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A method to optimize the shield compact and lightweight combining the structure with components together by genetic algorithm and MCNP code

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HIGHLIGHTS

- A method to optimize the shield combining the structure with components together was carried out.
- Six types of materials were presented and optimized.
- Geometry effect of four geometries used in practice has checked.

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ABSTRACT

To optimize the shield for neutrons and gamma rays compact and lightweight, a method combining the structure and components together was established employing genetic algorithms and MCNP code. As a typical case, the fission energy spectrum of ^{235}U which mixed neutrons and gamma rays was adopted in this study. Six types of materials were presented and optimized by the method. Spherical geometry was adopted in the optimization after checking the geometry effect. Simulations have made to verify the reliability of the optimization method and the efficiency of the optimized materials. To compare the materials visually and conveniently, the volume and weight needed to build a shield are employed. The results showed that, the composite multilayer material has the best performance.

1. Introduction

Radiation shielding is an important part of the nuclear facilities. For the facilities have abundant space, such as nuclear reactors and accelerators, the shield is quite simple because concrete is relatively inexpensive and could provide adequate shielding for the neutrons and gamma rays which are mainly considered during the shielding design. However, for the facilities whose space are limited, such as compact pressurized water nuclear reactor (Tunes et al., 2017), compact accelerator-driven neutron source (Hu et al., 2017) and some other compact systems or mobile devices, the shield becomes much more difficult. It must be compact, lightweight, and might be very specialized (Wielopolski et al., 2007). Even for the most experienced shielding designers, they may do not know whether their design is optimal in any sense. Thus, it is important to have a study on the shielding design for the compact systems and mobile devices.

In general, the method of shield designing is a "brute force" trial-and-error procedure which is tempered by experience (Schaeffer, 1973). However, optimization techniques using genetic algorithms, linear programming, sequential quadratic programming and transmission matrix methods (Guang Hu et al., 2017; Hu et al., 2008; Kebwaro et al., 2015; Leech and Rohach, 1972; Tunes et al., 2017) have gradually applied to improve it in recent years. Several composite materials and multilayer materials with excellent performance have presented in the studies, and these studies demonstrated that it is efficient to design the shielding material based on optimization algorithms.

However, there still exists a problem that the shields are almost designed by varying the thickness or component of the material alone. There lacks an integrated design of the shield combining the structure and components together (The "structure" means the thickness ratio and total thickness of the multilayer shielding material, the "components" means the components of the each layer). Moreover, due to the change of energy spectrum, the optimum thickness ratio of the multilayer material should be varied with its total thickness. But the previous studies are all tended to optimize it using a small thickness, and apply the solution to a larger thickness then. It is improper to do as that. Thus, it is necessary to carry out an effective method to design the shield compact and lightweight combining the structure and components together. This study exactly addresses this problem.

First, the shielding of neutrons and gamma rays are analyzed, and

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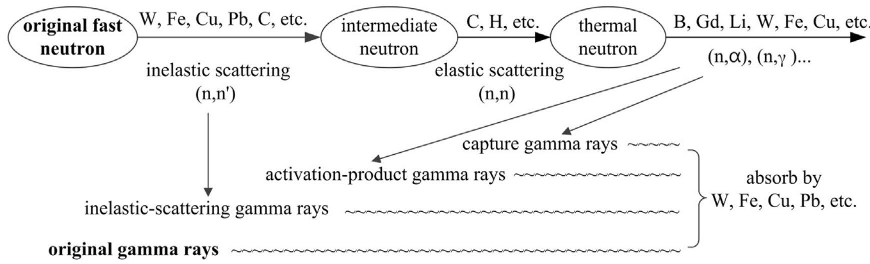

Fig. 1. Main interactions should be considered in the shielding of neutrons and gamma rays.

six types of materials are presented, then the calculation models and the method to optimize the shielding material are studied (Section 2). Second, the six types of materials are optimized, and comparisons between them with some conventional materials available are made (Section 3). The shortcomings and outlooks of this study are reviewed at last.

2. Methodology

2.1. Shielding principle of neutrons and gamma rays

The shielding principle of neutrons and gamma rays are based on the interactions between them and the materials, as shown in Fig. 1. For neutrons, the interactions include scattering and absorption. Objectively, all the interactions could occur in the whole energy range, but the main mechanisms to attenuate neutrons may vary with the energy and the material. The inelastic scattering dominates the fast neutron range, the elastic scattering dominates the medium energy range, and the capture reaction dominates the thermal energy range. Moreover, secondary gamma rays would be generated in the process of inelastic scattering and the reactions such as (n, γ), (n, α), (n, 2n), etc. It implies that the gamma rays should also be considered in the shielding of neutrons. For gamma rays, the interactions contain photoelectric absorption, Compton scattering and pair production. Thus, the shielding of neutrons needs materials contain both heavy and light elements, while the gamma rays only need heavy elements.

Obviously, to make a shield compact and lightweight, each of its compositions must be fully functioning and the elements undesirable (with drawbacks or useless) must be as low as possible. In this study, considering the cost of the material, the elements Fe, Pb, C, B and H are selected to make up the shield in the form of composite material and multilayer material. Among these elements, Fe and Pb are set as simple substances, while B and H are set as B_4C and polyethylene (PE) respectively. The PE is also the matrices of the composite shielding material.

As a typical case, the fission energy spectrum of ^{235}U (beam intensity is 10^{10} fission/s) which mixed neutrons and gamma rays was adopted in this study. It releases 2.407 neutrons (Watt fission energy spectrum) and 7.77 gamma rays every event. An empirical formula for the prompt gamma rays spectrum was employed (Schaeffer, 1973):

$$N(E_\gamma) = \begin{cases} 6.6 & 0.1 < E_\gamma \le 0.6\,MeV \\ 20.2\exp\ (-1.78E_\gamma) & 0.6 < E_\gamma \le 1.5MeV \\ 7.2\exp\ (-1.09E_\gamma) & 1.5 < E_\gamma \le 10.5MeV \end{cases} \quad (1)$$

In this study, calculations to design the optimal shielding are performed using the MCNP5 code and the ENDF/B-VI cross section set. Mode n p is used. The NCRP-38 (Rossi and Chairman, 1971) neutron flux-to-dose rate conversion factors and the 1977 ANSI/ANS (Battat, 1977) photon flux-to-dose rate conversion factors are used. To improve the calculation of the scored quantity, variance reduction techniques such as weight windows are used. 3×10^6 particles are simulated in the optimization process, and 2×10^8 particles are simulated in the other calculations. The calculation during optimization has a standard deviation less than 10%, while the others less than 5%.

2.2. Forms of the shielding material

In general, there have three forms of shielding material – single homogenous material, single composite material and multilayer material. Of which, each layer of the multilayer may also be composite materials. As mentioned previous, the single homogenous materials are not a good choice for the shielding of neutrons. Thus, this study only discusses the latter two forms.

For the multilayer materials, they utilize the material physically separate, that makes them maximize the role of each substance, and provide extra degrees of freedom for tuning the neutrons and gamma rays to energies where they can be effectively absorbed without excessive low energy tailing (Hong, 2002). For the composite materials, they can be formed into any shapes at one time, and the elements needed could be added into them easily. Thus, six types of shielding material are presented in this paper, as shown in Fig. 2. The structures of the materials are described below:

(a) Three-layer material, from left to right is Fe, PE and Pb respectively. The first layer Fe was set to attenuate the gamma rays, as well as slow down the fast neutrons to intermediate energy by inelastic scattering, the second layer PE was set to further moderate the neutrons to thermal energy by elastic scattering, and the last layer Pb was set to attenuate the secondary gamma rays and the original gamma rays.
(b) Three-layer material, from left to right is Fe, BPE and Pb respectively. The second layer BPE means a composite material consists of PE and B_4C. The B_4C was added to reduce the thermal neutrons and secondary gamma rays.
(c) Two-layer material, from left to right is Fe and a composite material consists of PE, B_4C and Pb.
(d) A block of composite material consists of PE, B_4C, Fe and Pb.
(e) Two-layer composite material both consists of PE, B_4C, Fe and Pb.
(f) Three-layer composite material all consists of PE, B_4C, Fe and Pb.

Because the reaction cross sections of neutrons and gamma rays are varied with the elements and energy, and different reaction has different energy losses, there may exists an optimal material for the shielding of specific neutrons and gamma rays. For the composite materials, it means an optimal component. For the multilayer materials, it means an optimal thickness ratio (may contains composite as well). Elbio Calzada (Calzada et al., 2011) has demonstrated that the optimum material composition is existed indeed by brute-force enumerate the shielding performance of all the components. In the same way, the optimal material thickness ratio should also exist for multilayer materials. Therefore, it is necessary to carry out a research about the method of optimization. The method may employ an optimization algorithms (such as genetic algorithms) and MCNP code. Considering large amounts of calculations are needed in the optimization process, and the time needed for the transport calculation by MCNP may be seconds even minutes (Intel i7–4790 CPU, 8 threads) per count, the calculation models should be studied before the optimization.