Criticality Safety Analysis of Advanced Neutron Absorbers for LEU+ Spent Fuel Pool

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***Keywords:** *Spent Fuel Pool, Neutron absorber, LEU+, Criticality safety analysis, MCNP*

1. Introduction

Conventional large light-water reactors (LWRs) operate with low-enriched uranium below 5 wt% U-235, whereas some of advanced reactor designs and small modular reactor (SMR) designs require LEU+ fuel (5–10 wt%) to achieve compact cores and extended fuel cycles [1,2]. Increasing fuel enrichment has also been discussed in large commercial reactors to improve fuel cycle efficiency and address spent fuel management challenges [3]. Therefore, managing criticality safety in spent fuel pools (SFPs) with higher enriched fuels has become increasingly important.

To achieve high storage density, SFP racks incorporate neutron absorbers [4]. Region I, which stores fresh and high-reactivity fuels, represents the most limiting design criteria. As illustrated in Fig. 1(a), two neutron-absorbing plates are installed between adjacent fuel assemblies, while Region II (Fig. 1(b)) generally employs a single absorber plate due to lower-reactivity spent fuel. Boron-based materials such as Boraflex™, BORAL®, and METAMIC™ are commonly used in the current designs. However, conventional absorbers such as METAMIC™ (31 wt% B_4C/Al) were developed for fuels of enrichments below 5 wt% and may not provide sufficient reactivity margin in LEU+ conditions. Moreover, boron-based absorbers can experience long-term degradation due to (n,α) reactions.

Gadolinium (Gd), whose natural thermal neutron absorption cross-section is approximately 64 times greater than that of boron, has been widely investigated as a control material in nuclear systems [6]. In this study, an advanced aluminum-matrix neutron absorber incorporating Gd_2O_3 and complementary materials is developed to enhance reactivity control in Region I while maintaining the geometric configuration of the existing AP1000 storage rack.

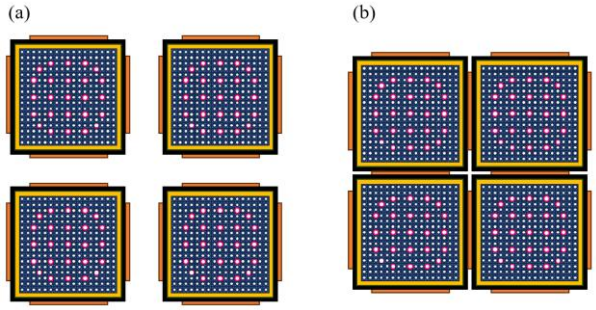

Fig .1. (a) Array of region I, (b) Array of region II

2. Safety analysis methodology

2.1 Analysis code

Criticality calculations for Region I were performed using 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 [7]. High-reactivity fresh fuel was modeled as uniformly distributed along the fuel rod length (see Section 2.2). Simulations were executed for 500 cycles with 20,000 neutron histories per cycle, excluding the first 250 inactive cycles to ensure fission source convergence. The resulting standard deviation of k_{eff} was within approximately 40 pcm.

2.2 Analysis model

2.2.1. Fuel assembly

As the standard nuclear fuel assembly used in the AP1000, the Westinghouse type 17x17 fuel assembly (W17x17) was applied to the modeling [8]. The specifications of W17x17 are as shown in Table 1. W17×17 fuel assembly consists of one instrumentation tube, 25 guide tubes, and 263 fuel rods. The fuel rods are composed of UO_2 fuel pellets and are clad with ZIRLO. The fuel pellets were modeled sequentially for LEU+ with enrichments ranging from 5 wt% to 10 wt%. The maximum fuel enrichment currently employed in operating AP1000 reactors is 4.80 wt% where this study adopts the specification as the reference case for comparative analysis.

2.2.2. Spent fuel pool rack region I

The AP1000 spent fuel pool storage system can accommodate a total of 889 fuel assemblies, of which 243 are allocated to Region I, 641 to Region II, and 5 to store defective fuel cells [9]. Although the fuel assemblies are arranged in a finite lattice, a conservative approach assumes an infinite lattice. According to NEI 12–16, a single cell stored in the Region I array was modeled by applying radial reflective boundary conditions to simulate an infinite lattice. To prevent neutron leakage and ensure a conservative analysis, water layers with a thickness of 30.48 cm (1 ft) were placed at both the top and bottom in the axial direction [10].

As shown in Table 1, the thickness of the neutron absorber is 2.692 mm. In this study, to optimize

performance without altering the existing geometric configuration of the AP1000 storage rack, the absorber thickness was fixed at this value for the design of the advanced neutron absorber. In addition, to ensure compatibility with industrial manufacturing processes and economic feasibility, an advanced neutron absorber was designed by retaining the existing aluminum alloy–based matrix while maximizing the neutron absorption performance for LEU+ fuel.

According to ASM Handbook, Volume 21 (Composites) which provides standard guidelines for metal matrix composite (MMC) design, the fabrication limit of particulate-reinforced MMCs is governed not by weight fraction but by the critical packing fraction of the reinforcing particles, i.e., their volume fraction (vol%). [11] Accordingly, following the criteria specified in Holtec HI-2084243, the critical particle content required to ensure the mechanical integrity of the absorber was set to 40 vol%. This criterion accounts for the fact that, when high-density absorber materials such as Gd or Hf are employed, a weight-fraction-based criterion (wt%) may distort the actual fabricability limit [12]. When this volume-fraction-based criterion is applied to the candidate high-density rare-earth materials, it corresponds to an approximate particle content of 70 wt%.

Table 1. Design parameters of W17x17 and Region I

Parameter	Dimension (cm)
Array size	17 x 17
Pellet Diameter	0.7840
Cladding Outside Diameter	0.8898
Cladding Inside Diameter	0.8001
Guide Tube Outside Diameter	1.124
Guide Tube Inside Diameter	1.204
Tube pitch	1.260
Active fuel length	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. Criticality safety analysis

The spent fuel pool must maintain subcriticality under all conditions. In accordance with U.S. NRC regulations [10], the safety analysis in spent fuel pool Region I must ensure that, when the racks are loaded with the most reactive fuel assemblies, the neutron multiplication factor remains within the following prescribed independent limits with a 95% probability at a 95% confidence level:

(1) In the case of racks flooded with unborated water, k_{eff} must remain below 1.0.

(2) When flooded with borated water, k_{eff} must not exceed 0.95.

3. Selection of neutron absorber materials

Gd, Eu, Sm, Cd, Dy, and Hf have been investigated as neutron-absorbing materials in nuclear systems [13]. Among them, Gd exhibits the highest thermal neutron absorption cross-section—approximately 64 times that of boron—making it the primary candidate. Its key isotopes, Gd-155 and Gd-157, provide excellent thermal absorption; however, compared with B-10, their attenuation in the epithermal and fast regions is reduced due to resonance valley effects and lower average cross-sections. Therefore, complementary materials were considered to enhance energy-dependent absorption behavior.

Based on evaluations of neutron cross-section characteristics, toxicity (safety hazard), thermal stability, density, and lifespan, Gd_2O_3, Eu_2O_3 and HfO_2 were selected as primary candidates for advanced SFP absorbers. CdO was excluded due to high toxicity and low melting point, while Dy_2O_3 and Sm_2O_3 were retained as secondary options. Gd_2O_3 serves as the main absorber, with Eu_2O_3 and HfO_2 providing complementary spectral absorption and improved volumetric performance. B_4C was maintained as the reference material. This selection accounts absorption efficiency, manufacturability, and long-term stability for advanced absorber design.

4. Development of advanced neutron absorber

4.1. Saturation onset

Due to the self-shielding effect, the effectiveness of the absorber (i.e., the reduction rate of k_{eff} with respect to the neutron-absorbing material) becomes small even at high absorber densities. In the analysis, the boundary between high and low effectiveness—referred to as the saturation onset—is observed.

Based on the criticality analysis, Hf has been excluded from the primary list of the neutron absorber candidates due to its poor absorption performance. As the Fig. 2, while Gd reaches its saturation onset very rapidly at approximately 1.0 at% and Eu at around 10.0 at%, it shows the powerful reactivity control, Hf exhibits a very gradual k_{eff} reduction, with its saturation point occurring only at 20 at% or beyond. Considering this insufficient performance along with economic disadvantages such as high material costs, Hf has been excluded in the further study. To optimize the design, a neutron absorber that a mixture of Gd_2O_3 and Eu_2O_3 has been proposed, employing an Al matrix loaded with Gd and Eu at atomic ratios corresponding to their respective saturation onsets, thereby maximizing absorption efficiency.

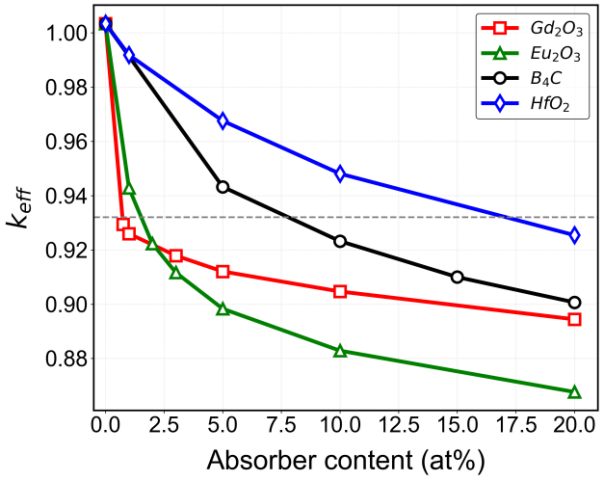

Fig. 2. Saturation onset of candidate materials as a function of concentration in Al matrix.

4.2. Criticality Calculation under Pure and Borated Water Conditions

As defined in Section 2.3, the maximum allowable multiplication factor $k_{eff,max}$ is set above the nominal value k_{eff}, establishing reference limits for pure water and borated water conditions. The optimized advanced aluminum-based absorber (Gd_2O_3 2.99 vol% / Eu_2O_3 37.01 vol%), based on the saturation-onset and sensitivity analyses, was evaluated in both pure water and borated water with varying fuel enrichment level and compared with the conventional B-based absorbers.

Under pure water conditions (Fig. 3), both absorbers maintain subcriticality until 7 wt% enrichment, with the advanced absorber providing an improved criticality margin compared with the conventional design.

Under borated water at 758 ppm conditions (Fig. 4), subcriticality is ensured across the entire enrichment range considered. The advanced absorber again provides enhanced reactivity suppression compared with the conventional absorber, indicating superior performance under these conditions.

4.3. Total criticality analysis of region I

As defined in Section 2.3, the maximum allowable multiplication factor $k_{eff,max}$ is set 0.018 above the nominal value k_{eff}, establishing reference limits of 0.982 for pure water and 0.932 for borated water conditions. The optimized advanced aluminum-based absorber (Gd_2O_3 2.99 vol% / Eu_2O_3 37.01 vol%), derived from saturation-onset and sensitivity analyses, was evaluated for fuel enrichments of 5–10 wt% and compared with conventional B_4C-based absorbers.

Under pure water conditions (Fig. 3), both absorber designs maintain subcriticality up to approximately 7 wt%. The conventional absorber remains subcritical up to 7.11 wt%, whereas the advanced absorber extends the limit to 7.36 wt%. Across the 5–10 wt% range, the advanced design provides an average additional criticality margin of 109.89 pcm. This improvement reflects enhanced spectral absorption performance of the proposed design, which cannot be achieved by increasing conventional absorber thickness due to self-shielding effects.

Under borated water conditions (Fig. 4), the subcriticality requirement is ensured across the entire LEU+ range considered. The conventional absorber maintains subcriticality up to 8.12 wt%, while the advanced absorber extends this limit to 8.50 wt%. The average additional criticality margin in this condition is 185.63 pcm, indicating significantly enhanced reactivity suppression compared with the pure water case.

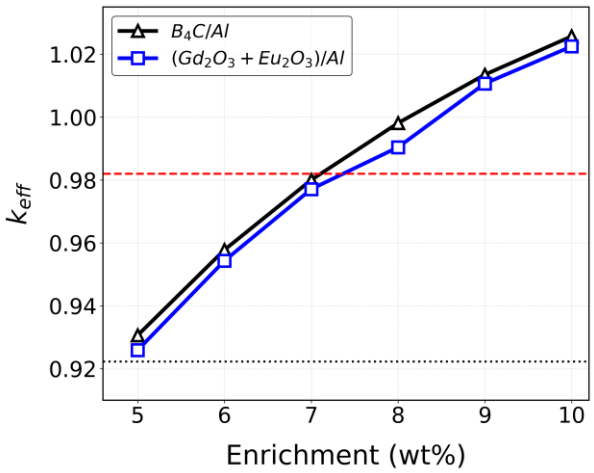

Fig. 3. Pure water criticality depending on fuel enrichment; Red: NRC k_{eff} limit; Black: 4.8 wt% enrichment k_{eff}

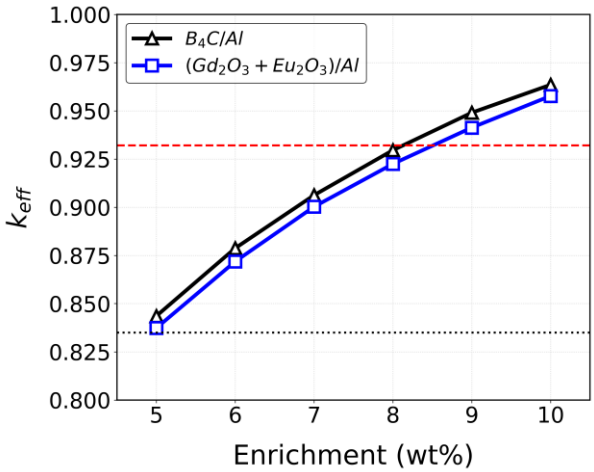

Fig. 4. Borated water criticality depending on fuel enrichment; Red: NRC k_{eff} limit; Black: 4.8 wt% enrichment k_{eff}

Consequently, because the pure water condition imposes the more limiting enrichment constraint, the maximum allowable enrichment can be increased from 7.11 wt% with the conventional absorber to 7.36 wt% with the advanced neutron absorber, corresponding to a total improvement of 0.25 wt% in enrichment. However, this increase is relatively modest, indicating that a new approach for managing criticality in the spent fuel pool under LEU+ conditions is required.

5. Conclusions and Further Works

This study developed and evaluated an advanced aluminum-based neutron absorber incorporating Gd_2O_3 and Eu_2O_3 for spent fuel pool (SFP) applications under LEU+ enrichment conditions. A systematic framework incorporating uncertainty treatment, material screening, and saturation-onset-point based optimization was established to identify an optimal absorber composition. HfO_2 was excluded due to its delayed saturation onset and limited reactivity attenuation capability, whereas Gd provides strong thermal neutron absorption and Eu complements reactivity suppression in the epithermal energy range.

The optimized composition (Gd 1.2 at% / Eu 15.26 at%; Gd_2O_3 2.99 vol% / Eu_2O_3 37.01 vol% in an Al matrix) maximizes spectral absorption efficiency within practical fabrication constraints. Criticality analyses for fuel enrichments from 5–10 wt% indicate that the advanced absorber extends the subcriticality limit to 7.36 wt% under pure water and 8.50 wt% under 758 ppm borated water conditions, compared with 7.11 wt% and 8.12 wt%, for the conventional B_4C-based absorber, respectively. Across the enrichment range, the advanced design provides additional criticality margins of 109.89 pcm under pure water and 185.63 ppm under borated water conditions.

Because the pure water condition governs the more limiting enrichment constraint, the increase in allowable enrichment is 0.25 wt% (from 7.11 to 7.36 wt%). The overall gains in allowable enrichment remains modest. This outcome indicates that, for LEU+ applications, criticality management in the SFP should be performed with moderation and geometric modifications. Absorber material optimization alone is insufficient to achieve substantial enrichment extension. Therefore integrated approaches will be necessary to effectively manage criticality under future high-enrichment scenarios.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Climate, Energy & Environment (MCEE) of the Republic of Korea (No. RS-2024-00398425). The authors would also like to acknowledge Keon Il Cha and Kyoon Ho Cha (Nuclear Engineering Department, Sejong University) for their assistance in this study

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