

PTRAC-Based Investigation of Radiation Transport and Interaction Phenomena in Polymer

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1. Introduction

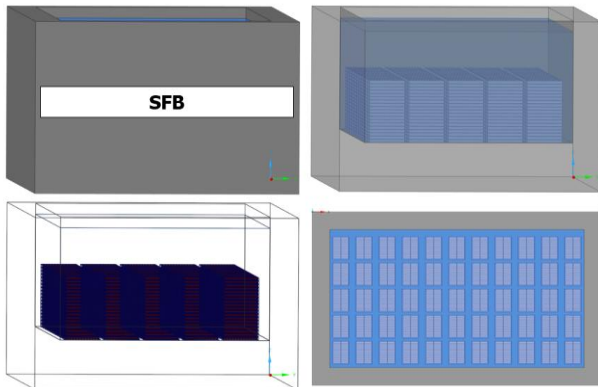


Fig. 1. Spent Fuel Bay (Containing spent nuclear fuel from a CANDU reactor) (CAD Model)

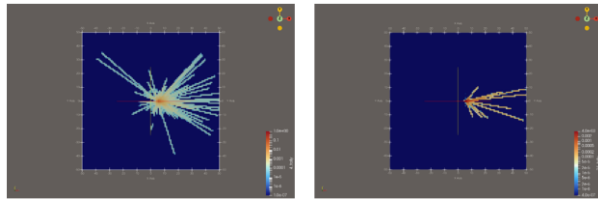


Fig. 2. MCNP Fmesh tally (Paraview)

The long-term integrity of wet storage facilities for spent nuclear fuel is threatened by aging degradation and leakage issues. Epoxy coatings on storage pool walls act as protective barriers, but their radiation-induced degradation mechanisms remain insufficiently understood. A systematic framework to analyze radiation-atom interactions in epoxy is therefore essential. Monte Carlo N-Particle (MCNP) simulations are widely used to estimate absorbed dose and flux. [1,2] However, conventional tally methods yield only bulk-averaged values, leading to significant uncertainties for thin polymer coatings. The Particle Track (PTRAC) [3,4] feature addresses this limitation by recording event-level interactions, enabling detailed assessment of microscopic transport, gamma-electron interactions, and depth-dependent energy deposition. This study employs PTRAC-based simulations to investigate gamma irradiation in thin epoxy coatings. By comparing tally outputs with PTRAC results, we clarify microscopic energy transfer processes and propose a methodology for predicting degradation

pathways. The outcomes provide insights for reliable design and performance assessment of epoxy-based coatings in nuclear fuel wet storage systems.

2. Methods and Results

In this section some of the techniques used to model the detector channel are described. The channel model includes a SiC detector, cable, preamplifier, amplifier, and discriminator models.

2.1 Geometry and Source Modeling

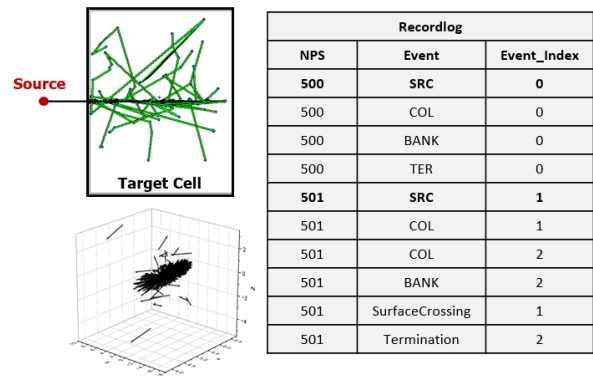


Fig. 3. PTRAC Individual-event record mechanism

All simulations were performed using the MCNP6.3 code with the PTRAC option enabled to generate event-level histories in HDF5 format. The system geometry consisted of thin epoxy slabs with varying thicknesses to represent protective coatings. The epoxy composition was defined as Bisphenol A resin cured with triethylenetetramine (TETA), and the corresponding atomic fractions were derived from the chemical structure and incorporated into the input deck [5]. As the radiation source, monoenergetic gamma rays of 1.17 and 1.33 MeV, representative of Co-60 decay, were employed. To accurately capture low-energy transport within thin films, a weight window variance reduction technique was implemented.

2.2 Physics Modeling and Data Processing

Photon-atom interactions, including photoelectric absorption, Compton scattering, and pair production, were tracked at the collision level using PTRAC. Event-

level information, such as particle type, energy, spatial coordinates, and interaction type, was recorded and exported in HDF5 format for subsequent analysis. Post-processing was conducted in Python, where secondary electron spectra generated from gamma interactions were reconstructed, and depth-dependent energy deposition profiles were obtained. For macroscopic reference, conventional F4 and F6 tallies were also calculated to evaluate flux and energy deposition. Comparative analysis between tally outputs and PTRAC results was performed to highlight the differences between bulk-averaged and event-resolved transport characteristics..

2.3 Tally Result

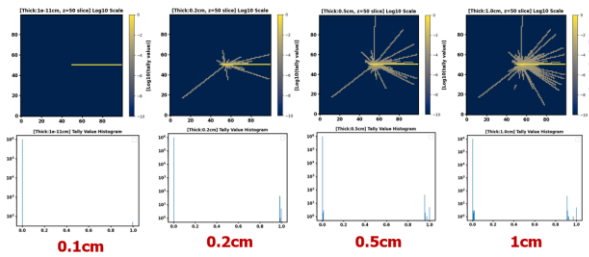


Fig. 4. Photon flux distribution obtained from MCNP mesh tally as a function of depth

Irradiation of beam-shaped radiation onto epoxy films revealed, as confirmed by the mesh tallies, that scattering increased markedly with target thickness. Table I summarizes the tally outcomes. The F6 tally quantified the deposited energy within the target, where the maximum peak corresponded to the γ -ray source energy, and a pronounced rise was observed in the 0–0.4 MeV range. Meanwhile, the Tally 8 pulse height results exhibited identical responses for electrons and photons, attributable to the fact that photons deposit energy exclusively via secondary electron production.

Table I: Tally Result (F4 tally, F6 tally)

Polymer Depth (cm)	F4 tally (#/cm ²)	F6 tally (MeV/cm ²)
0.1	0.00322278	0.000114702
0.2	0.00324939	0.000114799
0.5	0.0033186	0.000114944
1	0.00341163	0.000114869

2.4 PTRAC Result

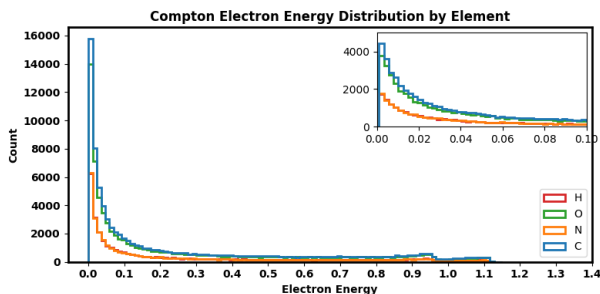


Fig. 5. Compton electron energy distributions for individual elements (C, H, O, N). The counts are plotted as a function of electron energy, showing a dominant contribution at low energies with a rapid decrease toward higher energies.

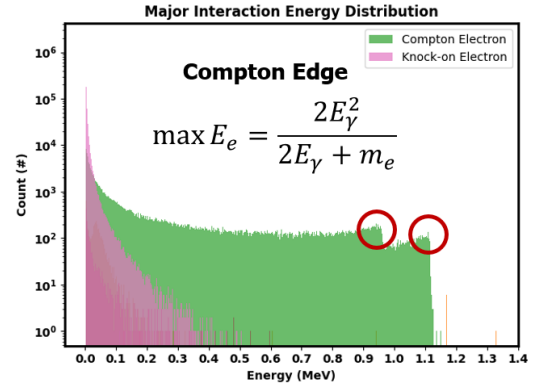


Fig. 6. Major interaction event Energy Distribution in Epoxy Polymer cell (Compton scattering, Knock-on scattering)

In Compton scattering, the energy transferred to the recoil electron strongly depends on the scattering angle of the photon. [6,7] When photons undergo forward scattering, which is by far the most probable case, only a small fraction of their energy is imparted to the electron, resulting in a large population of low-energy electrons. In contrast, high-energy electrons are produced only when photons are scattered at large angles, but such events occur with very low probability. Consequently, the overall electron energy distribution is dominated by low-energy electrons and decreases rapidly toward higher energies, exhibiting a quasi-exponential trend.

3. Conclusions

This study employed the PTRAC feature of the MCNP6.3 code to investigate radiation transport and interaction phenomena within epoxy-based polymer materials using an event-resolved approach. By overcoming the limitations of conventional bulk-averaged tallies (e.g., F4 and F6), the analysis enabled detailed characterization of energy deposition profiles and scattering behavior induced by photon and electron interactions. The results demonstrated that most energy transfer occurs through low-energy electrons generated via Compton scattering, while high-energy electrons appear with low probability, yielding an exponentially decreasing electron energy distribution. Furthermore, increased specimen thickness led to enhanced scattering and distinct depth-dependent behaviors between electrons and photons. These findings confirm that PTRAC-based simulations provide valuable insights into the microscale physics of radiation interactions and serve as a reliable methodology for the performance assessment and shielding design of nuclear fuel storage systems.

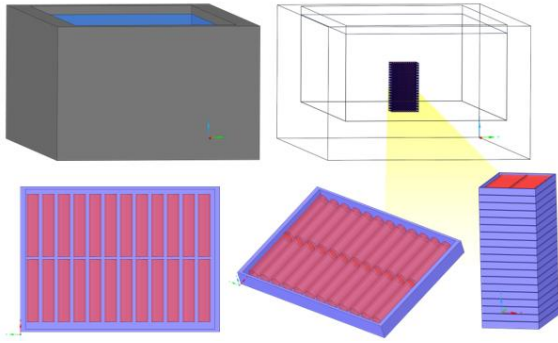


Fig. 7. SFB and Spent fuel Modeling (CAD Model)

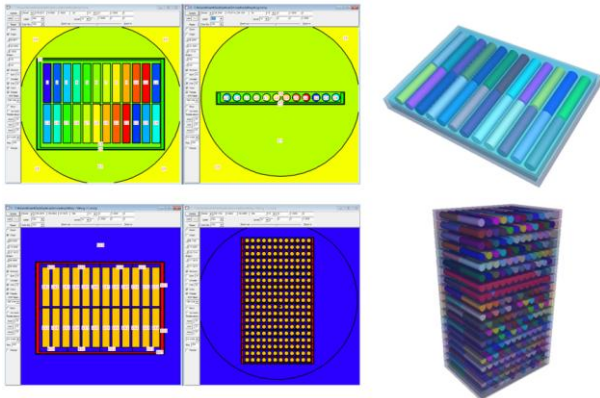


Fig. 8. CANDU Spent fuel Modeling with MCNP6 and Visualization with Visual Editor

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