The Optimization of Shielding Structure in Neutron-Gamma Well Logging Instrument

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Abstract

Neutron-gamma well logging instrument was widely used in well logging processing. The D-D controlled neutron generator, which produced 2.45 MeV neutrons, was used as the neutron source in the logging instrument. However, one part of the 2.45 MeV neutrons will directly reach the detector of the logging instrument and deposited energy in it. Thus the secondary photons will be arose and made adverse effect on the measurement accuracy of the instrument. A shielding structure, which was between the neutron source and detector, can reduce the effect caused by the radiation particles. However it is hard to design an efficient shielding structure.

This study was aimed to design the shielding structure of the well logging instrument. The shape of the shielding structure was set as a cylinder and its length was fixed as 10 cm. The MCNP code was invoked by the Genetic Algorithm to optimize the shielding structure from 7 shielding materials.

Two shielding structures were obtained by the optimizing program. The first structure was with three layers, gadolinium oxide-polyethylene-lead and each length of the layers was 5.2 cm, 1.3 cm and 3.5 cm, respectively; the other structure was with four layers, boron carbide- polyethylene- boron carbide-lead and each length of the layers was 1.0 cm, 0.9 cm, 4.6 cm, 3.5 cm, respectively. The results showed that, the optimized shielding structures can effectively reduce the deposited energy in the detector.

Keywords：Shielding structure, Optimization, Neutron-gamma well logging instrument, D-D Neutron source

1. Introduction

Radiation shielding is an important part of nuclear facilities. It can limit the radiation damage to the people and device around the nuclear facilities[1–3]. Many issues, such as volume, length, weight, price and shielding effectiveness will be considered when designing new shielding structure.

Neutron-gamma (N-G) well logging instrument is widely used in the well logging process because of its accuracy measurement. It contains several parts, such as neutron source, detector, shielding structure and electronic device. The neutron source will generate the neutron during the logging period. These neutron will interact with the stratum's elements which surrounding the instrument. As the result, the specific gamma rays will be emitted. After that, the detectors within the logging instrument will detect and analyze the gamma rays' signal. Finally, the component of the stratum was obtained.

However, the neutron source will evenly release neutron into surrounding area. Part of the neutron will directly go into the detector. These neutron and their secondary particles will deposit energy in the detector. As the result, the errors may occur during the logging process. A shielding structure, which was between the neutron source and detector, can relieve this problem[4]. Unfortunately, the space in the N-G well logging instrument is limited. Only a small room can be used for shielding structure. Thus, it is a challenge to design the shielding structure in the limited space, especially for the multilayer shielding structure.

Many optimization techniques, such as genetic algorithm, linear programming, sequential quadratic programming and transmission matrix method can be used for designing the shielding structure[5–9]. Several excellent shielding materials which can be used in reactor and accelerator have presented in the studies. These studies demonstrated that it was a good way to design the shielding structure by optimization algorithms.

However, in these studies, the most important constraint condition is that the absorb dose at a certain distance should below than a threshold. The optimization parameters of the shielding material, such as the weight, volume, shape and price must follow this condition. The situation is different in the well logging instrument. Because of the limitation of the instrument's space, the volume and the shape of the shielding structure is fixed. Therefore, the primary constraint condition of optimizing the shielding structure in well logging instrument is that the shape of the structure is fixed. Based on this condition, the aim of this study is minimizing the deposited energy in the detector while the shape of detector is fixed. The procedure of this study is shown as below:

First, simplify the structure of the D-G well logging device and construct the simulating model which can be calculated by MCNP software;

Second, optimize the shielding structure by genetic algorithm and MCNP calculation;

Third, obtained the optimized shielding structure which with different number of layers.

2. Methodology

2.1 Modeling of N-G well logging instrument

The structure of the N-G well logging instrument is shown in Fig.1. There are several devices in N-G well logging instrument, such as neutron source, shielding structure, detector, electronic device, iron tube and so on. This study aims to develop a novel shielding structure of the instrument. Thus the simulating model should contain at least three parts, the neutron source, shielding structure and detector. The rest of the device is not necessary and can be ignored in the simulating model. In the commercial well logging instrument, the neutron source, shielding structure and detector are coaxial. Their simulating model also should be coaxial.

A miniaturized controlled neutron generator was used in the N-G well logging instrument. 2.45 MeV neutron was produced by D-D fusion. The formula of fusion reaction is show as below:

$$ {}_{1}^{2}D + {}_{1}^{2}D \rightarrow {}^{3}He + n \tag{1} $$

The shape of the neutron source can be simplified as a cylinder which diameter is 2.5 cm and height is 10 cm. Although neutron will evenly emitted into surrounding area, only neutron that directly fly to the detector may influence on the logging result. Thus direction of emitted neutron was set as one direction, faced to the detector. And this direction also defined as an axial positive direction.

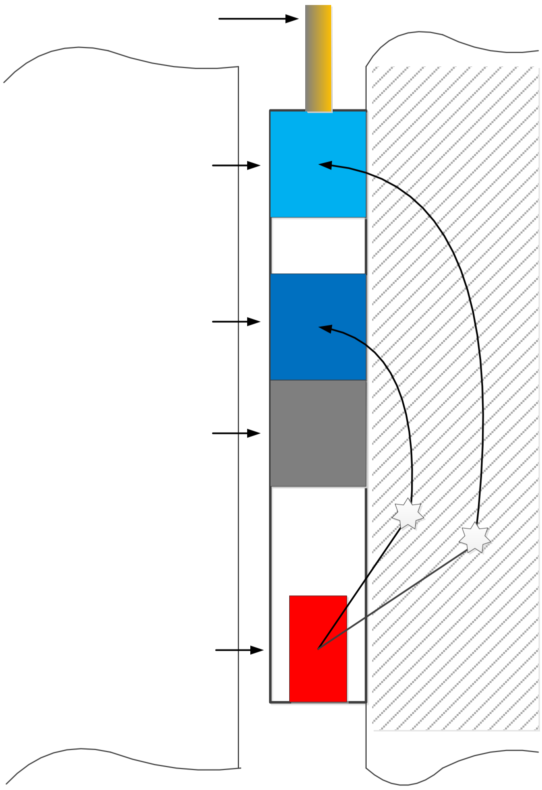

Fig. 1. The structure of D-G well logging instrument.

The distance between neutron source and shielding structure was 50 cm. The space which will insert the shielding structure was a cylinder. The diameter and the length of the cylinder were 5 cm and 10 cm, respectively. Because, in this study, the shielding structure was multilayer, the first layer of the structure was defined as the one which close to the neutron source. Then the second layer and so on. There were two types of shielding structure, the one with 3 layers and 4 layers.

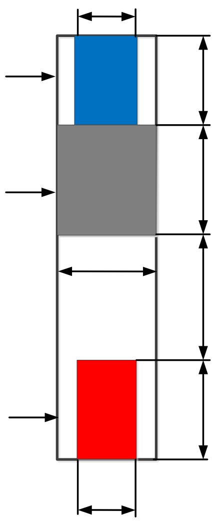

Fig. 2. The simulating model of the well logging instrument.

A cylinder sodium iodide detector was constructed in the model. The diameter and the length of the cylinder were 2.54 cm and 7.62 cm. It was close to the shielding structure. The simulating model was shown in Fig.2.

2.2 Forms of the shielding material

In this study, a D-D fusion neutron generator was used in the N-G well logging instrument. The 2.45 MeV neutron will interact with the elements of shielding structure. These interactions include elastic scattering, inelastic scattering and radiation capture. The gamma rays with different energy will be emitted after the reactions. Thus, the shielding structure should prevent both neutron and gamma ray reach the detector. For this purpose, the shielding structure should at least contain 3 parts:

1st part should promptly reduce the neutron energy. Mostly, the materials with high inelastic scattering cross section, such as iron and tungsten will be used;

2nd part can efficiently absorb the low-energy neutron and polyethylene (PE), lead-boron polyethylene (PB202), boron carbide (B_4C), gadolinium oxide (Ga_2O_3) will be selected;

3rd part will be used to prevent gamma rays. Tungsten, lead, such metal with high density are the good options.

Based on this information, a form of the shielding material can be established. The data of the selected material was shown in Table 1.

Table 1 Data of the shielding material

Name	component / wt%	density/g•cm^{-3}
Iron	Fe: 100	7.86
Tungsten	W: 100	19.35
PE	H: 14.3, C: 85.7	0.95
PB202	H: 0.0271, B: 0.0077, O: 0.1652, Pb: 0.8	3.42
B_4C	B: 76.9, C: 23.1	2.52
Ga_2O_3	O: 27.3, Ga: 72.7	7.407
Lead	Pb: 100	11.344

2.3 Optimal design of the shielding structure by genetic algorithm

The genetic algorithm (GA), which is based on natural selection, is widely used for solving optimization problems. It works on a population of individuals, and repeatedly modifies the potential solutions relying on bio-inspired operators such as mutation, crossover and selection. Over successive generations, the population "evolves" toward an optimal solution. In this study, a GA program developed by Andrew Chipperfield and Peter Fleming was selected for optimization. It has excellent global search capabilities and optimization efficiency.

There were two kind of parameters should be considered in this designing problem, length of each layer within the shielding structure and its material. The optional shielding materials were shown in Table 1. It can be easily invoked by the GA algorithm. The length of each layer should follow two constraint conditions:

1) The range of each layer's length should be from 0 cm to 10 cm;

2) Total length of shielding structure is 10 cm.

Based on the 1) condition, the expectation value of each layer was 5 cm. If the GA algorithm directly generated each length of layers l_i, the expectation value of total length will reach to 5•n cm, where n the number of shielding layers. Therefore, total length of shielding structure will beyond 10cm. To solve this problem, GA algorithm generated several percentages p_i of total length instead of the length of layers l_i. The range of p_i was from 0 to 1. The proportion of each layer can be calculated by the binary tree method. Every proportion of layer can be obtained by multiplying several percentage p_i. The calculating process was shown in Fig.3.

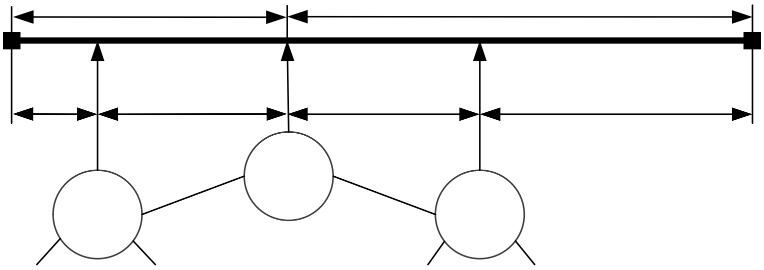

Fig. 3. The calculation process of each layer's proportion. Thick line is the total length of the shielding structure. It can be divided by several proportions.

When the neutron and gamma ray reached the detector, they will deposit energy into the detector and the light will be emitted. This light will be used for analyzing the stratum's element. Part of the neutron and their secondary particles will directly go into the detector and they also deposited energy into the detector. We named this part of deposited energy as direct deposited energy. Thus, the error will be occurred during the well logging process. The shielding structure can limit this error. It means that the objective function of this optimization was minimized the direct deposited energy E_d. The objective function was shown below:

$$f(x) = \min(E_d(x)) \tag{2}$$

After the shielding structure had been generated, MCNP software will be invoked to calculate the direct deposited energy. In this study, calculations to design the optimal shielding were performed using the MCNP6 code and the ENDF/B-VI cross section set. Mode n p was used. The flow chart of the optimization program was shown in Fig.4.

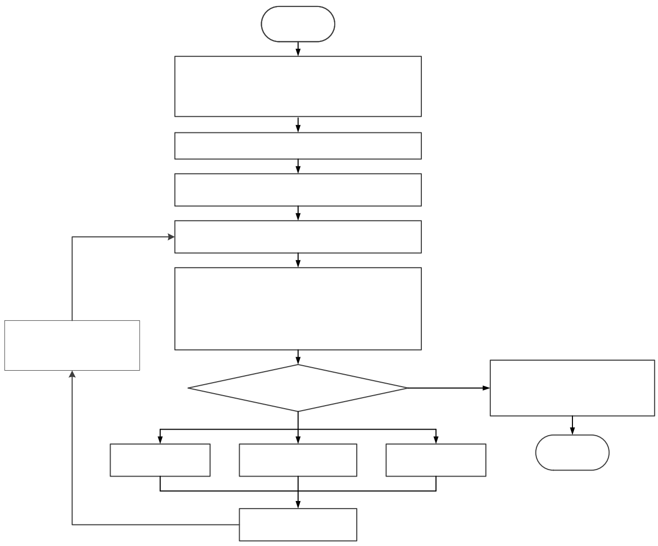

Fig.4. The optimization program algorithm.

3. Result

In order to find the optimal shielding structure, the domain constraint of each variable was set at 0–1 (the total thickness was set at 0–10 cm), the population size was set at 70 according to the number of variables, the gap between generations was set at 0.9, and the number of generations was set at 80 after several trials.

By running the program, two types of shielding structures presented were obtained, as presented in Table 2.

Table 2 Optimized shielding structures

Number of shielding layer	Material	Length of layer/ cm	Deposited energy / $MeV \cdot g^{-1}$
3	Ga_2O_3	5.2	1.242×10^{-5}
	PB202	1.3	
	Pb	3.5	
4	B_4C	1.0	0.917×10^{-5}
	PE	0.9	
	B_4C	4.6	
	Pb	3.5	

As mentioned above, shield 2.45 MeV neutron need three major steps: moderating neutron, absorbing neutron and absorbing gamma ray. The optimized shielding structures followed this principle. The whole shielding structure can be separated into two parts: neutron shielding domain and gamma shielding domain. The neutron shielding domain arranged at the front layers. Neutron moderation and absorbing materials were set in this area. The gamma shielding domain located at the last layer. It can protect detector from the secondary gamma rays.

Comparing with two types of shielding structures, four layers structure specified and modified the neutron shielding domain and the direct deposited energy was lower than three layers structure. This result shows that: 1) shield neutron can reduce the direct deposited energy in the detector and 2) specified neutron shielding structure is more efficient than the single layer structure.

4. Conclusion

Thus far, the method to optimize multilayer shielding structure of the N-G well logging instrument was established employing genetic algorithms and MCNP code. The optimization factors and objective function were presented as well. The optimized shielding structures with three and four layers have presented in this study. The direct deposited energy can be reduced by specified and modified the neutron shielding domain.

However, this study was focused on the well logging instrument with D-D neutron generator. The neutron energy was only 2.45 MeV. It is noted that the D-T neutron generator also employed in the N-G well logging instrument. D-T neutron generator has higher neutron yield and the neutron energy is over 14MeV. Thus, the shielding structure in the D-T N-G well logging instrument can be designed in future work.

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