Preliminary Assessment of La_2O_3-Al_2O_3-SiO_2 Doped ATF and Evaluation of Cycle Length Compensation by Enrichment Adjustment

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1. Introduction

There have been active studies on developing accident tolerant fuel (ATF) since the Fukushima daiichi nuclear accident in 2011 [1, 2]. The most promising concept is the Cr-coated zirconium-based alloy cladding ATF (Cr-coated ATF) [3]. The preliminary difference between current nuclear fuel [4] and ATFs in terms of assembly [5] and core depletion in APR1400 [6] was demonstrated in a previous paper.

In addition to the development efforts in cladding material, PWR fuel vendors have been looking into doping ATF to further enhance its thermo-mechanical properties. Doping the fuel entails introducing a trace amount of an element to a standard UO2 pellet. This sort of doped UO2 pellet design technology has previously been successfully commercialized for the BWRs, and it is currently being reviewed for PWR application. Oxide like Cr_2O_3, Al_2O_3, SiO_2 and La_2O_3 are used to dope the pellets.

Due to an increase in the neutron absorber in the core caused by the application of various fuel pellet additives and Cr-coating at Zircaloy clad, the excess reactivity of the core lowers and has an impact on the critical boron concentration (CBC) and power distributions.

In this study, the effects of La2O3-Al2O3-SiO2 (LAS) as a dopant to the fuel pellets with Cr-coated zircaloy cladding are assessed when they are used with an APR1400 core. To examine the effects of LAS and Cr-coating, core criticality and burnup calculations were carried out utilizing nTRACER, a neutron transport code developed by the SNU [7], and the results are compared with the reference core values. It turns out that the cycle length reduction caused by the use of ATF can be made up for by a slight change to the fuel enrichment.

2. Methodology

This section describes the reference APR1400 core configuration and the LAS doped, Cr-coated ATF specification

2.1 APR1400 2D Core

The 2D configuration of the APR1400 core is shown in Fig. 1 [4]. The reference core is loaded with three main types of assemblies with different enrichment. The 2D core model is created as closely as possible to the precise shape and substance of the fuel pin, fuel assembly, barrel, reflector, assembly gap, and so forth in order to improve the reliability of the comparison.

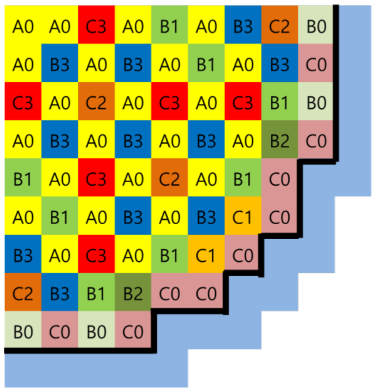

Fig. 1. APR1400 2D core configuration.

2.2 LAS Doped Fuel Pellet and Cr-Coated Cladding

As shown in Fig. 2, LAS doped Cr-coated fuel rods are made by applying an additive LAS to the fuel pellet and a thin Cr coating to the zircaloy cladding. The doped LAS concentrations are considered in two ways: 1000 ppm and 2000 ppm. And the chrome coating thickness was set at 13 ㎛.

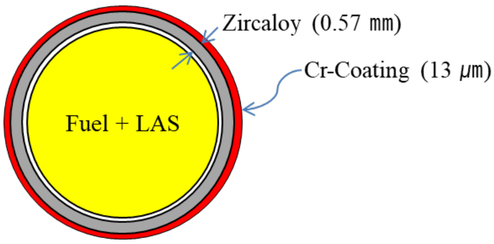

Fig. 2. Schematic of LAS doped with Cr-coating fuel.

The number density for each nuclide in the LAS doped fuel was calculated, and the results are shown in Table I.

Table I: Nuclide number density of LAS doped fuel

Nuclide	Number density
U235	3.9830E-04
U238	2.2605E-02
O	4.6308E-02
La	1.7923E-06
Al	5.8076E-05
Si	1.0578E-04

2.3 Compensation of Cycle Length

The calculation for the APR1400 core with both LAS and Cr-coating was performed while adjusting the enrichment of all assemblies in the core to compensate for the reduced initial CBC.

3. Calculation Results and Assessments

Utilizing the models described in Sections 2.1 and 2.2, core calculations by nTRACER code were carried out for comparison purpose. For nTRACER calculation, the ray condition was set to 0.05/16/4 (Ray Spacing /Azimuthal Angle/Polar Angle).

3.1 Critical Boron Concentration (CBC)

Calculations for the four scenarios were done for the core reactivity evaluation in terms of CBC: (1) Reference condition, (2) 0 ppm-LAS & Cr-coating, (3) 1000 ppm-LAS & Cr-coating, and (4) 2000 ppm-LAS & Cr-coating. Table II shows the outcome.

Table II: Critical boron concentration of LAS doped condition

Condition	Reference	13 μm Cr-Coating		
		0 ppm	1000 ppm	2000 ppm
CBC [ppm]	1075.7	1047.4	1045.8	1044.3

When the Cr coating was applied, there was a CBC difference of about 30 ppm when compared to the reference. There was no discernible difference after using LAS.

3.2 Power Distributions

The core power distribution for the reference condition is shown in Fig. 3. Figures 4 to 6 depict the relative difference (%) in power distribution when compared to the reference condition.

0.850	0.822	1.016	0.864	1.103	0.940	1.051	1.147	1.081
0.822	0.931	0.839	0.983	0.910	1.137	0.945	1.064	1.124
1.016	0.839	1.064	0.870	1.097	0.930	1.137	1.094	0.991
0.864	0.983	0.870	1.001	0.899	1.048	0.950	1.019	0.791
1.103	0.910	1.097	0.899	1.140	0.936	1.145	1.137	
0.940	1.137	0.930	1.048	0.936	1.041	1.108	0.830	
1.051	0.945	1.137	0.950	1.145	1.108	0.870		
1.147	1.064	1.094	1.019	1.137	0.830			
1.081	1.124	0.991	0.791					

Fig. 3. Reference core power distribution

1.11%	1.03%	0.89%	0.71%	0.47%	0.23%	-0.07%	-0.39%	-0.54%
1.03%	0.97%	0.86%	0.66%	0.45%	0.19%	-0.08%	-0.38%	-0.52%
0.89%	0.86%	0.73%	0.59%	0.37%	0.14%	-0.13%	-0.39%	-0.51%
0.71%	0.66%	0.59%	0.43%	0.24%	0.03%	-0.20%	-0.40%	-0.48%
0.47%	0.45%	0.37%	0.24%	0.08%	-0.12%	-0.34%	-0.47%	
0.23%	0.19%	0.14%	0.03%	-0.13%	-0.30%	-0.47%	-0.52%	
-0.08%	-0.07%	-0.13%	-0.20%	-0.34%	-0.47%	-0.49%		
-0.39%	-0.38%	-0.39%	-0.41%	-0.47%	-0.51%			
-0.54%	-0.53%	-0.51%	-0.49%					

Fig. 4. Power distribution difference (13 μm Cr-coated)

1.04%	0.97%	0.82%	0.66%	0.43%	0.20%	-0.09%	-0.37%	-0.47%
0.97%	0.90%	0.80%	0.60%	0.42%	0.18%	-0.10%	-0.35%	-0.47%
0.82%	0.80%	0.68%	0.53%	0.33%	0.12%	-0.13%	-0.36%	-0.45%
0.66%	0.60%	0.53%	0.38%	0.22%	0.01%	-0.19%	-0.36%	-0.43%
0.43%	0.42%	0.33%	0.22%	0.05%	-0.12%	-0.31%	-0.41%	
0.20%	0.17%	0.12%	0.01%	-0.12%	-0.28%	-0.42%	-0.46%	
-0.09%	-0.08%	-0.13%	-0.19%	-0.31%	-0.42%	-0.46%		
-0.37%	-0.36%	-0.37%	-0.36%	-0.40%	-0.45%			
-0.48%	-0.47%	-0.45%	-0.44%					

Fig. 5. Power distribution difference (1000 ppm LAS doped)

0.96%	0.90%	0.75%	0.60%	0.38%	0.17%	-0.10%	-0.33%	-0.41%
0.90%	0.82%	0.73%	0.54%	0.37%	0.14%	-0.10%	-0.32%	-0.40%
0.75%	0.73%	0.61%	0.47%	0.28%	0.10%	-0.13%	-0.32%	-0.38%
0.60%	0.54%	0.47%	0.33%	0.18%	-0.01%	-0.17%	-0.31%	-0.38%
0.38%	0.37%	0.28%	0.18%	0.04%	-0.12%	-0.26%	-0.34%	
0.17%	0.14%	0.10%	-0.01%	-0.12%	-0.26%	-0.36%	-0.40%	
-0.10%	-0.10%	-0.13%	-0.17%	-0.27%	-0.36%	-0.40%		
-0.34%	-0.32%	-0.32%	-0.32%	-0.34%	-0.39%			
-0.42%	-0.41%	-0.38%	-0.38%					

Fig. 6. Power distribution difference (2000 ppm LAS doped)

3.3 Power Peaking Factor

The power peaking factor, F_r value was calculated through 2D core analysis. Similar to the previous calculation, the Cr-coated condition had a larger difference in peaking factor. The core characteristics was unaffected when LAS was applied. In Table III, the results are summarized.

Table III: Power peaking factor of LAS doped condition

Condition	Reference	13 μm Cr-Coating		
		0 ppm	1000 ppm	2000 ppm
Peaking Factor	1.388	1.319	1.316	1.312

3.4 Burnup Calculation

The burnup calculation was performed under ARO and HFP conditions. Fig. 7 shows the core depletion results for the four scenarios. The cycle length changes due to LAS doping and Cr coating are shown in Table IV. Use of LAS-doped, Cr-coated ATF shortens around 10 EFPDs of cycle length for the reference core.

Table IV: Cycle length of LAS doped condition

Condition	Reference	13 μm Cr-Coating		
		0 ppm	1000 ppm	2000 ppm
Cycle Length [EFPD]	867.5	858.4	858.1	857.8

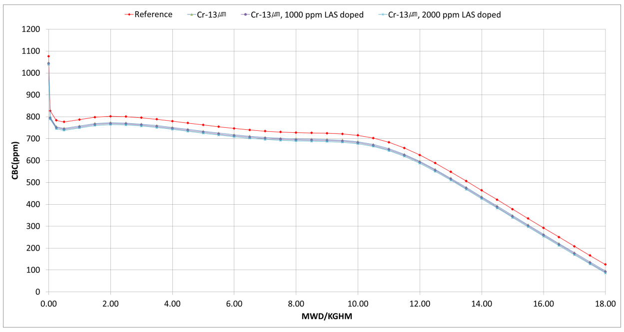

Fig. 7. Burnup calculation results of LAS-doped, Cr-coated condition

3.5 Fuel Enrichment Adjustment

Table V shows how the initial CBC and peaking factor changed with increasing enrichment. A series of calculations revealed that increasing the enrichment by 0.03% brings the initial CBC, i.e., cycle length, is close enough to the reference condition. Nonetheless, increasing the fuel enrichment raises the power peaking factor.

Table V: Initial CBC and power peaking factor with increased enrichment

Type	Ref.	Increased Enrichment [%]				
		0.1	0.06	0.05	0.04	0.03
CBC [ppm]	825.7	913.5	867.3	855.7	844.2	832.6
F_r	1.388	1.399	1.396	1.395	1.393	1.392

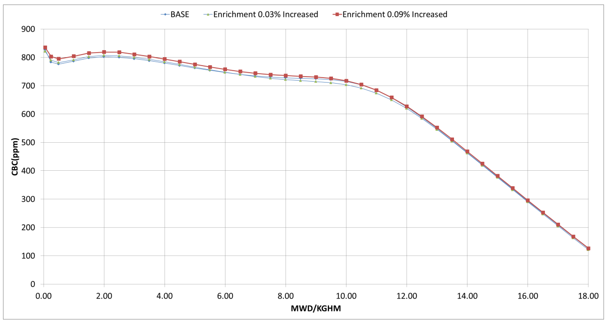

Fig. 8. Burnup calculation results of fuel enrichment adjusted

4. Summary and Conclusion

Differences in several core factors, including initial CBC, power distribution, power peaking factor, and cycle length, were investigated for LAS-doped, Cr-coated ATF. This demonstrated that the impact of Cr-coating outweighed the impact of LAS doping. This study demonstrated that the reduction in cycle length caused by ATF could be compensated for by adjusting the fuel enrichment slightly. Because of the increased fuel enrichment, the peaking factor rises but remains within the acceptable design limit.

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