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Verification of Burned Core Modeling Method for Monte Carlo Simulation of HANARO

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1. Introduction

The MCNP code has been used for the design of facility and device at HANARO, such as In-Pool Assembly (IPA) for cold neutron source and neutron screen for uniform irradiation of an Si ingot. Although the reactor core has been managed well by the HANARO core management system called HANAFMS, the heterogeneity of the irradiation device and core made the neutronic analysis difficult and sometimes doubtable. To overcome the deficiency, MCNP was utilized in neutron transport calculation of the HANARO.

For the most part, a MCNP model with the assumption that all fuels are filled with fresh fuel assembly showed acceptable analysis results for a design of experimental devices and facilities. However, it sometimes revealed insufficient results in the design, which requires good accuracy like neutron transmutation doping (NTD), because it didn't consider the flux variation induced by depletion of the fuel.

In this study, a depleted-core modeling method previously proposed was applied to build burned core model of HANARO and verified through a comparison of the calculated result from the depleted-core model and that from an experiment.

2. Depleted-core Modeling Method

2.1 Management of HANARO Core

HANARO core is filled with twenty hexagonal assemblies with 36 fuel rods, and twelve circular fuel assemblies with 18 rods. The fuel is U_3Si-Al and its axial length is 70 cm. The reactor is controlled by hafnium control rods

Unlike commercial reactor, there is no specific fuel assembly designed for an initial core. Although all control rods are fully inserted to the bottom of core, the core filled with entire fresh fuel assemblies exceeds critical. Therefore, several dummy assemblies were loaded at the start of reactor operation. As excess reactivity decreased corresponding to fissile consumption, dummy assembly was changed to fresh fuel assembly. By adopting this strategy, HANARO reached to equilibrium condition with entire fuel assemblies in a core.

Currently, the reactor core is managed by HANAFMS, which utilizes WIMS for the lattice calculation and VENTURE for the core calculation [1].

2.2 Depleted-Core

While the geometry and cross-section library can be clearly defined, the material assignment and description of the source distribution make the establishment of a depleted-core model for Monte Carlo simulation difficult and uncertain[2].

The material composition and source distribution of the depleted-core were determined by using the core management code. Initially, the burnup-dependent isotopic number density as a function of burnup was calculated for each fuel rod of respective type of fuel assembly by WIMS. The power and burnup of each region of the fuel rod loaded at HANARO were calculated by VENTURE. On the basis of the burnup-dependent isotopic number density, the isotopic composition corresponding to the respective burnup was assigned to each region of the irradiated fuel rod of the MCNP model. The material composition of a burned fuel rod was assigned to fourteen nodes with a 5 cm axial length each. Only important nuclides in terms of absorption reaction were considered in describing the material composition of the irradiated fuel.

The cross-section library generated from the ENDF-VII nuclear data with the same temperature as used in the WIMS was used in the MCNP calculation. It should be noted that the temperature feedback is not considered in the HANAFMS system.

3. Comparison Results

3.1 Reactor Condition and Irradiated Ingots

In this study, a comparison was carried out using experimental data of NTD for 8 in. Si ingots obtained in the 59th end-of-cycle of HANARO operation. Irradiation of the same Si ingots was carried out two times, batch name of D1703-1 and D1703-2, respectively, with some interval during the cycle. The reactor was steadily operated without any unexpected incidents during the respective 2 hour irradiation, and four pieces of Si ingots were irradiated within the irradiation device. The irradiation device was rotated from the beginning of the irradiation to obtain a uniform radial reaction rate distribution.

3.2 Calculation and Experimental Methods

The depleted-core models corresponding to reactor condition at which the batch of D1703-1 and D1703-2 were irradiated, respectively, were established using the modeling method explained above. The number of neutrons emitted from each cell of irradiated fuel needed for the source distribution was deduced from the thermal power estimated by HANAFMS. The geometry and material of the irradiation device containing Si ingots were also explicitly described without approximation in the model. The control rod was positioned at the average value of historical movement for a irradiation period. The reaction rate of ^{30}Si(n, γ) ^{31}Si was calculated at the same locations of the irradiated specimens.

The zirconium activation method was used to obtain the reaction rate profile in the experiment performed by the Korea Atomic Energy Research Institute. A zirconium specimen with 0.5 cm (width) × 0.5 cm (width) × 0.05 cm (thickness) was attached to the center of each surface of the ingots. The 724 and 757 keV gamma-rays from ^{95}Zr in the irradiated zirconium plate were measured using a high purity germanium detector by the gamma-scanning method. The saturated activity distributions were determined by considering the decay time. The lead slit size of the gamma-scanning system was 4 mm. Because the Si ingot is loaded to the core along the downward direction, the bottom part of the ingot is irradiated for a little longer time than the upper part. This effect was also considered when the experimental data was dealt with.

The resistivity measurement method by a customer was also used to deduce the reaction rate profile. An increase of the phosphorus atom concentration by NTD for the silicon crystal is expressed using Eq. (1)

$$[G] = 4.624 \times 10^{15} \left(\frac{1}{\rho_f} - \frac{2.73}{\rho_i}\right) \tag{1}$$

where $[G]$ = the atom concentration of ^{31}P in the unit of atoms/cm^3,

ρ_f = resistivity after irradiation, and

ρ_i = initial resistivity.

Because the half-life of the beta decay from ^{31}Si to ^{31}P is very short, the increase of ^{31}P is almost equal to ^{31}Si produced by NTD. Therefore, the absorption reaction rate is deduced by dividing the value of $[G]$ by the total irradiation time.

3.3 Results and Discussions

When the experiment was carried out, four pieces of 8 in. Si ingots with 13.3, 15.6, 14.1, and 15.1 cm length, respectively, were loaded within the device. Therefore, the zirconium specimens were positioned at five locations. And these locations for the batch of D1703-1 and D1703-2 are different, because shuffling of the ingots was done at D1703-2 irradiation for axially uniform dopant distribution.

Through the comparison with the zirconium activation method, it was found that the calculated neutron flux distribution for the batch of D1703-1 agreed well within 1% difference compared with the measured values. In case of the batch of D1703-2, maximum difference was revealed to be 2%.

Table 1 shows comparison results of calculated and measured reaction rate of ^{30}Si(n, γ) ^{31}Si. The listed values represent the average values of each surfaces for respective piece of Si ingot. It should be reminded that each piece of Si ingot was irradiated two times during the cycle. As can be seen in the table, the difference was revealed to be about 1-4%. And RMSE (root mean square error) was shown to be 3.16%.

Table 1 Comparison result of ^{30}Si(n, γ) ^{31}Si reaction rate

Ingot ID	Calculated Value^a [10^9/cm^{2}s]		Experimental Value ^{b} [10^9/cm^{2}s]		Difference (a-b)/b × 100	
	top	bottom	top	bottom	top	bottom
D1	6.89	6.83	6.688	6.750	3.05	1.25
D2	6.83	6.82	6.621	6.595	3.22	3.43
D3	6.99	6.94	6.761	6.737	3.42	3.05
D4	6.94	6.84	6.646	6.675	4.46	2.53
Avg.	6.92	6.86	6.679	6.689	3.54	2.56

4. Conclusions

The modeling method to establish a depleted-core model for the Monte Carlo simulation was verified by comparing the neutron flux distribution obtained by the zirconium activation method and the reaction rate of ^{30}Si(n, γ) ^{31}Si obtained by a resistivity measurement method. As a result, the reaction rate of ^{30}Si(n, γ) ^{31}Si also agreed well with about 3% difference. It was therefore concluded that the modeling method and resulting depleted-core model developed in this study can be a very reliable tool for the design of the planned experimental facility and a prediction of its performance in HANARO.

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