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Analysis of Energy-dependent Displacement Damage on High Thermal Absorber by Neutron Irradiation

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1. Introduction

The research analysis of displacement per atom (dpa) in the neutron irradiation area has mainly focused on materials such as various kinds of metals. Furthermore, material damage in terms of dpa is known to be primarily influenced by fast neutrons rather than thermal neutrons. Meanwhile, various research institutions have been developing a variety of neutron absorbers designed for specific purposes in fields such as nuclear and radiation industries, defense, and aerospace[1]. Neutron absorbers, widely used in the nuclear industry, are composed of materials with large thermal neutron absorption cross-sections with the capability to effectively absorb and control neutrons. To ensure appropriate utilization of neutron absorbers according to its intended purposes, it is essential to satisfy requirements for mechanical integrity in addition to chemical stability. Therefore, to assess the material integrity of neutron absorbers, it is necessary to evaluate the impact of displacement per atom from thermal neutrons, which has not been actively conducted in the irradiation test field.

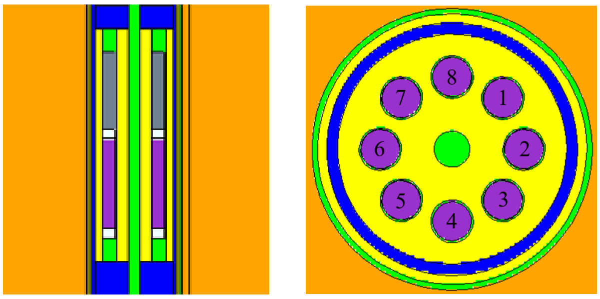
This study aims to confirm the material integrity of neutron absorbers irradiated from the HANARO reactor. In this study, the energy-dependent displacement distributions of the neutron absorbers were derived and analyzed along with the neutron absorption reaction characteristics.

2. Computational Model and Target Materials

This study is assumed to be conducted based on the OR3 (Outer Region 3) hole of the HANARO reactor, which can provide sufficient neutron flux. Although the neutron flux in the OR holes is relatively lower compared to CT (Central Thimble) or IR (Inner Region) holes, it remains sufficiently high (~10^{13} #/ $cm^2 \cdot sec$) and is influenced by thermal and epithermal neutrons. This distinguishes them from irradiation holes located in the external reflector region, which have a considerably degraded neutron spectrum. Therefore, these holes are utilized for material testing or nuclear fuel experiments.

In this study, neutron transport analysis was performed with MCNP6.1[2]. The reactor power was assumed to be set as 30 MW with the equilibrium core condition, and the control rod was fixed to 450 mm above the bottom of the fuel. This study assessed enriched boron carbide with a density of 1.8 g/cm^3 as a neutron absorber target material focusing on material damage. For the assessment over a one-year period, it was assumed that boron would burn up at a rate of 2% every 100 days.

Figure 1 shows the axial cross-section of the irradiation hole and the radial cross-section of loaded neutron absorber target materials. The jig is designed to load 8 identical target material specimen, and the interior of the capsules is filled with helium gas.



(a) (b)

Fig. 1. The conceptual model to load target neutron absorbers; (a) the vertical view and (b) the horizontal view of the irradiation capsules

3. Computational Model and Target Materials

The calculated four-group neutron flux ($\overline{\phi_{V,g}}$) of target materials is presented in Figures 2. Group 1, 2, 3, and 4 correspond to neutron flux energy ranges up to 6.25E-07 MeV, to 0.1 MeV, to 1.0 MeV, and to 100 MeV, respectively. The statistical errors for the calculation of the neutron flux were less than 1% in all four groups.

The target boron material has a high thermal neutron absorption cross-section, the neutron flux in Group 1 appears low. Although the OR3 irradiation hole is situated in the external core, relatively high-energy epithermal neutron flux is observed due to core characteristics. The average neutron flux in the radial direction of 8 specimens was compared. As a result, the target materials closer to the core generally showed higher neutron flux, indicating a maximum difference of approximately 3×10^{13} #/$cm^2 \cdot sec$ in total neutron flux.

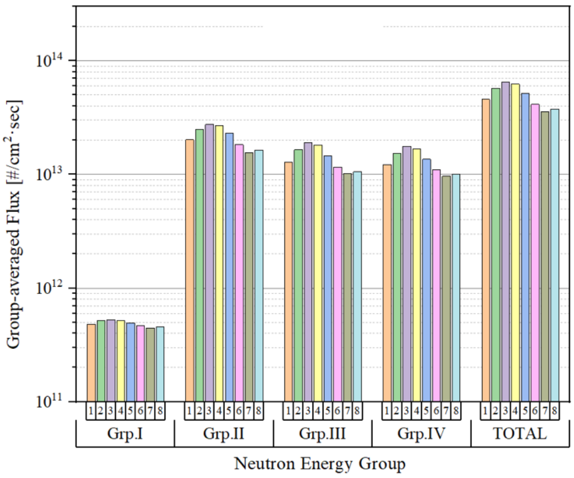


Fig. 2. Four-groups neutron flux on 8 locations of neutron absorbers

The target material showing the highest neutron flux is the 3rd specimen located in the southeast (SE) direction of the irradiation hole, while the material showing the lowest neutron flux is the 7th specimen positioned in the northwest (NW) direction, where the most obstacles exist between the target material and the reactor core.

Figures 3 shows the relative changes in neutron flux for each group as a function of the boron depletion. The increase in neutron flux is prominently observed particularly in the lower energy groups, as the low-energy neutron absorption capability of boron is reduced with its depletion.

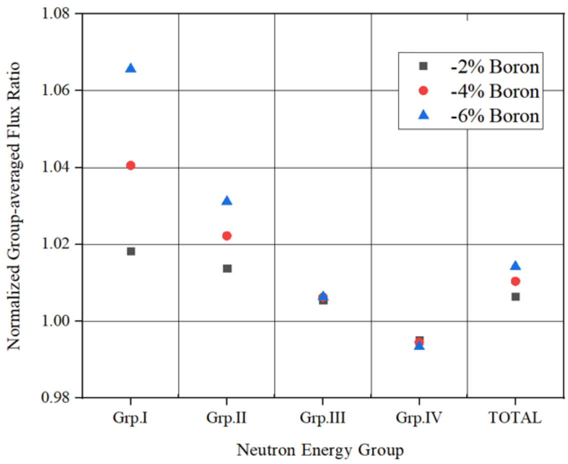


Fig. 3. Normalized four-group flux distribution with burnup of neutron absorber

4. Displacement Per Atom (DPA) Spectrum

The primary nuclear reaction of the B-10 involves the capture of a neutron, which then undergoes nuclear transformation process into the B-11 isotope. During this process, high-energy alpha particle (He-4) and Li-7 nuclei are produced.

$$^{10}B + n \rightarrow \{^{11}B\} \rightarrow {}^{4}He + {}^{7}Li + 2.79\ MeV \qquad (1)$$

Figures 4 represents the ENDF/B.VIII nuclear displacement reaction cross-sections for boron[3]. In general, the displacement cross-section of most nuclides tends to be higher in high neutron energy regions. However, for boron, the neutron absorption cross-section in the thermal neutron region is high, leading to a greater probability of displacement occurring in the low-energy range.

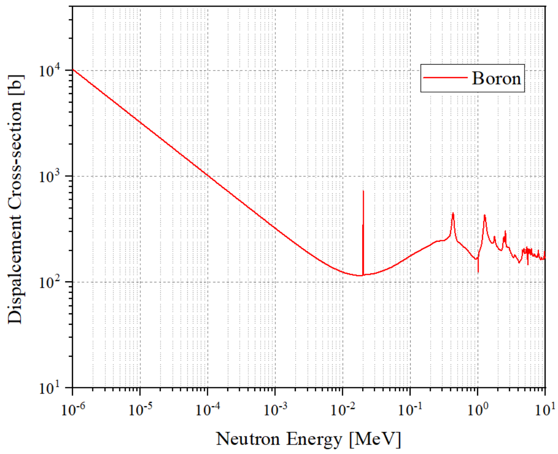


Fig 4. Nuclear displacement reaction cross-section as a function of neutron energy

The neutron absorption rate, reflecting the rate at which neutrons are absorbed as they interact with atoms within a material, varies according to the structure and the state of atomic nuclei as well as the energy and the velocity of neutrons. The neutron absorption reaction rate is calculated as a function of neutron energy as follows.

$$(R.R._{Abs})_n = NF\int_a^b \Phi(E) RF_{Abs}(E)dE, \qquad (2)$$

where,

$(R.R._{Abs})_n$: *the* n^{th} *neutron absorption reaction rate,*

$\Phi(E)$: *energy dependent fluence (n/cm*^{2}*),*

$RF_{Abs}(E)$: *response function for neutron absorption cross-section,*

NF : *normalization factor,*

a : *the* n^{th} *energy bin,*

b : *the (n+1)*th *energy bin.*

Figures 5 shows the calculated neutron absorption reaction rate spectra of the target materials along with neutron energies. The neutron absorption reaction rate depends on the absorption cross-section as a function of energy. Therefore, it exhibits a high rate in the low-energy range and gradually decreases as the energy increases.

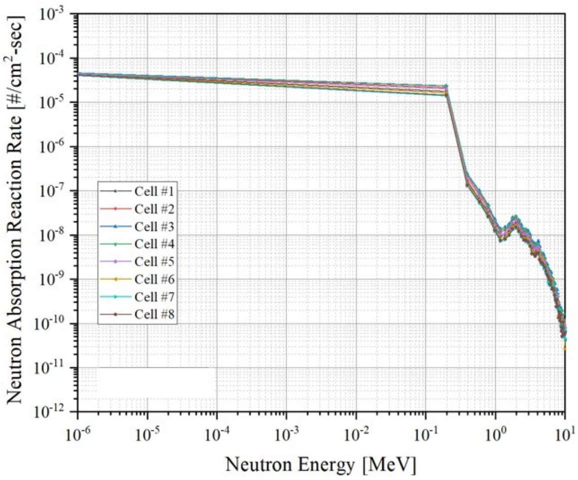


Fig. 5. Neutron absorption reaction rates as a function of neutron energy

This study employs the Monte Carlo method to derive solutions using Equation (3) for calculating displacement per atom values, allowing for quantitative assessment of material damage.

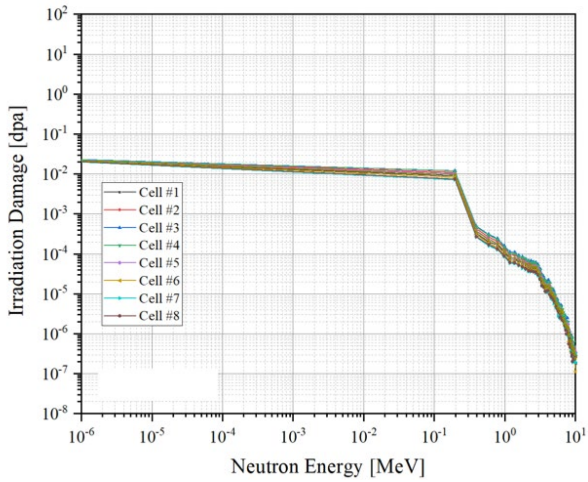
$$dpa = \frac{E_a}{cE_d} \quad (3)$$

The methodology is based on the NRT (Norgett, Robinson, Torrens) model[4] and assumes certain irradiation conditions. E_a represents the total energy resulting from radiation-matter interactions, and E_d denotes the average threshold energy required to displace an atom from the material's lattice structure. In this study, the 'E_d' for the targeted boron is 25 eV. The correction factor 'c' accounts for situations where energy generated by neutron reactions is absorbed without causing displacement damage, commonly applying a constant value of '2'. 'E_a' can be determined by Equation (4).

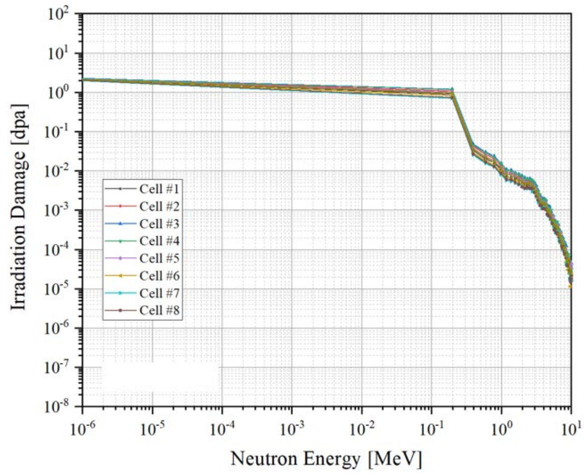
$$E_a = \frac{\bar{\nu}}{Q_f} R_d \eta \times \sum_{i=1}^{n} P_i t_i \quad (4)$$

The '$\bar{\upsilon}$' and 'Q' represent the normalized scaling factors of the total neutron source, indicating the average number of neutrons generated and the energy released per fission, respectively. Additionally, 'η' denotes the efficiency correction factor, 'P' the reactor power, and 't' the irradiation time.

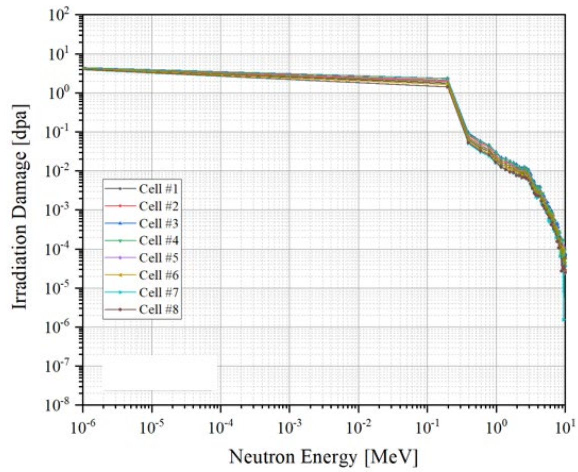
Figure 6 shows the calculated results of material damage distribution along with the neutron energy in terms of dpa over the neutron irradiation period of 365 EFPD (1 year).



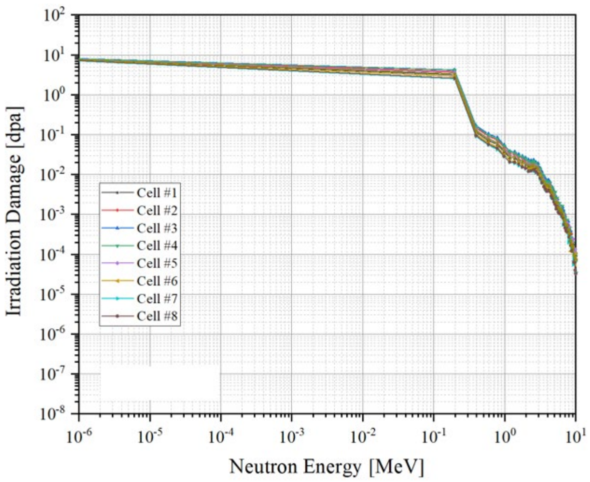
(a) After 1 day of neutron irradiation



(b) After 100 days of neutron irradiation



(c) After 200 days of neutron irradiation



(d) After 365 days of neutron irradiation

Fig. 6. Energy-dependent displacement damage distributions along with irradiation time

The calculation results are closely related to the intensity of the radial neutron flux distributions, the reaction cross-sections by neutron energy, and the neutron absorption rates. Although the neutron flux in the low-energy range are relatively low compared to those in higher energy area, the neutron absorption cross-sections are notably high in the low energies, resulting in a high absorption rate. Consequently, material damage increases in the low-energy range where strong absorption occurs. Comparing the material damage levels of the 8 target specimens located at the same height along the axial direction, target materials closer to the core generally exhibited higher neutron flux, resulting in relatively higher assessed material damage levels.

5. Conclusions

In this study, the nuclear characteristics and mechanical integrity of neutron absorbers were confirmed through Monte Carlo transport analysis based on the neutron irradiation environment of the HANARO research reactor.

The degree of material damage was closely associated with the intensity of radial neutron flux distributions, neutron reaction cross-sections by energy, and neutron absorption reaction rates. Due to its high neutron absorption characteristics, the target absorber materials were evaluated to cause relatively significant material damage compared to conventional metal alloys such as steel.

The results of this study can be used as fundamental data for verifying the nuclear characteristics and mechanical integrity of neutron absorbers with high thermal neutron absorption cross-sections.

ACKNOWLEDGEMENT

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