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Protection Capability Assessment of Nuclear Emergency Medical Shelter

Heng Lu*, Meng Wang, Maolin Xiong, Yi Gu, Qingxian Zhang, Liangquan Ge

College of Applied Nuclear Technology and Automation Engineering, Chengdu University of Technology, Chengdu, China
Email: *lh752061402@vip.qq.com

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Abstract

The Monte Carlo model of the nuclear emergency medical shelter was set according to the national standard. The absorbed dose of ICRU balls, on behalf of emergency personnel in the shelter, caused by major radionuclides (^{60}Co, ^{85}Kr, ^{131}I, ^{133}Xe, ^{137}Cs) in the air around nuclear facilities was obtained by Monte Carlo simulation. The functional relationship between the maximum working time of emergency rescuers in the shelter and the activity concentration of radionuclide outside the shelter was given. Taking ^{137}Cs as an example, the fitting curve of shielding lead layer quality and shielding effect was obtained according to the simulation result. When the thickness of the shielded lead layer reaches 5 mm, the working time of emergency rescuers in the shelter can be effectively improved from 1 hour to 2.5 hours under the activity concentration of 7.72E+09 Bq/m^3.

Subject Areas

Nuclear Physics

Keywords

The Nuclear Emergency Medical Shelter, ICRU Ball, Working Time, Effective Dose, Activity Concentration

1. Introduction

The nuclear emergency medical shelter can be used to transport and provide effective protection for equipment and personnel in an emergency. The design schemes of medical shelter applicable to automobiles and ships have been proposed for a long time [1]-[6]. Most of these schemes are designed for military fields. Otherwise, these schemes do not consider the effective doses of the rescuers inside the shelter during the rescue process. Therefore, in the design of the nuclear emergency medical shelter, it is necessary to consider that the shielding effect of it to ensure the effective dose of the rescuers in the nuclear emergency event is within the allowable range.

In this paper, the radiation protection capability of a medical designed according to the GBJ 6109-2007 CAF60 standard shelter was assessed. The absorbed dose of humans in the shelter caused by radionuclides around nuclear facilities air was simulated by Monte Carlo method. The functional relationship between the working time in the shelter and the activity concentration of radionuclide outside the shelter is given under the precondition of the guidance values for the exposure dose of emergency response workers. In order to increase the effective working time of emergency rescuers in the shelter in the nuclear emergency, a shielding lead layer was added in the shelter with the examples of ^{137}Cs. It provides a basis for shielding design of nuclear emergency medical shelter.

2. Physical Model of Medical Shelter

The model of the nuclear emergency medical shelter was set according to the GBJ 6109-2007 CAF60 standard, as shown in **Figure 1**. The size of the medical cabin body is 6.058 m × 2.438 m × 2.100 m. 1.5 mm thick aluminum was distributed both inside and outside the shelter, 49 mm thick polyurethane in the middle. Two ICRU balls were set in the middle and edge shelter to represent the human tissue.

3. Calculation Method of Human Absorbed Dose

Around nuclear facilities, the radionuclides in the air mainly exist in the form of gaseous (^{85}Kr and ^{133}Xe) or aerosol (^{60}Co, ^{131}I, and ^{137}Cs) [7] [8] [9] [10] [11]. The energy and release probability of these radionuclides γ rays is shown in **Table 1**. The simulation was completed by MCNPX. To reasonably estimate the human

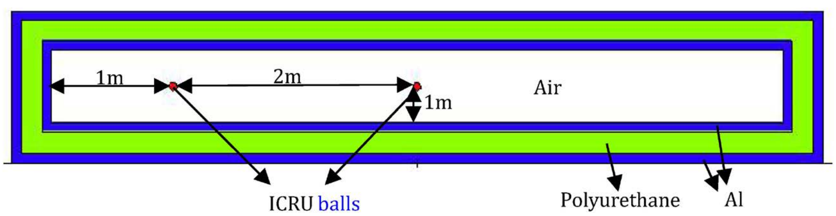

Figure 1. Model of nuclear emergency medical shelter.

Table 1. Rdionuclide ray energy and its release probability.

Radionuclides	Energy (γ)/keV	Total release probability
^{60}Co	1170, 1330	2.00
^{137}Cs	661	0.85
^{85}Kr	514	0.43
^{131}I	30, 80, 177, 284, 364, 503, 637, 773	0.97
^{133}Xe	31, 81, 161, 223, 303, 384	0.84

absorbed dose, the ICRU ball represented the body membrane, and *F6 card, a tool to calculate the average deposition energy over a cell in MCNPX program, was used for recording. The ICRU ball was set according to ICRU specifications, with a density of 1 g/cm^3 and a diameter of 30 cm. The mass percentages of hydrogen, carbon, nitrogen, and oxygen are 10.1%, 11.1%, 2.6%, and 76.3%, respectively.

The result recorded by *F6 card is the contribution of each source particle to the tissue absorbed dose called the normalized absorbed dose D_0 [jerks/g].The source unit activity dose rate $\dot{D}_0$ [(nGy/h)/Bq] is calculated and then converted into unit concentration absorbed dose rate $\dot{D}_1$ [(nGy/h)/(Bq/m^3)].

$$\dot{D}_0 = D_0 \times 1 \times Q \times 10^9 \times 10^9 \times 3600 \times 10^3 \tag{1}$$

$$\dot{D}_1 = \dot{D}_0 \times V \times 1 \tag{2}$$

Q is the expected value of the γ ray emission probability per unit activity of the radionuclide, while V is the sampling volume (m^3) of the geometric model radioactive source.

The dose rate of human tissue in the medical shelter can be calculated by the following formula:

$$\dot{D} = \dot{D}_1 \times A \tag{3}$$

A is the activity concentration of the radionuclide in the air.

Then the effective dose of the human body from R-type radiation within t time can be expressed as:

$$E = \sum_T \sum_R W_T \times W_R \times \dot{D}_1 \times A \times t \tag{4}$$

W_T is the tissue weighting factor of human tissues T. W_R is the radiation weighting factor of R-type radiation. For γ radiation, the value of W_R is 1.

4. Dose Estimation

When simulating and calculating the absorbed dose of human in the shelter caused by radionuclides, medical shelter is placed on the ground. While the inside and outside of the shelter are air, and the radionuclides are evenly diffused in the air. The sampling simulation of radioactive materials in the extravehicular atmosphere is set as a cube space. To improve the efficiency of simulation calculation while ensuring the accuracy of sampling, it is necessary to establish the saturation boundary. Refer to the theoretical formula (5), the attenuation ratio of different energy rays in the air was calculated.

$$I = B \times I_0 \times \mathrm{e}^{-\mu_m \times X_m} \tag{5}$$

X_m is the travel distance of γ ray in the air; B is the accumulation factor; μ_m is the mass attenuation coefficient of γ ray in the air; I and I_0 are the energy of γ ray before and after X_m travel distance in the air.

According to the changing trend of attenuation intensity with γ-ray travel distance, the side lengths of the sampling boundary are set differently, as shown in Table 2.

4.1. Dose Caused by Aerosol Radionuclides outside the Shelter

The radionuclides are evenly distributed in the air outside the shelter. According to the formulas in chapter 3, $\dot{D}_0$ and $\dot{D}_1$ caused by aerosolradionuclides were calculated, as shown in Table 3.

4.2. Dose from Inert Radionuclides inside and outside the Shelter

The medical shelter is designed with an air filtration purification system; however, the inert gas is difficult to filter out. At this time, the concentration of inert radionuclides inside and outside the medical cabin tends to be the same. According to the formulas in chapter 3, $\dot{D}_0$ and $\dot{D}_1$ caused by inert gas radionuclides were calculated, as shown in Table 4. The absorbed dose rate of human tissues caused by the unit concentration of inert radionuclides in the shelter is far lower than that caused outside the shelter.

4.3. Evaluation of Radiation Protection Capability of Medical Shelter

The guidance values for the exposure dose of emergency rescuers are shown in Table 5 according to the standards promulgated by IAEA in 2014 [12].

Table 2. The side length of the outer cube sampling boundary of different radionuclides.

Radionuclides	Length of the sampling boundary/m
^{60}Co	800
^{85}Kr	600
^{131}I	400
^{137}CS	600
^{133}Xe	300

Table 3. Simulation results of absorbed dose induced by outside radionuclides.

	Site	Normalized absorbed dose/jerks·gram^{-1}·nps^{-1}	RSD/%	Absorbed dose rate per unit concentration/nGy·h^{-1}·(Bq/m^3)$^{-1}$
^{60}Co	Middle	2.27E−34	±5.34	3.28E−01
	Side	2.28E−34	±5.35	3.31E−01
^{137}Cs	Middle	2.51E−34	±3.71	6.47E−02
	Side	2.43E−34	±3.81	6.28E−02
^{85}Kr	Middle	1.93E−34	±3.77	2.53E−02
	Side	1.97E−34	±3.70	2.59E−02
^{131}I	Middle	3.63E−34	±2.46	3.19E−02
	Side	3.66E−34	±2.48	3.21E−02
^{133}Xe	Middle	7.14E−35	±2.86	2.29E−03
	Side	7.82E−35	±2.79	2.51E−03

To ensure that the dose of emergency rescuers is within the guidance value, the protective performance of the medical shelter is necessary to be evaluated. The relationship between the maximum working time of emergency rescuers in the medical shelter and the concentration of radionuclides outside the shelter within the guideline value was obtained according to formulas in chapter 3. The rescuers in the shelter are irradiated uniformly; therefore, the value of the tissue weighting factor W_T is 1. In contrast, the guide value of the radiation dose for emergency rescuers is 500 mSv.

$$t = \frac{500 \times 10^{-3}}{\dot{D}_1 \times A \times 10^{-9}} \tag{6}$$

t is the working time of emergency rescuers, while A is the activity concentration of radionuclide outside the shelter. Introducing the coefficient $K = \frac{5 \times 10^8}{\dot{D}_1}$:

$$t = \frac{K}{A} \tag{7}$$

The value of K without lead shield was shown in Table 6.

Table 4. Absorbed dose rate due to inert radionuclides.

	Site	Absorbed dose rate per unit concentration the outside/nGy·h^{-1}·(Bq/m^3)$^{-1}$	Absorbed dose rate per unit concentration the inside/nGy·h^{-1}·(Bq/m^3)$^{-1}$
^{85}Kr	Middle	2.53E−02	4.75E−04
	Side	2.59E−02	4.29E−04
^{133}Xe	Middle	3.19E−02	7.48E−04
	Side	3.21E−02	6.77E−04

Table 5. The guidance values for the exposure dose of emergency response workers.

Emergency action	The guidance values
Action to save the life	<500 mSv
Actions to prevent the severe deterministic effect	<500 mSv
Actions to prevent disasters that may have a major impact on humans and the environment	<500 mSv
Actions to avoid large collective doses	<100 mSv

Table 6. Value of K without lead shield.

Radionuclide		Value
^{60}Co	Middle	1.52E+09
	Side	1.51E+09
^{137}Cs	Middle	7.72E+09
	Side	7.96E+09
^{131}I	Middle	1.57E+10
	Side	1.56E+10

The influence of internal exposure needs to be considered for ^{85}Kr and ^{133}Xe. According to ICRP Document No. 61, effective dose conversion factors of ^{85}Kr and ^{133}Xe are 2.2E−11 Sv/(d·Bq/m^3) and 1.2E−10 Sv/(d·Bq/m^3), respectively. The relationship between the maximum working time of emergency rescuers inside the medical shelter and the concentration of radionuclides outside the shelter is expressed by the following formula.

$$t = \frac{500\times 10^{-3}}{\left(\dot{D}_1 \times 10^{-9} + \frac{L}{24}\right)\times A} \tag{8}$$

Introducing the coefficient $M = \frac{500\times 10^{-3}}{\dot{D}_1 \times 10^{-9} + \frac{L}{24}}$:

$$t = \frac{M}{A} \tag{9}$$

The value of M without lead shield was shown in Table 7.

When the activity concentration of ^{137}Cs outside the shelter is 7.72E+09 Bq/m^3, the maximum allowable working time of emergency rescuers in the medical shelter is one hour. To increase the maximum working time of emergency rescuers, a lead shielding layer should be added to the structural materials of the medical shelter.

5. Protection Performance Improved through the Lead Shield

Taking ^{137}Cs as an example. The shielding effect curve of the two ICRU balls in the shelter with being a lead shield was shown in Figure 2. The fitting curve can describe the relationship between the quality of the lead and the shielding effect. With the 5 mm thickness of the lead layer, the absorbed dose in the middle and edge of the shelter was reduced to 60.2% and 61.66%, respectively. At this time, the coefficient K in formula (7) can be calculated. The value of M within 5 mm thickness of the lead layer was shown in Table 8.

As shown in Figure 3, when the activity concentration of ^{137}Cs outside the shelter is 7.72E+09 Bq/m^3, the maximum working time of emergency rescuers is 2.5 hours with 5 mm thickness of the lead layer. Compared with the calculation results without the lead layer, the setting of the lead layer shielding can effectively increase the working time of emergency rescuers in the medical shelter and provide sufficient time for emergency rescue.

Table 7. Value of M without lead shield.

Radionuclide		Value
^{85}Kr	Middle	1.91E+10
	Side	1.86E+10
^{133}Xe	Middle	1.79E+11
	Side	1.66E+11

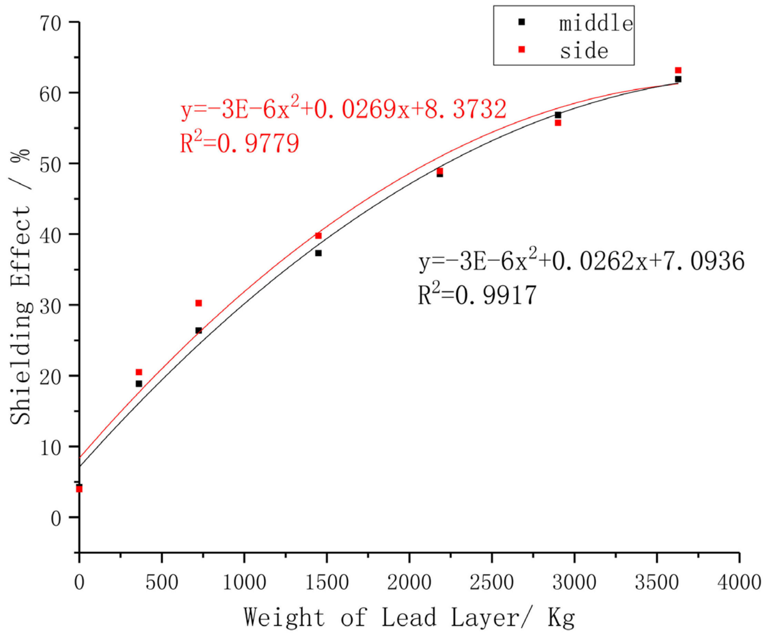

Figure 2. The relationship between the shielding effect and the weight of the lead layer.

Table 8. Value of *M* with 5 mm thickness of the lead layer.

Radionuclide		Value
^{137}Cs	Middle	1.94E+10
	Side	2.08E+10

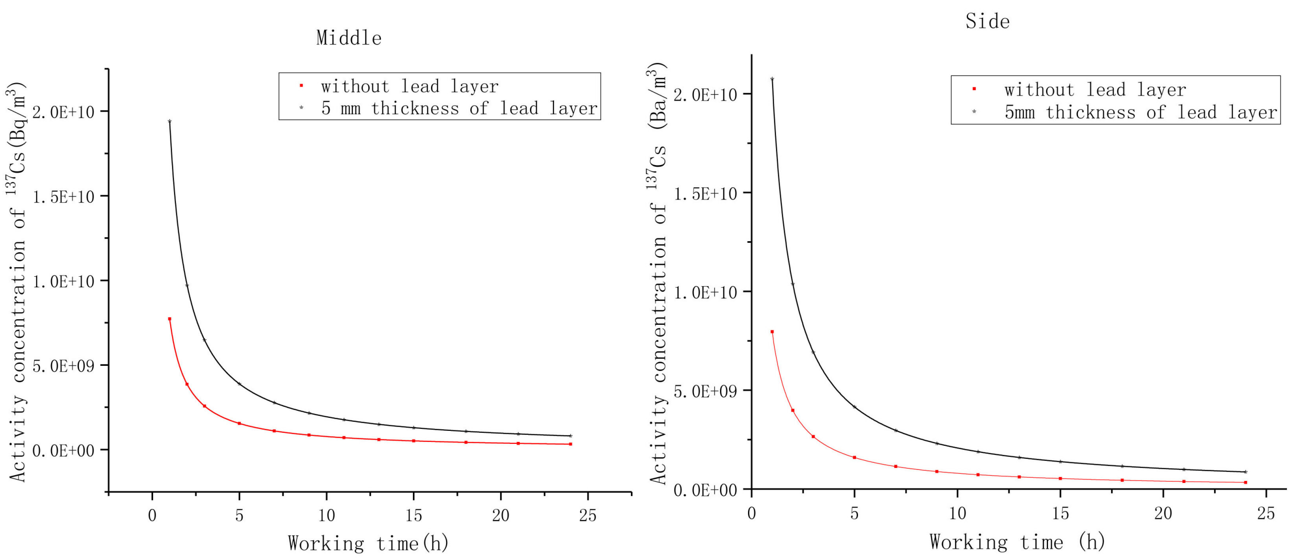

Figure 3. Working time curve of Emergency rescuers

6. Conclusion

The human absorbed dose caused by radionuclides in gases and aerosols around nuclear facilities before and after setting up the medical cabin was obtained by Monte Carlo simulation. The formula for calculating the maximum working time of emergency rescuers in the medical shelter under the guidance value of the exposure dose was given. Comparing the working time curves of the medical shelter without lead layer and that with 5 mm thickness of the lead layer, when the activity concentration of ^{137}Cs outside the shelter is 7.72E+09 Bq/m^3, the maximum working time of emergency rescuers was increased from 1 hour to 2.5 hours.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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