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Optimization of radiation shielding material aiming at compactness, lightweight, and low activation for a vehicle-mounted accelerator-driven D-T neutron source

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HIGHLIGHTS

- Optimization of radiation shielding material aiming at low neutron activation, etc.
- Optimization of the shielding material both during operation and after shutdown.
- The types of radionuclide, the energy spectrum, and the variation in decay were computed.

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ABSTRACT

To minimize the size and weight of a vehicle-mounted accelerator-driven D-T neutron source and protect workers from unnecessary irradiation after the equipment shutdown, a method to optimize radiation shielding material aiming at compactness, lightweight, and low activation for the fast neutrons was developed. The method employed genetic algorithm, combining MCNP and ORIGEN codes. A series of composite shielding material samples were obtained by the method step by step. The volume and weight needed to build a shield (assumed as a coaxial tapered cylinder) were adopted to compare the performance of the materials visually and conveniently. The results showed that the optimized materials have excellent performance in comparison with the conventional materials. The "MCNP6-ACT" method and the "rigorous two steps" (R2S) method were used to verify the activation grade of the shield irradiated by D-T neutrons. The types of radionuclide, the energy spectrum of corresponding decay gamma source, and the variation in decay gamma dose rate were also computed.

1. Introduction

Because many bridges and large facilities are nearing the end of their design life, it is necessary to investigate them to decide whether their service should be extended. Considering their complex composition and thick layers, fast-neutron imaging is one of the most promising and recommended methods to solve this problem (Lehmann et al., 2005). Thus, it is important to develop a vehicle-mounted neutron source.

The reaction T(d, n) ^{4}He produces fast neutrons of energy 14 MeV, whose Q-value is + 17.59 MeV (Lou, 2003). This implies that the reaction has no threshold energy. In addition, the Kulun barrier of the reaction is low because of the small atomic number of deuterium and tritium. Thus, the energy of incident deuterium could be comparatively small, and the size of the accelerator could be small as well (Csikai, 1987). Thus, the vehicle-mounted accelerator-driven D-T neutron source was developed.

The problem of fast neutron shielding occurs during the removal of the vehicle-mounted accelerator-driven D-T neutron source. It is quite difficult to shield the fast neutrons, which lead to the biological shield of the accelerator generally quite bulky. In addition, to protect workers from unnecessary irradiation after the equipment shutdown, the activation of the shielding material must be controlled. Therefore, it is necessary to develop a method to design the shielding material that is compact, lightweight and low activation. This study exactly addresses this problem.

First, the shielding of fast neutrons and the necessity for optimization are analyzed, then, the method to optimize the composite shielding

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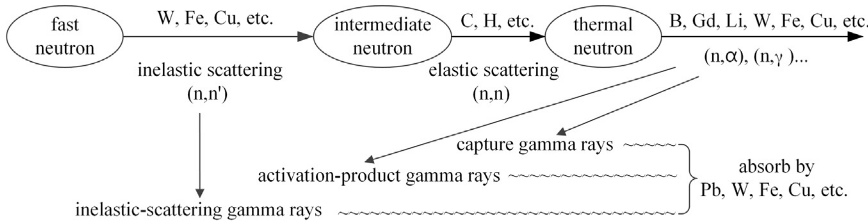

Fig. 1. Main interactions considered in the shielding of fast neutrons.

material is studied. The computational tools and models are presented in Section 2. Second, the composite shielding material compactness, lightweight, and low activation are optimized step by step and are compared with those of some conventional materials available. The variation in decay gamma dose rate is calculated, in addition to the types of radionuclides and the energy spectrum of corresponding decay gamma source. These problems are presented in Section 3. The shortcomings and outlooks of this study are discussed in Section 4.

2. Methodology

2.1. Fast neutron shielding principle

The principle of fast neutron shielding is based on the interactions between neutrons and matters, which involves scattering and absorption as shown in Fig. 1. Objectively, all the interactions could occur in the whole energy range, but the main mechanisms to attenuate neutrons may vary with the energy. The inelastic scattering dominates in the fast neutron range, the elastic scattering dominates in the medium energy range, and the capture reaction dominates in the thermal energy range. Moreover, the inelastic scattering would lead to inelastic scattering gamma rays, capture of thermal neutrons would lead to capture gamma rays, and several reactions such as (n, γ), (n, 2n), (n, 3n), (n, α), and (n, p) would even produce radionuclides with half-life ranging from seconds to years. The secondary gamma rays are always energetic and play an important role in the shielding process. The gamma rays from activation products would also be important and of particular concern after the equipment shutdown (Schaeffer, 1973).

As shown in Fig. 1, the heavy elements play an important role in the shielding process. They could slow down the fast neutrons by inelastic scattering, absorb the thermal neutrons by capture, and attenuate the gamma rays by several interactions. However, they also produce serious secondary gamma rays including inelastic scattering gamma rays, capture gamma rays, and activation gamma rays. To ensure the excellent performance of the shield, an appropriate proportion of heavy metal element is required. Considering the side effects of secondary gamma rays, they are incompatible for compactness, lightweight, and low activation. Thus, a balance of these properties has to be realized by optimization, which is exactly the goal of this study, and it is presented in Section 2.2.

As mentioned previously, a material that contains both heavy elements and light elements may be a good choice for the shielding of fast neutrons. In general, these materials have two forms: composite material and multilayer material. The composite material is mainly studied in this paper, and the multilayer material would be researched in the near future.

Obviously, to make a shield compact and lightweight, each of its composition must be fully functioning and it should be ensured that an undesirable element (with side effects or useless) is as low as possible. In this study, the elements W, Fe, Cu, C, B, and H were selected to make up a shield in the form of a composite material. Among these elements, W, Fe, and Cu were set as simple substances, while B was set as B_4C and H as polyethylene (PE). The PE is also the matrices of the composite shielding material. Because Pb is toxic and poor to slow down the fast neutrons, it is not considered in this study.

2.2. Optimal design of the composite shielding material by genetic algorithm

In general, the method of material designing is a “brute force” trial-and-error procedure, which is tempered by experience (Schaeffer, 1973). However, modern intelligent algorithms have been gradually applied to improve it in recent years (Ashayer et al., 2012; DiJulio et al., 2016; Hu et al., 2008; Wang et al., 2015). The genetic algorithm (GA), which is based on natural selection, is widely used for solving both constrained and unconstrained optimization problems. It works on a population of individuals and repeatedly modifies the potential solutions relying on bio-inspired operators such as mutation, cross-over, and selection. Over successive generations, the population “evolves” toward an optimal solution. In this study, a GA program called the GENOCOP (Michalewicz and Janikow, 1996) developed by Michalewicz and Janikow was selected for optimization, and it has excellent global search capabilities and optimization efficiency.

To design a compact, lightweight, and low-activation shielding material, the density and several dose equivalents penetrated have to be considered. In other words, it is a multi-objective optimization problem, and the objective function can be written as follows:

$$f(X) = a\frac{H_T(X)}{H_{T0}} + b\frac{\rho(X)}{\rho_0} + c\frac{H_g(X)}{H_T(X)} + d\frac{H_a(X)}{H_{a0}} \tag{1}$$

where

$$H_T(X) = H_n(X) + H_g(X) \tag{2}$$

$$\rho(X) = 1/\sum_{i=1}^{N}\frac{x_i}{\rho_i} \tag{3}$$

Therefore, the optimization problem can be represented as follows:

$$\min f(X) \tag{4}$$

$$s.\ t.\ \sum_{i=1}^{N} x_i = 1 \tag{5}$$

$$L \le X \le U \tag{6}$$

where N is the number of components in the composite material; $X = (x_1, x_2, \ldots, x_N)$ is the variable vector, mass components matrix in the composite material; L is the component vector of minimum; U is the component vector of maximum; $f(X)$ is the total fitness function value; a, b, c, and d are the weight coefficients; $H_T(X)$ is the total dose equivalent, Sv; $\rho(X)$ is the density of the composite material, g/cm^3; $H_n(X)$ is the dose equivalent of neutrons, Sv; $H_g(X)$ is the dose equivalent of secondary gamma rays, Sv; $H_a(X)$ is the dose equivalent of activation gamma rays, Sv; H_{T0}, ρ_0, and H_{a0} are the reference values to make the function dimensionless. In this study, we set $H_{T0} = 1.06 \times 10^{-18}$ Sv/n and $\rho_0 = 8.9$ g/cm^3, which are both parameters of Cu because it is a comparatively better shielding material for neutron whose energy is 14 MeV, H_{a0} was set at 1.39×10^{-10} Sv/s, just the dose limit of general public.

It is necessary to note that the density constraint was set as an inequality constraint in the previous study (Hu et al., 2008). Differently, in the present study, it was considered an objective function in this study. Because the optimal material composition is closely related to the energy of neutrons, the density is not an appropriate constraint. In