

Effects of Polyethylene Configuration and Mass Fraction on the Neutron Shielding Performance of a Self-Shielded Medical Cyclotron

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1. Introduction

Neutrons generated by medical cyclotrons can induce activation in its self-shield. Therefore, accurate evaluation of neutron fluence distributions within the self-shield is important. As shown in Fig. 1 for the self-shield, PE is irregularly distributed within the shielding in the form of spherical particles. A previous study [2] reported that a random arrangement model of B₄C spheres requires a greater modeling effort than periodic arrangement models and that, under 14.1 MeV fast-neutron irradiation, differences in shielding performance due to particle spatial arrangement are limited. Although the B₄C particles considered in that study function as neutron absorbers, whereas PE serves as a neutron moderator in the present study, the results suggest the potential for simplifying high-energy neutron transport models using periodic particle arrangements. Accordingly, in this study, a discrete PE-sphere model was constructed using a periodic body-centered cubic (BCC) arrangement instead of explicitly representing the irregular distribution of PE spheres. The model was compared with a compositionally equivalent homogeneous model to evaluate the feasibility of simplifying the Monte Carlo simulation through homogenization. In addition, the effects of PE spatial configuration and mass fraction on neutron shielding performance were investigated.



Fig. 1. Cyclotron concrete self-shield
(Siemens Eclipse™)

2. Materials and Methods

The self-shield was modeled with a thickness of 80 cm and cross-sectional dimensions of 80 cm × 120 cm. Seven models were evaluated using three PE configurations—discrete, homogeneous, and layered—two

PE mass fractions of 22.36 and 41.28 wt%, and a PE-free reference model.

2.1 Material Composition and Density

The reference composition was adopted from the cyclotron self-shield reported in [1]. Representative constituent densities were obtained from technical literature, databases, and supplier data [3–6]: 3.150, 2.650, 2.510, and 0.950 g/cm³ for Portland cement, sand, B₄C, and PE, respectively. The calculated densities of borated concrete and the reference and maximum-packing homogeneous models were 2.873, 1.978, and 1.565 g/cm³, respectively. The shielding compositions are summarized in Table I.

Table I. Mass fractions of constituent materials (wt%)

Material	Maximum packing PE	Reference PE [1]	PE-free concrete
Portland cement	28.9936	38.3387	49.3827
Sand	28.9936	38.3387	49.3827
Polyethylene	41.2880	22.3642	-
B ₄ C	0.7248	0.9584	1.2346
Total	100.000	100.000	100.000

2.2 Shielding Model Geometry

The discrete PE-sphere model was constructed by periodically repeating BCC unit cells containing 0.94-cm-diameter PE spheres using the MCNP Universe and FILL features. The unit-cell dimensions were adjusted to reproduce either the reference (22.36 wt%) or maximum-packing (41.28 wt%) PE content. The homogeneous model represented the corresponding composition as a single uniformly mixed material region. In the layered model, PE was placed upstream of the borated-concrete matrix, and its thickness was determined from the corresponding PE volume fraction to preserve the total PE content. The model geometries are shown in Fig. 2.

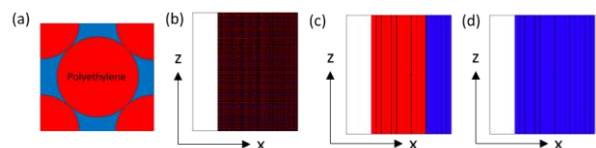


Fig. 2. Shielding geometries: (a) BCC unit cell, (b) discrete PE-sphere model, (c) layered PE model, and (d) homogeneous model

2.3 Neutron Source and MCNP6 Simulation

A simplified 11 MeV monoenergetic neutron source was employed to compare the effects of shielding configuration under identical source conditions. Neutrons were uniformly emitted from a rectangular planar source with dimensions of 80 cm × 120 cm, located 20 cm from shielding surface. A monodirectional parallel beam normal to the shielding surface along the +x direction was applied consistently to all shielding models. MCNP6 simulation was performed using 10^8 source neutron histories. F2 tally was used at 5 cm intervals from 0 to 80 cm of shielding depth to determine the surface-averaged neutron fluence per source neutron.

3. Results and Discussion

The calculation results are presented in Fig. 3. In all models, the neutron fluence at a depth of 5 cm was higher than that at the shielding surface. The MCNP F2 tally accounts not only for neutrons traveling in the incident direction but also for backward- and obliquely traveling neutrons generated by scattering within the shielding. Therefore, the higher surface-averaged neutron fluence observed at 5 cm is attributed to the increase in multidirectional neutron components caused by scattering near the front region of the shielding. At greater depths, neutron fluence continuously decreased as neutron moderation, absorption, and leakage became dominant. A similar trend was reported in a previous study [7], in which neutron collisions increased within the first 10 cm of borated concrete containing PE aggregate and subsequently decreased with increasing depth. For all models, the neutron fluence at 80 cm was reduced by more than 99.85% relative to the surface value. To quantitatively compare the shielding performance among the models, the rear-surface neutron fluence at 80 cm was normalized to that of the PE-free model, and the results are summarized in Table II.

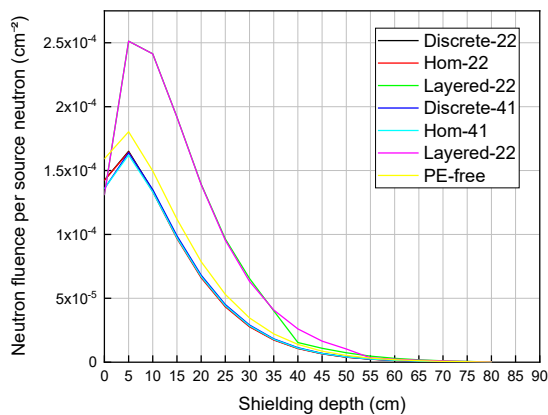


Fig. 3. Depth-dependent neutron fluence for different shielding models

Table II. Comparison of neutron shielding performance among shielding models

Model	Φ_5	Φ_{80}	Φ_{80} Normalized (PE-free = 1.000)
Hom-22	1.65×10^{-4}	9.01×10^{-8}	0.842
Discrete-22	1.65×10^{-4}	9.15×10^{-8}	0.855
Hom-41	1.62×10^{-4}	9.96×10^{-8}	0.931
Discrete-41	1.64×10^{-4}	1.02×10^{-7}	0.953
PE-free	1.80×10^{-4}	1.07×10^{-7}	1.000
Layered-41	2.51×10^{-4}	1.85×10^{-7}	1.729
Layered-22	2.51×10^{-4}	1.86×10^{-7}	1.738

4. Conclusions

The discrete and homogeneous models exhibited comparable depth-dependent fluence trends at the same PE mass fraction, while the influence of PE mass fraction was generally comparable to or greater than the difference between these two representations. The layered models showed higher rear-surface neutron fluence than the distributed PE configurations. Under the present calculation conditions, the results support the use of a homogeneous model as a simplified representation of the discrete PE-sphere model.

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