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Evaluation of Gamma-Ray Shielding Efficiency in Smart Polymer Materials: A Monte Carlo Approach with MCNPX Code

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ABSTRACT: Gamma-ray shielding materials play a critical role in nuclear and medical applications, where effective radiation attenuation is essential. In this study, the gamma-ray shielding performance of several polymer-based materials, including polyurethane (PUR), silicon carbide (SiC), polypropylene (PP), polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), and polyvinylidene fluoride–hexafluoropropylene (PVDF-HFP), was evaluated and compared with lead (Pb) using the MCNPX Monte Carlo code. The mass attenuation coefficient (MAC), half-value layer (HVL), and photon mean free path (MFP) were calculated for gamma-ray energies of 122, 356, 511, 662, 1170, 1275, and 1330 keV corresponding to common radioactive sources. The results indicate that lead exhibits the highest shielding efficiency across all energies. However, among the polymeric materials, the SiC polymer shows superior attenuation performance, followed by PTFE, particularly at low and intermediate energies. These materials demonstrate lower HVL values and shorter MFPs compared to other polymers. Overall, the findings suggest that SiC and PTFE-based polymers can be considered promising lightweight and practical alternatives to lead for gamma-ray shielding applications in low- to medium-energy ranges.

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1- Introduction

In recent decades, the significant increase in the application of radiation across various fields has led to heightened attention toward the investigation of parameters associated with gamma radiation. This issue is particularly important in areas such as nuclear physics, electronic industries, and medical sciences. In this context, polymers play a notable role in gamma-ray shielding due to their unique properties [1]. Owing to their diverse characteristics and wide range of physical and chemical properties, polymers are extensively utilized in numerous applications. Features such as flexibility, insulating capability, and elasticity are among the most prominent advantages of these materials. Carbon, hydrogen, and oxygen-based polymers are recognized as suitable candidates for radiation shielding applications because of their low atomic number, non-flammability, and stability at elevated temperatures. Moreover, their capability for large-scale production has led to their widespread use across various industries [2, 3]. Conventional materials used for gamma-ray attenuation include lead, steel, tin, bismuth, iron, stainless steel, and tungsten. Among these, lead has been widely employed due to its relatively low cost and effective shielding performance, making it a common choice in many industrial applications. However, as a heavy and highly toxic metal, lead presents serious challenges in terms of personal and environmental protection. Consequently, there is a growing demand for alternative shielding materials that are non-toxic, lightweight, and efficient. Polymers, due to their non-toxic nature, biocompatibility, and low density, are considered promising candidates for radiation shielding applications. In addition, polymeric materials are frequently used as tissue-equivalent materials and phantoms in various biological studies and have found extensive applications in radiation protection research [4, 5]. The mass attenuation coefficient is one of the most fundamental parameters in the analysis of gamma radiation. The interaction of ionizing radiation with matter involves several processes that depend on both the properties of the absorbing material and the radiation intensity. Gamma rays, owing to their high penetration capability, follow different absorption mechanisms compared to other types of radiation, making the investigation of their behavior in various materials particularly important [4]. Photons within the energy range of 1500 keV play a crucial role in medical applications, especially in the measurement of radiation dose rates. This energy range is widely utilized in diagnostic imaging and therapeutic procedures and is of great importance for optimizing the safety and effectiveness of radiotherapy and medical imaging techniques [6]. In the future, radiation shielding is expected to face significant challenges, as the design and fabrication of large-scale, high

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atomic number materials are complex and costly, making them less economically viable compared to polymeric materials. Therefore, research efforts have been directed toward investigating the feasibility of using low atomic number materials for radiation shielding purposes. Nevertheless, only a limited number of studies have comprehensively examined gamma-ray attenuation properties alongside the mechanical and thermal characteristics of polymers or their combination with doped elements [2, 5].

2- Research Theories

According to the Lambert-Beer law, when gamma rays with a given radiation intensity pass through an absorbing material, their intensity decreases relative to the initial intensity of the source [7]. Eq. (1) describes the attenuation of incident radiation as a function of absorber thickness. In this equation, μ represents the linear attenuation coefficient $\left(cm^{-1}\right)$, I_0 denotes the initial intensity in the absence of the absorber, and I corresponds to the transmitted intensity in the presence of the absorbing material:

$$I = I_0 exp(-\mu x) \tag{1}$$

The linear attenuation coefficient (LAC) is influenced by several factors, including the type of shielding material, the energy of the incident gamma rays, and the density of the absorber [8]. By rearranging Eq. (1), the LAC can be expressed as follows:

$$\mu = -\frac{1}{x} Ln(\frac{I_0}{I}) \tag{2}$$

The mass attenuation coefficient (MAC), $\mu\left(\mathrm{cm^2 \cdot g^{-1}}\right)$, is defined as the ratio of the LAC of the absorber to its density. This parameter plays a crucial role in the calculation of various photon interaction characteristics and is of considerable importance in the analysis of the radiation properties of materials [9]. The relationship between the LAC and the MAC is given by:

$$\mu_m = \mu \frac{1}{\rho} \tag{3}$$

In Eq. (3), ρ denotes the density of the target. In general, the effectiveness of a shielding material is commonly evaluated using the half-value layer (HVL) parameter. The HVL is defined as the thickness of an absorber required to reduce the intensity of the incident radiation to one-half of its initial value [10]. The HVL, which is directly dependent on the LAC, is expressed by the following equation:

$$HVL = \frac{ln2}{\mu} = \frac{0.693}{\mu} \tag{4}$$

Using Eq. (4), the required thickness of polymeric materials can be calculated to achieve a reduction of gamma-ray intensity to half of its original value. This thickness, represented by the HVL, depends on both the molecular structure of the polymer and the energy of the incident gamma radiation [11]. Such dependence highlights the critical importance of appropriate polymer material selection in radiation shielding and radiation control applications.

3- Numerical Modeling and Experimental Validation

In this study, the MAC and HVL of polymeric targets for various radioactive sources were calculated using the MCNPX F4 cell-averaged flux tally. After providing a complete description of the simulation and presenting the results, the experimental values reported in Ref. [12] were compared with those from the XCOM library for validation purposes. The experimental and MCNPX-simulated MAC values for the polymers are presented in Table 2. In addition, the percentage deviations (PD) between the MCNPX-simulated MAC values and the corresponding experimental and XCOM values were calculated.

In the present simulation, two collimators were employed to achieve effective beam collimation and directional control of the incident gamma radiation. The geometric configuration of the collimation system is illustrated schematically in Fig. 1 The radiation sources were modeled as ideal point sources and positioned at the entrance of the first collimator to ensure minimal beam divergence.

After passing through the first collimator, the gamma rays formed a narrow, quasi-parallel beam that was directed toward the investigated polymer targets (see Table 1). The incident photons interacted with the polymeric materials through various photon–matter interaction processes, leading to partial attenuation and scattering within the targets. The emergent gamma photons, carrying information related to the attenuation characteristics of the materials, were subsequently guided into the second collimator. This collimator was designed to suppress undesired scattered photons and to select the transmitted photons primarily, thereby improving measurement accuracy. Detection of the collimated transmitted gamma photons was performed using a NaI (Tl) scintillation detector. The corresponding photon flux within the detector volume was quantified by means of the MCNPX F4 cell-averaged flux tally, providing an accurate basis for the evaluation of radiation shielding characteristics and attenuation coefficients (linear from Eq. (2) and mass from Eq. (3)). The distance between the radiation source and the detector was fixed at 30 cm throughout the simulation. This separation was carefully chosen to optimize statistical reliability while minimizing the influence of secondary scattering and background radiation. Overall, the adopted geometry closely approximates an ideal narrow-beam

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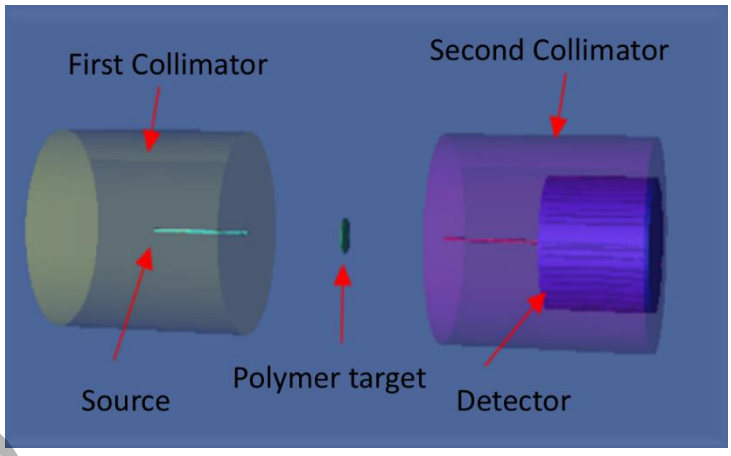


Fig. 1. Schematic of the setup in the MCNPX code.

Table 1. Specifications of the polymeric targets used in the MCNPX simulation.

Smart Polymers + Lead	Chemical Formula	Density (g/cm^3)
Polyurethance (PUR)	$C_{27}H_{36}N_{20}O_{10}$	1.5
Silicon Carbide (SiC)	SiC	3.21
Polypropylene (PP)	$C_{16}H_{14}O_3$	0.89
Polytetrafluoroethylene (PTFE)	C_2F_4	2.2
Polyvinylidene fluoride (PVDF)	$C_2H_2F_2$	1.78
Poly (vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP)	$C_5H_2F_8$	1.77
Lead (Pb)	Pb	11.35

configuration, ensuring high precision in the simulated measurements and enhancing the reliability of the obtained results (see Fig. 1).

Based on the materials in Table 1, MCNPX simulations were performed to investigate their radiation shielding performance. The analysis focuses on a set of fundamental attenuation parameters derived from the simulated data in order to systematically evaluate and compare the shielding effectiveness of the selected polymers. Specifically, the linear attenuation coefficient (μ) is first examined as an intrinsic material property independent of density, followed by the mass attenuation coefficient (μ/ρ) which incorporates the actual material density and directly governs the exponential attenuation behavior. Finally, the mean free path (MFP) is analyzed to provide a physically intuitive interpretation of photon–matter interactions and to assess the suitability of the investigated materials for practical shielding applications. Fig. 2 presents the variation of the MAC (μ/ρ) as a function of photon energy for the investigated polymeric materials. In addition to the polymers, lead (Pb) is included in the analysis as a reference shielding material due to its well-established superior photon attenuation capability. The inclusion of lead provides a benchmark for evaluating the relative shielding performance of the polymeric materials under identical simulation conditions. As expected, lead exhibits significantly higher μ/ρ values over the entire energy range, reflecting its high atomic number and density, which enhance photon–matter interaction probabilities. In contrast, the polymeric materials display lower mass attenuation coefficients with closely spaced trends, indicating comparable intrinsic attenuation behavior among the studied polymers. The observed decrease in μ/ρ with increasing photon energy is consistent with the dominant interaction mechanisms governing photon attenuation in this energy region.

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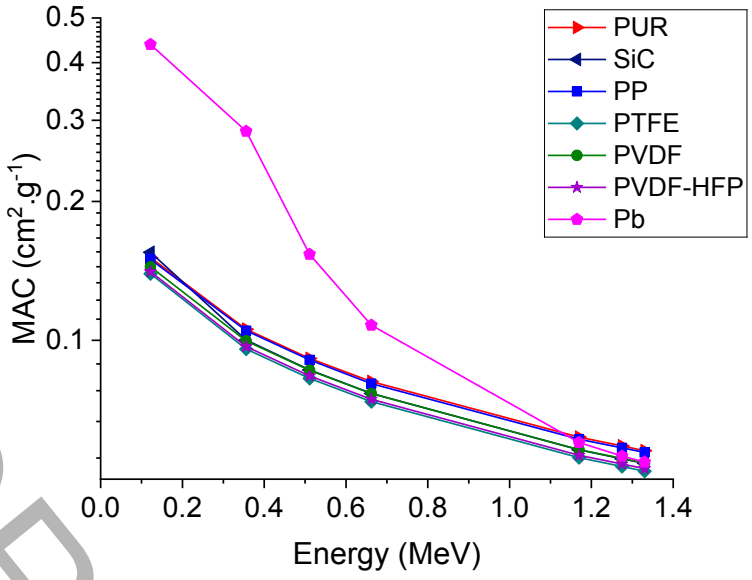


Fig. 2. Simulated MAC (μ/ρ) versus photon energy for the investigated polymeric materials and lead (Pb).

Table 2. HVL values calculated using MCNPX simulation for the targets.

Energy (KeV)	PUR	SiC	PP	PTFE	PVDF	PVDF-HFP	Pb
	HVL (cm)						
122	3.06	1.39	5.20	2.26	2.70	2.78	0.14
356	4.37	2.15	7.42	3.29	3.91	4.04	0.21
511	5.06	2.50	8.59	3.81	4.52	4.68	0.40
662	5.68	2.81	9.66	4.28	5.08	5.25	0.57
1170	7.49	3.73	12.76	5.66	6.72	6.95	1.02
1275	7.83	3.90	13.31	5.92	7.02	7.26	1.09
1330	8.02	3.99	13.63	6.05	7.18	7.43	1.12

Table 2, presents the HVL of the investigated polymeric materials in comparison with lead (Pb), which is used to quantitatively evaluate shielding effectiveness and provide a direct measure of radiation attenuation performance, while the corresponding HVL trends are illustrated Fig. 3, with lead included as a reference due to its well-established superior shielding capability.

Building on the HVL results, the Mean Free Path (MFP) of photons in free space was calculated as a reference, as shown in Fig. 4, highlighting the extent of radiation attenuation achieved by the simulated materials.

4- Results and discussion

From the standpoint of radiation shielding parameters, lead is undoubtedly one of the most effective materials for gamma-ray shielding due to its high atomic number and density. However, its heavy structure, toxicity, and high cost significantly limit its practical applications. Therefore, this study focused on polymer-based materials as alternative shielding candidates that offer lower weight, improved mechanical properties, and economic advantages. According to the MCNPX simulation results from polymeric targets summarized in Table 1 the HVL was used as a key parameter for evaluating shielding performance. At low gamma-ray energies (below 700 keV), the SiC polymer exhibited the best shielding capability among the investigated polymers, with an average HVL value of 2.21 cm. This was followed by PTFE with an average HVL of 3.41 cm, while PVDF and PVDF-HFP showed HVL values of 4.05 cm and 4.18 cm, respectively, indicating their suitability for low-energy

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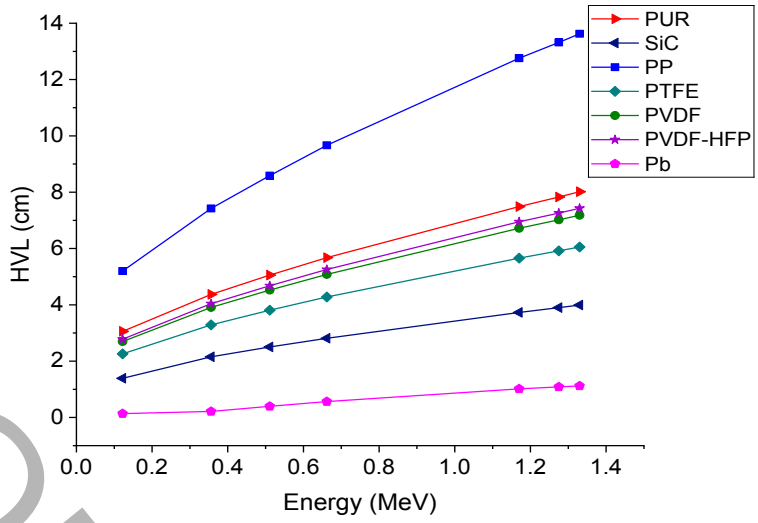


Fig. 3. HVL of the simulated materials as a function of photon energy, illustrating their shielding effectiveness.

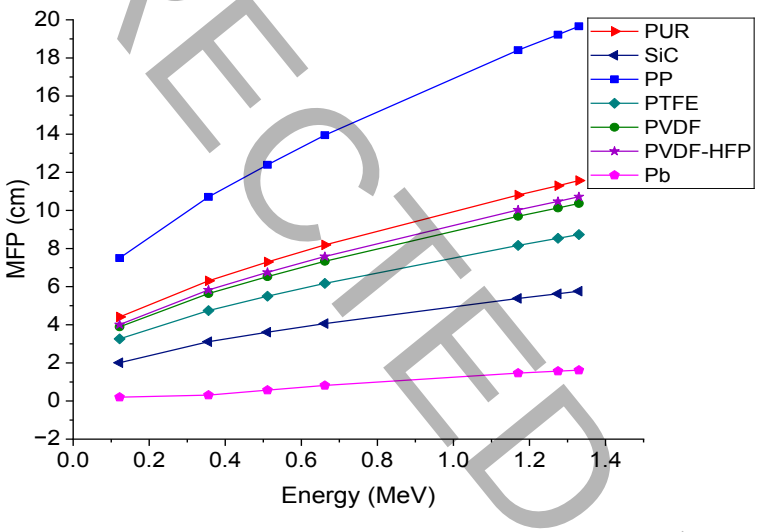


Fig. 4. MFP of photons in free space for the simulated materials, illustrating the reference level for radiation attenuation.

gamma shielding applications (see Table 2 and Fig. 3). The variation of the MAC with photon energy is illustrated in Fig. 2. As expected, μ/ρ decreases with increasing gamma-ray energy for all materials, which is mainly attributed to the reduced contribution of the photoelectric effect at higher energies. Lead exhibits the highest MAC over the entire energy range; however, among the polymer-based materials, the SiC polymer shows comparatively higher μ/ρ values, particularly at low photon energies, confirming its superior attenuation capability relative to other polymers. The MFP as a function of gamma-ray energy is presented in Fig. 4. The results demonstrate that the MFP increases with increasing photon energy for all materials, indicating that higher-energy photons travel longer distances before interaction. Lead shows the shortest MFP due to its high attenuation efficiency, while among the investigated polymers, SiC and PTFE exhibit shorter MFP values compared to other polymeric materials, making them more effective for gamma-ray shielding purposes. At higher gamma-ray energies (1000-1400 keV), the shielding effectiveness of all materials decreases, as reflected by lower μ/ρ values and larger MFPs. Nevertheless, the SiC polymer maintains favorable shielding

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Table 3. Comparative analysis of Mass Attenuation Coefficients of smart polymers based on experimental results [12], MCNPX simulations, and XCOM reference data.

Polymers + Lead	122 KeV					356 KeV				
	Exp	PD	simulation	PD	XCOM	Exp	PD	simulation	PD	XCOM
PUR	0.141	2.83	0.145	0.69	0.144	0.107	0.94	0.106	6.19	0.113
SiC	0.138	1.45	0.140	1.41	0.142	0.101	0.99	0.100	6.54	0.107
PP	0.139	2.87	0.143	0.71	0.142	0.105	0.10	0.105	6.25	0.112
PTFE	0.128	3.12	0.132	0.76	0.131	0.096	0.21	0.096	5.88	0.102
PVDF	0.133	4.51	0.139	2.21	0.136	0.100	0.30	0.100	6.54	0.107
PVDF-HFP	0.129	2.32	0.136	3.02	0.132	0.097	0.10	0.097	6.73	0.104
Pb	-	-	0.438	1.62	0.431	-	-	0.284	1.42	0.280

Polymers + Lead	511 KeV					662 KeV				
	Exp	PD	simulation	PD	XCOM	Exp	PD	simulation	PD	XCOM
PUR	0.093	2.15	0.091	1.09	0.092	0.086	5.81	0.081	1.22	0.082
SiC	0.087	1.15	0.086	1.15	0.087	0.081	4.93	0.077	0.39	0.077
PP	0.092	1.09	0.091	0.33	0.091	0.085	4.71	0.081	0.49	0.081
PTFE	0.084	1.19	0.083	0.36	0.083	0.077	3.90	0.074	0.54	0.074
PVDF	0.087	1.15	0.086	0.12	0.086	0.081	4.94	0.077	0.52	0.077
PVDF-HFP	0.085	1.18	0.084	0.36	0.084	0.078	5.13	0.074	1.33	0.075
Pb	-	-	0.154	3.35	0.149	-	-	0.108	0.92	0.109

Polymers + Lead	1170 KeV					1275 KeV				
	Exp	PD	simulation	PD	XCOM	Exp	PD	simulation	PD	XCOM
PUR	0.074	2.70	0.072	5.88	0.068	0.063	6.35	0.059	1.66	0.060
SiC	0.070	2.85	0.068	6.25	0.064	0.059	6.78	0.055	1.79	0.056
PP	0.074	6.75	0.069	2.98	0.067	0.062	6.45	0.058	1.69	0.059
PTFE	0.067	5.97	0.063	3.27	0.061	0.056	5.36	0.053	1.85	0.054
PVDF	0.070	2.85	0.068	6.25	0.064	0.059	6.78	0.055	1.79	0.056
PVDF-HFP	0.068	2.94	0.066	6.45	0.062	0.057	5.26	0.054	1.81	0.055
Pb	-	-	0.060	3.22	0.062	-	-	0.056	6.66	0.060

Polymers + Lead	1330 KeV				
	Exp	PD	simulation	PD	XCOM
PUR	0.059	1.69	0.058	5.45	0.055
SiC	0.055	1.81	0.054	3.85	0.052
PP	0.058	1.72	0.057	3.64	0.055
PTFE	0.053	1.89	0.052	4	0.050
PVDF	0.055	1.81	0.054	3.85	0.052
PVDF-HFP	0.054	1.85	0.053	6	0.050
Pb	-	-	0.054	3.57	0.056

performance with an average HVL of 3.87 cm, followed by PTFE with an average HVL of 5.88 cm. Considering their lower density, flexibility, and availability, these materials can be regarded as practical and more accessible alternatives to lead in this energy range. Overall, although lead remains the most efficient shielding material, polymer-based composites-especially SiC and PTFE-demonstrate a promising balance between radiation attenuation performance and practical engineering advantages. The consistency observed between HVL, MAC, and MFP trends further validates the reliability of the MCNPX simulations and highlights the potential of these materials for advanced gamma-ray shielding applications.

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5- Conclusions

Based on the outcomes of this study, it is recommended that polymer-based shielding materials be considered as practical alternatives to conventional lead shielding in applications where weight, flexibility, and material safety are critical design factors. In particular, SiC- and PTFE-based polymers are suggested for gamma-ray shielding in low- to medium-energy ranges, where they provide a favorable balance between attenuation efficiency and structural advantages.

For higher-energy gamma radiation, the use of multilayer or composite shielding configurations incorporating these polymers alongside high-Z materials is recommended to enhance overall shielding performance while reducing the total weight of the system. Additionally, future studies are encouraged to investigate the optimization of filler concentration, material thickness, and composite architecture to further improve shielding efficiency. Experimental validation of the simulation results, as well as assessments of long-term durability, thermal stability, and mechanical performance under irradiation, are also recommended to support the practical implementation of these materials in nuclear and medical radiation protection systems.

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