear reactors and plants are supposed to be installed at various sites. The radioactive substances are used to produce called nuclear energy from these reactors. Moreover, the radioactive substances are highly active substances and continuously emitting the radiations. These emitted radiations may be gamma rays or X-rays, which are known to be highly energetic and penetrating radiations. The origin of gamma radiations is de-excitation of daughter products of radioactive substances from its excited states and that for X-rays are of atomic phenomena.The longer exposure to these radiations is harmful to the all living tissues and may results into cancer, nausea, illness or death [1]. To survive from these kinds of effects it is necessary to shield nuclear power plants with appropriate thickness of materials of high density and high atomic number.

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After the nuclear incident at Fukushima Japan, it was essential for welfare of human kind to study the photon interaction parameters of various materials of different compositions. The traditional materials like lead, concrete etc. were used at nuclear sites as gamma ray shielding materials. But these materials had disadvantages: lead is toxic in nature and the moisture content in concrete material disappears because of heating caused by multiple scattering of photons with the target material [2]. Further, rigidity and production of secondary ionizing radiations in case of pure leadwere additional disadvantages of prime concern [3]. To compensate this discrepancy, pure substances have been replaced with composite materials, alloys, glasses, polymers and compounds.

Many researchers have done a lot of work in this area by exploring the gamma radiation shielding parameters for composites, glasses, polymers, compounds and alloys. The parameters such as the mass attenuation coefficient, effective atomic number, mean free path, electron density, half value layer and tenth value layer have been studied to check feasibility of different materials as gamma ray shielding materials.

The effective atomic number Z_{eff} is an energy dependent parameter. It is used to assign the number to mixture or compounds analogous to atomic number of elements. As in case of mixtures and compounds atomic number Z is not uniquely identified by a single number for each process of gamma ray interaction with target material because material is composed of different elements which are differently weighted. Murty et al. [4] studied the effective atomic number for W/Cu ($W_{65}Cu_{35}$ and $W_{60}Cu_{40}$) alloy using transmission geometry and reported no well energy dependence due to edge effects. Singh et al. [5] measured effective atomic numbers of glasses in the system xBi_2O_3 (1-x) B_2O_3 (x= 0.30, 0.25, 0.40, 0.45 and 0.55) at 356, 662, 1173 and 1332 keV energies using a narrow beam transmission method. Singh et al. [6] calculated effective atomic number for composite materials using Rayleigh to Compton ratio. Sharma et al. [7] derived the effective atomic number by back scattering technique in Pb-Sn, Pb-Zn and Sn-Zn alloys of different compositions at 662 keV energy.

The mean free path is the parameter which helps to calculate the average distance travelled by gamma photons between two successive interactions with atoms of the target material. This parameter depends upon density of target material. Recently Kaur P. et al. [8] and Kaur S. et al. [9] determined mean free path values for heavy metal oxide glasses and Pb-Sn alloys respectively.

Half value layer (HVL) is the measure of reduction of intensity of radiation to half of its original value; whereastenth value layer (TVL) is measure of reduction of radiation intensity to tenth value of its original intensity. Akrut et al. [10] determined these two parameters for measuring radiation attenuation ofboron doped clay for 662, 1173 and 1332 keV gamma rays.

In the present work, an attempt has been made to visualize the shielding effectiveness of some Pb-Zn binary alloys on the basis of gamma rays shielding parameters viz. effective atomic number, mean free path, half value layer and tenth value layer.

II. Materials And Methods

The combination of Zinc (Zn) and Lead (Pb) elements in different compositions has been taken in the study of alloy. The atomic numbers of choosing elements are 30 and 82 respectively. Further, the alloy weighted ratio is PbxZn100-x (where x= 20%, 40%, 60%, 80%). The alloys were prepared using melt quench technique. This process involves the different proportions of Zn and Pb alloy taken in alumina crucible and followed by melting of both metal compositions in a muffle furnace at 450ºC. Then pouring of molten material poured into iron mould (2×2×2 cm^3 dimensions) at room temperature. Archimedes's principle was used to measure the density of alloys in which benzene was used as immersion medium. The formula used in the calculation of density

$$\rho = \frac{W_A}{W_A - W_B} \times 0.876 g/cm^3 \quad (1)$$

Where, W_A is the weight of sample in air, W_B weight of sample in benzene and benzene density is 0.876 g/cm^3.

The measured density values for the selected alloy composition are shown in Table I.

TABLE I
PROPERTIES OF PREPARED ALLOYS

Alloy Sample	Pb Conc. %	Zn Conc. %	Density (g/cc)	Z_{eff} (Experimental)
Pb20Zn80	20	80	4.19	58.7
Pb40Zn60	40	60	5.33	63.0
Pb60Zn40	60	40	7.74	70.8
Pb80Zn20	80	20	9.62	76.6

It has been observed that the density increses with the increase in percentage of Pb concentration in the alloy samples.

III. Computational Work

The mass attenuation coefficient values obtained from WinXCom database [11] which is window version of XCom database [12] for $_{82}Pb$, $_{30}Zn$ and selected alloy compositions in the energy range of 1keV – 100GeV. From this theoretical values of mass attenuation coefficient; molecular cross-section, atomic cross-section and electronic cross-section were computed using the expressions given below [13]:

Molecular Cross-section

$$\sigma_m = \frac{(\mu)_m \sum_i n_i A_i}{N} \quad (2)$$

Atomic Cross-section

$$\sigma_a = \frac{\sigma_m}{\sum_i n_i} \quad (3)$$

Electronic Cross-section

$$\sigma_e = \frac{1}{N} \sum_i \frac{f_i A_i \mu_i}{Z_i} \quad (4)$$

The effective atomic number Z_{eff}can be computed using the ratio of atomic to electronic cross-sections.

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \quad (5)$$

Mean free path is inversely proportional to linear attenuation coefficient which is product of density (listed in Table 1) and mass attenuation coefficient (μ_m). The expression for mean free path is [8]:

$$\lambda = \frac{1}{\rho \times \mu_m} \quad (6)$$

Half-value layer (HVL) for prepared alloys willbe obtained by using the following equation [10].

$$HVL = \frac{0.693}{\mu} \quad (7)$$

Tenth-value layer (TVL) can be obtained using following expression [10].

$$TVL = \frac{2.303}{\mu} \quad (8)$$

IV. ResultsAnd Discussion

Fig.1 depicts the variation of effective atomic number with incident photon energy. It has been seen that effective atomic number value for the selected alloy compositions lies between 30 and 82 i.e. between its constituent elements ($_{30}Zn$ and $_{82}Pb$). In the lower energy region (10 keV to 100 keV), the dominant process is photoelectric absorption process. The cross-section of this process is proportional to atomic number as Z^{4-5} and inversely proportional to photon energy as $E^{3.5}$. The absorption edges of Zn and Pb play an important role in this energy region and helps in understanding the drastic change in effective atomic numbers of the prepared binary alloys. In case of Zinc, K and L absorption edges appears at 9.659 keV and 1.020 keV - 1.194 keV respectively. Similarly absorption edges of Lead appears at 88.0 keV (K - edge), 13.04 keV – 15.86 keV (L - edge) and 2.484 keV – 3.851 keV (M - edge) respectively. In the intermediate energy region where the Compton scattering effect dominates, the effective atomic number decreases with further increase in energy because cross-sectionvaries linearly with atomic number Z and decresases with energy. This energy region lies between 200 keV – 1MeV and shows constant behaviour of effective atomic number with energy. Above 1.022 MeV energy, the pair production process dominates and almost shows constant variation of effective atomic number with the incident photon energy because in this region cross-section is proportional to Z^2 and log E. Among the selected alloys, Pb20Zn80 shows the minimum and Pb80Zn20 shows the maximum effective atomic number value.

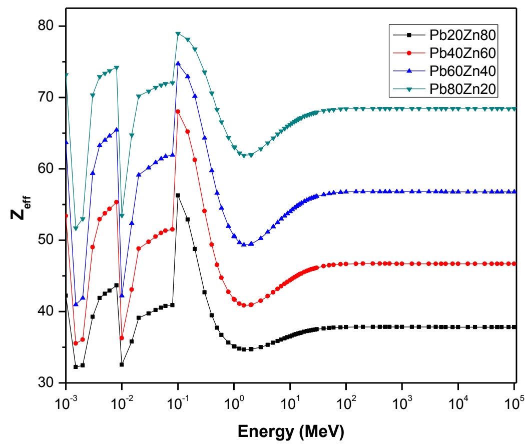

Fig. 1 Variation of effective atomic number with incident photon energy for Pb-Zn alloy compositions.

It has been found from Fig. 2 that in the lower energy region values of mean free path are very small and increases slowly with increase in energy for the intermediate energy region. Above 5 MeV, there is exponential decrease in mean free path values with increase in photon energy. This behavior can also be explained on the basis of interaction processes of gamma photons with matter. In this maximum and minimum value of mfp has been found for Pb20Zn80 and Pb80Zn20 compositions respectively. At a particular energy lower is the mfp value, better will be shielding material.

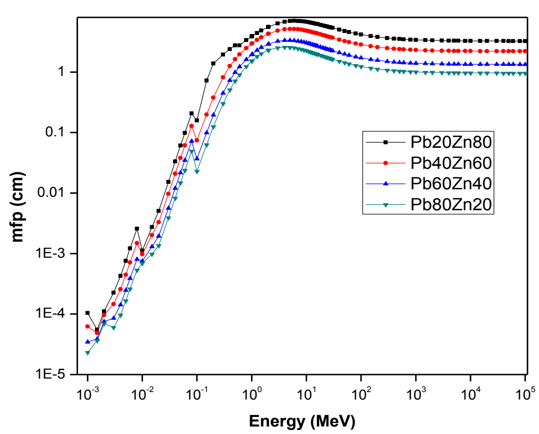

Fig. 2 Variation of mean free path with incident photon energy for Pb-Zn alloy compositions

Figs. 3-4 represents the variation of half value and tenth value layer as a function of energy. It shows that thickness (cm) required to reduce gamma photons intensity to half and one-tenth of its value is small (in fraction) at lower energy regions; where as significant thickness is required to reduce the intensities at higher energy regions greater than 1MeV.

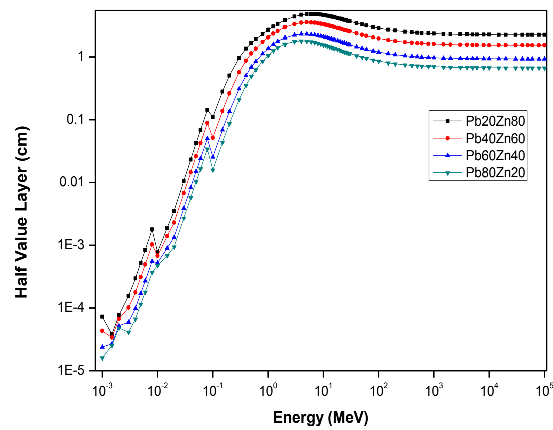

Fig. 3 Variation of Half value layer with incident photon energy for Pb-Zn alloy compositions

The thickness of 10cm of any of prepared alloy is sufficient to reduced the intensity of the incident photon beam by one tenth in the higher energy region from 1 MeV to 100 GeV. Whereas for the same thickness (10 cm) of alloy sample, the intensity reduction factor is even more at lower energies; nearly 1/100 at 1 MeV, □ 1/1000 times at 100 keV and 10^{-5} times at 1 keV.

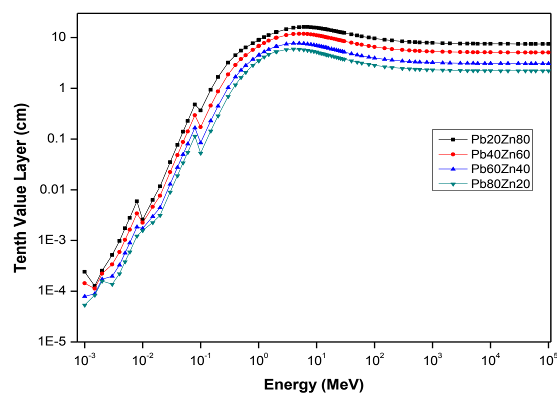

Fig. 4 Variation of Tenth value layer with incident photon energy for Pb-Zn alloy compositions.

V. Conclusion

Following conclusions have been made after analyzing the variation of effective atomic number, mean free path, half value layer and tenth value layer of the selected alloys with respect to energy:

- The effective atomic number values found to be maximum in the entire energy range for Pb80Zn20 alloy. This means that an alloy with high percentage of high atomic number as one of the constituent element offers higher value for effective atomic number.
- Mean free path, HVL and TVL is inversely proportional to effective atomic number values.

Among the selected alloy samples Pb80Zn20 shows maximum value of Z_{eff} and lowest values of mfp, HVL and TVL. Hence, shows better gamma rays shielding properties.

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