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Feasibility study for the criticality calculations of the LEU+ with ATF fuels

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1. Introduction

Nuclear power is an economically efficient and environmentally friendly energy source, with most global generation occurring in Light Water Reactors (LWRs) using Low Enriched Uranium (LEU) as fuel [1,2]. Following the Fukushima accident, there has been a focus on developing Accident Tolerant Fuels (ATFs) to improve the safety and reliability of nuclear power plants [3]. In September 2023, the U.S. NRC issued draft guidance allowing U^{235} enrichment up to 8% for ATF [4]. Along with the characteristics of these ATFs, increasing fuel enrichment is also being considered for the economic and efficient operation of nuclear power plants [5]. More recently, on August 8, 2024, The Westinghouse Company delivered the first ADOPT nuclear fuel pellets developed under DOE's ATF program to the Vogtle-2 power plant, which is expected to be commercially available in 2025 [6].

While front-end fuel cycle applications of LEU+ and ATF are well-researched, less attention has been given to the back-end cycle, such as fuel storage and transportation. This paper evaluates the use of additional neutron absorbers in the APR-1400's nuclear fuel storage system to ensure criticality safety when using PLUS7 with ATF (hereafter referred to as ATF) and LEU+.

2. Criticality Modeling

In this study, Korean PWR model APR-1400 was utilized to assess additional neutron absorbers into a nuclear fuel storage system loaded with ATF and LEU+ could meet criticality requirements. The ATF model employed CrAl-coated Mo metallic microcell UO_2 pellets developed by KAERI [7,8].

2.1 PLUS7 with ATF

Mo metallic microcell UO_2 pellet with CrAl coating concept developed by KEARI were selected as ATF. The fuel assembly consists of a 16 x 16 array of 236 fuel rods, four guide tubes, and an instrument tube. The fuel material is uranium dioxide (UO_2) and additive Mo (95 vol% UO2 - 5 vol% Mo), the cladding material is Zr-based alloy ZIRLO, and the coating material is CrAl (85 wt% of Cr – 15 wt% of Al). 0.02 cm thick layer of CrAl is coated on the outside of the cladding. Detailed information of fuel assembly model is described in Table 1.

Table 1. Design Parameters of Fuel Assembly

Description	PLUS7[a]	ATF[b]
Fuel type	UO_2	UO_2-5 vol% Mo
Pellet density [g/cm^3]	10.313	10.506
Fuel pellet radius [cm]	0.4096	0.4096
Cladding material	ZIRLO	ZIRLO
Cladding inner radius [cm]	0.41785	0.41785
Cladding outer radius [cm]	0.475	0.475
Coating material	-	CrAl (85 w/o Cr – 15 w/o Al)
Cr coating thickness [cm]	-	0.02
Fuel rod pitch [cm]	1.2852	1.2852
G/I tube material	ZIRLO	ZIRLO
G/I tube inner radius [cm]	1.143	1.143
G/I tube outer radius [cm]	1.2445	1.2445
Assembly width [cm]	20.5632	20.5632
Active fuel length [cm]	381	381

*a, b: adopted from [7,8], respectively.

2.2 Spent Fuel Pool (Region 1)

Region 1 is modeled as a water reflector with no soluble boron, maintaining the same temperature and density as the moderator in the active fuel region, and does not use burnup credit, while being treated as a single cell with radially periodic boundary conditions and a 30.48 cm water layer on the top and bottom axially to prevent neutron leakage for conservative calculations [9]. One fuel assembly is stored in racks made of 0.25 cm stainless steel, and four neutron absorber plates (METAMIC) using boron carbide (B_4C), and aluminum composite material are attached to each rack to maintain subcriticality [10].

The specifications of the Region 1 are as shown in Table 2, and due to the lack of detailed information of METAMIC, B_4C volume ratio for Region 1 was roughly estimated to be 22.4%.

Table 2. Design Parameters of Region 1

Description	Value
Cell height [cm]	459
Cell width [cm]	22
Cell pitch [cm]	27.5
Rack material	SS304
Rack thickness [cm]	0.25
Neutron absorber material	METAMIC
B4C vol%	22.4 %
Neutron absorber thick. [cm]	0.25
Neutron absorber width [cm]	18
Neutron absorber sheath material	SS304
Neutron absorber sheath thickness [cm]	0.06

2.3 Neutron Absorber

The additional neutron absorbers were placed on the four sides of the existing neutron absorbers by fitting them tightly each other. The composition is similar to the original METAMIC, but the volume of B_4C is 28.64% (≒30wt%).

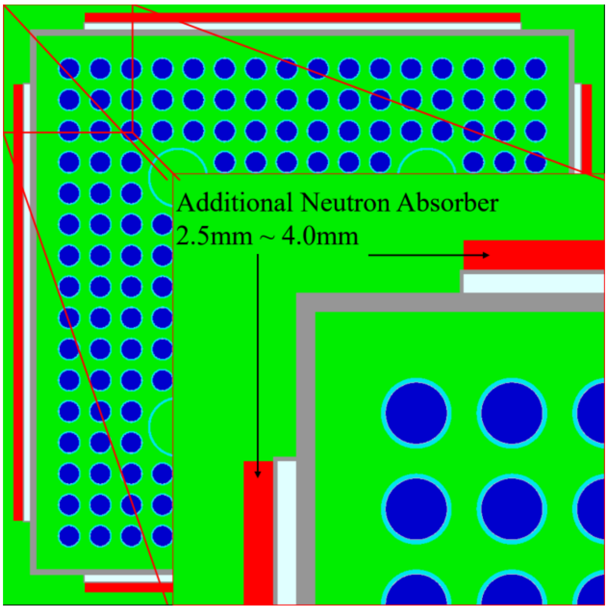

Figure 3. Assembly with additional neutron absorber

Region 1 of the Spent Fuel Pool (SFP) was evaluated with fresh fuel, and the assessment was conducted using LEU+ enriched to 5wt% to 8wt% U^{235} in accordance with NRC guidance. Criticality calculations were performed using the CSAS6/KENO-VI module of the SCALE 6.3.1 code for continuous-energy Monte Carlo neutron transport, with the ENDF/B-VIII.0 neutron cross-section library [11].

The additional neutron absorbers adjusted the B_4C content and thickness, which is expressed as Boron Areal Density (g/cm²) [12].

3. Results

The criticality calculations were performed for PLUS7 fuel and ATF fuel from 5wt% to 8wt%, and it was found that the criticality values of several items did not satisfy the criticality limit of the nuclear fuel pool (Table 3.).

Table 3. Criticality Result (std ≒ 0.00010)

U^{235} (wt%)	5%	6%	7%	8%
PLUS7	0.90365	0.93176	0.95342	0.97109
ATF	0.88322	0.91194	0.93462	0.95317

The criticality calculations were performed for PLUS7 fuel and ATF fuel from 5wt% to 8wt%, and it was found that the critical values of several items did not satisfy the criticality limit of the nuclear fuel pool (Table 3.). The results of the criticality reduction due to the additional neutron absorbers placed are shown in Figure 4,5.

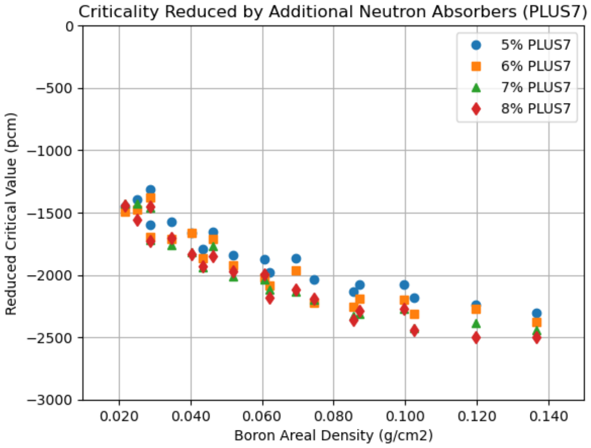

Figure 4 Criticality Reduced by Additional Neutron Absorbers (PLUS7)

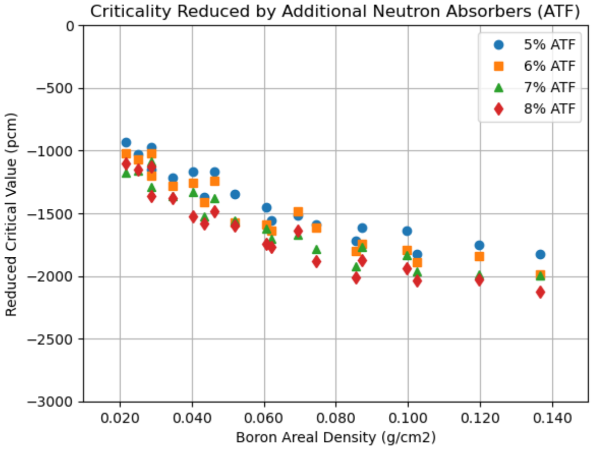

Figure 5 Criticality Reduced by Additional Neutron Absorbers (ATF)

For PLUS7 case, it was possible to reduce up to 2500 pcm, below 0.95 at 8wt%. In the case of ATF, reduced to 2127 pcm.

4. Conclusion

The nuclear fuel with increased enrichment (LEU+, ATF) in a commercial reactor would exceed the criticality limit of the spent fuel pool. Therefore, additional neutron absorbers were added to ensure that the criticality limit was satisfied.

The additional neutron absorbers affect the criticality according to the increase of boron areal density. However, simply increasing the thickness does not continuously reduce criticality. The impact of the water gap (i.e., flux trap) between assemblies must be considered, making it essential to optimize the thickness through a sensitivity analysis when adding more neutron absorbers. As part of the future work in this paper, planning to conduct sensitivity analyses on various neutron absorber placement scenarios and thicknesses.

Acknowledgement

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