A study on method for accurate radioactive dose rate calculation in thick shields

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1. Introduction

It is of importance to calculate the activations of the irradiated materials accurately in terms of radiation safety. One of the ways to calculate the material activations is the rigorous two-step method (R2S) [1] which performs transport and inventory calculations separately. Although the R2S method is useful to estimate dose rates that result from activation, one has to note that underestimated or overestimated results can be obtained when the cells in the simulations are too large. This is because it is assumed that radioactive nuclei produced through nuclear interactions are distributed uniformly in the cells in this method. As a result, radiations from radioactive products are less appropriately described as the sizes of cells become larger. To solve the problem, cells have to be divided properly.

In this study, dose rates in the area around the proton beam dump of Nuclear data production system (NDPS) [2,3] are calculated. NDPS is the experimental system, which will be used for nuclear data measurement, especially for the high energy neutron induced reactions. The proton beam dump consists of a Faraday cup and a chamber. They will be made of copper and stainless steel, respectively. Concrete or lead will be placed outside of them for radiation shielding. To calculate the dose rates, both MCNP and FISPACT are used. The former gives the information of the radioactive products that originated from protons and secondary neutrons while radiations over time from the products are deduced using the latter. Variations of dose rates are investigated according to the change of the methods that dividing cells of the shielding of the proton beam dump.

2. Methods and Results

MCNPX version 2.7.0 [4] is used to calculate particle transport and nuclear interactions. Also, inventory calculations are performed using FISPACT 2010 [5,6].

2.1 Geometry of the simulation

The proton beam dump of NDPS is designed as a structure of a Faraday cup. It will be located in the cylinder chamber as shown in Fig. 1. For the materials of them, copper and stainless steel are considered, respectively. Insides of the Faraday cup and chamber pipe are vacuum and the proton beam dump requires a water cooling system. Shielding material, concrete or lead, will be placed around the proton beam dump.

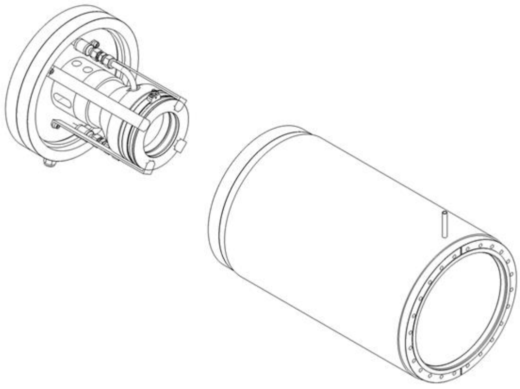

Fig. 1. The drawing of the proton beam dump of NDPS

A simplified geometry is used for the MCNP simulation of the activation of the proton beam dump. The copper cylinder that is filled with water is hit by the proton beam of 82.7 MeV and 15.6 μA. The source is located right after the copper. They are surrounded by stainless steel. To shield the radiations from the proton activation, shielding material will be placed outside of them. 10cm, 30cm, and 50cm thick concrete are taken into account as well as 10cm and 30cm thick lead as shielding materials. The geometry of the simulation and detailed shapes and sizes of the materials are presented in Fig. 2 and Table I, respectively.

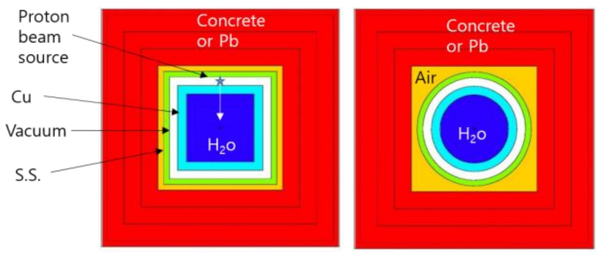

Fig. 2. Geometry of the proton beam dump for MCNP simulation

Table I: Shapes and sizes of the materials

Material	Shape	Size (cm)
Water	Cylinder	12(H) ×12(Φ)
Copper	Cylinder	15(H) ×15(Φ) (thickness: 1.5cm)
Vacuum	Cylinder	18(H) ×18(Φ)
Stainless steal	Cylinder	20(H) ×20(Φ) (thickness: 1cm)
Air	Box	22(W) ×22(D) ×22(H)

Shielding (concrete, lead)	Box	42(W) ×42(D) ×42(H) or 82(W) ×82(D) ×82(H) or 102(W) ×102(D) ×102(H)

2.2 Calculation method of activation

To estimate the photon dose rates originated from proton activation, the R2S method is exploited. The calculations of the dose rates at 10cm, 20cm, 30cm, 50cm, and 100cm away from the concrete or lead shield are performed through the following steps:
(1) Transport of particles (neutron, proton, and photon) and nuclear reactions are calculated by using MCNP code.
(2) FISPACT code calculates the total number of gammas and gamma energy spectrum of each material using the MCNP result from (1) and its data library.
(3) MCNP calculates the dose rates by using the gamma data as the source.

Here, it is assumed that the proton beam irradiation continues for 40 days and dose rates are calculated for 0~7, 10, 15, 20, and 30 days after beam stop. Three different types of shield divisions are applied for the 10cm thick shield and four different types of shield divisions are applied for the 30cm and 50cm thick shields. First, activation calculation was performed without dividing the shield (1-layer). Then the same processes are applied for the cases that the cells of the shielding material are divided into four (4-layer1) and eight layers (8-layer1) with equal intervals. Finally, the same calculations are performed for the cases that the number of layers is equal but the thicknesses of cells become gradually thinner as they are located outside of the shield (4-layer2 and 8-layer2). The thicknesses of each cell are denoted in Table II.

Table II: Thickness of cells

	Thickness of shield	Thickness of each cell
4-layer1	10cm	2.5cm×4
	30cm	7.5cm×4
	50cm	12.5cm×4
4-layer2	10cm	3cm×3, 1cm×1
8-layer1	10cm	1.25cm×4
	30cm	3.75cm×4
	50cm	6.25cm×4
8-layer2	30cm	5cm×4, 3cm×3, 1cm×1
	50cm	10cm×4, 3cm×3, 1cm×1

2.3 Results

Calculated dose rates described in section 2.2 are presented in Fig. 3 and 4 as the values of the ratio. In the case of the 10cm thick concrete shield, dividing the shield does not give a large impact. Deviations of results do not exceed 3% regardless of the number of divisions and method. However, as the thickness of the shield increase, the effect of the division of cells become larger. Figure 3 shows calculated dose rates at 10cm away from 30cm (top) and 50cm (bottom) thick concrete shielding. In the case of the 30cm thick concrete, the dose rate right after beam stop which calculated without dividing the shield is about 1.5 times larger than those of the others. As the number of cells increases, calculated dose rates decrease. The same trend can be seen in the 50cm thick concrete calculation result. The remarkable difference between the calculation results of 30cm and 50cm thick concrete shielding is the magnitude of the values of the ratio. The overall calculation results of 50cm thick concrete shielding, especially the ratios of 1-layer and 8-layer1, are larger than those of 30cm thick shielding. This is because the radioactive nuclides are assumed to be uniformly distributed in the cell in R2S method, the dose rates are estimated incorrectly as the thickness of each cell increases.

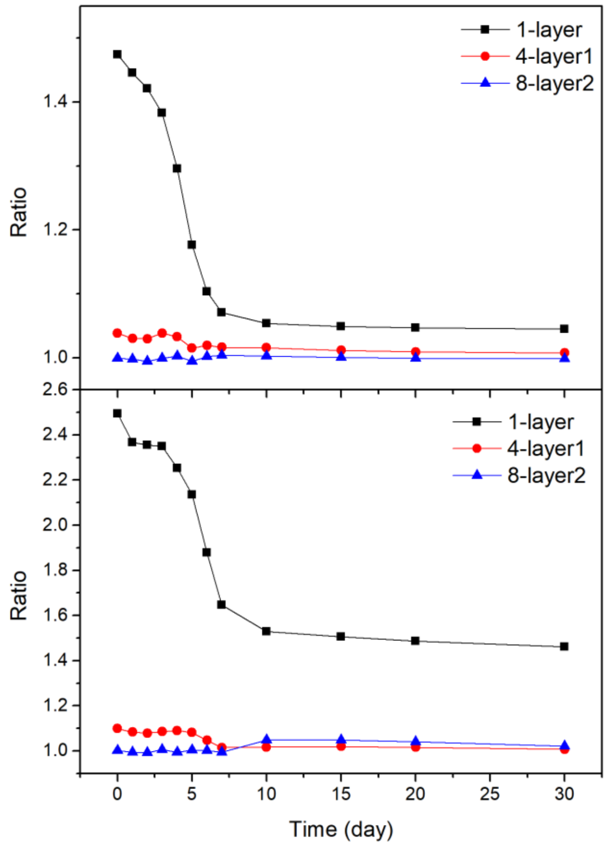

Fig. 3. Calculated dose rates at 10cm away from 30cm (top) and 50cm (bottom) thick concrete shielding. All the results are divided by those of 8-layer1 and thus results are presented as the ratios.

The effect of dividing the cells of shielding is more noticeable when lead shielding is used as can be seen from Fig 4. While dividing the shield does not affect on the calculated dose rate from 10cm thick concrete shied, the effect is clear depending on whether the shielding is divided in 10cm lead. Moreover, all the calculated dose rates of 30cm thick lead shieling show quite different results depending not only on the number of cells but also on the method that dividing the cells. Especially, calculated dose rates without dividing the shielding material are at least 10 times the results of dividing the cells. Also, unlike the previous cases, the results are different depending on how the cells are divided.

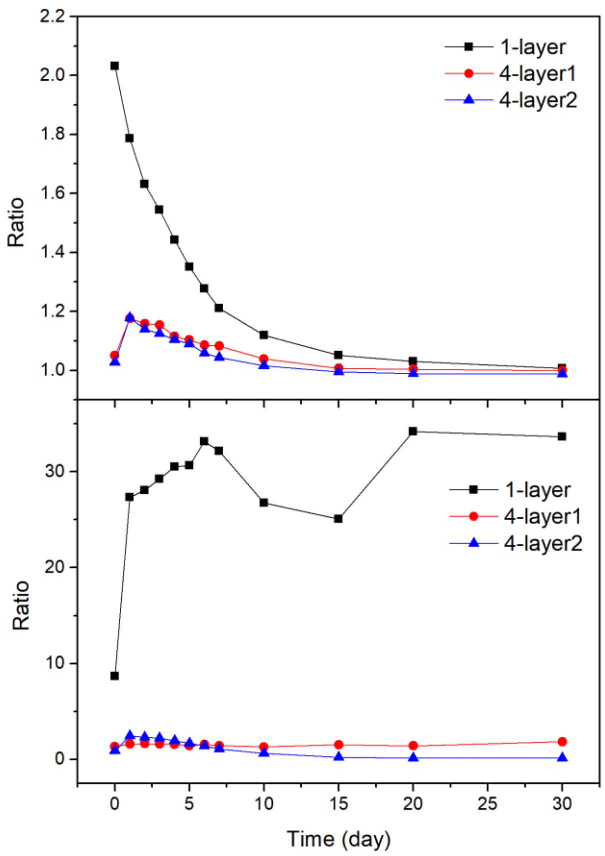

Fig. 4. Calculated dose rates at 10cm away from 10cm (top) and 30cm (bottom) thick lead shielding. All the results are divided by those of 8-layer1 and thus results are presented as the ratios.

It seems like there is no need to divide the cells for the 10cm thick concrete shield. However, as the thickness of the shield increases or the material of the shield changes (ex. lead), shielding materials have to be divided properly for correct calculations. Based on the calculation results, we can see that self-shielding effects have a great influence on the dose rate calculation. If the shielding material is not divided into multiple cells, the self-shielding is not considered properly. As a result, calculated dose rates are overestimated. Whereas, the smaller the cell is, the more the results converge. They are tentatively considered as the correct values.

In this study, just a few cases of calculations are performed as the preliminary study but further investigations are planned to find the optimized method that dividing the cells of shield for various conditions. Moreover, the outer layer thickness which is important in dose rate calculation will be optimized by using sensitivity calculations.

3. Conclusions

In this work, the variances of activation dose rates are calculated to find the effect of dividing shielding material in activation calculation. R2S method is used for the design of the NDPS proton beam dump and various methods that divide the shielding materials are considered. By comparing the results from different ways that dividing the shielding material, it is found that necessity and proper methods for given thickness and materials of shielding. In the further study, more systematic research will be performed to find the method that dividing the cells of shielding into optimized numbers and thicknesses for various shielding materials and thicknesses.

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