Robust Determination of Mass Attenuation Coefficient, Effective Atomic and Electron Number of Polyester Composites

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Abstract:

Polyester / Magnetite CUP/Mag ($\rho=2.75 \text{ g}\cdot\text{cm}^{-3}$) and Polyester / Ilmenite CUP/Ilm ($\rho=2.7 \text{ g}\cdot\text{cm}^{-3}$) composites used as radiation attenuation shields for a variety of applications are investigated in terms of gamma rays attenuation parameters. Linear attenuation coefficient μ (cm^{-1}) was experimentally determined by utilizing the narrow beam transmission geometrical experimental setup. Three gamma quanta (0.662, 1.173 and 1.332 MeV) obtained by Cs-137 and Co-60 radioactive sources and NaI(Tl) scintillation detector were considered for the source and detection term respectively. Experimentally evaluated mass attenuation coefficient (μ/ρ) could be obtained by dividing the experimental linear attenuation coefficient $\mu \text{ cm}^{-1}$ by composites densities ρ ($\text{g}\cdot\text{cm}^{-3}$). In addition the same parameter was obtained by two theoretical techniques, the WinXCom program and MCNP5 computer code. The effective atomic numbers Z_{eff} and electronic density N_{el} were evaluated for the concerned composites using both experimental and theoretical obtained data. The investigation was made to figure out a broader pattern of radiation parameters for the two polyester composites.

Keyword: - Polyester Composites, Gamma rays attenuation parameters, Effective atomic numbers (Z_{eff}), Electronic density (N_{el}).

1. Introduction

Due to the increasing use of radiation sources in various medical and technological uses the study of gamma interaction parameters such as linear attenuation coefficient, mass attenuation coefficient, effective atomic number and effective electron density in materials is of significant importance. Recently, there was a continuous demand for improved polymers for use as shielding materials. Therefore, composite materials were used for this purpose. Composites are materials brought about by combining elements differing in composition or form a macroscale for the purpose of obtaining specific characteristics and properties. Composites consist from two components: matrix and reinforcement [1]. Reinforcement materials played the important role to improve the matrix properties. Since polymeric materials are on their own hydrocarbonic substances we would expect good neutron moderation then, with the good choice of metallic fillers, gamma rays and X-rays could be also shielded [2].

Polyester based composites are heat sensitive and mainly initiate degradation due to thermal changes. It is classified in the group of general purpose thermoset which are characterized by

having average mechanical properties, low resistance to temperature, high coefficients of expansion and low cost. The overall cost can be reduced by blending the polymer with low cost filler materials [3, 4].

Polymeric materials are mainly hydrocarbonic substances, and in our study the polyester contains large proportion of carbon and hydrogen which guarantees good neutron attenuation [5, 6].

With the addition of heavy minerals such as magnetite and ilmenite, gamma rays would be attenuated as well, since magnetite contains (Fe_2O_3 67.34 % and FeO 5.22 %) and ilmenite contains (Fe_2O_3 50.56% and TiO_2 36.06%) [7].

In the present work, experimental study of gamma-ray interaction with CUP/Mag and CUP/Ilm for photons of energies (0.662, 1.173 and 1.332 MeV) was carried out to measure the linear attenuation coefficient μ (cm^{-1}). The results were divided by the composites densities to obtain μ/ρ values. Moreover, WinXCom program and MCNP5 code were used to compute the same parameters theoretically [8, 9].

As well, the parameters, effective atomic number Z_{eff} and effective electronic density N_{el} and their variation upon incident photons energy change are of prime importance for materials characterization [10].

The values of Z_{eff} and N_{el} were experimentally evaluated and theoretically calculated for the three concerned gamma energies [11].

2. Evaluation formulas and theoretical basis

2.1 Mass attenuation coefficient (μ/ρ)

When monoenergetic beams of gamma-ray traverse a composite, Beer-Lamberts law applies and the transmitted intensity after thickness t (cm) is given by the following relation:

$$I = I_0 e^{-\mu t} \quad (1)$$

Where I_0 is the transmitted intensity with no samples and μ (cm^{-1}) is the linear attenuation coefficient of composite. If composite density is ρ ($\text{g}\cdot\text{cm}^{-3}$), then the mass attenuation coefficient is μ/ρ ($\text{cm}^2\cdot\text{g}^{-1}$). This term is more accurate for characterizing the composites since it is independent on physical state of material [12, 13].

In addition, these parameters were theoretically computed by two means; first by using the state of art WinXCom program [8] and second, by MCNP5 computer code [9]. A MCNP5 model was designed for the geometrical block diagram presenting the experimental setup found in [14]. The source term SDEF card was introduced once for Co-60 then for Cs-137 radioactive sources.

As well, variance reduction method DXTRAN sphere was used for the detection zone to improve the results accuracy.

From the code results, μ (cm^{-1}) could be calculated and mass attenuation coefficient was obtained by dividing such results by density.

2.2 Determination of Z_{eff} and N_{el}

In this study, the effective atomic number Z_{eff} and effective electronic number N_{el} were theoretically computed and experimentally evaluated. In the first theoretical technique, Z_{eff} and N_{el} were calculated using WinXCom program, based on mixture and compound rule [11, 15, 16]. We find that;

$$\left(\frac{\mu}{\rho}\right) = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (2)$$

Where (μ/ρ) is the total mass attenuation coefficient for composite, $(\mu/\rho)_i$ present each constituent parameter and w_i is each element weight share in composite.

The weight share w_i is given by:

$$w_i = \frac{n_i A_i}{\sum_j n_j A_j} \quad (3)$$

Where A_i is the atomic weight of the i_{th} constituent and n_i is the number of formula units.

As well, total molecular cross-section (σ_m) could be obtained from the following relation;

$$\sigma_m = (\mu/\rho) \frac{M}{N_a} \quad (4)$$

Where $M = \sum_i A_i n_i$ is the molecular weight of composite and N_a is Avogadro's number. The average cross-section σ_{ta} can be obtained by the following relation

$$\sigma_{ta} = \sigma_m \frac{1}{\sum_i n_i} \quad (5)$$

As well, the average electronic cross-section σ_e could be obtained as follows:

$$\sigma_e = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} (\mu/\rho)_i \quad (6)$$

Where f_i is the fractional abundance of each constituent and Z_i is their atomic number.

From definition Z_{eff} could be given by:

$$Z_{eff} = \sigma_a / \sigma_t \quad (7)$$

And, the effective electronic density could be derived as follows [6, 11].

$$N_{eff} = \frac{(\mu/\rho)}{\sigma_e} \quad (8)$$

Simultaneously, Z_{eff} and N_{el} were experimentally evaluated. To obtain these parameters, the experimentally evaluated mass attenuation coefficient from the present study as well as, such values for individual elements obtained from previous work will be utilized [17].

3. Experimental measurement of gamma-ray attenuation.

Narrow beam transmission geometry was set as the block diagram of experiment found in previous work [10].

The source term consisted of two radioactive sources, the Cs-137 and Co-60 with activity about 3.7 GBq and 0.4 GBq respectively.

The detection term was the 5x5 NaI(Tl) of 8% energy resolution at 662 KeV along with its associated electronic system.

The gamma ray spectra were accumulated using Mystro and counts under full energy peaks were obtained for different sample thicknesses.

In addition maximum counting time of fixed preset was maintained so that statistical uncertainty was kept below 0.3%. Results for different sample thicknesses were obtained and count from incident I_0 and transmitted I intensities were utilized to evaluate the mass attenuation coefficient (μ/ρ) by an experimental method.

4. Results and Discussion

Samples of different thicknesses ranging from 4 to 22 cm were aligned on the samples shoulder. Incident I_0 and transmitted beam intensity I for each sample were measured. The obtained values were used to draw attenuation relations and, by applying equation 1, we can evaluate the linear attenuation coefficient μ (cm^{-1}) for each composite. As well, the same results will be used to

evaluate; mean free path λ (cm), Half Value Layer (HVL) and Tenth Value Layer (TVL). All results are presented in table 1.

Table 1. Attenuation parameters for CUP/ Mag and CUP/Ilm composites.

	Energy (MeV)	μ (cm ⁻¹)	λ (cm)	H.V.L. (cm)	T.V.L. (cm)
CUP/Mag	0.662	0.18850	5.305040	3.677173	12.21531
	1.173	0.15454	6.470817	4.485228	14.89961
	1.332	0.14351	6.968156	4.829957	16.04477
CUP/Ilm	0.662	0.19056	5.247691	3.637422	12.08326
	1.173	0.14981	6.675122	4.626842	15.37004
	1.332	0.14105	7.089685	4.914195	16.32460

From the table we can realize a decrease in attenuation capability as gamma ray energy increases.

To evaluate the mass attenuation coefficient from the experimental data, the linear attenuation coefficients were divided by the composites respective densities. As well, the two theoretical tools, WinXCom and MCNP5 were used to compute the same parameter theoretically. The evaluated and computed results are presented in table 2, and reasonable agreement between the three data columns could be realized which validates the MCNP5 modeling process.

Figure 1 present the mass attenuation coefficient for the investigated samples using WinXCom over the energy range (10^{-3} to 10^5) MeV.

a)

b)

Figure 1 (a, b) Mass attenuation coefficient for the investigated samples using WinXCom over the energy range (10^{-3} to 10^5) MeV.

As shown in fig. 1 (a,b), for total interaction it can be easily seen that there are three energy ranges according to dominance of different partial interaction processes. First comes rapid decrease in μ/ρ according to prevalence of photoelectric effect, then comes slight decrease according to Compton scattering reaction, and last is slight increase for the pair production.

Table 2. Experimentally evaluated and theoretically calculated mass attenuation coefficient.

	Energy (MeV)	Experimentally evaluated μ/ρ (cm^2/g)	WinXCom μ/ρ (cm^2/g)	MCNP5 μ/ρ (cm^2/g)
CUP/Mag	0.662	0.0686	0.0763	0.0788
	1.173	0.0562	0.0578	0.0636
	1.332	0.0522	0.0542	0.0521
CUP/Ilm	0.662	0.0706	0.0756	0.0799
	1.173	0.0559	0.0573	0.0637
	1.332	0.0522	0.0537	0.0522

Both parameters, effective atomic number Z_{eff} and electronic density N_{el} were experimentally evaluated and theoretically calculated and are presented in table 3. It is realized that good agreement between both evaluation techniques exists.

Table 3 Z_{eff} and N_{el} for the investigated composites.

	Energy (MeV)	Z_{eff}		N_{el}	
		Exp.	Theo.	Exp.	Theo.
CUP/Mag	0.662	7.530030	8.360829	2.63E+23	2.92E+23
	1.173	8.115388	8.393078	2.83E+23	2.93E+23
	1.332	8.048536	8.391112	2.81E+23	2.93E+23
CUP/Ilm	0.662	8.064306	8.575197	2.72E+23	2.9E+23
	1.173	8.332118	8.605249	2.81E+23	2.91E+23
	1.332	8.387999	8.603146	2.83E+23	2.91E+23

Figures 4 present the Z_{eff} and N_{el} over the gamma ray energy range 10^{-3} to 10^5 MeV for the concerned composites.

Figure 4. Composites variation of Z_{eff} and N_{el} with photon energy for a) total photon interaction-with coherent, b) photo electric absorption, c) coherent scattering, d) incoherent scattering, e) pair production in nuclear field and f) pair production in electric field.

The parameters Z_{eff} and N_{el} for total and individual interactions are discussed below:

a) Total (with coherent) photon interaction.

Both polyester composites are considered heavy weight materials and for the low energy range $E < 0.01$ MeV the parameters Z_{eff} and N_{el} are similar and give maximum value since there is a Z^4 dependence for the photoelectric absorption. Over the intermediate region ($0.05 \text{ MeV} < E < 5 \text{ MeV}$) where compton scattering prevails, the parameters decrease with energy. For high energies and around 100 MeV the parameters are constant, but smaller than over the low energy range since dominance of pair production, and the cross-section has a Z^2 dependence.

b) Photo-electric absorption

For such reaction, both parameters show variations below a threshold at 10 MeV; afterwards there is a sharp increase with energy and no significant variation comes later.

c, d) coherent and incoherent scattering.

Both parameters show a sharp increase with energy, first in the energy range (1 – 200 MeV) and second in the range (1 – 400 MeV) for each reaction respectively. Afterwards the reaction becomes energy independent for both composites.

e, f) pair production (nuclear and electric field)

For both composites and the two parameters Z_{eff} and N_{el} it is shown that the parameters decrease with increase in photon energy; for the ranges (1 to 200 MeV) and (1 to 2000 MeV) respectively. Afterwards they are almost independent of energy.

Conclusion

Both CUP/Mag and CUP/Ilm composites proved to be efficient in terms of the different attenuation parameters the linear attenuation coefficient (μ), mean free path λ (cm), Half Value Layer (HVL) and Tenth Value Layer (TVL).

The experimentally evaluated mass attenuation coefficient μ/ρ and both theoretically calculated parameters using the WinXCom program and MCNP5 code are within reasonable agreement. The experimental and theoretical parameters Z_{eff} and N_{el} show almost the same values and it is concluded that the two polymeric composites have the potential for radiation shielding.

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