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Investigating Systematic Effects on Nuclear Heating Calculation for Radioisotope Production in HANARO using MCNP6

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1. Introduction

HANARO is a 30-MW research reactor at the Korea Atomic Energy Research Institute used for various applications such as radioisotope (RI) production, neutron activation analysis, and neutron transmutation doping through neutron irradiation on various samples [1, 2, 3]. However, during neutron irradiation, the irradiated materials, including reactor structural materials and irradiated samples, experience an increase in temperature due to nuclear heating. Nuclear heating originates from prompt neutrons and gamma rays, as well as delayed gamma and beta rays from fission and activation products. To ensure thermal-hydraulic safety and prevent accidents like the leakage of radioactive materials, it is crucial to evaluate the nuclear heating of the irradiated materials before conducting any irradiation experiment.

This paper aims to calculate the nuclear heating rates of the irradiated materials when producing ^{177}Lu and ^{166}Ho using isotope production (IP) irradiation holes of HANARO. Direct measurement of nuclear heating of the irradiated materials in the IP irradiation hole is challenging due to the complexity of the experimental setup. Therefore, we used MCNP6 to calculate the nuclear heating rates. In particular, to conduct a systematic analysis of the nuclear heating that occurs during RI production using HANARO, we separately evaluated the nuclear heating rates of the RI production target with a high neutron capture cross-section and the surrounding structure.

2. Materials and Methods

2.1 Monte Carlo simulation

MCNP6 (version 6.2.0) was used to calculate the nuclear heating rates of the RI production target and RI capsule when producing ^{177}Lu and ^{166}Ho using the IP15 irradiation hole of HANARO. Yb_2O_3 and Dy_2O_3 were used as RI production targets for the production of ^{177}Lu and ^{166}Ho, respectively. The RI capsule was made of aluminum 1050 and consisted of inner and outer capsules. The RI production target was sealed at the bottom of a quartz capsule and loaded inside the inner capsule. The inner capsule was filled with air and loaded inside an outer capsule filled with helium gas. Four sets of RI capsules containing the RI production target were axially loaded into the RI rig, which was loaded into the IP15 irradiation hole. The nuclear heating rates were calculated for the third RI capsule with the highest neutron flux, which was attributed to the control rod height of 450 mm from the bottom of the core.

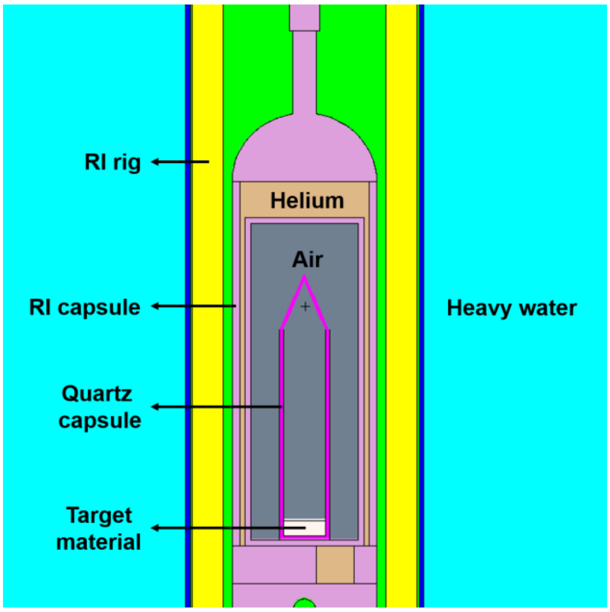

Fig. 1. Vertical cross-section of the RI capsule loaded in the IP irradiation hole.

The nuclear heating rates calculated by MCNP6 can only simultaneously consider the contribution of radiation from the RI production target and RI capsule. In order to evaluate the nuclear heating rate of the RI production target alone, it is necessary to distinguish the contribution of the RI capsule to the nuclear heating rate. Therefore, by calculating the nuclear heating rate without an RI production target (replacing the RI production target with air), the contribution of the RI capsule was distinguished. In this study, we did not calculate the nuclear heating rate by delayed radiation because its contribution to nuclear heating is relatively small compared to that of prompt radiation.

3. Results and Discussion

3.1 Nuclear heating rates

Tables 1 and 2 present the nuclear heating rates of the RI production target and RI capsule, respectively. The nuclear heating rate of Dy_2O_3 was significantly higher than that of Yb_2O_3 because the neutron capture cross-section of Dy is much larger than that of Yb. In addition, the nuclear heating rates without an RI production target (i.e., the contribution of the reactor structural materials) were relatively much smaller than those with the RI production target.

Table 1. Nuclear heating rates of RI production target.

Nuclear heating rate (W)	
Yb_2O_3	5.53×10^{-1}
Dy_2O_3	1.79
Air	4.60×10^{-3}

The nuclear heating rates of the RI capsule and the quartz capsule exhibited a smaller discrepancy compared to the RI production targets. This may be because of the low amount (0.5 g) of the RI production target loaded into the RI capsule. The nuclear heating contribution of Yb_2O_3 to the RI capsule and quartz capsule was found to be similar to that in the absence of the RI production target. However, Dy_2O_3 contributed significantly to the nuclear heating in the inner RI capsule and quartz capsule. Hence, when carrying out a neutron irradiation experiment involving a target material with a high neutron capture cross-section, it is crucial to assess the nuclear heating in both the target material and the surrounding structures.

Table 2. Nuclear heating rates of RI capsule.

Nuclear heating rate (W)			
Irradiated material	Loaded material		
	Yb_2O_3	Dy_2O_3	Air
Inner RI capsule	13.9	15.3	14.0
Outer RI capsule	11.4	11.9	11.4
Quartz capsule	2.37	3.46	2.38

4. Conclusions

We used MCNP6 to calculate the nuclear heating rates of the RI production target and RI capsule during the production of ^{177}Lu and ^{166}Ho through the IP irradiation hole of HANARO. The nuclear heating rates for Yb_2O_3 and Dy_2O_3 in the third RI capsule of the IP15 irradiation hole were 0.553 W and 1.79 W, respectively. RI capsules exhibited higher nuclear heating rates when loaded with Dy_2O_3 compared to Yb_2O_3. Conducting a more comprehensive thermal-hydraulic safety analysis in the future would be possible by obtaining the temperature distribution inside the IP irradiation hole using a reliable finite element analysis program like COMSOL Multiphysics. Furthermore, incorporating factors such as water flow and delayed radiation into the calculation can result in a more precise evaluation of nuclear heating.

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