

RESEARCH ARTICLE

Gamma-Ray Shielding and Fast-Neutron Removal Properties of Phosphate-Cadmium-Zinc Oxide Glasses Doped with Tm^{3+}

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ABSTRACT: The gamma-ray shielding properties, effective atomic parameters, and fast-neutron removal cross sections of phosphate-cadmium-zinc oxide (PZCdO) glasses were computationally investigated using MIKE software over 15 keV–15 MeV. Two compositions, $50\text{P}_2\text{O}_5$ – 30ZnO – 20CdO and its 3 mol% Tm_2O_3 -doped counterpart, were evaluated. The densities were 3.462 and 3.5819 g/cm³, respectively. The Tm-doped glass exhibited higher mass and linear attenuation coefficients below approximately 0.5 MeV, while both compositions converged at higher energies. The doped glass consistently showed lower half-value and tenth-value layers, indicating improved photon shielding. Its effective and equivalent atomic numbers were also higher across the investigated energy range. Distinct buildup-factor maxima occurred in the Compton region, with resonance-like behavior observed near 0.06 MeV at greater penetration depths. In contrast, Tm_2O_3 incorporation produced negligible changes in fast-neutron removal cross sections, remaining approximately 0.099 cm⁻¹. These findings demonstrate enhanced photon shielding while preserving neutron attenuation performance.

Keywords: Phosphate Glass; Thulium Doping; Gamma-Ray Shielding; Effective Atomic Number; Fast-Neutron Removal Cross Section; Build-Up Factors

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1. INTRODUCTION

The unique physical and chemical characteristics of phosphate-based glasses have attracted considerable

scientific interest over the past several decades. These materials exhibit low melting temperatures, high thermal expansion coefficients, exceptional optical transparency across a broad spectral range, and tunable refractive indices, making them highly versatile for numerous technological applications [1, 2]. Compared to silicate and borate glass systems, phosphate glasses demonstrate superior solubility for rare-earth ion doping and serve as excellent gain media for high-power laser applications owing to their favorable thermo-optic properties and high stimulated emission cross sections [3]. Among the various phosphate glass compositions, the PZCdO glass system, comprising phosphorus pentoxide, zinc oxide, and cadmium oxide, has emerged as a particularly promising host matrix for luminescent ions including Tm^{3+} , Nd^{3+} , and Yb^{3+} , which exhibit strong emission characteristics across the ultraviolet, visible, and near-infrared spectral regions [4].

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Beyond their established optical applications, glass-based materials have recently gained significant attention as potential candidates for ionizing radiation shielding applications. These materials offer distinct advantages over traditional lead-based shielding compounds, which present considerable toxicity concerns and environmental hazards [5, 6]. The increasing demand for lead-free, lightweight, and optically transparent shielding materials in medical physics, nuclear medicine, diagnostic radiology, and industrial radiography has driven extensive research into oxide glass systems incorporating heavy elements such as CdO, PbO, Bi₂O₃, WO₃, and BaO [7–10]. At low to intermediate photon energies, photoelectric absorption constitutes the dominant interaction mechanism, and the incorporation of high-atomic-number components substantially elevates the effective atomic number (Z_{eff}) of the glass matrix, thereby enhancing the photoelectric absorption cross section [11].

Thulium, a rare-earth element with atomic number 69, when introduced as Tm₂O₃ at concentrations of 30000 ppm (3 mol%) in a glass host, significantly modifies both the optical and structural characteristics of the glass network. This modification potentially leads to increased density and enhanced photon-interaction cross sections, particularly in energy regions where photoelectric effects are most prominent [4, 12]. Al-Assiri and coworkers successfully synthesized and characterized pure PZCdO and PZCdO:Tm glasses using the conventional melt-quenching technique, reporting densities of 3.462 g/cm³ and 3.5819 g/cm³, respectively, with corresponding optical energy gaps of 2.5 eV and 3.3 eV [4].

Recent investigations have extensively explored the radiation shielding characteristics of various glass systems. Studies on thulium-doped multicomponent borosilicate glasses have demonstrated that the addition of Tm₂O₃ content leads to improvement in the shielding efficiency, with 2.0 mol% Tm₂O₃-doped glasses showing better gamma-ray attenuation capability compared to undoped samples [10]. The influence of cadmium oxide on the radiation shielding properties of zinc-sodium-phosphate glass containing barium revealed successive improvement of shielding properties against fast and slow neutrons with increasing CdO concentrations [2]. Furthermore, the elastic and radiation shielding properties of cadmium and lead-incorporated zinc barium phosphate glass demonstrated that phosphate glass containing PbO and CdO + PbO is more suitable for radiation shielding applications [12]. Structural, thermal, and radiation shielding investigations of B₂O₃-TeO₂-Bi₂O₃-CdO-Tm₂O₃ glasses showed that incorporating Tm₂O₃ into the glass matrix significantly improved the shielding and thermal properties, with a dose of 1.2025 μ Sv/h emitted from a fast neutron source absorbed by 35.1574% in pure glass and 40.0391% in glass doped with 5 mol% Tm₂O₃ [11]. The photon and neutron shielding performance of boron phosphate glasses for diagnostic radiology facilities established that boron-doped phosphate glasses serve as superior shielding materials for both gamma rays and neutrons [15]. Additionally, the integration between radiation shielding performance, structural evolution, and mechanical

features of co-doped sodium phosphate glasses demonstrated that Nb₂O₅-MnO co-doped sodium phosphate glasses exhibit promising radiation shielding capabilities with macroscopic removal cross-sections for fast neutrons ($\Sigma_r = 0.0956 \text{ cm}^{-1}$) outperforming conventional materials like concrete [16–20].

Despite these advances, a systematic investigation of the gamma-ray shielding capabilities, effective atomic parameters, and fast-neutron removal characteristics of the PZCdO glass system, particularly with respect to thulium doping effects, has remained notably absent from the scientific literature. The existing studies have largely focused on other glass compositions or have not comprehensively evaluated the full spectrum of shielding parameters including mass and linear attenuation coefficients, half-value and tenth-value layers, mean free path, effective and equivalent atomic numbers, effective electron density, atomic and electronic cross sections, exposure and energy-absorption build-up factors, and fast-neutron removal cross sections within a unified framework for this specific glass system.

The novelty of the present work lies in its comprehensive computational investigation of the PZCdO glass system, both in its pure form and with Tm₂O₃ doping, addressing the critical gap in understanding how thulium incorporation affects the multifaceted radiation shielding performance. Unlike previous studies that examined either optical properties or shielding parameters in isolation, this research integrates the evaluation of gamma-ray shielding, effective atomic parameters, and fast-neutron removal properties within a single systematic framework, providing a holistic assessment of the multifunctional shielding potential of these glasses. The use of the MIKE software package enables accurate computation of shielding parameters across a broad energy range from 15 keV to 15 MeV, while comparison with the PCKNT glass series and other standard reference materials provides valuable context for evaluating the relative performance of these compositions. Furthermore, the investigation of anomalous resonance-like features observed in build-up factors at significant penetration depths adds a new dimension to understanding the behavior of Tm-doped phosphate glasses under high-energy photon irradiation, an aspect that has not been previously reported in the literature for this particular glass system.

In this paper, we report a comprehensive computational analysis of the gamma-ray shielding characteristics, effective atomic parameters, and fast-neutron removal cross sections of pure PZCdO and PZCdO:Tm glasses using the MIKE software package over the photon energy range of 15 keV to 15 MeV. The shielding parameters investigated include mass and linear attenuation coefficients, half-value and tenth-value layers, mean free path, effective and equivalent atomic numbers, effective electron density, atomic and electronic cross sections, exposure and energy-absorption build-up factors, and fast-neutron removal cross sections. The results are compared with the PCKNT glass series and other standard reference materials to establish the relative performance of these compositions for potential applications in multifunctional optical-shielding devices.

2. EXPERIMENTAL DETAILS

2.1. Glass Composition and Synthesis

Two glass compositions were investigated in the present study, both belonging to the phosphate-cadmium-zinc oxide glass system. The first composition, designated as pure PZCdO, consisted of 50 mol% P₂O₅, 30 mol% ZnO, and 20 mol% CdO. The second composition, designated as PZCdO:Tm, maintained the same base molar proportions but incorporated 30000 ppm (equivalent to 3 mol%) Tm₂O₃ as a dopant. The synthesis of both glass samples was accomplished using the conventional melt-quenching technique, as previously described by Al-Assiri and co-workers [4].

High-purity reagent-grade chemicals were employed as starting materials, including ammonium dihydrogen phosphate (NH₄H₂PO₄) as the phosphorus pentoxide source, zinc oxide (ZnO), cadmium oxide (CdO), and thulium oxide (Tm₂O₃) with purity exceeding 99.9%. The raw materials were accurately weighed according to their nominal molar compositions and thoroughly homogenized by grinding in an agate mortar to ensure uniform distribution of all constituents. The resulting powder mixtures were subsequently transferred into covered platinum crucibles and subjected to heat treatment in a programmable muffle furnace at 1250°C for 30 minutes. This high-temperature melting step facilitated complete decomposition of the phosphate precursor and promoted homogeneous mixing of the molten oxide components. Following the initial melting stage, the molten mixtures were mechanically stirred to enhance compositional homogeneity, returned to the furnace at 1100°C for an additional 10 minutes to ensure complete fusion, and then rapidly cast into preheated steel moulds to obtain glass samples with desired dimensions. The cast glasses were immediately transferred to an annealing furnace maintained at 420°C for 2 hours to relieve internal stresses and prevent cracking during subsequent cooling.

Table 1. Chemical composition (mol%) and density of the glass samples studied.

Parameter	PZCdO pure	PZCdO:Tm
P ₂ O ₅ (mol%)	50	50
ZnO (mol%)	30	30
CdO (mol%)	20	20
Tm ₂ O ₃ (mol%)	0.0	3.0 (30000 ppm)
Density, ρ (g/cm ³)	3.462	3.5819

The annealing process was followed by slow cooling to room temperature at a controlled rate to preserve the structural integrity of the glass network. The densities of the prepared glass samples were determined at ambient temperature using

Archimedes' principle with distilled water as the immersion fluid. Density measurements yielded values of 3.462 g/cm³ for pure PZCdO and 3.5819 g/cm³ for PZCdO:Tm, with the observed increase in density upon thulium incorporation attributed to the higher atomic weight of thulium compared to the network-forming cations it partially substitutes [4]. The chemical compositions and corresponding densities of both glass samples are summarized in Table 1 for clarity and reference throughout this investigation.

2.2. Computational Methodology

All shielding parameters and effective atomic quantities were computed using the MIKE software package, a sophisticated MATLAB-based computational tool specifically developed for investigating the radiation attenuation, optical, and physical properties of shielding materials. The calculations were performed across a comprehensive photon energy range spanning from 15 keV to 15 MeV, covering the energy regimes where photoelectric absorption, Compton scattering, and pair production processes dominate gamma-ray interactions with matter. The mass attenuation coefficients (MAC) were calculated using the standard mixture rule, which combines the weighted contributions of each constituent element according to their mass fractions. For validation purposes, the MAC results were cross-checked at selected energies using the WinXCom program, which is based on the well-established XCOM database developed by the National Institute of Standards and Technology. The exposure build-up factors (EBF) and energy-absorption build-up factors (EABF) were determined at penetration depths of 1, 5, 10, 15, 20, 25, 30, 35, and 40 mean free paths (mfp) using the Geometric Progression (G-P) fitting approach. This method employs five fitting coefficients, namely b, c, a, X_k, and d, which were extracted from the comprehensive ANSI/ANS-6.4.3 standard reference database [17].

The G-P fitting technique enables accurate estimation of build-up factors by accounting for the multiple-scattering contributions that become increasingly significant at larger penetration depths. The equivalent atomic numbers required for interpolating the G-P coefficients were obtained from the ratio of the Compton partial mass attenuation coefficient to the total mass attenuation coefficient. The fast-neutron removal cross sections (FNRCS) for both glass compositions were calculated using the partial molar and mass fractions of the constituent elements, employing the elemental mass removal cross sections available in the literature [18]. This approach provides a reliable estimation of the neutron attenuation capability based on the elemental composition without requiring extensive neutron transport simulations.

3. THEORETICAL FRAMEWORK

3.1. Mass and Linear Attenuation Coefficients

The attenuation of a mono-energetic photon beam traversing a medium is described by the Beer-Lambert law, which relates the transmitted intensity I to the incident intensity I_0 through the exponential attenuation relationship [15]:

$$I = I_0 \exp(-\mu d) \quad (1)$$

Where μ represents the linear attenuation coefficient expressed in cm^{-1} and d denotes the thickness of the absorbing medium in centimeters. The mass attenuation coefficient, denoted as MAC and expressed in cm^2/g , is obtained by dividing the linear attenuation coefficient by the density of the material ($\text{MAC} = \mu/\rho$). For composite materials containing multiple constituent elements, the mass attenuation coefficient is calculated using the mixture rule, which sums the weighted contributions of each elemental component according to their respective mass fractions [15, 16]:

$$\text{MAC} = \left(\frac{\mu}{\rho}\right)_{\text{max}} = \sum \left[w_i \left(\frac{\mu}{\rho}\right)_i \right] \quad (2)$$

Where w_i represents the weight fraction of the i -th constituent element and $(\mu/\rho)_i$ denotes its corresponding mass attenuation coefficient.

3.2. Half-Value Layer, Tenth-Value Layer, and Mean Free Path

The half-value layer (HVL) corresponds to the thickness of material required to reduce the intensity of an incident photon beam by fifty percent. This parameter is inversely proportional to the linear attenuation coefficient and is calculated using the following relationship:

$$\text{HVL} = \ln(2)/\mu = 0.693/\mu \quad (3)$$

Similarly, the tenth-value layer (TVL) represents the thickness necessary to attenuate the beam intensity to one-tenth of its original value:

$$\text{TVL} = \ln(10)/\mu = 2.303/\mu \quad (4)$$

The mean free path (MFP) denotes the average distance a photon travels between successive interactions within the material and is defined as the reciprocal of the linear attenuation coefficient:

$$\text{MFP} = 1/\mu \quad (5)$$

3.3. Effective Atomic Number and Equivalent Atomic Number

The effective atomic number (Z_{eff}) is a crucial parameter that characterizes the radiation attenuation properties of composite materials by representing an equivalent single-element atomic number that would exhibit similar photon interaction behavior. It is computed from the ratio of the atomic cross section (σ_a) to the electronic cross section (σ_e) as follows [13]:

$$Z_{\text{eff}} = \sigma_a / \sigma_e = \left[\sum f_i A_i \left(\frac{\mu}{\rho}\right)_i \right] / \left[\sum f_i \left(\frac{A_i}{Z_i}\right) \left(\frac{\mu}{\rho}\right)_i \right] \quad (6)$$

Where f_i denotes the fractional abundance of element i , A_i represents its atomic weight, Z_i is its atomic number, and $(\mu/\rho)_i$ is its mass attenuation coefficient.

The equivalent atomic number (Z_{eq}) is derived from the ratio R of the Compton partial mass attenuation coefficient to the total mass attenuation coefficient. This ratio is interpolated against tabulated R values for single elements available in standard reference databases [13]:

$$Z_{\text{eq}} = (Z_1 \log R_2 - Z_2 \log R_1) / (\log R_2 - \log R_1) \quad (7)$$

Where Z_1 and Z_2 are the atomic numbers of the adjacent elements in the reference table whose R values bracket the calculated R for the material under investigation.

The effective electron density (N_{eff}), representing the number of electrons per unit mass of the material, is determined from the effective atomic number and the effective atomic weight:

$$N_{\text{eff}} = N_A \times Z_{\text{eff}} \times \rho / A_{\text{eff}} \quad (8)$$

Where N_A is Avogadro's number, ρ is the material density, and A_{eff} represents the effective atomic weight of the composite.

The atomic cross section (σ_{ACS}), expressed in barns per atom, is calculated from the mass attenuation coefficient and the effective atomic weight:

$$\sigma_{\text{ACS}} = \left(\frac{\mu}{\rho}\right) \times A_{\text{eff}} / N_A \quad [\text{barn/atom}] \quad (9)$$

The electronic cross section (σ_{ECS}), expressed in barns per electron, is obtained by dividing the atomic cross section by the effective atomic number:

$$\sigma_{\text{ECS}} = \sigma_{\text{ACS}} / Z_{\text{eff}} \quad [\text{barn/electron}] \quad (10)$$

3.4. Exposure and Energy-Absorption Build-up Factors

The exposure build-up factor (EBF) and energy-absorption build-up factor (EABF) account for the contribution of

multiply-scattered photons to the total photon fluence at a given point within the shielding medium. These factors are computed using the Geometric Progression (G-P) fitting method, which employs coefficients derived from the ANSI/ANS-6.4.3 standard reference database [17]. The build-up factor is expressed as:

$$B(E, x) = 1 + [(b - 1)/(K - 1)]x(K^x - 1)[K! = 1] \quad (11)$$

where x represents the penetration depth expressed in mean free paths, and $K(x)$ is a dose-multiplicative function that depends on the five G-P fitting coefficients: b , c , a , X_k , and d . These coefficients are energy-dependent and material-specific, and they are interpolated based on the equivalent atomic number of the shielding material.

3.5. Fast-Neutron Removal Cross Section

The macroscopic fast-neutron removal cross section (FNRCs), denoted as σ_R and expressed in cm^{-1} , quantifies the ability of a material to attenuate fast neutrons through scattering and absorption processes. This parameter is determined using the precise mass fractions and elemental removal cross sections of the constituent elements [16]:

$$\sigma_R = \rho \times \sum \left[\left(\frac{w_i}{\rho_i} \right) \left(\frac{\sigma_R}{\rho} \right)_i \right] \quad (12)$$

where w_i is the weight fraction of element i , ρ_i is its elemental density, and $(\sigma_R/\rho)_i$ is the mass removal cross section of element i , which represents the removal cross section per unit mass. The summation is performed over all constituent elements of the composite material.

4. RESULTS AND DISCUSSION

4.1. Mass Attenuation Coefficient and Linear Attenuation Coefficient

The mass attenuation coefficients (MAC) and linear attenuation coefficients (LAC) for both PZCdO pure and PZCdO:Tm glasses are presented in Figure 1 as functions of photon energy across the range from 15 keV to 15 MeV. Examination of these data reveals a dramatic decrease in both parameters with increasing photon energy, with values dropping from approximately 30 cm^2/g for MAC and 100 cm^{-1} for LAC at 15 keV to less than 0.1 cm^2/g and 0.1 cm^{-1} , respectively, above a few MeV. This pronounced energy dependence reflects the transition from photoelectric absorption dominance at low energies to Compton scattering dominance at intermediate energies, with pair production becoming increasingly significant at the highest energies examined.

A particularly noteworthy observation is the differential

behavior between the two compositions. The MAC and LAC values of PZCdO:Tm are substantially greater than those of pure PZCdO only below approximately 0.3 to 0.5 MeV, whereas above this energy threshold the two curves converge and become virtually indistinguishable up to 15 MeV. This behavior is entirely consistent with the underlying physics of photon interactions with matter. The photoelectric cross section exhibits a steep dependence on atomic number, scaling approximately as Z^4 to Z^5 , which explains why the incorporation of thulium ($Z = 69$) significantly enhances attenuation in the low-energy photoelectric-dominated region. In contrast, Compton scattering cross sections scale approximately linearly with atomic number, and the modest increase in average Z resulting from 3 mol% Tm_2O_3 substitution produces minimal impact in this energy regime. The representative MAC and LAC values at selected photon energies are compiled in Table 2 for quantitative reference and comparison.

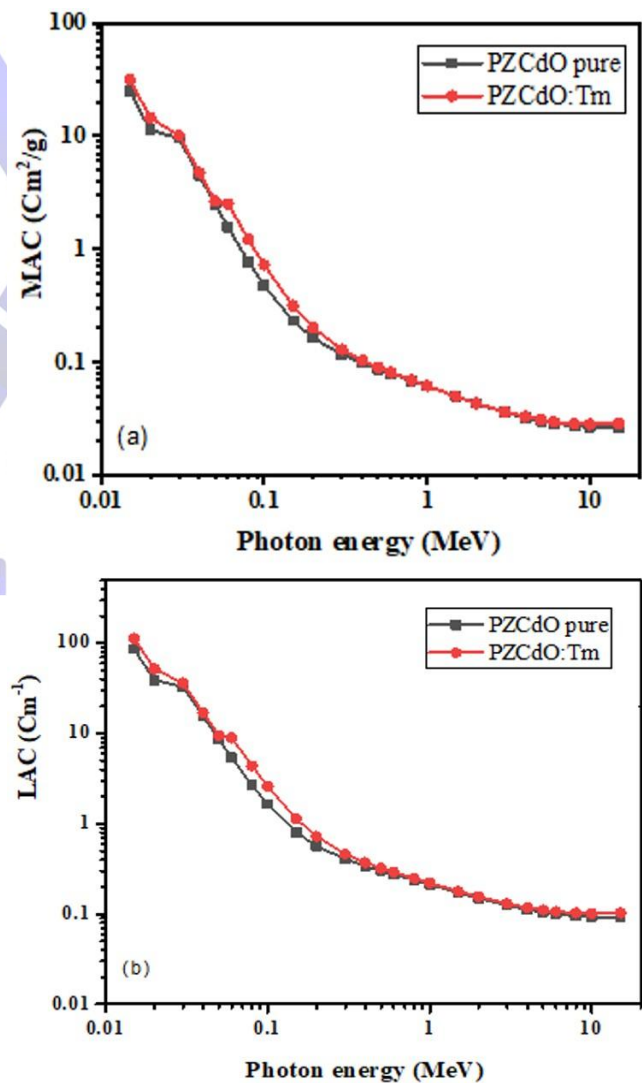


Fig. 1. (a) Mass attenuation coefficient (MAC) and (b) linear attenuation coefficient (LAC) as functions of photon energy for PZCdO pure and PZCdO:Tm glasses over the energy range 15 keV to 15 MeV.

Table 2. Mass attenuation coefficients (MAC, cm²/g) and linear attenuation coefficients (LAC, cm⁻¹) for PZCdO pure and PZCdO:Tm at selected photon energies as computed using the MIKE software.

Energy (MeV)	MAC Pure	MAC Tm	LAC Pure	LAC Tm
0.015	24.80754	31.50248	85.8837	112.83875
0.060	1.56019	2.50258	5.40137	8.964
0.150	0.23239	0.31602	0.80454	1.13194
0.511	0.08725	0.09022	0.30206	0.32315
1.000	0.06152	0.06174	0.21299	0.22114
15.00	0.02675	0.0286	0.09259	0.10244

4.2. Half-Value Layer, Tenth-Value Layer, and Mean Free Path

The half-value layers (HVL) and tenth-value layers (TVL) for both glass compositions are illustrated in Figure 2 (a, b), with corresponding numerical values provided in Table 3. Both parameters increase monotonically with photon energy, ranging from approximately 0.006 to 0.008 cm at 15 keV to about 7 cm for HVL and 23 cm for TVL at 15 MeV. This monotonic increase reflects the decreasing probability of photon interactions at higher energies, necessitating greater material thickness to achieve equivalent attenuation.

In stark contrast to the MAC and LAC behavior, PZCdO:Tm exhibits consistently lower HVL and TVL values compared to pure PZCdO across almost the entire energy spectrum investigated. The most substantial relative differences are observed in the 0.03 to 0.3 MeV region, where the doped glass requires noticeably thinner layers to achieve 50% or 90% beam attenuation. This enhancement in shielding efficiency is attributed to the combined effects of increased density and elevated effective atomic number resulting from thulium incorporation. Above approximately 3 MeV, the two curves converge once again, consistent with the convergence observed in MAC and LAC values in the same energy range.

The mean free path (MFP) behavior, shown in Figure 2(c), reveals a more nuanced picture. Up to approximately 1 MeV, the MFP values for pure and doped glasses are nearly overlapping, indicating similar average photon travel distances between interactions. However, above approximately 5 MeV, the two curves clearly diverge, with PZCdO:Tm reaching saturation at a lower plateau of about 9.7 cm at 10 to 15 MeV, compared to approximately 10.7 cm for pure PZCdO. This high-energy divergence, where attenuation is governed by Compton scattering and pair production, suggests that even outside the photoelectric domain, the modest increase in density and Z_{eff} due to thulium doping significantly reduces the average photon travel distance. For comparative context, Hussein and colleagues [16] reported HVL values of 0.443, 0.432, and 0.424 cm at 45 keV for phosphate-titanite glasses (PCKNT series) with increasing TiO₂ content, which are substantially larger than the sub-0.1 cm HVL values obtained for the

PZCdO system at comparable low energies. This difference arises from the higher effective atomic number contribution of cadmium ($Z = 48$) in the PZCdO matrix compared to calcium ($Z = 20$) and sodium ($Z = 11$) in the PCKNT compositions.

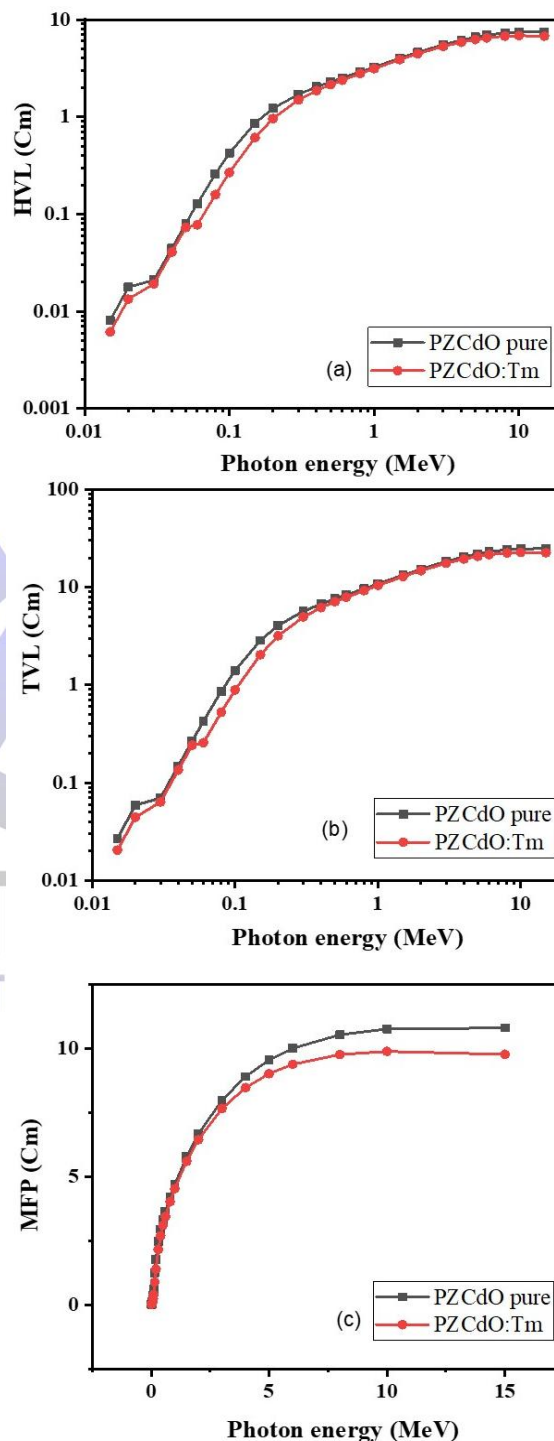


Fig. 2. (a) Half-value layer (HVL), (b) tenth-value layer (TVL), and (c) mean free path (MFP) as functions of photon energy for PZCdO pure and PZCdO:Tm glasses. The MFP is presented on a linear energy scale from 0 to 15 MeV to highlight the high-energy saturation plateau.

Table 3. Half-value layer (HVL, cm), tenth-value layer (TVL, cm), and mean free path (MFP, cm) for PZCdO pure and PZCdO:Tm at selected photon energies.

Energy (MeV)	HVL Pure	HVL Tm	TVL Pure	TVL Tm	MFP Pure	MFP Tm
0.060	0.12833	0.07733	0.4263	0.25687	0.18514	0.11156
0.511	2.29472	2.14496	7.6229	7.12541	3.31058	3.09453
1	3.25443	3.13449	10.811	10.41256	4.69516	4.52212
5	6.61662	6.24553	21.97993	20.74722	9.54576	9.0104
10	7.45551	6.84707	24.76667	22.74548	10.75603	9.87824
15	7.48604	6.7664	24.8681	22.4775	10.80008	9.76185

Table 4. Effective atomic number (Z_{eff}), equivalent atomic number (Z_{eq}), and effective electron density (N_{eff} , $\times 10^{23}$ electrons/g) for PZCdO pure and PZCdO:Tm at selected photon energies.

Energy (MeV)	Z_{eff} Pure	Z_{eff} Tm	Z_{eq} Pure	Z_{eq} Tm	N_{eff} Pure	N_{eff} Tm
0.015	27.493	33.015	18.855	20.622	6.153	6.969
0.060	32.474	41.912	28.147	33.334	7.268	8.848
0.511	13.236	14.378	30.476	37.321	2.962	3.035
1	12.929	13.718	30.660	37.690	2.894	2.896
15	15.992	17.768	19.586	22.401	3.579	3.751

4.3. Effective Atomic Number, Equivalent Atomic Number, and Effective Electron Density

The effective atomic number (Z_{eff}) as a function of photon energy is presented in Figure 3(a) for both glass compositions. The Z_{eff} values increase from approximately 27 to 33 at 15 keV to local maxima of roughly 37 to 42 at 0.03 to 0.07 MeV, followed by a broad minimum at approximately 1 to 2 MeV, and subsequent increase to about 16 to 18 at 15 MeV where pair production begins to contribute significantly. This characteristic energy dependence reflects the changing dominance of different photon interaction mechanisms with energy. The photoelectric contribution of the high-Z Tm³⁺ dopant is unequivocally confirmed by the consistently higher Z_{eff} values of PZCdO:Tm compared to pure PZCdO at all energies, with the largest absolute differences of approximately 4 to 5 units occurring at the low-energy maxima.

The equivalent atomic number (Z_{eq}) profile, shown in Figure 3(b), exhibits distinctly different characteristics. Both glasses rise rapidly from approximately 19 to 21 to a wide plateau between approximately 0.1 and 1 MeV, followed by steep decline above approximately 1 to 2 MeV. Importantly, the plateau value for PZCdO:Tm of approximately 37 to 38 substantially exceeds that for pure PZCdO at approximately 30 to 31, and this difference persists into the decreasing branch above 1 MeV where PZCdO:Tm remains 3 to 5 units higher than pure glass up to 15 MeV. This systematic offset in Z_{eq} directly influences the exposure and energy-absorption build-up factor outcomes, since Z_{eq} is used to interpolate the G-P build-up coefficients from the ANSI/ANS-6.4.3 standard database [17].

The effective electron density (N_{eff}), depicted in Figure 3(c), follows the same qualitative energy pattern as Z_{eff} . Values commence at approximately 6×10^{23} electrons/g at 15

keV, reach peaks of 8 to 9×10^{23} electrons/g near 0.05 to 0.07 MeV, decline to minima of approximately 3×10^{23} electrons/g around 1 to 2 MeV, and subsequently increase slightly. Over the entire energy range, PZCdO:Tm exhibits slightly greater N_{eff} compared to pure PZCdO, with the difference most apparent around the 0.05 to 0.1 MeV peak. This enhancement is consistent with the higher electron density resulting from the Tm³⁺ ions and the increased glass density. The numerical values for Z_{eff} , Z_{eq} , and N_{eff} at selected photon energies are compiled in Table 4.

4.4. Exposure and Energy-Absorption Build-up Factors

The exposure build-up factors (EBF) and energy-absorption build-up factors (EABF) for both glass compositions are presented in Figures 4 and 5 as functions of photon energy at penetration depths ranging from 1 to 40 mean free paths. The pure PZCdO glass exhibits the expected smooth trends characteristic of photon build-up behavior. Values remain near unity below approximately 0.1 MeV because photoelectric absorption effectively removes photons before multiple-scattering accumulation can occur. The EBF and EABF values rise sharply between 0.1 and 0.3 to 0.5 MeV, reaching broad maxima in the Compton-dominated region of approximately 0.3 to 1 MeV that scale with penetration depth from approximately 1 to 3 at 1 mfp up to approximately 150 to 250 at 40 mfp. Beyond this region, values gradually decrease toward higher energies as pair production becomes significant and absorption processes reduce the multiply-scattered photon contribution.

The PZCdO:Tm composition reproduces the general envelope of the pure glass at low penetration depths but exhibits an unusual anomaly that is entirely absent in the undoped composition.

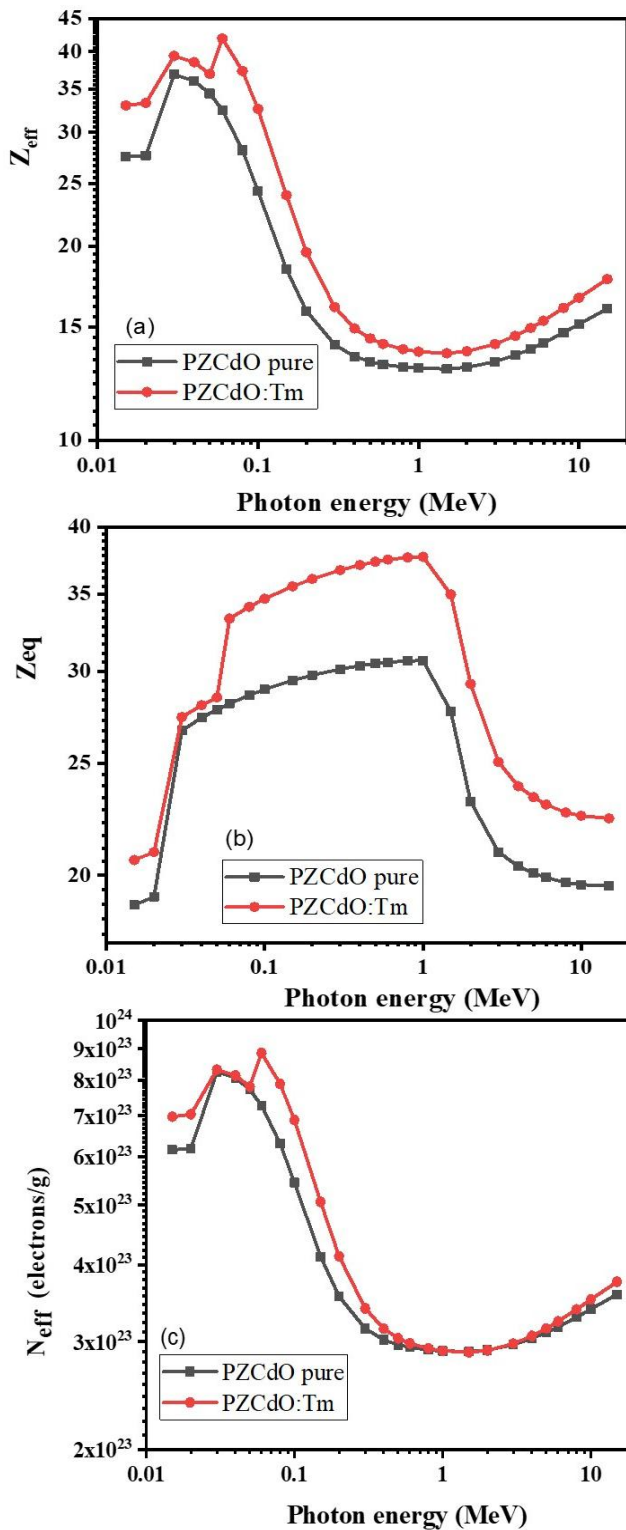


Fig. 3. Variation of (a) effective atomic number (Z_{eff}), (b) equivalent atomic number (Z_{eq}), and (c) effective electron density (N_{eff} , electrons/g) with photon energy for PZCdO pure and PZCdO:Tm glasses.

A sharp resonance-like spike in both EBF and EABF appears centered near 0.06 MeV, with magnitude growing exponentially with penetration depth and reaching values on

the order of 10^7 to 10^9 at 35 to 40 mfp. This represents several orders of magnitude higher than the smooth Compton-region maximum observed for both compositions. At large mean free paths, the dramatic increase in build-up factors arises from the exponential dependence of the G-P coefficient $K(x)$, consistent with an absorption-edge-related discontinuity in the G-P fitting coefficients. This discontinuity is likely associated with the cadmium K-edge at approximately 26.7 keV or represents an artifact in the interpolation process near the thulium and cadmium absorption structure utilized in the Z_{eq} -based coefficient lookup procedure from the ANSI/ANS-6.4.3 standard [17].

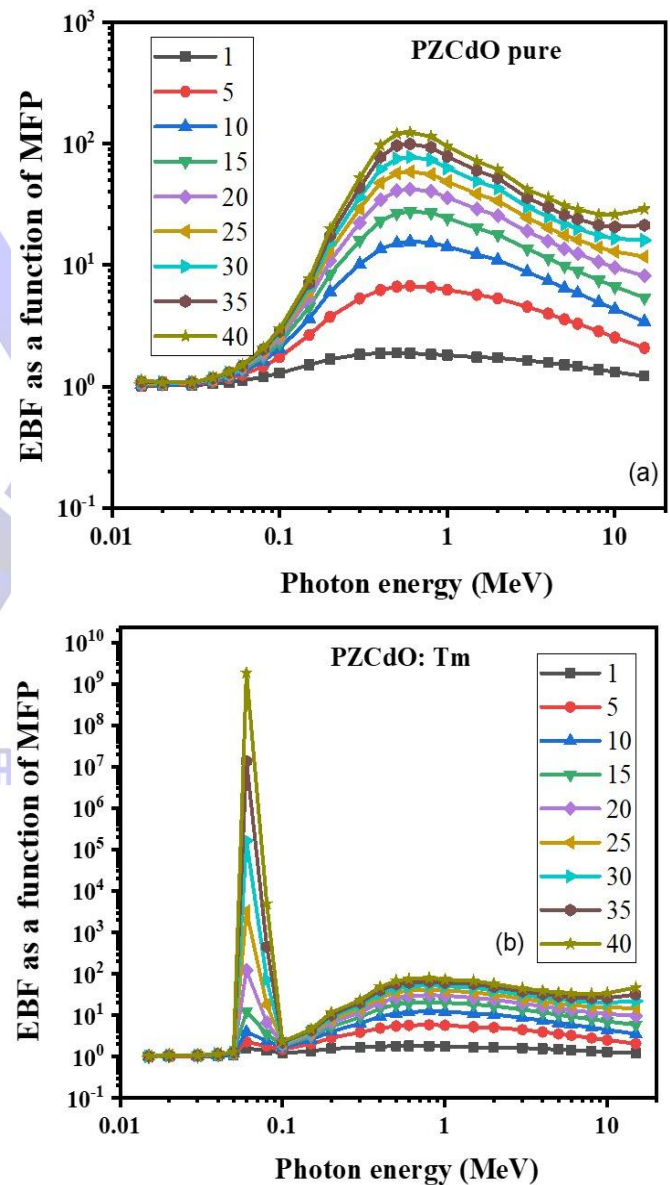


Fig. 4. Exposure build-up factor (EBF) as a function of photon energy at penetration depths of 1 to 40 mean free paths for (a) PZCdO pure and (b) PZCdO:Tm glasses. The anomalous low-energy resonance feature unique to the Tm-doped composition is clearly visible at approximately 0.06 MeV.

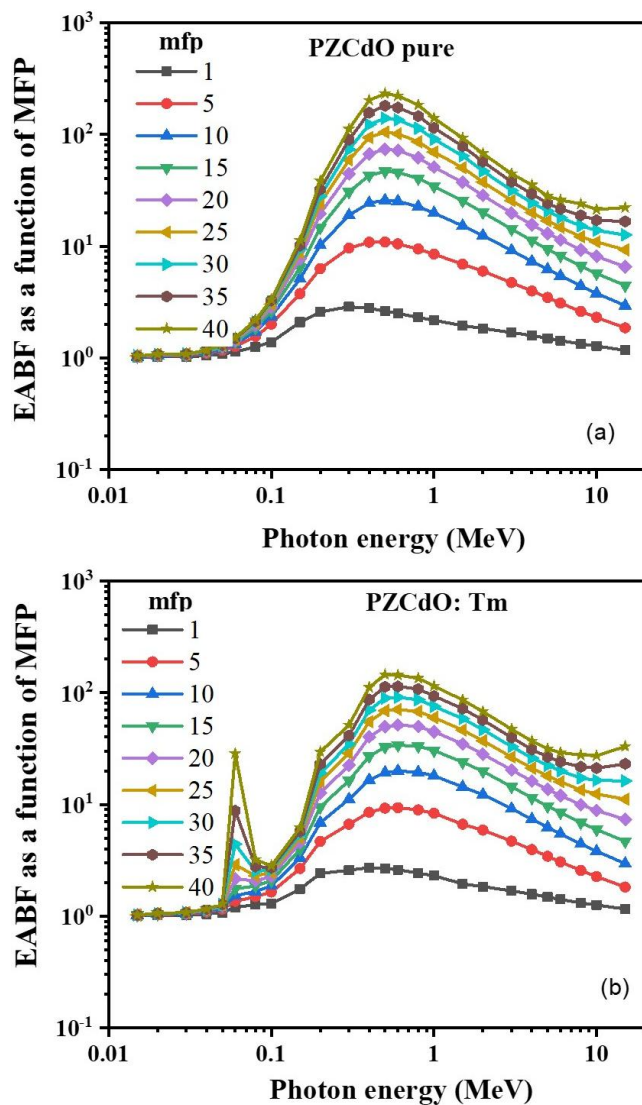


Fig. 5. Energy-absorption build-up factor (EABF) as a function of photon energy at penetration depths of 1 to 40 mean free paths for (a) PZCdO pure and (b) PZCdO:Tm glasses.

Below 10 mfp, the anomaly remains relatively minor, and above 0.15 MeV, the EBF and EABF for PZCdO:Tm revert to the smooth, Compton-dominated profile observed in pure glass, with 0.3 to 1 MeV peak values that are similar to or slightly lower than those of pure PZCdO at equivalent depths. The G-P fitting coefficients (b, c, a, X_k , d) for both compositions are presented in Figure 6. Both compositions exhibit smooth and comparable magnitude for coefficient b, which represents the build-up factor at 1 mfp. However, coefficient d displays a strong downward excursion at 1 to 2 MeV, while coefficient a shows dip and rebound behavior between 0.1 and 4 MeV. The anomalous EBF and EABF spike observed for the doped composition is likely caused by these characteristics of the underlying G-P coefficients rather than representing a physical resonance in the glass. The build-up factors at 1 MeV as functions of penetration depth are compiled in Table 5 for quantitative comparison between

compositions. It should be noted that the low-energy, high-mfp build-up values should be verified against Monte Carlo simulations using codes such as MCNP or Geant4 to confirm this behavior before application in practical shield thickness calculations.

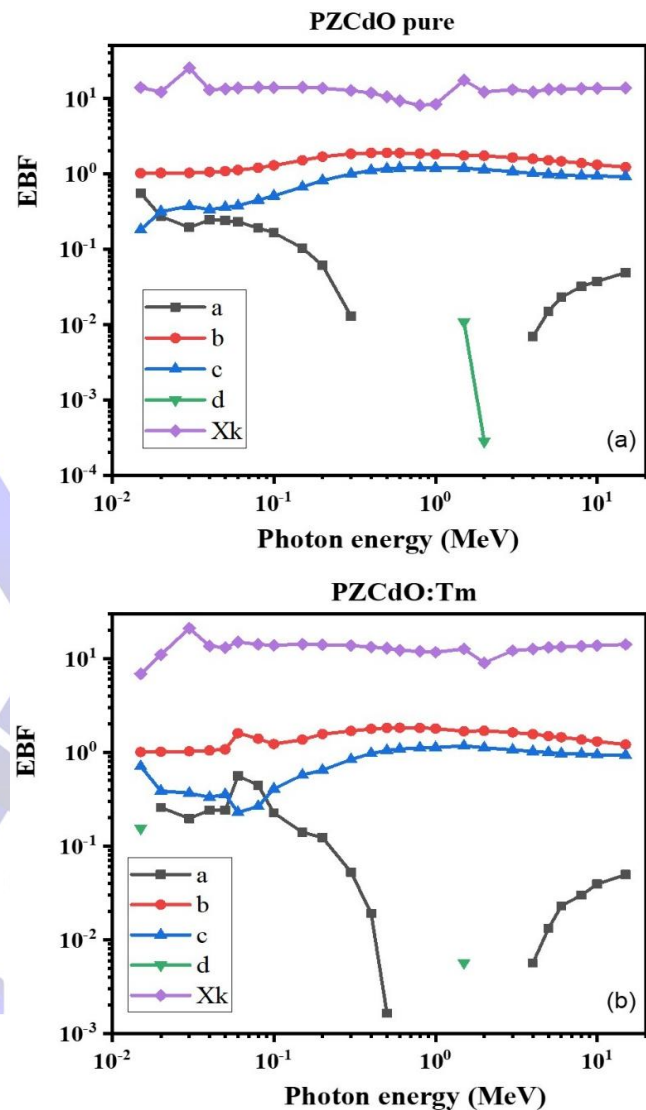


Fig. 6. Geometric Progression fitting coefficients (a, b, c, d, X_k) as functions of photon energy for (a) PZCdO pure and (b) PZCdO:Tm glasses. These coefficients were used to generate the EBF and EABF curves presented in Figures 4 and 5.

4.5. Fast-Neutron Removal Cross Section

The fast-neutron removal cross sections (FNRCs) for both glass compositions are presented in Figure 7 as a bar chart comparison. The FNRCs values for PZCdO pure and PZCdO:Tm (3.0 mol% Tm₂O₃) remain close to 0.099 cm⁻¹ for both compositions, demonstrating that the fast-neutron removal efficiency remains essentially unaffected by the modest amount of Tm₂O₃ added to the host matrix. This observation stands in stark contrast to the photon shielding

parameters, which exhibited significant enhancement upon thulium incorporation.

Table 5. Exposure build-up factor (EBF) and energy-absorption build-up factor (EABF) values for PZCdO pure and PZCdO:Tm at 1 MeV as functions of penetration depth (mean free paths).

Depth (mfp)	EBF Pure	EBF Tm	EABF Pure	EABF Tm
1	1.01158	1.00665	1.00986	1.00665
5	1.02004	1.01729	1.01843	1.01729
10	1.02994	1.01937	1.0253	1.01937
20	1.06249	1.02291	1.03893	1.02291
40	1.1248	1.02694	1.04038	1.02694

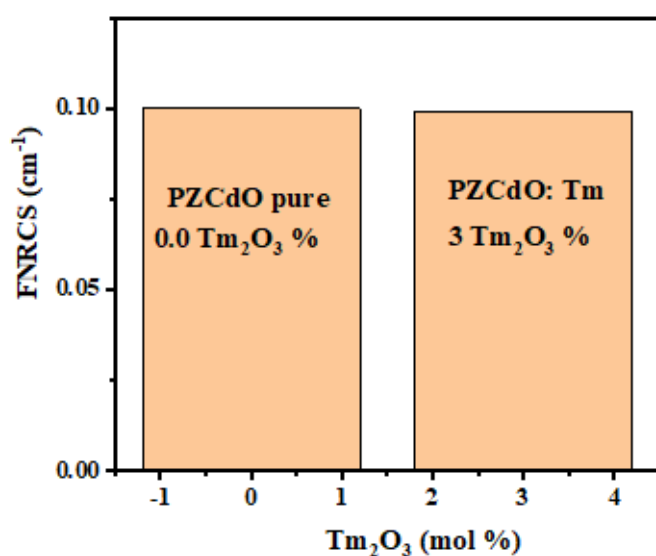


Fig. 7. Fast-neutron removal cross section (FNRCs, cm⁻¹) for PZCdO pure (0.0 mol% Tm₂O₃) and PZCdO:Tm (3.0 mol% Tm₂O₃) glasses. Both compositions exhibit nearly identical values of approximately 0.099 cm⁻¹.

5. CONCLUSION

This comprehensive computational investigation has systematically evaluated the gamma-ray shielding characteristics, effective atomic parameters, and fast-neutron removal cross sections of pure PZCdO glass and its Tm₂O₃-doped counterpart across the photon energy spectrum from 15 keV to 15 MeV. The incorporation of 30000 ppm (3 mol%) Tm₂O₃ resulted in enhanced mass and linear attenuation coefficients below approximately 0.5 MeV, with convergence at higher energies, while consistently reducing half-value and tenth-value layers throughout the entire energy range examined. Mean free paths diverged above 5 MeV with the doped glass attaining lower saturation values of approximately 9.7 cm compared to 10.7 cm for the pure composition, whereas below 1 MeV the two glasses

remained nearly equivalent. The PZCdO:Tm glass exhibited superior effective atomic numbers and equivalent atomic numbers across all measurements, with a distinct plateau region of approximately 37 to 38 for Z_{eq} observed between 0.1 and 1 MeV for the doped glass, contrasting with values of 30 to 31 for the undoped system. The build-up factors revealed an anomalous resonance-like feature at 0.06 MeV for the Tm-doped glass at significant penetration depths, which was attributed to characteristics of the underlying G-P fitting coefficients rather than a physical resonance in the glass. Notably, the fast-neutron removal cross sections remained essentially unaltered upon Tm₂O₃ incorporation, with both compositions yielding values of approximately 0.099 cm⁻¹. These findings demonstrate that PZCdO:Tm enhances photon shielding performance in photoelectric and low Compton-energy regions while preserving the fast-neutron attenuation capabilities of the undoped host matrix. The low-energy, high-mfp build-up values warrant verification through Monte Carlo simulations before practical application in shield thickness calculations.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

Jomanh M. Alshahrani: Formal Analysis, Data Curation, interpretation of results and Original draft preparation; Manar A. Asiri: Sample preparation, Experimental Work, Data collection, and interpretation of results.

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