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A Calculation of Nuclear Heating by Activation Product of Structure Materials for the In-core Irradiation Hole in the HANARO

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1. Introduction

One of the important requirements for the structure materials of the nuclear reactor is a small reaction cross-section with neutron. In spite of this requirement, irreplaceable structure materials have been irradiated for a long time and activated by neutrons in the reactor. Some of activation products of these structure materials are radioactive, and they decay with radiation emission depending on its half-life. When the emitted radiation interacts with materials in the reactor, heat is generated by energy deposition. Among the emitted radiations from the structure materials, gamma-ray contributes to the heating dominantly because of its long mean free path. Only delayed gamma heating is considered in this paper. Contribution of the delayed gamma heating is expected to be negligible for the reactor power. For the neutron irradiation, however, the contribution of delayed gamma heating is not negligible issue, and it should be evaluated for safety analysis. Additionally, in the case of temperature-sensitive irradiation targets, the delayed gamma heating should be evaluated precisely.

For the HANARO, the delayed gamma heating has been evaluated by modifying the library data of the calculation code [1, 2] or by assuming the heating to be conservative value based on prompt gamma heating [3]. For the method of modifying the library data, however, it should be able to estimate isotopes which contribute to heat generation exactly. And furthermore, it should be concerned to determine modified emission yield of gamma-rays depending on the half-life. For the method of assuming conservative value, it is hard to determine whether the assumed heating value is enough conservative or not.

In this study, a methodology for evaluation of nuclear heating by structure materials irradiated for a long time is established with the ORIGEN and MCNP codes. And this method is applied to determine the nuclear heating of the RI capsule in the IR2 irradiation hole in the HANARO.

2. Calculation Method

The calculation procedure of heating value by delayed radiation is described as follows. First, one-group integrated reaction rates and neutron flux are calculated by using the MCNP code [4]. Next, a set of the one-group effective cross-sections is calculated by using the one-group integrated reaction rates and neutron flux. These calculated effective cross-sections are used by the ORIGEN code [5, 6]. Next, the activities of radioisotopes are calculated by the ORIGEN code based on the composition of materials in the reactor, irradiation time and neutron flux. The activities of radioisotopes are used to define the delayed gamma source distribution (See chapter 2.2). The delayed gamma source distribution is defined by repeating above calculation procedure for all structure materials considering their positions. Finally, the heating value by the delayed radiation is estimated by using the MCNP code with the radiation source distribution. Among the emitted radiations, only photon is considered because of its long mean free path. A schematic of the calculation procedure is drawn in figure 1.

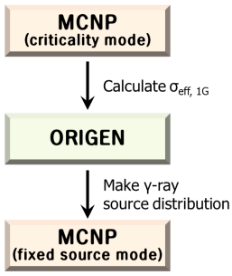


Figure 1. Flow chart of calculation procedure

2.1 One-group Cross-Section

In order to generate the ORIGEN library, the one-group effective cross-sections are calculated with the MCNP code for each segment of the structure materials. The calculated cross-sections are averaged at each segment. The one-group effective cross-section is defined as below equation.

$$\bar{\sigma} = \frac{\int dE\sigma(E)\varphi(E)}{\int dE\varphi(E)} = \frac{R_{MCNP,1G}/N}{\varphi_{MCNP,1G}}$$

Where $R_{MCNP,1G}$ and $\varphi_{MCNP,1G}$ are one-group integrated reaction rate and flux calculated by MCNP, respectively. And N means number density of isotope based on theoretical physical density and composition information.

2.2 Source Distribution

Photon emission rate is proportional to the activity of radioisotope. It means that the source distribution can be estimated with the activities of each isotope at each position. The activities of the radioisotopes from the structure materials were obtained by the ORIGEN. And the source distribution of the MCNP code was determined by considering the activities of the radioisotopes whose specific activity is larger than 0.01 Ci/g, photon emission yield and energy [7].

2.3 Heat Generation by Delayed Gamma-ray

From the calculated gamma-ray distribution, the input of the MCNP fixed source mode was written, and the F6 tally was used for calculation of gamma heating. Because the result of the MCNP means a statistical result for a single particle, it needs to multiply the result by total number of particles so called the scaling factor. In this calculation, the MCNP result is a gamma heating and the scaling factor is the number of emitted photons per second such as the radioactivity in Bq unit.

2.4 HANARO Model

The reactor core of the HANARO was modeled using the MCNP as follows. All fuels are assumed to be fresh fuel. Control assemblies are assumed to be withdrawn 450 mm from the core bottom, and shutdown assemblies are removed fully from the core. In the CT, IR and OR irradiation holes, dummy assemblies are assumed to be loaded. Figure 2 shows the horizontal cut-view of the HANARO core of the MCNP model.

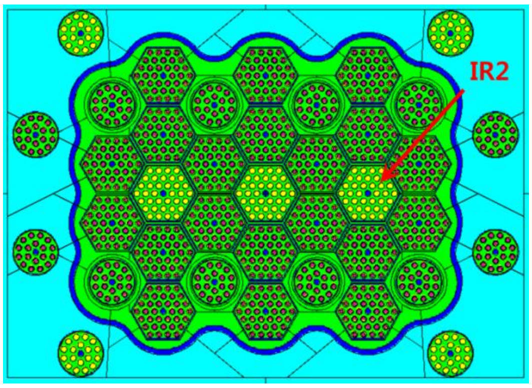


Figure 2. Radial core map of the HANARO

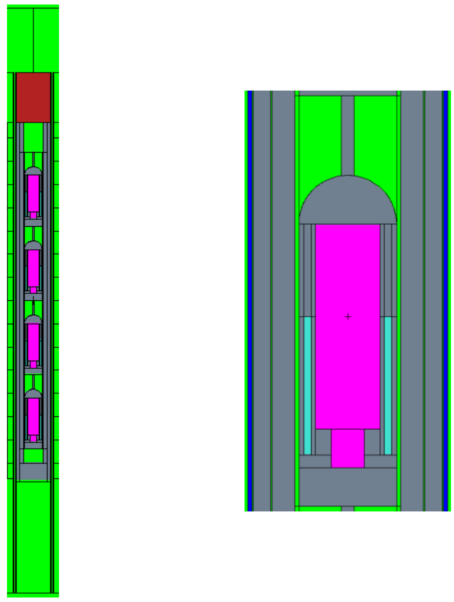
In the ORIGEN ver. 2.1, there is a limit of the number of use of the IRF or IRP options which define the neutron irradiation, and of the DEC option which defines the cooling time [5]. Because the number of these options is not enough to simulate real operation cycle of the HANARO, pseudo operation cycle was used to calculate the activities of the structure materials. It was assumed that the structure materials were irradiated for 71 cycles with 28 days of operation and 14 days of cooling time in accordance with the recent operation cycles of HANARO [8, 9]. Reactor power was assumed to be 1 MW.

3. Results

3.1 Target

IR2 vertical hole was selected a target of gamma heating. Since the IR2 is one of the irradiation holes where the neutron flux is highest, it is expected to be heated hotter than other holes.

It is assumed that the IR rig is loaded in the IR2 after 71 operation cycles. Four capsules are modeled in the IR rig. The capsule is assembled with inner and outer capsules, which are made from AA-1060 alloy based on aluminum. The pictures of the IR rig and capsules are shown in figure 3.



(a) Vertical view of IR rig

(b) Vertical view of one capsule (enlarged picture)

Figure 3. IR rig and inside capsule in IR2

All of the fixed structures of HANARO are made from zircaloy-4, whereas cladding, cap and central tie rod in fuel assembly are AA-1060 and they are removed with fuel discharge. And chimney is made from AA-1060, and grid plate which is a lower structure of the core is made from SS-304.

3.2 Radiation Source

Photon source of the MCNP was separated two groups (first and second rings) according to the distance from the IR2 in this study. Two groups of the photon source are shown in figure 4. In the first and second rings, flow tube and central tie rod made of zircaloy-4 in the fuel assemblies were defined as radioactive materials. As mentioned in chapter 2, structure materials are divided into many segments, and gamma-ray emission rate at individual segment is averaged for volume of the segment. There are eight small segments of 8 cm height nearby center of the fuel. Other upper and lower parts of the structure materials are divided into two big segments or not divided because it is expected to contribute little heat generation in these parts due to lower neutron irradiation.

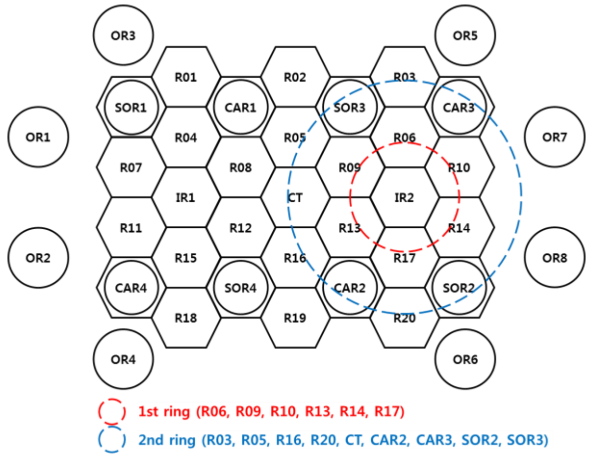


Figure 4. Index of the first and second ring from IR2

The zircaloy-4 is mainly composed of zirconium. Radioisotopes of zirconium are produced by neutron capture, Zr-95 and Zr-97. The Zr-95 and Zr-97 decay to Nb-95 and Nb-97 respectively, which are radioisotopes. Four isotopes may contribute dominantly to the gamma heating of RI capsules in IR2. Table 1 shows specific activities of main radioisotopes at flow tube of CT assembly in the second ring shown in figure 4. Isotopes, which have specific activity larger than 0.01 Ci/g, are considered as gamma-ray emitters, and these are indicated by bold type in the table 1. Activities of these isotopes account for 70 percent of total activity of whole radioisotopes in the CT assembly. Energy of emitted gamma-ray from main radioisotopes are indicated in the table 1.

Table 1. Specific activities and energies of considered gamma-rays of main radioisotopes at flow tube of CT assembly

Height (cm)	Specific activity (Ci/g)				
	^{95}Zr	^{97}Zr	^{95}Nb	^{97}Nb	^{97m} Nb
40 ~ 49.1	1.65e-3	5.34e-4	1.54e-3	5.34e-4	5.06e-4
32 ~ 40	3.52e-3	2.43e-3	3.29e-3	2.43e-3	2.30e-3
24 ~ 32	5.40e-3	5.19e-3	5.05e-3	5.19e-3	4.91e-3
16 ~ 24	8.52e-3	8.29e-3	7.98e-3	8.29e-3	7.84e-3
8 ~ 16	**1.20e-2**	**1.18e-2**	**1.12e-2**	**1.18e-2**	**1.11e-2**
0 ~ 8	**1.52e-2**	**1.50e-2**	**1.42e-2**	**1.50e-2**	**1.42e-2**
-8 ~ 0	**1.70e-2**	**1.69e-2**	**1.59e-2**	**1.69e-2**	**1.60e-2**
-16 ~ -8	**1.69e-2**	**1.65e-2**	**1.58e-2**	**1.65e-2**	**1.56e-2**
-24 ~ -16	**1.48e-2**	**1.46e-2**	**1.38e-2**	**1.46e-2**	**1.38e-2**
-32 ~ -24	**1.10e-2**	**1.07e-2**	**1.03e-2**	**1.07e-2**	**1.01e-2**
-40 ~ -32	8.18e-3	5.54e-3	7.65e-3	5.54e-3	5.25e-3
-63 ~ -40	1.97e-3	6.10e-4	1.84e-3	6.10e-4	5.77e-4
Considered ɣ-ray energy (keV)	724.19 756.73	743.36	765.80	657.94	743.36

3.3 Gamma Heating

Table 2 and 3 shows the gamma heating to four capsules in IR2. The gamma heating means the total heat generation over all of capsule parts and iridium samples. The heat generation by prompt radiations is calculated with MCNP criticality mode by neutron and photon. Gamma heating by delayed gamma-rays is calculated with MCNP fixed source mode based on the gamma-ray source distribution.

Table 2. Heat generation for capsules in IR2 by prompt radiations (neutron + gamma-ray) with 1 MW operation

Capsule	Heat generation [MeV/sec] (tally statistical error)
1st capsule (top)	1.14E+14 (0.0007)
2nd capsule	2.03E+14 (0.0005)
3rd capsule	2.35E+14 (0.0005)
4th capsule (bottom)	1.69E+14 (0.0005)

Table 3. Gamma heating for capsules in IR2 by delayed gamma-rays with 1 MW operation

Capsule	Heat generation [MeV/sec] (tally statistical error)	
	1st ring	2nd ring
1st capsule (top)	3.12E+09 (0.0968)	5.14E+08 (0.1447)
2nd capsule	3.49E+10 (0.0254)	3.77E+09 (0.0557)
3rd capsule	5.20E+10 (0.0204)	4.97E+09 (0.0476)
4th capsule (bottom)	1.79E+10 (0.0341)	2.36E+09 (0.0722)

From the results, heat generation by the first ring is from 6 to 10 times larger than by the second ring. It means that the contribution of gamma heating is decreased rapidly along a distance, and the heat generation from the third or farther rings can be negligible.

The peak of gamma heating is shifted downward along height direction due to the control rod position. It is assumed that the control rods were inserted 250 mm from top of the core during reactor operation. It makes higher neutron flux at lower parts of the core. As a result, the number of emitted gamma-rays is higher at lower parts.

The percentage of the heat generation by delayed gamma-ray over heat generation by prompt radiation is enough low to be negligible. The largest value is only 0.024% at the third capsule.

4. Conclusion

In this paper, the methodology for evaluation of heat generation by irradiated structure materials was established by using the ORIGEN and MCNP codes. And it was applied to estimate the heating value of the RI capsules at the IR2 hole of HANARO. Four capsules which were composed of inner and outer capsule were assumed to be loaded into the RI rig. Heating value which was generated from the structure materials at the first ring was estimated more than 6 times larger than those at the second ring. From this result, the contribution by farther structures was expected to be negligible. Meanwhile, heat generation by delayed gamma-ray was calculated less than 0.03% of heat generation by prompt radiations.

The result of this study indicates that there are some remaining issues for the real situation of the neutron irradiation at HANARO. In the future study, the real operation cycle of HANARO will be considered to define the gamma source distribution. In addition, calculated results will be compared with the experimental data.

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