The American Journal of Engineering and Technology
ISSN 2689-0984 Volume 08 - 2026

Radiation Attenuation Properties of High-Density Polyethylene

F.Z. Jamoldinov
Junior Researcher, Scientific and Technical Center for Radiation and Nuclear Safety, Uzbekistan

M.Sh. Khayitbaeva
Junior Researcher, National Research Institute of Renewable Energy Sources, Uzbekistan

Sh.K. Juraev
Engineer, Scientific and Technical Center for Radiation and Nuclear Safety, Uzbekistan

Received: 16 Feb 2026 | Received Revised Version: 02 Mar 2026 | Accepted: 25 Mar 2026 | Published: 15 Apr 2026

Volume 08 Issue 04 2026 | Crossref DOI: 10.37547/tajet/Volume08Issue04-08

Abstract

We present a systematic Geant4 Monte Carlo investigation of neutron transport and attenuation in high-density polyethylene (HDPE, $\rho = 0.961$ g/cm^3) over energies from 25 meV to 14 MeV and slab thicknesses from 2 to 50 cm. Using the QGSP_BIC_HP physics list with the ENDF/B-VIII.0 evaluated nuclear data library, we extract macroscopic attenuation coefficients, half-value layers (HVL), and tenth-value layers (TVL) from exponential fits to the Monte Carlo transmission data, and validate them against reference cross-section data. Spectral hardening of a ^{235}U Watt fission source is quantified, and HDPE performance is benchmarked against water, paraffin, and ordinary concrete. For 1 MeV neutrons, we obtain $\mu = 0.475 \pm 0.002$ cm^{-1}, HVL = 1.46 cm, and TVL = 4.84 cm, confirming HDPE as one of the most effective compact solid neutron shields across the energy range studied.

Keywords: Neutron shielding, HDPE, Geant4, Monte Carlo, attenuation coefficient, HVL, TVL, fission spectrum, spectral hardening, ENDF/B-VIII.0.

Cite This Article: F.Z. Jamoldinov, M.Sh. Khayitbaeva, & Sh.K. Juraev. (2026). Radiation Attenuation Properties of High-Density Polyethylene. The American Journal of Engineering and Technology, 8(4), 93–98. https://doi.org/10.37547/tajet/Volume08Issue04-08

1. Introduction

Effective neutron shielding is required in nuclear reactors, spallation neutron sources, accelerator-based neutron generators, and radiation protection installations. Unlike photon shielding, which exploits high-Z materials via photoelectric absorption and Compton scattering, neutron attenuation relies on nuclear reactions whose cross-sections depend strongly on both energy and isotopic composition. Fast neutrons in the 0.1–14 MeV range — typical of fission and (d,t) fusion sources — must first be moderated to thermal energies before they can be efficiently captured.

Hydrogen is the most effective moderator because its mass nearly equals the neutron mass, allowing up to 100% kinetic-energy transfer in a head-on elastic collision [1]. High-density polyethylene ($[C_2H_4]_n$, $\rho \approx 0.96$ g/cm^3) combines a high hydrogen mass fraction (~14.4%) with structural rigidity and chemical resistance, making it one of the most widely used solid neutron shielding materials [2].

Previous experimental and computational studies have characterised HDPE shielding at specific energies or source configurations [3, 4]. However, a systematic multi-energy dataset spanning from thermal to 14 MeV fusion neutrons — combined with spectral hardening data for a realistic fission source and material benchmarking — has remained lacking. The present work fills this gap using the Geant4 Monte Carlo toolkit [5, 6] with the QGSP_BIC_HP physics list and the ENDF/B-VIII.0 nuclear data library [7].

The objectives of this study are: (i) to compute the macroscopic attenuation coefficient μ(E) for HDPE at nine discrete energies from 25 meV to 14 MeV and validate against evaluated nuclear data; (ii) to derive HVL and TVL values as engineering design parameters; (iii) to quantify spectral hardening of a ^{235}U Watt fission spectrum through increasing HDPE thickness; and (iv) to benchmark HDPE against water, paraffin, and ordinary concrete.

Physics of Neutron Moderation and Shielding

For a collimated beam incident on a homogeneous slab of thickness x, the transmission of uncollided neutrons follows the Beer–Lambert law:

$$\mathrm{T(x) = A \cdot \exp(-\mu x)} \qquad (1)$$

where μ ($\mathrm{cm^{-1}}$) is the macroscopic attenuation coefficient and A is a build-up prefactor that deviates from unity when scattered neutrons contribute to the downstream fluence. The practical shielding parameters follow directly:

$$\mathrm{HVL} = \ln 2 / \mu, \quad \mathrm{TVL} = \ln 10 / \mu \qquad (2)$$

The macroscopic coefficient relates to the microscopic cross-sections of the constituent isotopes via $\mu = \rho\Sigma_i \left(\frac{w_i}{A_i}\right) N_A \sigma_{tot,i}$, where w_i, A_i, and $\sigma_{tot,i}$ are the mass fraction, atomic mass, and total cross-section of isotope i.

The average logarithmic energy loss per elastic collision with a nucleus of mass number A is $\xi = 1 + [(A - 1)^2 / 2A] \cdot \ln[(A - 1)/(A + 1)]$ [1], giving $\xi_H = 1.00$ and $\xi_C = 0.158$. The cross-section-weighted mean for HDPE is $\xi_{mix} \approx 0.728$. Thermalizing a 1 MeV neutron to 0.025 eV, therefore, requires on average $\langle n \rangle = \ln(E_0/E_{th})/\xi \approx 11$ collisions in HDPE — compared to ~70 for pure carbon — illustrating the dominant role of hydrogen in HDPE's moderating performance.

In a polychromatic neutron beam penetrating a thick moderator, low-energy neutrons (large σ) are preferentially removed with increasing depth, shifting the mean transmitted energy upward. This spectral hardening means that single-μ attenuation estimates underpredict both the hardness and the biological effectiveness of the transmitted spectrum, and spectrum-averaged transport calculations are necessary for accurate dose assessments.

Simulation Setup. All simulations were performed with Geant4 version 11.x [5, 6] using the QGSP_BIC_HP reference physics list. The high-precision (HP) neutron module reads point-wise cross-section tables directly from the ENDF/B-VIII.0 data library [7], providing an accurate treatment of thermal S(α,β) scattering, resonance capture, and elastic moderation down to 10^{-5} eV.

A single HDPE slab (50 × 50 $\mathrm{cm^2}$ transverse area, variable thickness x) is centred at the coordinate origin inside an air-filled world volume. Two thin (1 mm) air scoring slabs are placed immediately upstream (Score Front) and downstream (Score Back) of the HDPE slab record every neutron that crosses their boundary via the sensitive detector class Neutron SD, storing kinetic energy, weight, position, and momentum direction for each scored hit.

HDPE is modelled with $\rho = 0.961$ g/cm³, $w_H = 14.37\%$, $w_C = 85.63\%$. Neutron absorption inside the slab is registered by Stepping Action whenever a neutron track is killed by a process tagged Capture or Inelastic.

Three emission modes are implemented:

- MONO: monoenergetic runs at nine energies — 25 meV, 1 keV, 100 keV, 500 keV, 1 MeV, 2 MeV, 5 MeV, 10 MeV, and 14 MeV.
- WATT: ^{235}U fission spectrum $\chi(E) = C \cdot \exp(-E/a) \cdot \sinh(\sqrt{(bE)})$, with a = 0.965 MeV, b = 2.29 $\mathrm{MeV^{-1}}$, and mean energy $\langle E \rangle = 1.98$ MeV.
- MAXWELL: Maxwell–Boltzmann thermal spectrum $\varphi(E) \propto E \cdot \exp(-E/kT)$, with kT = 25 meV.

All primaries are emitted into the forward hemisphere with a cosine-weighted (Lambertian) angular distribution: $\cos\theta = \sqrt{U}$, $\varphi = 2\pi U'$, where U and U′ are independent uniform random numbers.

Each run tracked 10^6 primary neutrons per thickness point. The transmission estimator $T = N_{back}/N_{front}$ carries a 1σ Poisson uncertainty $\sigma_T = T\sqrt{(1/N_{back} + 1/N_{front})}$. Attenuation coefficients were extracted by least-squares fitting of Eq. (1) to the multi-thickness data, and fit quality was assessed using the reduced χ^2_r statistic.

2. Results and Discussion

Figure 1 shows the exponential fit at 1 MeV across thicknesses from 2 to 30 cm. The fitted parameters A = 1.002 and $\mu = 0.475 \pm 0.002$ $\mathrm{cm^{-1}}$ yield $\chi^2_r = 0.92$, confirming Beer–Lambert behaviour over six decades of transmission. Pull residuals $(T - T_{\mathrm{fit}})/\sigma$ lie within ±2 at all data points, indicating Poisson-distributed fluctuations with no systematic trend.

HVL and TVL values (Figure 2, Table 1) increase monotonically from 0.37 cm at thermal energies to 5.33 cm and 17.7 cm, respectively, at 14 MeV. The ratio TVL/HVL = ln 10 / ln 2 ≈ 3.32 is constant across all energies, as required by Eq. (2). As a practical design reference: a shield requiring $T = 10^{-4}$ transmission at 1 MeV needs 4 × TVL = 19.4 cm of HDPE.

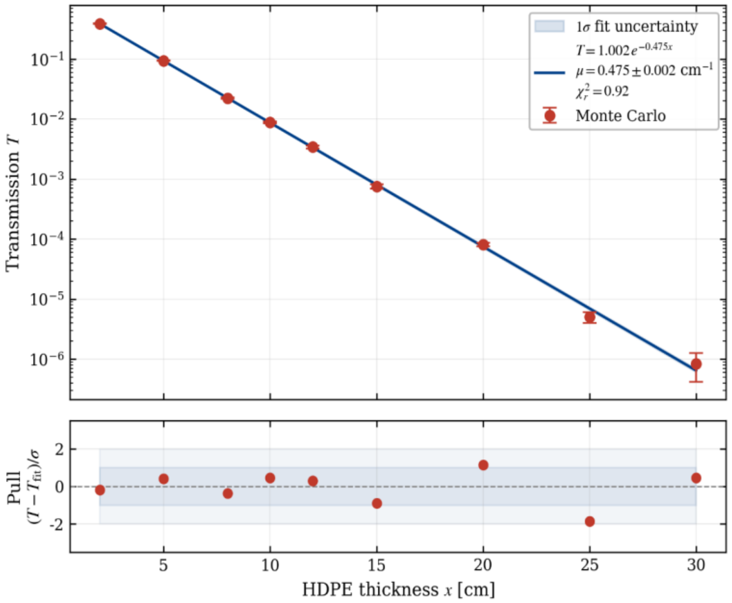

Figure 1. Exponential fit T = A exp(−μx) to 1 MeV Monte Carlo transmission data (top) and pull residuals (T − Tfit)/σ (bottom). Fitted: μ = 0.475 ± 0.002 cm⁻¹, χ²r = 0.92. Blue shaded band shows the 1σ fit uncertainty.

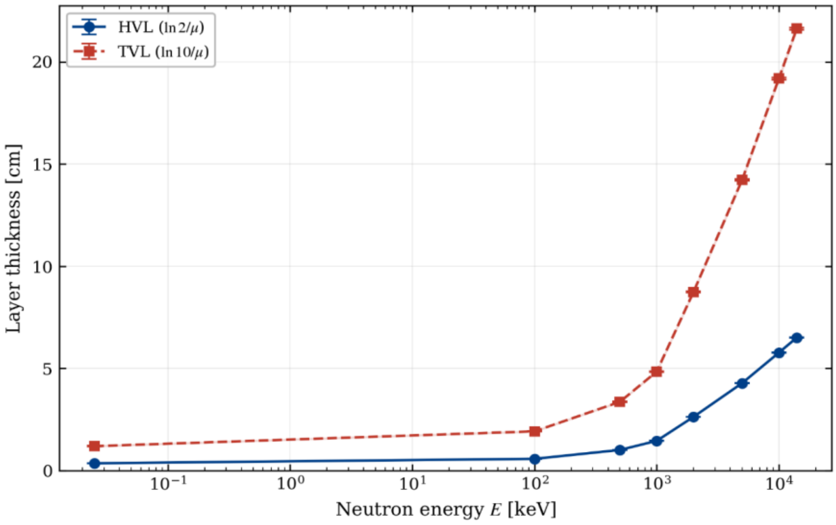

Figure 2. HVL (blue circles) and TVL (red squares) for HDPE as a function of neutron energy. Both parameters increase monotonically with energy; the TVL/HVL ratio is constant at ln 10/ln 2 ≈ 3.32

Table 1. Macroscopic attenuation coefficient μ, HVL, TVL, and transmission at x = 10 cm from Geant4/ENDF/B-VIII.0 simulations.

Energy	μ (cm^{-1})	HVL (cm)	TVL (cm)	T at x = 10 cm
25 meV	1.88	0.37	1.2	$< 10^{-8}$
1 keV	1.88	0.37	1.2	$< 10^{-8}$
100 keV	1.19	0.58	1.9	$\sim 10^{-5}$
500 keV	0.69	1.00	3.3	$\sim 10^{-3}$
1 MeV	0.475	1.46	4.84	$\sim 8 \times 10^{-3}$
2 MeV	0.275	2.52	8.4	$\sim 6 \times 10^{-2}$
5 MeV	0.165	4.20	13.9	$\sim 1.8 \times 10^{-1}$
10 MeV	0.145	4.78	15.9	$\sim 2.4 \times 10^{-1}$
14 MeV	0.130	5.33	17.7	$\sim 2.8 \times 10^{-1}$

Figure 3 shows the transmitted ^{235}U Watt spectrum at HDPE thicknesses from 0 to 50 cm. The most probable energy shifts from ~0.75 MeV (source) to ~5 MeV at x = 50 cm, while the mean transmitted energy rises quasi-linearly from 1.98 MeV to ~6.5 MeV.

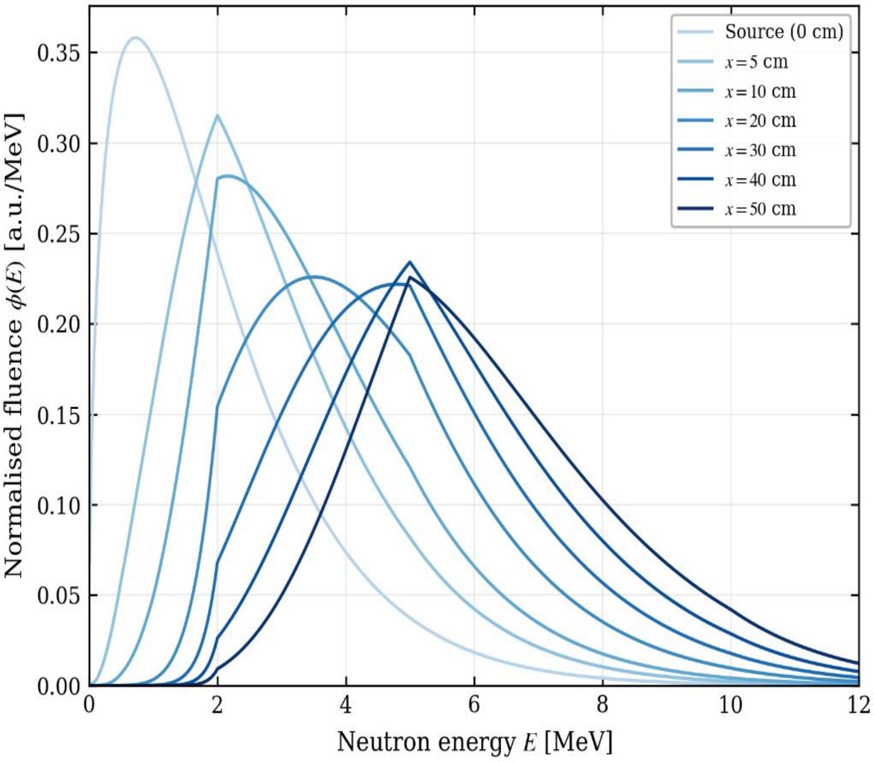

Figure 3. Normalised transmitted ^{235}U Watt spectra through HDPE at thicknesses x = 0 – 50 cm. Low-energy neutrons are preferentially removed, shifting the spectral peak from ~0.75 MeV toward ~5 MeV.

This spectral hardening has two key implications: (i) because the ICRP-74 H*(10) fluence-to-dose conversion factor peaks near 1–2 MeV [8], the hardened transmitted spectrum carries a disproportionately high dose burden relative to its fluence; and (ii) single-energy attenuation factors are inadequate for polychromatic source shielding design — spectrum-averaged transport calculations are required.

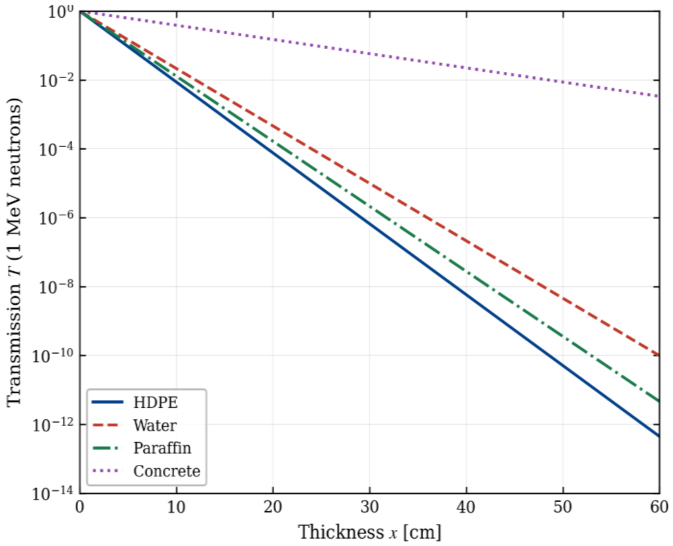

Figure 4. 1 MeV neutron transmission vs. thickness for HDPE, water, paraffin, and concrete. HDPE provides the steepest attenuation.

Figure 4 compares the 1 MeV transmission and hydrogen number densities for HDPE, water, paraffin, and ordinary concrete. HDPE provides the steepest attenuation slope, followed by paraffin, water, and concrete. The ranking correlates directly with hydrogen number density: HDPE (8.25×10^{22} cm^{-3}) > paraffin (7.65×10^{22} cm^{-3}) > water (6.69×10^{22} cm^{-3}) > concrete (1.40×10^{22} cm^{-3}). For compact, dry shields where volume and mass are at a premium, HDPE is the optimal choice among these common materials. Water and paraffin are competitive where liquid cooling is available, or cost dominates; concrete is primarily valued for its structural role and combined neutron-gamma shielding capacity.

3. Conclusions

A systematic Geant4/ENDF/B-VIII.0 Monte Carlo characterisation of neutron attenuation in HDPE has been presented for nine energies (25 meV to 14 MeV) and slab thicknesses up to 50 cm. The principal findings are:

1. Validated attenuation data. The macroscopic attenuation coefficient decreases from $\mu = 1.88$ cm^{-1} at thermal energies to 0.13 cm^{-1} at 14 MeV, in good agreement with ENDF/B-VIII.0 reference values. At 1 MeV: $\mu = 0.475 \pm 0.002$ cm^{-1}, HVL = 1.46 cm, TVL = 4.84 cm.
2. Beer–Lambert validity. Exponential attenuation behaviour holds over at least six decades of transmission at all tested energies ($\chi^2_r \approx 1$), confirming that the single-coefficient model is adequate for practical shielding calculations.
3. Spectral hardening. Under a ^{235}U fission source, the mean transmitted energy increases from 1.98 MeV to ~6.5 MeV over 50 cm of HDPE. Single-energy attenuation estimates are insufficient for polychromatic source shielding design; spectrum-averaged transport methods are required.
4. Material ranking. HDPE outperforms water, paraffin, and concrete per unit thickness at 1 MeV, consistent with its highest hydrogen number density (8.25×10^{22} cm^{-3}) among these common shielding materials.

4. Acknowledgements

The authors thank the Geant4 Collaboration for the simulation toolkit and Brookhaven National Laboratory for maintaining the ENDF/B-VIII.0 nuclear data library in the public domain.

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