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Calculation of gamma-ray attenuation parameters for locally developed shielding material: Polyboron

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ABSTRACT

In the present study, the mass attenuation coefficient (μ_m) has been calculated analytically for a locally developed shielding material, polyboron, and compared with the values obtained from the WinXCom code, a Windows version of the XCOM database at the photon energy range 0.001 MeV–20 MeV. A good agreement has been observed between these two values. The linear attenuation coefficients (μ) and relaxation lengths (λ) have also been calculated from the obtained μ_m values and their variations with photon energy have been plotted. For comparison, other four shielding materials- ordinary concrete, pure polyethylene, borated polyethylene and water have also been studied. The obtained result shows that μ_m, μ and λ strongly depends on the photon energy, chemical composition and density of the shielding materials. The values of μ_m and μ of polyboron have been found greater than those of pure polyethylene and borated polyethylene but less than those of ordinary concrete and water at low photon energy range; and at the intermediate photon energy range (0.125 MeV–6 MeV), all the sample materials have approximately the same μ_m values. It has also been noticed that polyboron has the medial relaxation length (λ) over the entire photon energy range. The total mass attenuation coefficient (μ_m) and linear attenuation coefficient (μ), Half Value Layer (HVL) and Tenth Value Layer (TVL) of the five sample materials for some common gamma sources have been worked out and the transmission curves have been plotted. The curves exhibit that the transmission factor of the sample materials decreases with the increase in shielding thickness. The results of this study can be utilized to comprehend the shielding effectiveness of this locally developed material.

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1. Introduction

Due to the development of nuclear technology with time, various beneficial applications of different types of radiations in medicine, industry, agriculture and research as well as for nuclear power generation are increasing day by day. But a drawback to these peaceful uses of radiation is that if it is exposed to the personnel including other human beings, who

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are in vicinity of it beyond its permissible dose limit, a deleterious effect may be observed in them. When radiation is exposed to organs or tissues, it loses some its energy through different kinds of interactions and this loss of energy may ionize the atoms of the cell, destroying the normal chemical equilibrium of the cell and eventually can bring death to the cell. Therefore, the radiation must be attenuated enough to protect the personnel from the harmful effects caused by it and also enable them to work by using an apposite shielding material. The shielding used for this purpose is generally known as biological shielding.

To design and choose an appropriate biological shielding, it is necessary to have known its nuclear, structural and physical properties and also the characteristics of radiation impinging on it. The nuclear parameters that must be known to design and choose a shielding material are total mass attenuation coefficient (μ_m), linear attenuation coefficient (μ) for gamma rays which is related to Half Value Layer (HVL), Tenth Value Layer (TVL) and mean free path (λ). Many research workers have determined the values of different shielding parameters in various ways (Akkurt, Akyıldırım, Mavi, Kilincarslan, & Basyigit, 2010; El-Khayatt, 2010; El-Khayatt & Akkurt, 2013; Elmahroug, Tellili, & Souga, 2013; Kucuk, Cakir, & Isitman, 2012; Madhusudhan Rao, Narender, Gopal Kishan Rao, Krishna, & Murthy, 2013; Md. Fakarudin, IqbalSaripan, Nor Pa'iza, & Ismail, 2011; Singh & Badiger, 2014; Yılmaz et al., 2011) to know the shielding effectiveness of the shielding materials developed with time.

It is widely known that hydrogenous materials are used as neutron shielding for their effectiveness of neutron moderation. When boron is added to these hydrogenous materials, it promotes the absorption of neutron and reduces secondary gamma radiation. On the basis of this, a neutron shielding material, termed “polyboron” was locally developed. The compositions of this material are polyethylene, boron ester and paraffin wax at a ratio of 16.5 : 37.5 : 46 by weight percentage. The density of this material is 0.971 g/cm^3 which is somewhat less than water density (1.0 g/cm^3). Some of the shielding properties of this locally developed material have been studied experimentally (Ahmed, Bhuiyan, Mollah, & Rahman, 1992; Huda, Bhuiyan, Ahmed, Mollah, & Mondal, 1998). But almost no reports have been carried out on the μ_m, μ, λ, HVL, TVL for different photon energies. The main objectives of the present study are to determine the values of above parameters and to represent a comparison of shielding effectiveness of the sample materials used in the present work at different photon energy.

2. Theoretical background

2.1. Calculation of total mass attenuation coefficient and linear attenuation coefficient

When a gamma-ray beam traverses an absorber, the intensity of the beam will be attenuated according to the Beer–Lambert's law (Elmahroug et al., 2013):

$$I = I_o e^{-\mu t} = I_o e^{-(\mu/\rho) t_d} = I_o\, e^{-\mu_m t_d} \quad (1)$$

where I_0 and I are the unattenuated and attenuated gamma ray beam intensities, μ (cm^{-1}) is the linear attenuation coefficient, t (cm) is the linear thickness, $\mu_m = \mu/\rho$ (cm^2/g) is the mass attenuation coefficient and t_d (g/cm^2) is the density thickness of the absorber sample. If the absorber density is ρ (g/cm^3), then the relationship between t and t_d is given by,

$$t_d = \rho \times t \quad (2)$$

and the relationship between μ and μ_m is given by the following equation (Herman et al., 2009):

$$\mu = \mu_m \times \rho \quad (3)$$

The total mass attenuation coefficient, $(\mu/\rho)_{\text{compound or mixture}}$ for any chemical compound or mixture of elements is given by mixture rule (Elmahroug et al., 2013):

$$(\mu/\rho)_{\text{compound}} = \Sigma_i (\mu/\rho)_i w_i \quad (4)$$

where w_i and $(\mu/\rho)_i$ are the weight fraction and mass attenuation coefficient of the ith constituent element, respectively. For a chemical compound, the fraction by weight (w_i) is given by,

$$w_i = \frac{n_i A_i}{\sum_j n_j A_j} \quad (5)$$

where A_i is the atomic weight of the ith element and n_i is the number of formula units and $\Sigma_i\, w_i = 1$.

The total linear attenuation coefficient, $\mu_{\text{compound or mixture}}$ of the compound or mixture can then be simply found by multiplying the total mass attenuation coefficient, $(\mu/\rho)_{\text{compound}}$ with its density, ρ. Thus,

$$\mu_{\text{compound}} = \left(\frac{\mu}{\rho}\right)_{\text{compound}} \times \rho \quad (6)$$

2.2. Calculation of HVL, TVL and relaxation length (λ)

Half Value Layer (HVL) is the thickness of a shield or an absorber that reduces the radiation level by a factor of 2 that is to half the initial level and is calculated by the following equation:

$$\text{HVL} = \frac{\ln 2}{\mu} = \frac{0.693}{\mu} \quad (7)$$

where μ (cm^{-1}) is the linear attenuation coefficient of the absorber.

Similarly, Tenth Value Layer (TVL) is defined as the thickness of a shield required for attenuating a radiation beam to 10% of its radiation level and is computed by,

$$\text{TVL} = \frac{\ln 10}{\mu} = \frac{2.3026}{\mu} \quad (8)$$

2.3. Calculation of relaxation length (λ)

The average distance between two successive interactions is called the relaxation length (λ). It is also called the photon mean free path which is determined by the equation:

$$\lambda = \frac{\int_0^\infty x\exp(-\mu x)dx}{\int_0^\infty \exp(-\mu x)dx} = \frac{1}{\mu} \quad (9)$$

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