



# Multi-Objective Optimization Design of Radiation Shadow Shield for Space Nuclear Power With Genetic Algorithm

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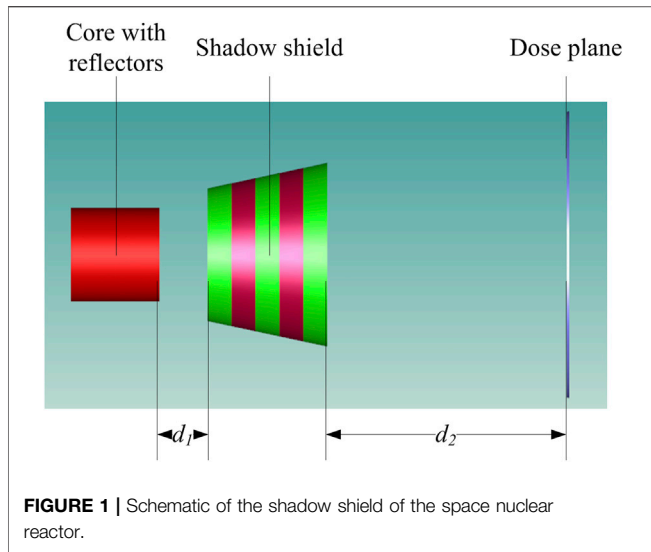
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The radiation shadow shield of the space nuclear power is an important component to protect the electronic device at the dose plane. In this paper, design of the radiation shadow shield is first modeled as a multi-objective optimization problem, and then converted into a single objective optimization problem by setting the other sub-objectives as constraints. An optimization method combining a single objective genetic algorithm with Monte Carlo simulation is developed to solve the optimization problem of shadow shield design. Through optimization, weight of the radiation shadow shield can be greatly reduced (14.7% of the weight of the initial design and 16.4% of the weight of the best individual of the first generation), while radiation dose at the dose plane is lower than the acceptable tolerance. The optimization method developed in this work is an automated optimization strategy by searching for the parameter space, which will not be subject to human preferences. The global optimal solutions can be obtained without the tedium of human manual work.

**Keywords:** space nuclear power, fission reactor, radiation shadow shield, multi-objective optimization, genetic algorithm

## INTRODUCTION

Deep space exploration and immense developments in space science and technology demand reliable, long life, and high-power energy sources. The fission nuclear reactor, due to its high-power density, compact configuration, and long lifetime deployment, is a suitable choice for the harsh environments of the outer planets. Many projects for space reactors ranging from low to high power have been constructed, such as the BUK and TOPAZ series (Stanculescu, 2005; El-Genk, 2009; Grasty, 1978; Johnson, 1982; Bennett, 1989; Sidiqi, 1999), the SNAP series, and the SP100 reactor (Angelo and Buden, 1985; Demuth, 2003; Bruno, 2008). A typical schematic of the space nuclear reactor is shown in **Figure 1**. The shadow shield is designed to protect the electronic system of the spacecraft from neutron and gamma radiation generated by the reactor core. Hydrogen contained materials such as LiH and ZrH<sub>2</sub> are usually chosen to slow down neutrons and heavy materials such as steel, lead, and tungsten are chosen to attenuate gamma rays. In recent years, tungsten doping with boron carbide (W-B<sub>4</sub>C) is used in shadow shield of space nuclear reactor, to attenuate gamma rays as well as to absorb neutrons (Ahmad et al., 2021). The radiation shadow shield is a considerable part of the total mass of the space nuclear reactor. The mass of the shadow shield in the designs of Kilopower, Topaz II, and SNAP-10A is 42.6%, 36.8%, and 17.4% of the mass of the whole nuclear system, respectively (Voss, 1984; Gibson et al., 2015). In addition, the total mass of the space nuclear reactor is closely related to the launching cost.



$D_1$  is the distance between the reactor and the shield to provide space for heat pipes to bend outside of the shield;  $d_2$  is the distance between the shield and the dose plane, where electronic systems are placed.

Currently, design of the shadow shield is mainly subject to the designer's expertise, which is essentially a manual iterative procedure using both the deterministic and Monte Carlo codes (Ahmad et al., 2021; Woodrow, 1987). The current design method is time-consuming, low-efficiency, and the optimal solution is always hard to obtain. Genetic algorithm is a stochastic method with the ability to find true or approximate solutions to the global optimization. In the recent years, genetic algorithm is applied to nuclear-related applications, such as the nuclear fuel loading and reloading optimization (Sobolev et al., 2017) and shielding design of the PWRs (pressurized water reactors) (Chen et al., 2019; Chen et al., 2020). In this paper, the typical multi-objective optimization problem of the shadow shield design of the space nuclear reactor is converted into a single-objective optimization problem by setting the rest of the sub-objectives as constraints. In addition, the optimization method combining genetic algorithm with the MCNP code is developed to solve the optimization problem of the shadow shield design.

## METHODOLOGY

### The Optimization Problem of the Shadow Shield Design

The purpose of the shadow shield of the space nuclear reactor is to protect the electronic device placed at the dose plane from radiation produced in the reactor core. Moreover, the shadow shield needs to be as light and compact as possible to reduce the launching cost. As a result, the target of the shadow shield design is to obtain a set of parameters, such as geometrical parameters of the shadow shield, making the weight of the shadow shield, energy deposition of gamma rays in silicon, and fast neutron fluence equivalent in silicon at the dose plane minimal, which can be described mathematically as

$$\begin{aligned} \min f(\vec{x}) &= \left( f_w(\vec{x}), f_g(\vec{x}), f_n(\vec{x}) \right)^T \\ \text{s.t.} \quad &\begin{cases} \vec{x} = (x_1, x_2, \dots, x_n), \vec{x} \in \mathbb{R}^n \\ L_j \leq x_j \leq U_j (j = 1, 2, \dots, n) \\ h_k(x_j) \leq 0 (k = 1, 2, \dots, q) \end{cases} \end{aligned} \quad (1)$$

where  $f_w(\vec{x})$ ,  $f_n(\vec{x})$ , and  $f_g(\vec{x})$  represent weight of the shadow shield, fast neutron fluence equivalent in silicon and energy deposition of gamma rays in silicon, respectively;  $\vec{x}$  is an  $n$ -dimensional variable vector of the design parameters;  $L_j$  and  $U_j$  represent the lower and upper bounds of the variables;  $h_k$  represents the inequality constraints of the design parameters.

**Equation 1** is the typical multi-objective optimization problem. As to shadow shield design of space reactors, the purpose is to obtain the optimal parameters with the minimum weight while the neutron and gamma radiation are at the dose plane lower than the tolerable limits, so the multi-objective optimization problem stated by **Equation 1** can be converted into a single-objective optimization problem, given as:

$$\begin{aligned} \min f_w(\vec{x}) \\ \text{s.t.} \quad &\begin{cases} f_g(\vec{x}) \leq f_{g,\text{limit}}(\vec{x}) \\ f_n(\vec{x}) \leq f_{n,\text{limit}}(\vec{x}) \\ \vec{x} = (x_1, x_2, \dots, x_n), \vec{x} \in \mathbb{R}^n \\ L_j \leq x_j \leq U_j (j = 1, 2, \dots, n) \\ h_k(x_j) \leq 0 (k = 1, 2, \dots, q) \end{cases} \end{aligned} \quad (2)$$

where  $f_{g,\text{limit}}$  and  $f_{n,\text{limit}}$  are the tolerable limits of the gamma dose and the neutron fluence in silicon.

**Equation 2** can be converted into the maximization problem by modifying the objective function, given as,

$$\max g_w(\vec{x}) = \frac{1}{1 + f_w(\vec{x})} \quad (3)$$

### The Evolution Operators of Genetic Algorithm

Genetic algorithm is employed to solve the single objective optimization problem given by **Equation 3** for its ability to obtain the global optimization solution (Holland, 1992). The population evolves via the evolution operators through many generations, breeding strong solutions while weeding out weak solutions to find the global optimal solution. The evolution operators involve encoding and decoding of the candidate solutions, fitness evaluation, parent selection, mating, and mutation (De Jong, 1975; Goldberg, 1989). Binary encoding method is adopted for its simplicity for implementation and designing the genetic operators (Zhou and Sun, 1999). The optimization parameter  $x$  is expressed with the binary strings  $a_l a_{l-1} \dots a_1$ . The corresponding decoding formula is given as

$$x = x_{\min} + \left( \sum_{i=1}^l a_i \cdot 2^{i-1} \right) \cdot \frac{x_{\max} - x_{\min}}{2^l - 1} \quad (4)$$

The genetic algorithm search operated on the Darwinian principle of "survival of the fittest". Hence fitness is a measure of how well an

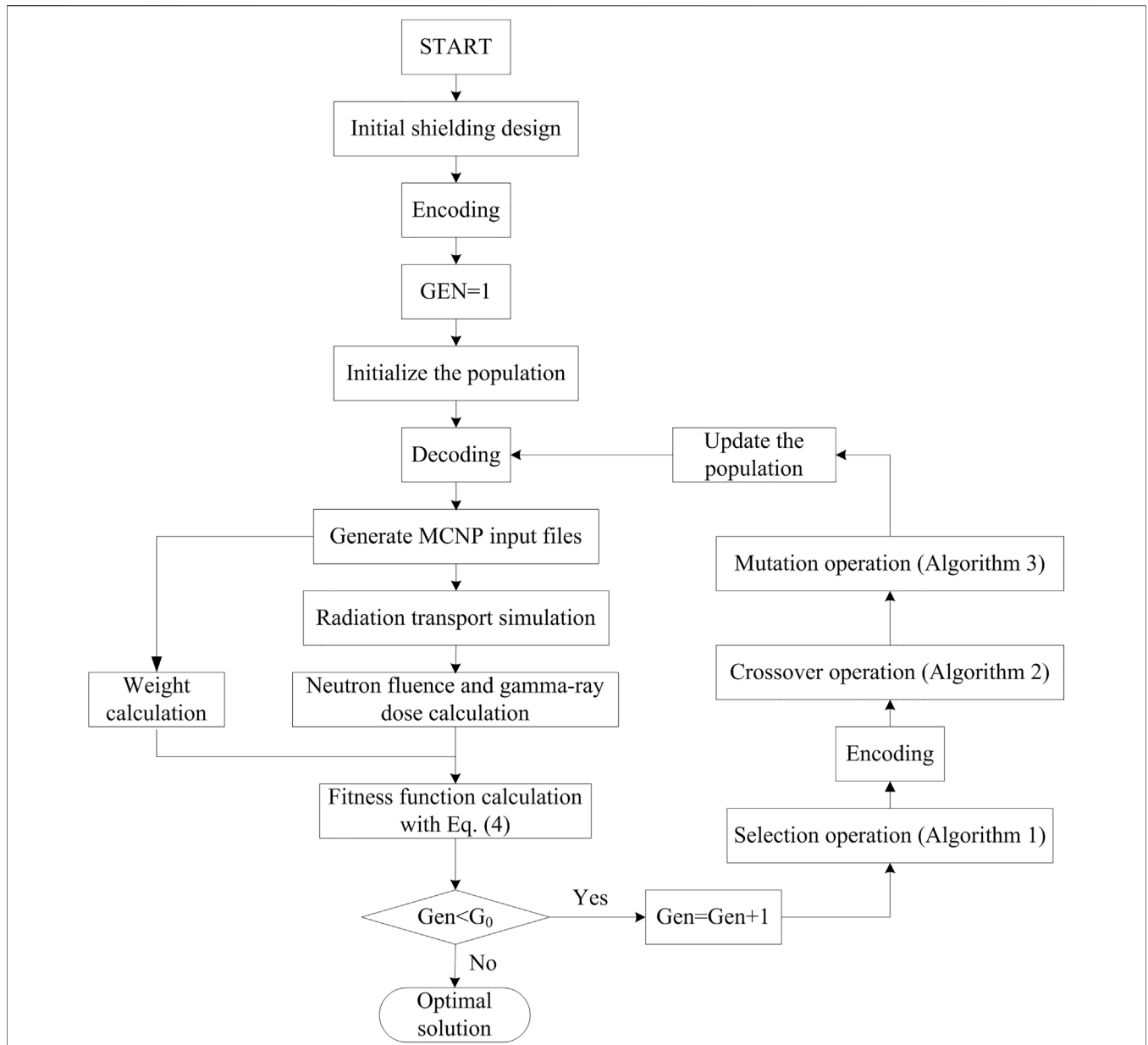


FIGURE 2 | Framework of the shadow shield design with genetic algorithm.

individual performs in its environment. In order to implement constraints of the sub-objectives during the optimization, candidates not satisfying the constraints are treated as lethal genes (Zhou and Sun, 1999), of which fitness values are set to be zeros, given as,

$$fit(\vec{x}) = \begin{cases} g_w(\vec{x}), & \text{if } f_g(\vec{x}) \leq f_{g,limit}(\vec{x}) \text{ and } f_n(\vec{x}) \leq f_{n,limit}(\vec{x}) \\ 0, & \text{else} \end{cases} \quad (5)$$

Equation 5 ensures candidates not satisfying constraints are eliminated in the next generations, and eventually converts the multi-objective optimization problem of shadow shield design of space nuclear reactor into a single-objective optimization problem.

Parent selection is random but biased such that the probability of selecting a candidate solution to be a parent increases with increasing

fitness. In this work, parents are selected using a technique known as tournament selection. With this technique, “tournaments” are held between randomly selected pairs of solutions; the solution with the highest fitness wins the tournament and is selected to be a parent. The process is repeated to find the mate (Zhou and Sun, 1999; Luke, 2016). Moreover, parents mate by interchanging parts of their encoded chromosome structure using a technique known as “crossover”. The crossover technique involves randomly selecting a site along the chromosome string as a crossover point. All the genetic information following that point is exchanged with the mate. The “two-point crossover” technique is employed in this work (Luke, 2016). The offspring solutions next experience mutation. Mutation is carried out by randomly and infrequently changing the state of one or

more bits within a chromosome. Sometimes the mutation produces a favorable effect by increasing performance, sometimes not. Bit-Flip mutation method is employed in this paper (Luke, 2016).

## Framework of the Shadow Shield Design Method

The optimization process of the shadow shield design is illustrated in **Figure 2**. The Monte Carlo code MCNP is applied to radiation transportation simulation for its ability to model the complexity geometry (X-5 Monte Carlo team, 2003). Moreover, the conversion factors provided by energy response function (DE/DF) cards allow MCNP to convert the predicted particle fluences to neutron fluence equivalent in silicon (DePriest, 2014). The framework of the shadow shield optimization design using genetic algorithm is depicted in **Figure 2**. First, an initial solution is given to start the optimization according to the initial structural and material parameters; then, a certain number of shield solutions are randomly generated to form an initial population. Generate MCNP input files for shield solutions in the population and calculate the shadow shield weight according to the corresponding parameters, and then perform the radiation transport simulations with the MCNP code to calculate neutron fluence and gamma-ray dose. Then the fitness functions are calculated with **Equation 5** and the population evolutions are performed employing the selection, crossover, and mutation operators illustrated in *The Evolution Operators of Genetic Algorithm* to update the MCNP input files until reaching the maximum generation.

MCNP simulations are performed with a multi-group and parallel computing mode. Besides, the based variance reduction technique utilized in MCNP runs to obtain satisfactory results with acceptable errors less than 10%. As a result, the MCNP simulations in the optimization procedure will obtain satisfactory results within an acceptable computational time.

## OPTIMIZATION RESULTS

### Reactor Model

The reactor is a typical fast reactor of 100 kWth power. The equivalent diameter and height of the reactor are 18 cm and 16 cm, respectively. The core consists of enriched UN fuel (90% enriched  $^{235}\text{U}$ ), heat pipes

**TABLE 1** | The composition of the shielding materials (Wt%).

	LiH (0.8 g/cm <sup>3</sup> )	W-B <sub>4</sub> C (11.59 g/cm <sup>3</sup> )
<sup>6</sup> Li	5.72E-02	—
<sup>7</sup> Li	8.17E-02	—
H	1.26E-01	—
<sup>10</sup> B	—	7.04E-02
<sup>11</sup> B	—	7.83E-03
C	—	2.17E-02
<sup>182</sup> W	—	2.36E-01
<sup>183</sup> W	—	1.29E-01
<sup>184</sup> W	—	2.76E-01
<sup>186</sup> W	—	2.59E-01

containing the liquid lithium to extract heat and control rods of B<sub>4</sub>C to control the reactivity. The BeO is chosen as a reflector with a thickness of 10 cm. The shadow shield is in the shape of a truncated cone that makes the half-angle of 12° on the face of the front reflector and shadows the electronic devices from radiation. The distance between the reactor and the shadow shield ( $d_1$  in **Figure 1**) is 20 cm to provide space for heat pipes to bend outside of the shield, and the distance between the shield and the electronic system ( $d_2$  in **Figure 1**) is 100 cm.

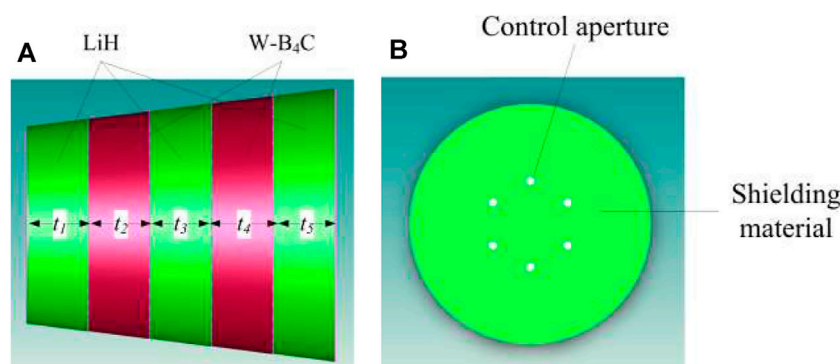
### The Optimization Parameters

The lithium hydride (LiH) is chosen to slow down neutrons, and the composite material W-B<sub>4</sub>C (<sup>10</sup>B enriched) is chosen to attenuate gamma rays as well as absorb neutrons. The compositions of LiH and W-B<sub>4</sub>C are listed in **Table 1**. The enrichment of <sup>10</sup>B is 90%.

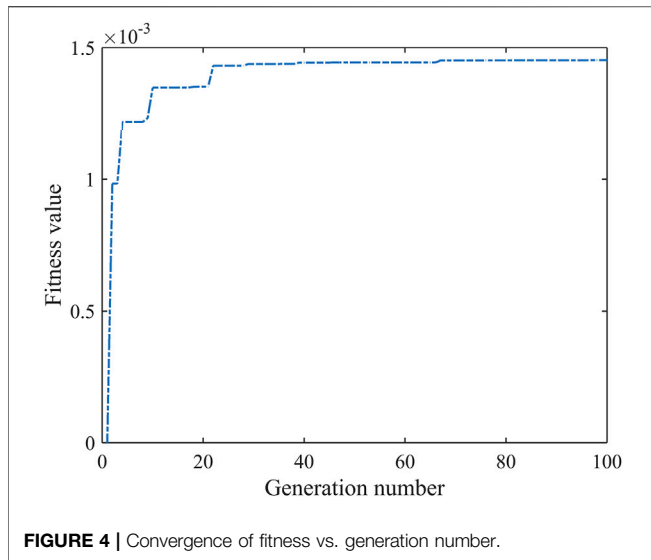
The axial and radial profiles of the shadow shield are shown in **Figure 3**. The structure of the shadow shield is designed as “LiH, W-B<sub>4</sub>C, LiH, W-B<sub>4</sub>C, LiH”. The thickness of each layer is treated as the optimization parameters of the genetic algorithm, such as  $t_1, t_2, t_3, t_4, t_5$ , shown in **Figure 3A**. Six control apertures are designed within the shadow shield for the control rods system, shown in **Figure 3B**.

### The Shielding Design Limits

The target of the shadow shield is to protect the electronic systems from radiation from the reactor core. According to the study in the El-Genk's literature, the tolerable limits of neutron fluence and gamma dose for the silicon are  $1.0 \times 10^{12}$  nvt (fast neutrons >0.1 MeV) and 1.0 Mrad, respectively (Ahmad et al., 2021; El-



**FIGURE 3** | The axial (A) and the radial (B) profiles of the shadow shield.



Genk et al., 2005). Considering the 10 years as design operational lifetime of the reactor, the limits for fast neutron flux and gamma dose rate at dose plane are  $3.17 \times 10^3 \text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$  and  $3.17 \times 10^{-3} \text{ rad}^{-1}$ , respectively.

### The Optimization Results

The genetic algorithm performs 100 generations with the population size of 50. The crossover rate and the mutation rate of the genetic algorithm are 0.7 and 0.5, respectively. Convergence of fitness value vs. generation number of the optimization is shown in **Figure 4**. The fitness value grows slowly while the generation reaches 70, so 100 generations are sufficient to the optimization.

Ranges of the optimization parameters are 0–150 cm. For compact design, the constraint of the optimization parameters, i.e.,  $h(x_j)$  in **Equation 1** is written as:

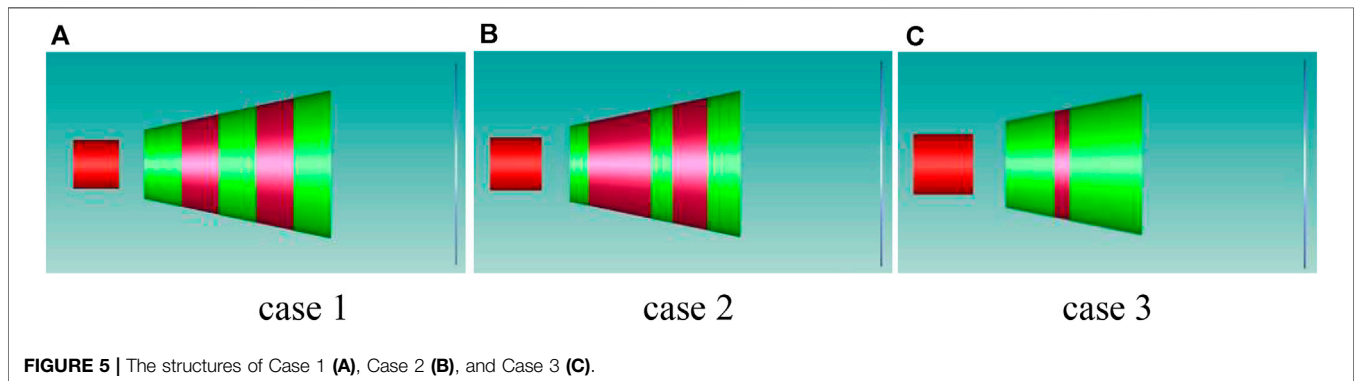
$$\sum_{i=1}^{n=5} t_i - 150 \leq 0 \tag{6}$$

The optimization method starts with the initial shielding design, and then a certain number of shield solutions are randomly generated to form an initial population, and through the genetic operators with many generations, the optimal individual is obtained. As a result, the objectives and parameters of three cases are studied, such as the initial design (Case 1), the best individual of the first generation (Case 2), and the optimal solution (Case 3). The optimization objectives and the parameters of the three cases are listed in **Table 2**, where  $f_n(\vec{x})$  and  $f_g(\vec{x})$  are calculated with the MCNP code with relative errors listed within the bracket below the objective values.

The sub-objective  $f_w(\vec{x})$  is competing with the sub-objectives  $f_n(\vec{x})$  and  $f_g(\vec{x})$ . As is shown in **Table 2**, the sub-objectives  $f_n(\vec{x})$  and  $f_g(\vec{x})$  of Case 1 and Case 2 are much less than the tolerable limits, indicating that the objective  $f_w(\vec{x})$  can be future optimized. However, sub-objectives  $f_n(\vec{x})$  and  $f_g(\vec{x})$  of Case 3 are slightly lower than the tolerable limits, indicating that  $f_w(\vec{x})$  of Case 3 is near the global optimal solution. The structures of the three cases are shown in **Figure 5**. The structure of case 1 is shown in **Figure 5A**, and the structure of case 2 is shown in **Figure 5B**. The optimal structure is “LiH, W-B4C, LiH,” shown in **Figure 5C**. Both light material (LiH) and heavy material (W-B4C) are needed to shield the neutron and gamma mixing field of the nuclear reactor. Among the combinations of LiH and W-B4C, the optimized structure is the most likely structure to obtain the minimal weight to ensure the radiation at the dose plane is below the tolerable limits. Compared

**TABLE 2** | Objectives and parameters of the initial design, best individual of the first generation and the optimized solution.

	$f_w(\vec{x})$ (kg)	$f_n(\vec{x})$ (n/cm <sup>2</sup> /s)	$f_g(\vec{x})$ (rad/s)	$t_1$ (cm)	$t_2$ (cm)	$t_3$ (cm)	$t_4$ (cm)	$t_5$ (cm)
Range	—	—	—	0–150	0–150	0–150	0–150	0–150
Case 1	4722.5	1.22E + 05 (0.04)	3.54E-05 (0.04)	30	30	30	30	30
Case 2	4208.7	1.75E + 05 (0.03)	5.02E-05 (0.04)	13.3	44.6	15.4	25.0	23.5
Case 3	691.9	3.06E + 05 (0.03)	0.0031 (0.01)	30.0	9.5	18.6	0.0	26.0



with Case 1 and Case 2, the weight of the shadow shield is much less when the radiation at the dose plane is below the tolerable limits.

## CONCLUSION

The radiation shadow shield of the space nuclear reactor is a vital component to protect electronic devices at the dose plane from radiation from the reactor core. The radiation shadow shield needs to be lightweight and compact to reduce the launching cost. The multi-objective optimization problem of designing the shadow shield is converted into a single-objective optimization problem by setting the sub-objectives as constraints. An optimization method combining a single objective genetic algorithm with Monte Carlo simulation is developed to solve the radiation shadow shield designing problem. Compared with the initial design and the best individual of the first generation, weight of the optimal solution is greatly reduced (14.7% of the weight of the initial design and 16.4% of the weight of the best individual of the first generation). In addition, the radiation dose at the dose plane of the optimal solution is lower than the acceptable tolerance. The optimization method developed in this work is an automated optimization strategy by searching

for the parameter space, which will not be subject to human preferences. The global optimal solutions can be obtained without the tedium of human manual work.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

BL designed the research and wrote the paper; HL conducted the research; HX performed the Monte Carlo simulations; XC and LL raised valuable questions that help improving the paper; BX, YT, and CC provided good suggestions for data analysis.

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