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Assessment of Rod Worth and Shutdown Margin with ATF Loaded APR1400 Core

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1. Introduction

After the accident at the Fukushima Daiichi nuclear facility in 2011, triggered by an earthquake and subsequent tsunami that resulted in significant reactor damage and the release of radioactive substances into the surroundings, there was a lot of focus on ensuring the safety of light water reactors. The heat generated from the chemical reaction between zirconium and water at high temperatures raises the fuel's temperature and promotes additional reactions, particularly when the safety mechanisms of the reactor are no longer functioning. In addition, the hydrogen released from the reaction can cause a hydrogen explosion in the reactor containment. Hence, the concept of accident tolerant fuel (ATF) was introduced to address public apprehensions regarding nuclear safety, while also aiming to enhance safety and effectiveness.

In Korea, multiple institutions are collaborating to conduct research for the development, study, and regulatory approval of ATF[1]. As part of these efforts, a study was carried out to apply ATF to the APR1400 core[2,3] and investigate its effect on neutron behavior under various conditions. Previous studies, however, concentrated on the parameters of 2D cores, while parameters and findings such as rod worth, Fq, and others that can be detected in a 3D core were not explored.

In this study, a 3D core model for APR1400 was developed. The outcomes obtained from 3D model was power distribution, power peaking factor (PPF, F_q), rod worth, and shutdown margin. The data obtained from the ATF loaded core was compared with data from the reference core to evaluate the impact of ATF on the core. To examine the effects of ATF loaded core, SNURPL-developed whole core transport code nTRACER[4] was utilized.

2. Methodology

This section describes the reference APR1400 core configuration and the specification of ATF.

2.1. APR1400 3D Core

The loading pattern of the benchmark problem is originated from the APR1400 document[5]. The loading pattern has quarter-core symmetry. Fig. 1 shows the radial configuration of the quarter core. The radial reflector consists of the moderator and the core shroud. The core shroud wraps the active core region with small moderator gap. In addition, the control rod arrangement is depicted in Fig. 2.

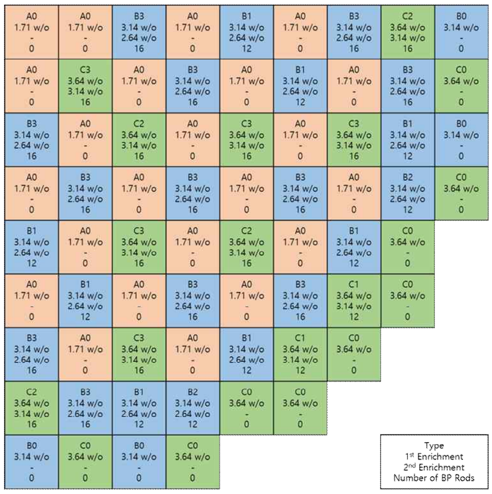

Fig. 1. APR1400 2D core configuration.

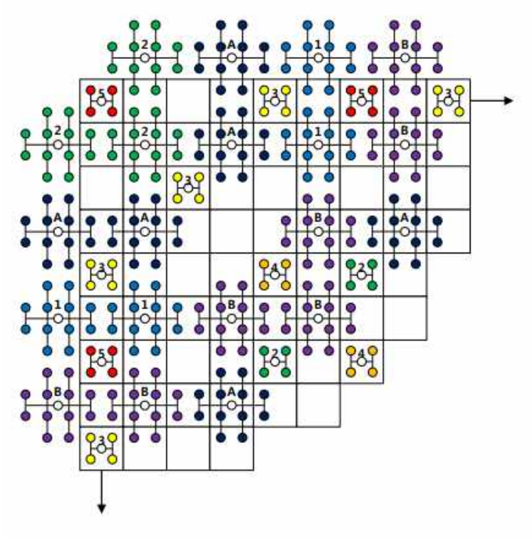

Fig. 2. APR1400 control rod arrangement[5].

2.2. Accident Tolerant Fuel Specifications

The diagram in Fig. 3 illustrates the design of ATF fuel. ATF fabrication involves the application of a thin layer of Cr onto the existing zircaloy cladding, resulting in micrometer-scale manufacturing, as seen in Fig. 3. The present thickness of Cr-coating developed measures approximately 15 μm. As a result, ATF loading simulations with coating thicknesses ranging from 13 to 20 μm were carried out. Moreover, nuclear fuel pellets are doped with LAS compounds as part of a strategy to increase grain size using this method.

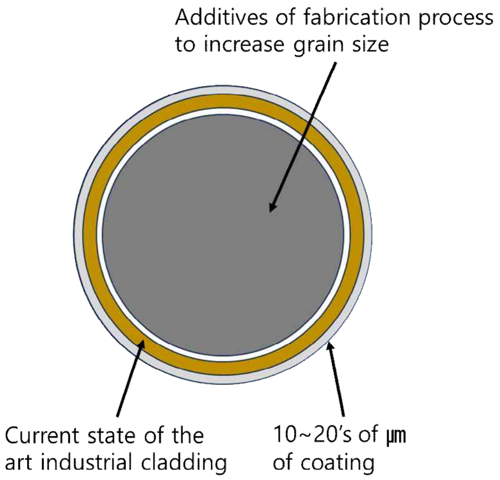

Fig. 3. Specifications of ATF.

3. Calculation Results and Assessment

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. Power Distribution

The averaged power distribution difference was compared to the power distribution of reference core. The ATF conditions of the Fig. 4 is 13 μm and 1000 ppm LAS doped. Except for the core centers, the power difference is less than 1.0%. For the other ATF conditions, the average power distribution difference results are summarized as root mean square (RMS) error. Table I displays the RMS error.

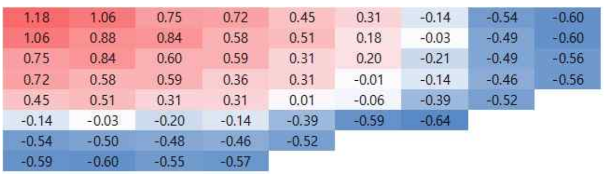

Fig. 4. Averaged power distribution difference

Table I: ATF applied core power distribution RMS difference

Type	Difference / Cr-coating Thickness			
LAS Conc.	13 μm	15 μm	17 μm	20 μm
0 ppm	0.004	0.008	0.005	0.009
1000 ppm	0.001	0.001	0.002	0.002
2000 ppm	0.003	0.003	0.004	0.004

3.2. Power Peaking Factor (PPF), F_q

In Table II the effect of ATF on the PPF is shown. Similar to the power distribution, the Cr-coating increased the propensity of difference. This demonstrates that LAS-doped fuel pellets have a limited effect on neutronics, but they can alter material or mechanical properties, resulting in an accident resistance effect.

Table II: ATF applied core power distribution RMS difference

Type	Difference / Cr-coating Thickness			
LAS Conc.	13 μm	15 μm	17 μm	20 μm
0 ppm	-0.5%	-0.6%	-0.7%	-0.8%
1000 ppm	0.1%	0.1%	-0.1	-0.1%
2000 ppm	0.3%	0.3%	0.4%	0.4%

3.3. Rod Worth

A comparison of the worth difference for each control rod insertion was done to assess the impact of ATF on control rod worth. The comparative results are shown in Table III. For the rod worth, the difference is less than 20 pcm.

Table III: ATF applied core rod worth difference

Inserted CR	Rod Worth [pcm]		Diff. [pcm]
	Ref.	ATF	
5	369.7	352.8.7	-16.9
5, 4	696.4	691.9	-4.5
5, 4, 3	1691.9	1704.8	12.8
5, 4, 3, 2	2743.7	2755.9	12.2
5, 4, 3. 2. 1	4766.2	4767.0	0.8
5, 4, 3. 2. 1, B	8892.9	8907.8	15.0
5, 4, 3. 2. 1, B, A	16133.5	16129.4	-4.2

3.4. Shutdown Margin

The shutdown margin was evaluated with the parameters in Table IV. The comparative results are shown in Table IV. The maximum BIL value of a similar plant is used because it is difficult to identify the most conservative core state using open APR1400 core data. This information was used to compute the shutdown margin of the core, and a modest increase in shutdown margin was seen, indicating that an acceptable shutdown margin had been established. The power distribution at the core's center plane is shown in Fig. 5. For conservative estimation of the scram worth, it is assumed that the control rod with the highest rod worth was stuck out, exposing more power in the area without control rod insertion.

Table IV: ATF applied core shutdown margin difference

Type	Ref.	ATF	Diff.[pcm]
Temperature Defect	2132	2109	-23
BIL Reactivity	240		-
Total Requirements	2372	2349	-23
Scram(N-1) Worth	10921	10904	-17
Uncertainty (4.65%) Applied Worth	508	507	-1
Required Shutdown Margin	8041	8048	7

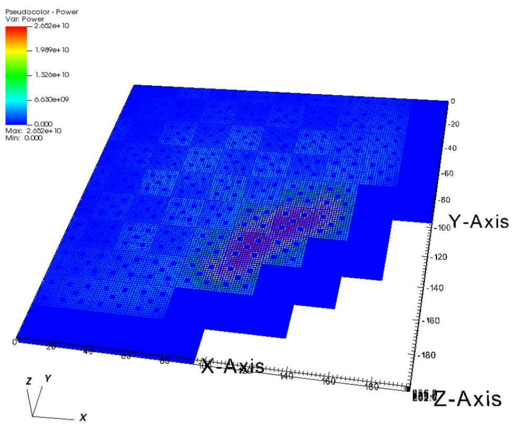

Fig. 5. Power distribution of scram (N-1) worth.

4. Summary and Conclusion

Various key parameters for LAS-doped, Cr-coated ATF core were investigated, including power distribution, PPF, rod worth, and shutdown margin. Obtained results show that the effect of ATF on the 3D whole core transport computations by nTRACER code in simulating the actual core was fairly minimal. This establishes credibility by demonstrating that ATF analysis can be consistently carried out using other code systems as well.

ACKNOWLEDGEMENT

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REFERENCES

[1] H. Kim et al., Development Status of Accident-tolerant Fuel for Light Water Reactors in Korea, Nuclear Engineering and Technology, Vol 48, Issue 1, pp. 1-15, 2016
[2] K. Park, T. K. Park, S. K. Zee, Preliminary Analysis of Burnup Effect on k-inf for Cr-Coated and SiC Cladding Accident Tolerant Fuel Rods with nTRACER, Transactions of the Korea Nuclear Society Spring Meeting, Jeju, R.O.Korea, May 19-20, 2022.
[3] K. Park, T. K. Park, S. K. Zee, Sensitivity Study of ATF Loaded APR1400 Core based on Cr Coating Thickness, Transactions of the Korea Nuclear Society Autumn Meeting, Changwon, R.O.Korea, October 20-21, 2022.
[4] M. Ryu, Y. S. Jung, H. H. Cho, H. G. Joo, Solution of the BEAVRS benchmark using the nTRACER direct whole core calculation code, Journals of Nuclear Science and Technology, Vol. 52, Issue 7-8, pp. 961-969, 2015.
[5] KEPCO & KHNP, APR1400 Design Control Document Tier 2, Chapter 4 Reactor, APR1400-K-FS-14002-NP, Revision 3, Aug. 2018.