Comparison of Primary Damage to Reactor Internal Materials in Kori Unit 1 and Hanbit Unit 3

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1. Introduction

The primary effect of neutron irradiation on material properties is through the displacement of atoms. High-energy neutrons can displace atoms from lattice positions and create point defects. While most defects are annihilated by recombination, a small fraction of residual defects can be involve in the formation of various microstructures. Point defects resulting from a displacement cascade can lead to the changes in physical, thermal, chemical or mechanical properties of reactor materials. The amount of displacement damage is proportional to point defect production, which is usually described as *dpa* (displacement per atom). Trans-mutation is another effect, but the changes in composition from transmutation reactions do not affect material properties significantly. Production of gas atoms (H and He), however, can have negative consequences for reactor components. Depending on the neutron spectra and irradiation time, the production of gas atoms is changed. The hydrogen is not thought to be a problem due to its high mobility in materials, whereas helium trapped in a cavity might lead to substantial swelling [1]. When the displacement damage and the production of gas atoms, resulting from neutron reactions with alloying elements, are defined as primary damage, the quantification of the damage is a starting point of tackling the radiation damage study [2].

Currently there are several types of pressurized water reactors (PWRs) in Korea. Although it has been shut down, the oldest one is Kori Unit 1, designed by Westinghouse. Among the OPR-1000 reactors, the one with the longest operating period is Hanbit Unit 3. In this work, we evaluate the production of primary damage to reactor internal materials for two different PWR types. First, we computed the neutron spectra for internal components, including baffle and barrel. Then, the primary damage to structure materials of SS 304 was evaluated using a computer code, SPECTER [3]. The damage parameters of interest include *dpa*, and H & He production. Moreover, one important feature of radiation damage, particularly due to thermal neutrons, in Ni-containing alloys is the transmutation of ^{58}Ni. The Ni two-step reactions, such as $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$, are another source of He production for a high thermal neutron fluence. This additional He production was also taken into account here.

2. Methods

In estimating primary damage to reactor components, we need to obtain the neutron flux at the specific locations from the neutron transport calculation. Then by using the SPECTER computer code [3], the amount of damage was calculated.

2.1 Neutron Flux Calculation

The transport of neutrons from the core to locations of interest was computed using 3-dimensional neutron transport code (RAPTOR-M3G) [4]. For given material input data, the neutron flux was estimated with the proper geometrical model for each reactor core, which includes Kori Unit 1 (Westinghouse) and Hanbit Unit 3 (OPR-1000). Fig. 1 shows the simplified geometry of an octant core in r-θ direction, where the locations of interest are specified with circled letters. They include three points in a baffle plate (~core shroud) and two points in a barrel. The flux was calculated based on the axial position z = 0 corresponding to the central cross section.

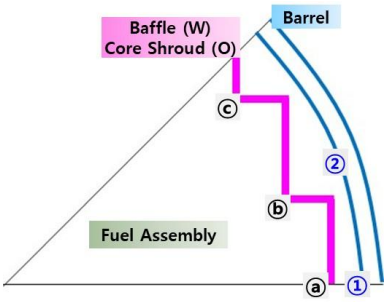


Fig. 1. Cross sectional view of an octant reactor core. The circled letters (ⓐ, ⓑ, ⓒ for baffle and ①, ② for barrel) represent the locations of interest.

2.2 Primary Damage Evaluation

We use the SPECTER to obtain damage parameters for a given neutron spectrum as an input. The code integrates over the cross section libraries to give the spectral-averaged results. The output includes the displacement damage in *dpa* and the production of transmutation gas H/He in *appm*.

2.3 Helium Production by Ni Two-Step Reactions

Helium can be produced by neutron reactions with nickel following the reactions of $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$. The production of He is given by [5]:

$$\frac{N_{He}(t)}{N_{Ni-58}} = \frac{\sigma_\alpha}{\sigma_T} - \frac{\sigma_\alpha \cdot \exp(-\sigma_\gamma \phi_T t)}{\sigma_T - \sigma_\gamma} + \frac{\sigma_\alpha \sigma_\gamma \cdot \exp(-\sigma_T \phi_T t)}{\sigma_T \cdot (\sigma_T - \sigma_\gamma)} \quad (1)$$

where N_{He} is the number of He atoms produced, $N_{Ni\text{-}58}$ is the initial number of ^{58}Ni atoms contained in alloys, ϕ_T is the neutron flux; t is the irradiation time; σ_α, σ_T, and σ_γ are the nuclear cross sections for $^{59}Ni(n,\alpha)$, ^{59}Ni total absorption, and $^{58}Ni(n,\gamma)$ reactions, respectively. Because this 2-step reaction dominantly takes place in the thermal-neutron energy region, we only consider the thermal neutron flux to estimate the He production.

3. Results

3.1 Neutron Flux and Primary Damage

In order to estimate the maximum primary damage, we selected the position for the maximum neutron flux, which corresponds to baffle ⓑ. The spectrum is composed of 47-group neutron energy ranging from 1 x 10^{-10} to 14.2 MeV. Fig.2 shows the neutron spectra for several locations of reactor internals in Kori Unit 1, which were marked in Fig. 1. The same information for Hanbit Unit 3 was displayed in Fig.3.

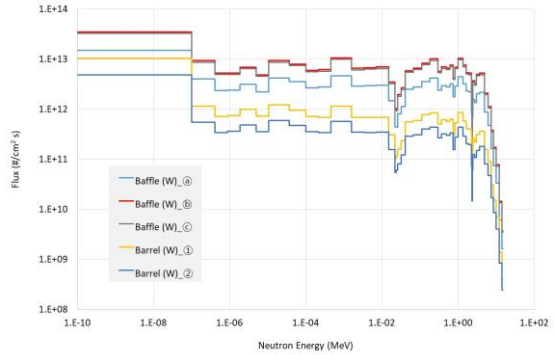


Fig. 2. Neutron spectra for reactor internals in Kori Unit 1

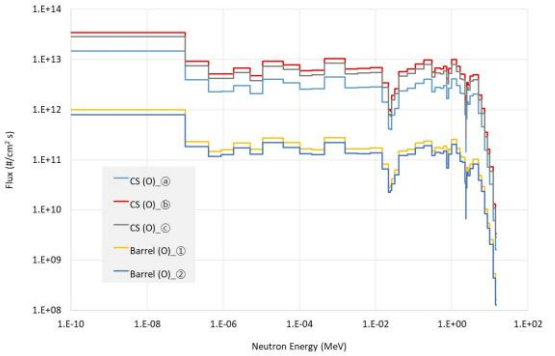


Fig. 3. Neutron spectra for reactor internals in Hanbit Unit 3

Damage parameters were calculated by assuming that reactor internals of baffle (~core shroud) and barrel, made of SS304, were irradiated with the flux without interruption, given in Figs. 2 and 3. In terms of EFPY (Effective Full Power Year), Kori Unit 1, decommissioned in 2017, is 30.04 EFPY, whereas Hanbit Unit 3 is 25.4 EFPY as of the end of 2026. Accordingly, all output parameters of *dpa* and gas production were based on per EFPY. Fig.4 shows the *dpa* for Kori Unit 1 (marked W) and Hanbit Unit 3 (marked O). The H and He production are given in Figs. 5 and 6, respectively.

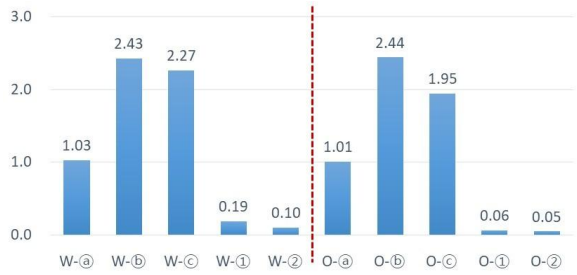


Fig. 4. *dpa*/EFPY in SS304 for reactor internals of a baffle and a barrel (W: Kori, O:Hanbit / refer to the specific locations in Fig. 1)

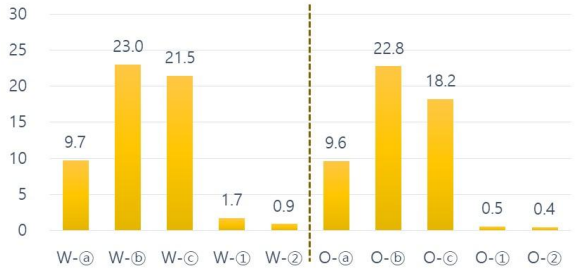


Fig. 5. H production (*appm*/EFPY) in SS304 for reactor internals of a baffle (~core shroud) and a barrel



Fig. 6. He production (*appm*/EFPY) in SS304 for reactor internals of a baffle (~core shroud) and a barrel

3.2 Additional Helium Production from Nickel

The accumulated He production from Ni two-step reactions in SS304 is shown in Fig. 7, as a function of EFPY. In this calculation, the effect of thermal neutrons was only taken into account. Although the contribution of epi-thermal and fast neutrons to He production is expected to be small, the detailed analysis will be provided in another study. The cross sections, included

in Eq. (1), are listed in Table 1, which were referenced from the ENDF/B-VII library [6].

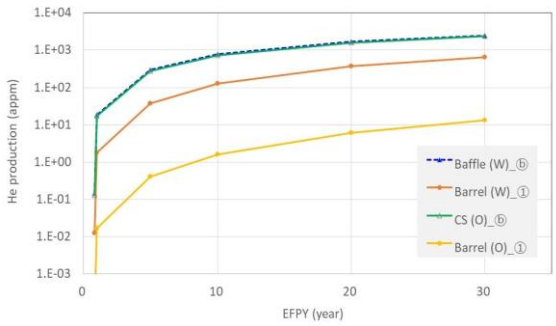


Fig. 7. Accumulated helium production from Nickel in SS304 by two-step thermal reactions of $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$

Table 1 Thermal cross sections included in Eq. (1)

Cross section	σ_T	σ_α	σ_γ
barn	346.1	48.7	12.7

4. Discussion

Primary damage to reactor internal materials was evaluated for two representative PWRs of Kori Unit 1 (Westinghouse) and Hanbit Unit 3 (OPR-1000), which was described by displacement damage and trans-mutation gas production. Among the internal structures, we calculated the amount of damage to a baffle (~core shroud) and a barrel by using the neutron spectra. No significant difference in primary damage to baffle was found between the two units. However, the damage to a barrel in Kori Unit 1 is higher than that in Hanbit Unit 3, which was caused by the spectral difference.

High concentration of He atoms was estimated in SS304 of reactor internals after thermal neutron irradiation via Ni two-step reactions. The He production due to these reactions is predominant after several years of reactor operation. Although phenomena such as He embrittlement and He-induced swelling were not found at the PWR operating temperature, the continuous accumulation of He atoms in the internal materials will be a critical factor that can cause problems during long-term operation.

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