**Article ID**：1007-4627(2011)01-0083-05

# Calculations of Neutron and γ Transport through Rare-earth Doped Polymer*

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**Abstract**：A series of shielding analyses have been performed to estimate the material composition and optimum thickness required for a new radiation shield with various rare-earth doped polymer and heavy metal mixtures. The neutron and $\gamma$ photon fluxes have been calculated by Monte Carlo N-Particle(MCNP) transport code. The results indicate that the relative fluxes of $\gamma$ photon and neutron in both traditional and new composite materials follow an exponential decay rule with the distance of penetration. It can be seen that the composite material consisting of rare-earth doped polymer and heavy metal has stronger neutron shielding performance than lead-boron polyethylene，but weaker $\gamma$ shielding effectiveness than W-Ni alloy. It is also found that materials with more components of rare earth elements don't always provide better neutron shielding performance.

**Key words**：nuclear shielding material；MCNP simulation；neutron and $\gamma$；rare-earth/polymer/heavy metal

**CLC number**：TL328 **Document code**：A

## 1 Introduction

Shield design is the first step of radiation protection. The most important property is the shielding effectiveness to neutron and $\gamma$ ray[1]. None of single traditional materials provide good comprehensive shielding effectiveness to both neutron and $\gamma$ ray. And they meet the conflict between shielding effectiveness and other performances such as mechanical performance，heat-resistant stability and anti-radiation property[2]. Therefore new composite shielding materials are needed in application.

Extensive studies of lead-boron polyethylene have been carried out since mid-1970s because of its comprehensive shielding effectiveness to fast neutron，thermal neutron and $\gamma$ ray[3]. In 1994，high effective shielding material lead-boron polyethylene has been developed by Nuclear Power Institute of China[3]. Now lead-boron polyethylene has been widely used in nuclear power reactor shields. The future study of shielding materials will focus on rare-earth doped polymer composite materials. Rare-earth elements，as the major strategic resource in China[2]，rank No. 1 in total reserves and production scale in the world. The thermal neutron absorption cross-sections of rare-earth elements (Sm 5600 b，Eu 4300 b，Gd 46000 b) are much larger than that of $^{10}B$(3750 b)[4]. Polymer materials with significant absorption cross-sections for fast neutrons，are easy-processing and corrosion-resistant[5]. In 1983 Ida developed a shielding material for neutron with rare-earth dosage lower

* **Received date**：30 Apr. 2010；**Revised date**：25 Jul. 2010

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than 10%[6]. Later, the rare-earth dosage has been increased over 50% by Liu Li and others[5].

To find a new composite shield from neutron and γ ray, it's necessary to choose several materials from many to satisfy the constraints[2]. Little information is available about neutron and γ transport in rare-earth doped polymer shields based on Monte Carlo simulation which reduces the number of experiments, cost, and experimenters' occupational exposure. In this paper, γ and neutron shielding effectivenesses of 7 shields consisting of rare-earth doped polymer and heavy metal were calculated by Monte Carlo N-Particle (MCNP) transport code[7].

## 2 Simulation

MCNP is a software package for simulating nuclear processes developed by Los Alamos National Laboratory. It is a general-purpose, continuous-energy, generalized geometry, time-dependent, coupled neutron, photon, electron Monte Carlo transport code system. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first-and second-degree surfaces and fourth-degree elliptical tori[7].

For neutrons, all reactions given in a particular cross-section evaluation are accounted for. Thermal neutrons are described by both the free gas and S(α, β) models. For photons, the code takes account of incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung[7].

### 2.1 Geometric modeling

As shown in Fig. 1, the shielding calculation was carried out with MCNP code using a symmetric geometry. An isotropic point source is fixed at the center of a 0.1 cm radius spherical space and surrounded by a spherical shielding wall consisting of rare-earth doped polymer and heavy metal.

### 2.2 Selection of materials

$Gd_2O_3$ was selected as the rare-earth component of shielding material due to the largest thermal neutron absorption cross-section of Gd among rare-earth elements. $C_2H_4$ is used as the polymer component taking advantage of its low density, low cost and good mechanical property. Non-toxic W-Ni alloy, which has higher melting point, hardness and compression strength compared with Pb, is chosen as γ ray absorber. Table 1 shows seven composite materials with varied quantities of rare-earth, polymer and heavy metal. Materials 8 and 9 are the lead-boron polyethylene: $B_4C$(1%), Pb(80%), $C_2H_4$(19%) and the W-Ni alloy: W(74%), Ni(15%), Fe(11%), respectively.

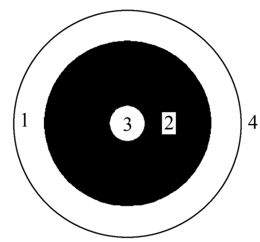


Fig. 1 Schematic diagram of shielding system for MCNP simulation (1. Vacuum, 2. Shielding material, 3. Isotropic point source, 4. Spherical tally).

**Table 1 The molar ratios of each component in shielding materials**

| Type of material | $Gd_2O_3$ | $C_2H_4$ | W-Ni alloy |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 5 | 3 | 1 |
| 3 | 3 | 5 | 1 |
| 4 | 3 | 1 | 5 |
| 5 | 5 | 1 | 3 |
| 6 | 1 | 3 | 5 |
| 7 | 1 | 5 | 3 |

### 2.4 Simulation and discussions

A series of nuclear analyses have been performed with varied quantities of shielding material components. By calculating neutron and γ photon transport in materials, neutron and γ photon relative flux are obtained for six different energy regions in seven materials. The results are shown in

Figs. 2 and 3 for six different energy regions.

Take Material 5 as an example, $\lg(I/I_0)$ is the logarithm of relative flux, $I$ and $I_0$ are respectively the number of neutrons (or γ photons) before and after the absorption of material. As shown in Fig. 2, $\lg(I/I_0)$ clearly varies with shield thickness and source energy. It decreases approximately linearly with increasing the shield thickness, and has a higher decreasing rate in the case of lower neutron energy. Further analysis revealed that for neutrons in a certain energy region, $\lg(I/I_0)$ decreases more rapidly in the case of larger thickness. We also conclude from Fig. 2 that for neutrons in energy region 5—10 MeV, $\lg(I/I_0)$ drops sharply at the thickness of 15 cm, which is significantly lower than those corresponding to neighboring thicknesses. Fig. 3 shows similar results with Fig. 2 except that $\lg(I/I_0)$ in Fig. 3 keeps better linear relation with shield thickness.

We define the shutdown thickness as the shield thickness at which the neutron and γ relative flux drops to 0.5%, as shown in Tables 2 and 3 for 7 materials with respect to energies of neutron and γ ray.

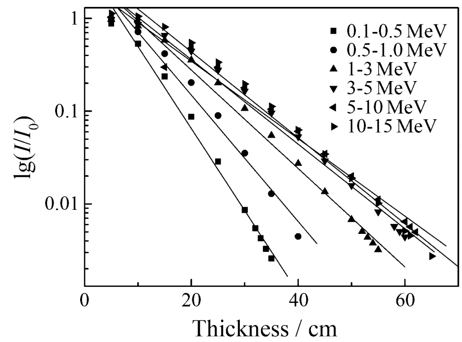


Fig. 2　The logarithm of neutron relative flux $\lg(I/I_0)$ in the shield as a function of shield thickness with various source energies.

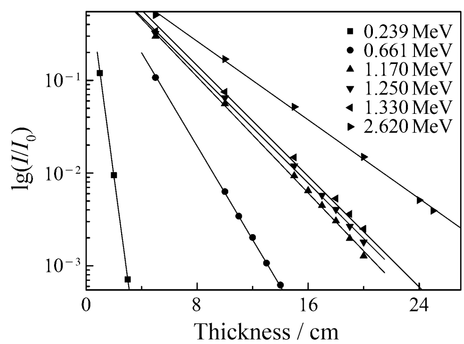


Fig. 3　The logarithm of γ photon relative fiux $\lg(I/I_0)$ in the shield as a function of shield thickness with various source energies.

**Table 2　Shutdown thicknesses of materials 1—8 for neutron shielding**

| | 0.1—0.5 MeV | 0.5—1 MeV | 1—3 MeV | 3—5 MeV | 5—10 MeV | 10—15 MeV |
|---|---|---|---|---|---|---|
| Material 1 (cm) | 22 | 28 | 41 | 49 | 57 | 59 |
| Material 2 (cm) | 25 | 32 | 46 | 55 | 61 | 61 |
| Material 3 (cm) | 19 | 25 | 38 | 49 | 59 | 64 |
| Material 4 (cm) | 30 | 37 | 47 | 54 | 57 | 58 |
| Material 5 (cm) | 33 | 40 | 53 | 59 | 62 | 61 |
| Material 6 (cm) | 19 | 25 | 35 | 42 | 51 | 58 |
| Material 7 (cm) | 17 | 22 | 33 | 42 | 54 | 64 |
| Material 8 (cm) | 31 | 41 | 54 | 59 | 68 | 77 |

**Table 3　Shutdown thicknesses of materials 1—7 and material 9 for γ ray shielding**

| | 0.239 MeV | 0.661 MeV | 1.17 MeV | 1.25 MeV | 1.33 MeV | 2.26 MeV |
|---|---|---|---|---|---|---|
| Material 1 (cm) | 3 | 13 | 21 | 22 | 23 | 30 |
| Material 2 (cm) | 4 | 14 | 22 | 23 | 24 | 32 |
| Material 3 (cm) | 5 | 14 | 28 | 30 | 31 | 41 |
| Material 4 (cm) | 2 | 10 | 15 | 16 | 17 | 22 |
| Material 5 (cm) | 3 | 11 | 17 | 18 | 19 | 25 |
| Material 6 (cm) | 3 | 12 | 19 | 20 | 21 | 27 |
| Material 7 (cm) | 4 | 18 | 29 | 30 | 31 | 42 |
| Material 9 (cm) | 1 | 4 | 7 | 8 | 8 | 10 |

Table 2 indicates that the shutdown thicknesses of our new composite materials 1—7 to neutron are smaller than those of traditional material 8 (lead-boron polyethylene) for neutrons in almost all energy regions. Materials 3, 6, 7 have relatively smaller shutdown thicknesses and better shielding effectivenesses.

As the absorption cross-sections of thermal neutrons, slow neutrons, and intermediate neutrons of rare-earth elements are all much larger than those of authoritative neutron absorption elements $^{10}B$ and Cd, even fast neutron cross-sections of rare-earth elements are also much larger than that of Cd, Liu Li et al[5] theoretically conclude that materials with higher component of rare earth elements provide better neutron shielding effectivenesses. But our simulation results indicate that materials with more components of rare earth elements don't always provide better neutron shielding effectivenesses. Table 1 shows the comparison of components of materials 1—7, we find a more effective shielding performance has been achieved with reducing levels of $Gd_2O_3/C_2H_4$ mixtures.

Here it is worth to note that although rare-earth elements own large neutron absorption cross-sections, unless enough polymer is provided to moderate most of the fast neutrons, materials with more components of rare-earth elements will provide better neutron shielding effectivenesses. In order to verify this conclusion, we will perform further simulation: to determine the needed dosage of polymer material to moderate fast neutrons, then investigate the liability for shielding effectiveness on component of rare-earth elements under this needed dosage of polymer.

From Table 2 we also find a better shielding performance has been achieved with reducing levels of $Gd_2O_3$/W-Ni alloy mixtures. This tendency cannot be well explained, further study is needed to reveal the reason.

Table 3 indicates that the shutdown thicknesses of materials 1—7 to γ ray are all larger than those of W-Ni alloy. Thus we can choose W-Ni alloy thickness in the case of γ ray shielding. In addition, materials 4, 5, and 6 show good shielding effectivenesses to neutron. In sufficient thickness, they effectively shield both the neutron and γ radiation. Combining the results from Tables 2 and 3, it can be seen that material 6 shows the best comprehensive shielding ability to neutron and γ ray. Consequently, the overall shielding effectiveness of composite shield consisting of rare-earth doped polymer and heavy metal is better compared to traditional shields.

## 3 Conclusion

We studied neutron and γ photon transport in shielding materials consisting of rare-earth doped polymer and heavy metal using MCNP code. The simulated results indicate that the relative flux of γ photons or neutrons in an absorber follow an exponential variation with the increasing distance of penetration. Our results show the composite material consisting of rare-earth doped polymer and heavy metal has stronger neutron shielding performance than lead-boron polyethylene, but weaker γ shielding effectiveness than W-Ni alloy. Meanwhile, materials with more components of rare earth elements don't always provide better neutron shielding performance. Among seven materials, the material 6 shows the best comprehensive shielding effectiveness to neutrons and γ photons. If we further consider the material's mechanical property, heat-resistance and anti-irradiation property, the materials will be more practical in engineering.

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# 中子、γ 射线在稀土-高分子材料中的输运*

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**摘　要**：为研究新型复合屏蔽材料的最佳厚度与各种成分最佳配比，用 MCNP 计算了中子、γ 射线在稀土-高分子与重金属复合材料中的通量。对中子、γ 射线在屏蔽体中变化规律进行了深入探索，同传统复合屏蔽材料的屏蔽性能进行了对比。结果表明，中子和 γ 射线通过屏蔽体时，其强度遵循指数衰减规律。新型屏蔽材料对中子的屏蔽效果均优于铅硼聚乙烯，对 γ 射线的屏蔽效果均劣于 W- Ni 合金，且并非稀土含量越高，材料对中子辐射屏蔽能力越强。

**关 键 词**：辐射屏蔽材料；MCNP 模拟；中子和 γ 射线；稀土-高分子-重金属材料

* **收稿日期**：2010-04-30；**修改日期**：2010-07-25

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