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Original Article

Estimation of nuclear heating by delayed gamma rays from radioactive structural materials of HANARO

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ABSTRACT

To improve the accuracy and safety of irradiation tests in HANARO, the nuclear energy deposition rate, which is called nuclear heating, was estimated for an irradiation capsule with an iridium sample in the irradiation hole in order. The gamma rays emitted from the radioisotopes (RIs) of the structural materials such as flow tubes of fuel assemblies and heavy water reflector tank were considered as radiation source. Using the ORIGEN2.1 code, emission rates of delayed gamma rays were calculated in consideration of the activation procedure for 8 years and 2 months of HANARO operation. Calculated emission rates were used as a source term of delayed gamma rays in the MCNP6 code. By using the MCNP code, the nuclear heating rates of the irradiation capsules in the inner core, outer core, and heavy water reflector tank were estimated. Calculated nuclear heating in the inner core, outer core, and heavy water reflector tank were 200–260 mW, 80–100 mW, and 10 mW, respectively.

1. Introduction

Various samples have been irradiated by neutrons at the irradiation holes of HANARO, a 30-MW multipurpose research reactor of Korea Atomic Energy Research Institute. In these irradiation experiments or tests, various types of radiation are generated, and temperature of the reactor and samples is increased by nuclear heating. Therefore, it is important to ensure in advance that irradiation materials are safe in terms of thermo-hydraulics. To accurately estimate the temperature increase of irradiation materials, detailed analysis of the nuclear heating caused by various types of radiation is required. Nuclear heating in the irradiation material arises from the local deposition of energy carried by neutrons and prompt gamma rays issued from fission, radiative capture and inelastic neutron scattering, and delayed gamma rays emitted by fission and activation product decay. Among these, however, delayed gamma-ray contribution has not so far been estimated in detail at HANARO [1].

It is not easy to experimentally estimate the activities of the radioisotopes (RIs) in structural materials because appropriate measuring methods should be applied for each RI according to the decay type [2]. Furthermore, it is impossible to obtain samples from various locations in the HANARO core. In HANARO, therefore, the Monte Carlo method has been used to correct the delayed gamma contribution to nuclear heating [1]. In this method, the nuclear data library of prompt gamma rays is replaced by the library of delayed gamma rays, and it is assumed that the production rate is the same as the removal rate for all RIs in the structural materials. This method is reasonable if the half-life of the RI is short; otherwise, however, it is not reliable. Other well-known methods to determine the delayed gamma contribution are coupling a Monte Carlo code with an activation analysis code [3] or using the recently developed Monte Carlo codes that contain a built-in module for the activation process [4–6]. In these methods, however, only activation and depletion processes of fuel elements can be considered [4,5]. In addition, tracking of delayed gamma rays after a long-term period of neutron irradiation, for example, several cycles of reactor operation, is not available in the stand-alone Monte Carlo code [6].

In this article, for irradiation capsules that contain an iridium sample, the nuclear heating rates caused by delayed gamma rays (delayed gamma heating) from radioactive structural materials are estimated using Monte Carlo and activation codes. Structural materials near the irradiation capsule are selected as radiation sources, and the activation process of the structural materials is simulated. In addition, the emission rates of the delayed gamma rays for each

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structural material are calculated. The results are presented and discussed in this article. The proposed method can be used in various material irradiation tests in HANARO, and it is expected to improve the reliability of the irradiation tests.

2. Materials and method

2.1. Calculation process

The Monte Carlo particle transport code, MCNP6 [6], and the activation code, ORIGEN2.1 [7], are used to calculate the delayed gamma heating by radioactive structural materials in HANARO. The coupled calculation system using the MCNP and ORIGEN codes is a well-known calculation tool and has been used for various objectives [8–10]. The calculation of the delayed gamma heating is divided into three steps.

In the first step, one-group effective cross sections for all RIs in the structural materials are calculated using the MCNP code in criticality mode. Among various neutron-induced reactions, (n, γ), (n, 2n), (n, α), and (n, p) cross sections are considered. The cross section is calculated using the following formula:

$$\bar{\sigma}_i = \frac{\int \sigma_i(E)\,\phi(E)\,dE}{\int \phi(E)\,dE} = \frac{R^i_{MCNP,1G}\big/N}{\phi_{MCNP,1G}} \qquad (1)$$

where $R^i_{MCNP,1G}$ and $\phi_{MCNP,1G}$ are the one-group reaction rate for RI i and the one-group neutron flux calculated using the MCNP code, respectively. N is the number density of the isotopes, which is calculated from the density and composition of the material. The real neutron flux of the structural material is calculated using

$$\phi_{1G} = \frac{\nu \times P}{\kappa \times k_{eff}} \times \phi_{MCNP,1G} \qquad (2)$$

where ϕ_{1G} is the one-group real neutron flux, and ν, P, κ, and k_{eff} are the number of neutron emissions per fission, reactor power, released energy per fission, and effective multiplication factor, respectively. In this study, P and κ were assumed to be 30 MW and 200 MeV/fission, respectively, and ν and k_{eff} were obtained from the MCNP calculation.

In the second step, the emission rates of the delayed gamma rays from the radioactive structural materials are calculated using the ORIGEN code. The one-group effective cross section in Eq. (1) is used for the nuclear data library of the ORIGEN code, and the one-group neutron flux in Eq. (2) is used for the averaged flux for all the operation cycles. As it is impossible to simulate the real operation cycles of HANARO because of the limitation of the ORIGEN code, pseudo operation cycles are assumed. In the pseudo operation cycles, the number of total cycles is 71, and each cycle has 28 operation days and 14 cooling days. In this operation cycle, the structural materials are irradiated by neutrons for approximately 8 years and 2 months at HANARO. Various types of radiation are emitted with specific energies from the radioactive structural materials during the decay process. The energy distribution and emission probability of the delayed gamma rays are calculated using the ORIGEN code. In the calculation, only delayed gamma rays are considered because alpha rays and beta rays can be negligible owing to their short mean free path. In the ORIGEN code, the energy levels of the emitted gamma rays are collapsed to 18 groups.

In the final step, the delayed gamma heating of the irradiation capsule is calculated using the MCNP code in the fixed source mode. The energy distribution and emission probability of the delayed gamma rays, which are calculated in the second step, are used for the source term of the MCNP calculation.

2.2. Radiation source and target

In the HANARO core, light water enters the core from the lower grid plate and exits to the upper chimney for reactor cooling. Fuel assembly is loaded into the coolant flow tube in the reactor core. The flow tube guides the coolant flow and isolates the coolant from other fuel assemblies or the reflector tank. The reflector tank is filled with heavy water and is separated from the core by the inner shell. Owing to the attenuation of the gamma rays, the delayed gamma heating of the irradiation material is inversely proportional to the square of the distance between the irradiation material and the structural material. Considering the distance from the irradiation capsule, the flow tubes, inner shell, and heavy water were selected as radiation sources in the calculation. These structures are irreplaceable materials and are irradiated for a long time in the core. In the case of the other structural materials, such as the grid plate or the upper chimney, the contribution of delayed gamma heating is negligible because they are located far from the reactor core. The neutron fluxes are small in these structures, and they are irradiated in relatively small amounts. The flow tubes and inner shell are made of Zircaloy-4. The composition of Zircaloy-4 is shown in Table 1.

RI capsules of aluminum alloy with iridium samples were considered as the irradiation material for the calculation of the delayed gamma heating. In the calculation, four sets of RI capsules were loaded into the RI rig. The RI rigs were considered to be loaded at three vertical irradiation holes, IR2, OR6, and IP11, as shown in Fig. 1. Because neutron flux and energy spectrum are different at the three irradiation holes, delayed gamma heating at various irradiation positions in the core can be considered. The IR2 irradiation hole is located in the inner core where the fast neutron flux is relatively high in comparison with the OR6 and the IP11 irradiation holes, and many flow tubes are installed nearby. In contrast, the OR6 irradiation hole located in the outer core is close to the inner shell; therefore, the epithermal neutron flux is relatively high in comparison with that of the IR2 and the IP11 irradiation holes. The OR6 irradiation hole is directly affected by the flow tubes, inner shell, and heavy water. Meanwhile, the IP11 irradiation hole is located in the reflector tank and far from the fuel; therefore, the total flux in the IP11 irradiation hole is lower than those in the IR2 and the OR6, but the thermal neutron flux is relatively high. Fig. 2 shows side views of the RI capsules in the IR2, OR6, and IP11 irradiation holes. The IR2 hole has a hexagonal shape, but the OR6 and IP11 holes are cylindrical in shape, with the same radius. The RI capsules used for the three different holes are of the same shape.

The neutron flux of the structural materials depends on the position of the structural material. Even in the same structural material, the neutron flux is different depending on the axial and radial directions in the material. To calculate the neutron flux and cross sections numerically, each structural material was divided into several segments in the calculation model. Each flow tube was divided into four segments in the axial direction, but it is assumed that the neutron flux is uniform in the radial direction. The inner shell was divided into five and 28 segments in the axial and radial

Table 1
Composition of Zircaloy-4 (density = 6.55 g/cm^3) [11].

Nuclide	Composition	Nuclide	Composition
Zr	98.24%	Sn	1.45%
Fe	0.21%	Cr	0.10%

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