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Worth and Flux Decomposition of Rod-Type Neutron Absorbers in LEU+ Spent Fuel Pool

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1. Introduction

Advanced reactor designs and extended fuel cycles for light-water reactors increasingly require LEU+ fuel with enrichments of 5–10 wt% U-235 [1,2]. Research on the LEU+ fuel cycle has been actively conducted in recent years. For instance, high burnup core designs employing LEU+ fuel have been developed for 4-loop PWRs together with full-core fuel performance assessments [3]. The higher reactivity of LEU+ fuel challenges the criticality safety of spent fuel pool (SFP) Region I, which stores fresh and high-reactivity assemblies. Conventional plate-type absorbers installed between storage cells were developed for enrichments below 5 wt% [4].

In our previous study [5], the insertion of rod-type neutron absorbers into the guide tubes of the stored fuel assembly has been proposed as a complementary measure, and its criticality feasibility is assessed. An inserted rod reduces reactivity through two distinct mechanisms: (i) neutron absorption, which suppresses the thermal flux in the assembly interior, and (ii) moderator displacement, which removes water from the guide tube and hardens the local neutron spectrum. Understanding the relative contribution of the two mechanisms is essential for the material selection and the abnormal-condition behavior of the rod-type absorber, since the displacement contribution depends on the moderator state whereas the absorption contribution depends on the rod material.

In this study, the rod worth of two representative materials, SS304 and B_4C/Al (31 wt% B_4C in Al matrix), is decomposed into the absorption and moderator displacement components, and the decomposition is independently cross-checked by a spectral flux decomposition using the same set of configurations.

2. Methodology

2.1 Analysis code

Criticality calculations were performed with MCNP6.3, a Monte Carlo transport code developed by Los Alamos National Laboratory (LANL), with the ENDF/B-VIII.1 continuous-energy cross-section library [6]. Calculations were run for 600 cycles with 20,000 histories per cycle, discarding the first 300 inactive cycles to ensure fission source convergence; the standard deviation of keff was within approximately 40 pcm (1σ).

2.2 Analysis model

A single Region I storage cell of the AP1000 rack containing a Westinghouse 17×17 fuel assembly was modeled with radially reflective boundary conditions and 30.48 cm axial water layers, following NEI 12-16 [7]. Fresh fuel without burnable absorber was assumed, and the B-10 content of the absorber plates was credited at 75% for conservatism. The rod-type absorbers were inserted into the 24 guide tubes of the fuel assembly; the central instrument tube was excluded. Design parameters which are applied for demonstration of the AP1000 geometry are shown in Table 1.

Table 1. Design parameters of W17x17 and Region I [8, 9]

Parameter	Dimension (cm)
Array dimension	17 x 17
Fuel pellet diameter	0.7840
Clad outer diameter	0.8898
Clad inner diameter	0.8001
Guide tube outer diameter	1.124
Guide tube inner diameter	1.204
Tube pitch	1.260
Active fuel height	426.72
Cell height	506.73
Cell inner width	22.352
Cell pitch	27.686
Rack thickness	0.1905
Neutron absorber thickness	0.2692
Neutron absorber width	19.05

2.3 Worth and flux decomposition

Four configurations were calculated under the unborated condition: the SS304 rod case, the B4C/Al rod case, a void rod case retaining the rod geometry without absorbing material, and the moderator-filled reference case. The worth components are defined as follows.

$$\Delta k_{total} = k_{moderator} - k_{rod} \quad \text{Eq. (1)}$$

$$\Delta k_{disp} = k_{moderator} - k_{void} \quad \text{Eq. (2)}$$

$$\Delta k_{abs} = k_{void} - k_{rod} \quad \text{Eq. (3)}$$

The displacement ratio is defined as $\Delta k_{disp}/\Delta k_{total}$. Note that Δk_{disp} is independent of the rod material by definition.

For the flux decomposition, the flux φ is defined as the sub-fast neutron flux (E < 0.1 MeV, covering the energy range of significant absorber cross sections) tallied inside the guide tubes, averaged over two tallied positions that agree within 0.15 percentage points. Applying the identical set of configurations, the local flux suppression is decomposed as follows in the same manner with Eqs. (1)–(3).

$$\Delta\varphi_{total} = \varphi_{moderator} - \varphi_{rod} \quad \text{Eq. (4)}$$

$$\Delta\varphi_{disp} = \varphi_{moderator} - \varphi_{void} \quad \text{Eq. (5)}$$

$$\Delta\varphi_{abs} = \varphi_{void} - \varphi_{rod} \quad \text{Eq. (6)}$$

The resulting flux-based displacement share, $\Delta\varphi_{disp}/\Delta\varphi_{total}$, is compared with the worth-based ratio.

3. Results and Dicussions

3.1 Worth decomposition

Fig. 1 presents the worth decomposition of the SS304 and B_4C/Al rods, and Fig. 2 shows the displacement ratio. The displacement and absorption components of the SS304 rod worth are comparable at low enrichments. As the enrichment increases, the displacement ratio steadily increases, and the displacement component becomes the dominant contribution in the upper part of the enrichment range considered. In contrast, the B_4C/Al rod worth is absorption-dominated regardless of enrichment.

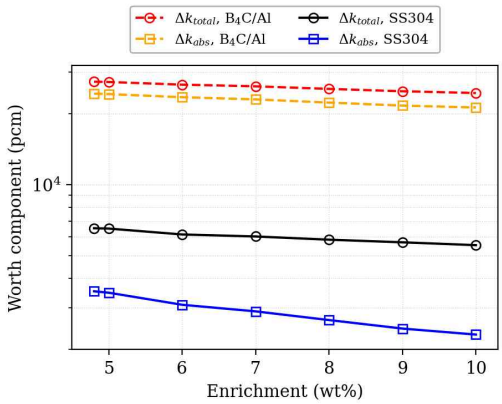


Fig. 1. Worth decomposition components of the SS304 and B_4C/Al rods as a function of fuel enrichment.

Since the displacement component is common to both rods, the contrast in the displacement ratio arises entirely from the absorption component, which is close to an order of magnitude larger for the B_4C/Al rods than for the SS304 rods. This difference originates from the thermal absorption cross sections of the two materials, which determine their optical thickness relative to the rod diameter. Owing to the large cross section of B-10, the thermal absorption mean free path of the B_4C/Al composition is far shorter than the rod diameter; the rod is therefore optically thick and absorbs essentially all incident thermal neutrons at its surface. Conversly, the mean free path of SS304 is much longer than the rod diameter, so the rod is optically thin, allowing most thermal neutrons to traverse it. Its absorption therefore scales with the local thermal flux and competes directly with U-235 for thermal neutrons.

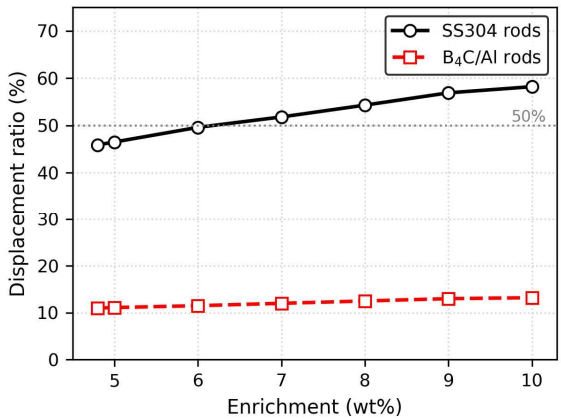


Fig. 2. Worth-based displacement ratio of the two rod types.

3.2 Flux decomposition

The flux decomposition was performed by applying Eqs. (4) to (6) to the sub-fast flux tallied inside the guide tubes by MCNP, and Fig. 3 presents the decomposition of the local flux suppression into the absorption and displacement components for the two rod types. For the SS304 rods, the displacement accounts for approximately half of the local flux suppression at the lowest enrichment and becomes the major contributor as the enrichment increases. For the B_4C/Al rods, the local flux suppression remains absorption dominated over the entire enrichment range. In addition, the tallied spectra show that the thermal flux fraction at the guide-tube position drops to a small fraction of the reference value when the B_4C/Al rod is inserted, which is consistent with the optically thick behavior described in Sec. 3.1.

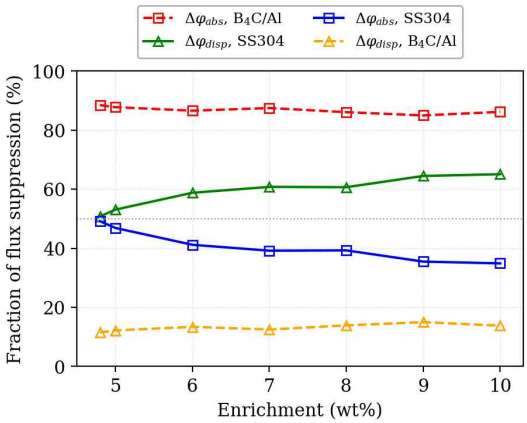


Fig. 3. Flux decomposition of the local flux suppression into absorption and displacement components.

3.3 Cross-check between the worth and flux analyes

Fig. 4 compares the flux-based displacement share with the worth-based ratio. For the B_4C/Al rods, the flux decomposition reproduces the worth-based ratio within the statistical uncertainty, since the sub-fast metric fully covers the epithermal range into which the B-10 absorption extends. For the SS304 rods, the flux-based share increases in parallel with the worth-based ratio and consistently exceeds it by a modest margin. The parallel trend indicates that the two independent decompositions capture the same underlying mechanism, while the systematic offset reflects the different spatial weighting of the two quantities. The displacement acts locally at the guide-tube position and is therefore emphasized in the locally tallied flux, whereas the optically thin SS304 absorption is distributed over the assembly interior and is weighted more heavily in the assembly-integrated worth. Consequently, the consistency between the two decompositions supports the reliability of the worth decomposition, and the offset itself provides additional evidence for the localized nature of the displacement mechanism.

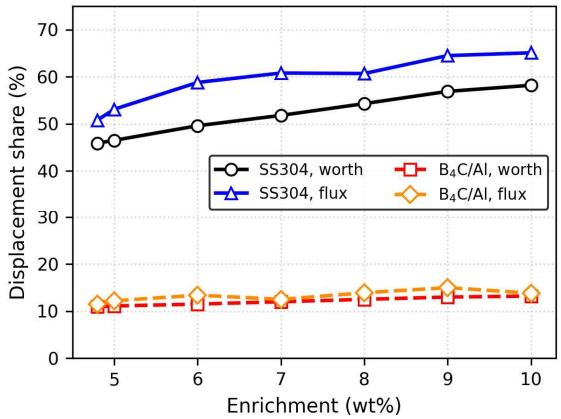


Fig. 4. Cross-check of the flux-based displacement share against the worth-based ratio.

4. Conclusions

The worth of rod-type neutron absorbers in an LEU+ spent fuel pool was decomposed into absorption and moderator displacement components, and the decomposition was independently confirmed by a spectral flux decomposition using the same configurations. For the SS304 rods, the two components are comparable in magnitude, and the displacement contribution grows with the fuel enrichment and exceeds the absorption contribution above approximately 6 to 7 wt%. In contrast, the worth of the B_4C/Al rods remains strongly absorption-dominated over the entire enrichment range considered. The contrast originates from the thermal absorption cross sections of the two materials, which render the B_4C/Al rod optically thick and the SS304 rod optically thin relative to the rod diameter. The flux decomposition reproduces the worth-based ratio within the statistical uncertainty for the B_4C/Al rods and shows a parallel trend with a small local offset for the SS304 rods, reflecting the localized nature of the displacement mechanism.

These results indicate that, at LEU+ enrichments, the reactivity suppression of a weakly absorbing rod such as SS304 relies increasingly on moderator displacement. Since the displacement contribution depends on the moderator state, the rod worth of a weakly absorbing material should be examined under varying moderator density and abnormal conditions.

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