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Comparative Study of Shielding Properties on High Density Polyethylene Using Experimental and ISOCS Techniques

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Abstract: The linear attenuation coefficients (μ_L), and half value layer (HVL) thickness for high density polyethylene (HDPE) polymer with thickness 1 and 2 mm have been experimentally investigated at different energies of gamma-rays. In addition, theoretical calculations of μ_L and HVL have been done using In Situ Object Calibration Software (ISOCS). Three different gamma-ray energies were used; 661.7 keV from ^{137}Cs, 1173 and 1332 keV from ^{60}Co for both the experimental and theoretical methods. The measurements were carried out using falcon 5000 which is a portable electrically-cooled high pure germanium (HPGe) detector and γ-spectrometer which provides radiation monitoring and nuclide identification and quantification. It is found that both experimentally and theoretically methods give nearly same results. Therefore, this task can be performed by any available method. In many situations, ISOCS calculations are preferred because of its cost in which includes money, effort, and time is lower than the experimental method. Also, it is found that ISOCS calculations are a very good method for the calculation of the linear attenuation coefficient and half value layer of the shielding materials at different photon energies.

Keywords: HDPE, ISCOS, Linear attenuation coefficient, Half value layer, γ-ray's energy.

1 Introduction

In general, the gamma-ray and neutron attenuation coefficients characterize the interaction of the radiation with the material [1,2,3,4,5,6]. As it is well-known that materials contain elements with a high atomic number (such as Ba, Pb, and Bi) are used to attenuate gamma- rays, while materials that contain elements with a low atomic number are preferred in attenuating neutron particles. However, the accurate values of the radiation attenuation parameters of materials containing elements with a low atomic number such as C, H, O, and N are very important in some applications. High density polyethylene (HDPE) is a polymer whose monomer is ethylene [4,5,6]. It is a thermoplastic with a very high strength to density ratio. It is a very versatile plastic that has a wide range of applications from pipes to storage bottles. When compared to other plastics, the melting point of HDPE is relatively high.

Shielding is using materials to lower the effects of incident radiation to an expectable level by reducing the intensity of radiation. Today the design and construction of radiation shielding used to protect people, equipment, and structures, from the harmful effects of radiation of the most important problems in nuclear engineering [7,8,9]. Radiation shields required some facilities to determine and calculate x-ray radiation, gamma-ray, and neutron. Gamma-ray facilities for the detection of defects in materials, radiation facilities, in food and plastics industries. The purpose of a radiation shield is to protect from external radiation and in this context does not include the prevention of internal biological radiation hazards due to eating, drinking or breathing radioactive material [1]. External radiation shielding is one of the main radiation protection principles for keeping the working condition safe [2]. Shielding design for neutron and gamma radiations is very important because any shield which attenuates these two rays will be effective for attenuating most of the other nuclear radiation [3, 4].

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The probability of interaction of gamma–rays per unit of length of a given absorber characterizes its linear attenuation coefficient µL. However, the linear attenuation coefficient depends on the material physical state and for this reason, it is usually substituted by $\mu_m = \mu L/\rho$ (where ρ is the density of the material) [5]. When a gamma radiation beam reach's some absorber material, the attenuation occurs in accordance with the material chemical composition and the photon energy resulting in a reduction of its intensity. The decrease of beam intensity results from the combination of photon absorption and deflection. Therefore, the mass attenuation coefficient depends on the absorber nature, as well as on the gamma-ray initial energy [6].

Investigation of the absorption of gamma- or neutron-radiations in protecting materials has been a critical topic in the domain of radiation material science. To plan the defensive protection around the atomic reactor, quickening agents and high radiation area, the information of the weakening of high vitality x-beams in protecting materials is basic. In general, different materials have been utilized for radiation protection in various applications. For instance, polyethylene, glasses, epoxy sap, colemanite, lead, and concentrate have been utilized for neutron and gamma shield while lead, Lipowitz composite, and Cu-Ag-polymer were utilized for electrons shield [7]. To depict the adequacy of γ-beam protecting, the half value layer HVL which is introduced the thickness of material required to diminish the power of the radiation to half [7, 8] as;

$$HVL = ln\,(2)\,/\,\mu L \;=\; 0.693\,/\,\mu L. \tag{1}$$

And, HVL is used to describe the effectiveness of gamma-ray shielding [9,10]. The In Situ Object Calibration Software (ISOCS) modeling allows performing absolute efficiency calibration for items of arbitrary container shape and wall material, matrix chemical composition, material full-height, uranium or plutonium weight fraction inside the matrix and even nuclear material/matrix with the nonhomogeneous distribution. Furthermore, in several cases, some key parameters such as matrix density and U/Pu weight fraction can be determined along with the analysis of nuclear material mass and isotopic composition. These capabilities provide a verification solution suitable for most cases where the quantitative and isotopic analysis should be performed [11,12,13,14]. Model-based methods have been used to calibrate nondestructive systems to characterize wastes contaminated with plutonium, uranium, and other radioactive isotopes. Model-based measurement methods, such as ISOCS, make use of knowledge of the measurement configuration to establish calibration parameters. Model-based measurement approach has been used for a variety of purposes at Oak Ridge National Laboratory (ORNL) including LLW/transuranic (TRU) sorting of a wide variety of radionuclides and waste streams in 55 gallons and over-pack drums [15].

The purpose of this research is to evaluate the performance and the high properties of HDPE material when used as a lining material in ground pools, with a view to storing solid and liquid radioactive waste extracted from petroleum fields.

2 Experimental Section

Polyethylene is a simple light, inexpensive and flexible polymer. The HDPE samples with two different thickness 1 and 2 mm were purchased from the Hema Plastic company manufactures membranes of the finest high-density polyethylene ores as their specifications comply with international specifications, and these membranes are used in various insulation and lining applications. Table (1) list the physical properties of HDPE. These membranes are manufactured with a thickness of between 750 microns and 3 mm in rolls up to 7 m wide. They are smooth in black in addition to carbon black to protect them from the impact of ultraviolet rays as well as areas of radiation protection. The samples were prepared with area 2x2 cm^2 for studying the radiation attenuation and shielding properties. The linear attenuation coefficient µL of samples under investigation has been determined by the usual attenuation equations;

$$I = I_o e^{-\mu_L x}, \tag{2}$$

where I is the gamma-ray intensity after the shield material, Io is the gamma-ray intensity before the shield material, (L) is the linear attenuation coefficient and x is the shield material thickness. Gamma-ray intensities behind samples with different thickness.

Table (1): The Physical Properties of HDPE.

Parameters	Value
Density	0.954 g/cm^3
Elastic Modulus (short term:1 min)	1.0 x 103 MPa
Ultimate tensile strength	26 MPa
Break elongation	750%
Brittle Temperature	≤ -70 ºC
Working Temperature	-80 ~ 100 ºC
Thermal conductivity	0.29 Kcal/m.hr ºC
Service life	> 50 years

Gamma spectrometer has been utilized for the test estimation. This spectrometer is a Falcon 5000 which is a portable electrically-cooled HPGe spectrometer that provides radiation monitoring and nuclide identification and quantification. The Falcon 5000 is supported by Canberra's industry-standard Genie 2000 spectroscopy software suite. The estimating lifetime is streamlined in two perspectives to accomplish great measurements. Specific gamma-ray energy, which is signature for ^{60}Co and ^{137}Cs, are used to study the attenuation coefficients of the samples. ^{60}Co was produced in 2007 with activity 1 μCi at Nuclear and Radiological Regulatory Authority (ENRRA). It is energy 1173.2 and 1332.5 keV and half lifetime 5.2714 y. While ^{137}Cs was produced in 2007 with activity 1 μCi at Nuclear and Radiological Regulatory Authority (ENRRA), Egypt. It is energy 661.7 keV, and half lifetime 30.719y.

The verified samples have a rectangular shape. Each sample was measured in such a way that its axis of symmetry is perpendicular to the extended axis of symmetry of the detector in front of the source. The distance between the source and the Al cap of the detector is 15 cm. Photon spectra were recorded in the following order firstly, the source spectrum recorded with the source but without sample, then the incident spectrum without attenuation Io was obtained. The transmitted spectrum recorded with source and sample, then after attenuation, I was obtained. For all gamma spectra, the photo-peak is Gaussian distribution. Each spectrum was recorded for a sufficient time of about 10 min to accumulate an adequate number of counts under the photo-peak to achieve good statistics (statistical errors are always kept below 1%.

Mathematical techniques as In Situ Object Calibration Software (ISOCS) and Lab SOCS which have undergone significant improvements and enhancements. In this method, the detector response was characterized by creating a set of fine spatial efficiency grids at 15 energies in the 0.045–7 MeV range. The spatial grids are created in (r,θ) space about the detector, with the radius r varies from 0 to 500 m, and the angle θ varying from 0 to 180o. The ISOCS technique was introduced into the Agency's Safeguards activities just a few years ago, and this methodology is being expanded to more and more NDA measurement techniques. Each sample was measured in such a way that its axis of symmetry is coincidence with the extended axis of symmetry of the detector. The distance between the sample and the Al cap of the detector is 25 cm. All measurements were carried out by adjusting the experimental setup in such a way that errors due to electronic losses were minimized (dead time did not exceed 2 %). Also, the measuring lifetime was optimized to achieve good statistics (statistical errors are always kept below 1%). Experimental setup configuration arranged to measure the absolute full-energy peak efficiency of the detector.

3 Results and Discussion

The relationship between the linear attenuation coefficient and the distance between the detector and 1 mm thickness of HDPE at photon energies 662.1, 1173, and 1332 keV is shown in Fig. 1. It is clear from the figure that, the linear attenuation coefficient (μ_L), is inversely proportional to the distance. Increasing the distance from the source leads to a decrease in the linear attenuation coefficient sharply up to 15 cm and then leveled off. The behavior is almost the same for different photon energy, however, the linear attenuation coefficient increases with increasing the energy of the photon. Figure 2 shows the correlation between the linear attenuation coefficient and the distance between the detector and 2 mm thickness of HDPE at photon energies 662.1, 1173, and 1332 keV. The linear attenuation coefficient decreases sharply with increasing the distance between the source and HDPE samples. Because the thickness of the HDPE is 2 mm which is double that in Fig. 1, (μ_L) is almost half of that for the 1 mm thickness sample. The theoretical calculation using ISOCS modeling is including in Figs. 1 & 2, it is clear from the figures, there is good agreement between the experimental (E) and theoretical (T) linear attenuation coefficient for both thicknesses of HDPE. For HDPE with thickness1mm, this result may due to the cross-linking density which increasing with γ-doses increased. While for HDPE with thickness 2 mm, and this may be due to very high densities of crosslinking and chain scission induced by irradiation. It has also been shown that the samples thickness has a significant effect on its oxidative degradation indicated that the rate of oxidation decreases with increasing polymer film thickness and that thick films displayed longer induction time than thin ones.

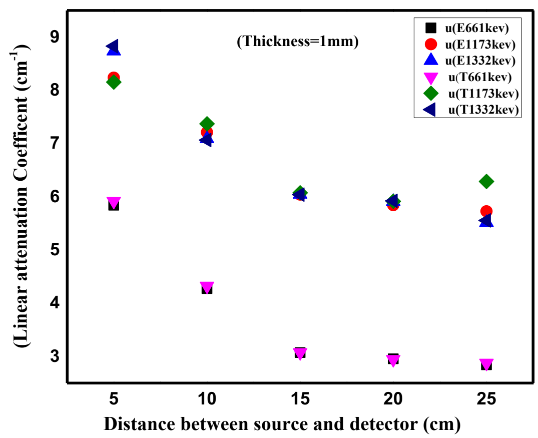

Figure 1: Variation of linear attenuation coefficient (μ_L) as a function of the distance between source and detector at different γ-ray energies for 1 mm thickness of HDPE; the symbol for experimental data (E) and theoretical ISOCS (T) calculations.

Figure 3 shows the relationship between half value layer (HVL) with the distance between the detector and the 1 mm thickness of the HDPE sample at photon energies 662.1, 1173, and 1332 keV. The theoretical calculation using ISOCS modeling is including in the figure. It is clear from the figure that, there is a very good agreement between the experimental data and theoretical ISOCS results. The HVL increases with increasing the distance between the source and detector up to 15 cm distance and then it is leveled off.

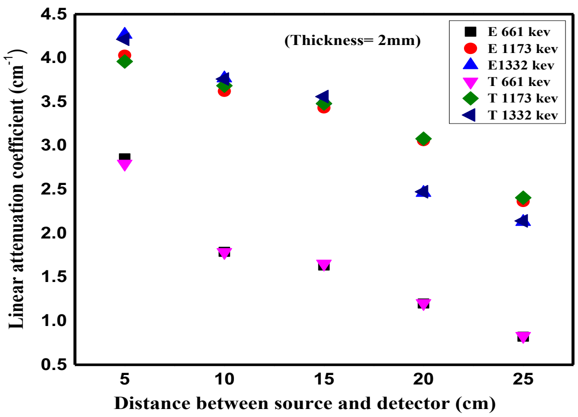

Figure 2: Variation of linear attenuation coefficient (μ_L) as a function of the distance between source and detector at different γ-ray energies for 2 mm thickness of HDPE; the symbol for experimental data (E) and theoretical ISOCS (T) calculations.

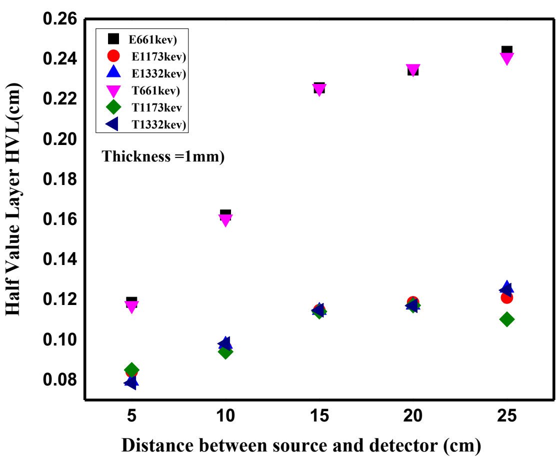

Figure (3): Variation of half value layer (HVL) is a function of the distance between source and detector at different r-ray energies for 1 mm thickness of HDPE; the symbol for experimental data (E) while lines for theoretical ISOCS (T) calculations.

In addition, the HVL increasing with increasing the γ-ray energy as HVL is higher at a photon energy of 662 keV than those at energies of 1173 and 1332 keV, i.e, the HVL is decreasing with increased the photon energies. For the 2 mm thickness of HDPE, the HVL increases quickly with increasing the distance between the detector and the sample at 662.1 keV photon energy as shown in Fig. 4. Included in the figure also, the theoretical calculation of *HVL* using the ISOCS program as shown in figure (4). For high photon energy (1173 and 1332 keV), the HVL increases slowly with increasing the distance indicating that photon energy has a very large effect on the HVL values. It is clear in Figs. 3 & 4 that there is an overlap between the HVL calculated using ISOCS and experimental methods showing a very good agreement between them.

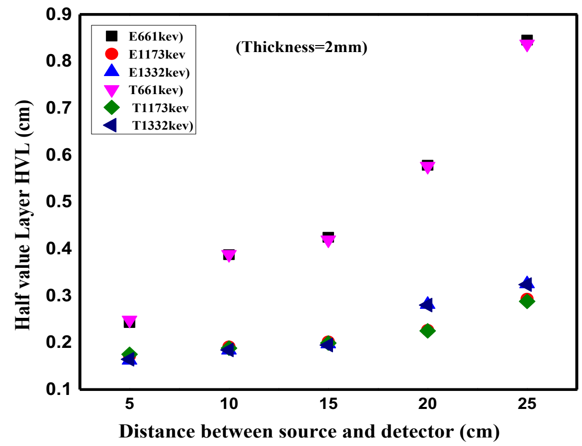

Figure 4: Variation of half value layer (HVL) is a function of the distance between source and detector at different r-ray energies for 2 mm thickness of HDPE, the symbol for experimental data (E) while lines for theoretical ISOCS (T) calculations.

4 Conclusions

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 HDPE may offer additional benefits in chemical resistance, physical durability, and portability. However, the HDPE composite material will not exceed the gamma attenuation characteristics of an equal mass of the components used in its construction. ISOCS calculations are a very good method for the calculation of the linear attenuation coefficient and half value layer of the shielding materials at different photon energies. Also, it was found that HDPE with thickness (1 mm) is more susceptible than HDPE with thickness (2 mm) according to the influence of radiation. Thus, the validity of the data and conclusions obtained are limited by the assumptions and material used. In order to produce more general data, it is desirable to make use of other complementary tests to better characterize the changes in the microstructure of the material due to the application of gamma radiation.

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