Preliminary Assessment of Neutron Energy Spectrum Hardening in ATF Rods and Assemblies

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1. Introduction

Following the accident at the Fukushima Daiichi nuclear power plant, intensive research programs have led to the development of chromium coated zirconium-based alloy cladding accident tolerant fuels (Hereafter, Cr-coated ATFs)[1]. A series of irradiation test for the Cr-coated Lead Test Rods (LTRs) and Lead Test Assemblies (LTAs) is scheduled in 2022, and the related topical reports will be ready for licensing application by 2029 in Korea. In proactive to the future regulatory reviews for the licensing of ATFs, a proper audit code system for the analysis of ATF loaded reactors are required. The primary objective of this study is to investigate that the current neutronics analysis methodology and code system are congruous with the ATF loaded cores. As a first step of this, the neutron energy spectra of ATF assemblies are generated and compared with base assemblies using OpenMC[2] and nTRACER[3].

2. Calculation Conditions

Three typical assembly types (A0, B2, C3) of APR1400[4] as shown in Fig. 1 are selected as the base assemblies. As for the treatment of the ATF claddings, two different Cr coating methods are considered; (1) smeared Cr coating in the existing cladding (Smeared Cr Cell), and (2) separate Cr coating outside of the existing cladding (Separate Cr Cell).

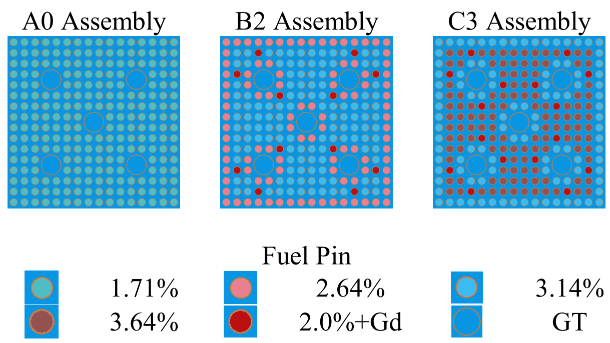

Fig. 1. Base Fuel Assemblies

3. Calculation Results

A series of sensitivity calculations with varying Cr coating thickness was performed to assess the changes in neutronic parameters due to the Cr coating. Results obtained from the sensitivity study show that there is no significant difference if the thin Cr coating applied on top of the existing Zr-based alloy cladding and treated as a smeared cell. There is no significant difference for separated cases as well. The following section describes the differences in the calculation result depending upon the Cr coating thickness and its treatment in more detail.

3.1 OpenMC

Effects of the Cr coating thickness on the 47 group neutron energy spectrum and the assembly multiplication factor (AMF) were evaluated by the OpenMC code. For the calculation, the OpenMC model is set up as follows; (1) number of particles=100,000, (2) number of inactive cycles=50, and (3) number of active cycles=200.

3.1.1 A0 Assembly

The A0 fuel assembly consisted only of guide tubes and 1.71% enriched fuel rods. With this assembly, the sensitivity analysis was performed on the thickness of the Cr coating in the range of 10 μm to 40 μm. As previously described, the analysis was performed for two different Cr coating treatment cases, namely Smeared cell and Separate cell, but the results obtained from two cases are almost same as mentioned above. Therefore only separated cases are reported in this paper. The changes in k_∞ according to Cr coating thickness are summarized in Table I. It was confirmed that the AMFs decreased by about 1000 pcm when the Cr coating thickness was 20 μm, and the confidence interval overlapped within 3σ for the difference between the two results.

The neutron energy spectrum changes are presented in Fig. 2. As the Cr coating thickness increases, the ratio of the fast neutron region of the spectrum increases slightly, however the effect is insignificant and there is almost no difference.

Table I：Multiplication Factor [A0 Assembly]

Cr [μm]	Separated Cr Cell		
	k_∞	stdv	diff.
Ref.	1.23055	0.00020	N/A
10	1.22510	0.00021	-0.00545
20	1.22029	0.00020	-0.01026
30	1.21566	0.00020	-0.01489
40	1.21087	0.00019	-0.01968

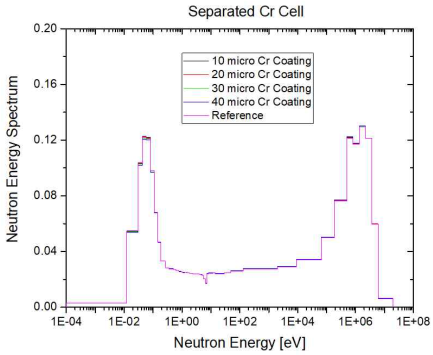

Fig. 2. Neutron Energy Spectrum [A0 Assembly]

3.1.2 B2 Assembly

In the B2 fuel assembly, 2.64% enriched fuel rods are placed at the assembly periphery and around the guide tube cells, and the remaining positions are filled with 3.14% enrichment fuel rods and burnable poison rods.

The sensitivity analysis was repeated with varying thickness of Cr coating in the range of 10 μm to 40 μm.

The changes in k_∞ according to Cr coating thickness are summarized in Table II. It was confirmed that the AMF decreased by about 700 pcm when the Cr coating thickness was 20 μm, and the confidence interval overlapped within 3σ for the difference between the two results.

The resultant neutron energy spectrum changes are presented in Fig. 3. Again, as the Cr coating thickness increases, the ratio of the fast neutron region of the spectrum increases somewhat, however the effect is insignificant and there is almost no difference. It can be seen that the weight of the fast neutron region is increased due to the use of nuclear fuel with a high enrichment compared with the A0 fuel assembly.

Table II : Multiplication Factor [B2 Assembly]

Cr [μm]	Separated Cr Cell		
	k_{eff}	stdv	diff.
Ref.	1.21337	0.00021	N/A
10	1.20983	0.00020	-0.00354
20	1.20656	0.00020	-0.00681
30	1.20330	0.00021	-0.01007
40	1.19960	0.00020	-0.01377

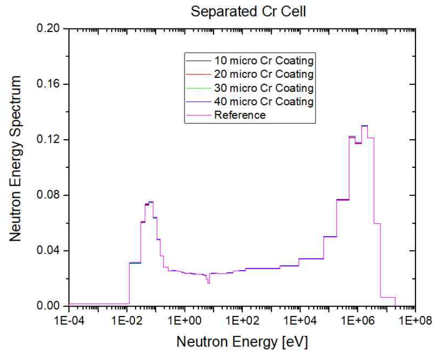

Fig. 3. Neutron Energy Spectrum [B2 Assembly]

3.1.3 C3 Assembly

In the C3 fuel assembly, 3.14% enrichment fuel rods are placed around the assembly periphery and guide tubes. 3.64% enrichment fuel rods and burnable poison rods are placed in the remaining positions.

The changes in k_∞ according to Cr coating thickness are summarized in Table III. It was confirmed that the reactivity value decreased by about 500 pcm when the Cr coating thickness was 20 μm, and the confidence interval overlapped within 3σ for the difference between the two results.

The conclusive neutron energy spectrum changes are presented in Fig. 4. Similar to the previous cases, there is almost no difference in the neutron energy spectrum. It can be seen that the weight of the fast neutron region is increased due to the use of nuclear fuel with a high enrichment compared with the A0 nuclear fuel assembly.

Table III : Multiplication Factor [C3 Assembly]

Cr [μm]	Separated Cr Cell		
	k_∞	stdv	diff.
Ref.	1.20909	0.00021	N/A
10	1.20676	0.00020	-0.00233
20	1.20410	0.00024	-0.00499
30	1.20074	0.00019	-0.00835
40	1.19785	0.00021	-0.01124

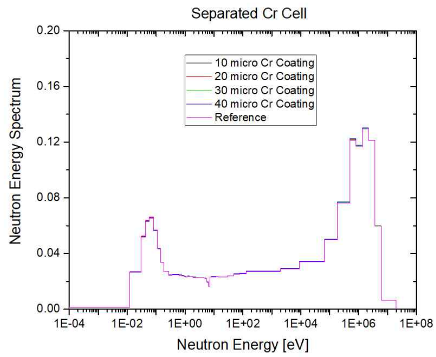

Fig. 4. Neutron Energy Spectrum 2 [C3 Assembly]

3.2 nTRACER

nTRACER is a 3-D direct whole core transport calculation code, which can calculate the AMF and power distribution without generating group constants. nTRACER deals with explicitly heterogeneous reactor core geometries including fuel pellets and claddings on the base of fine energy groups with spatial homogenization for each region.

A planar MOC(Method of Characteristics) method and a 3-D CMFD(Coarse Mesh Finite Difference) method was adopted to nTRACER adopts to execute 3-D transport calculations. For this sensitivity study, the nTRACER ray condition was set as; 0.05 cm ray spacing, 16 azimuthal ray, and 4 polar ray angles.

The same assembly problems were solved with nTRACER code and the results of neutron energy spectrum from nTRACER code were omitted because the results of neutron energy spectrum were quite similar with the results of OpenMC code.

3.2.1 A0 Assembly

The changes in k_∞ according to Cr coating thickness are summarized in Table IV. In both cases, it was confirmed that the AMF value decreased by about 950 pcm when the Cr coating thickness was 20 μm. The power distribution was shown in Figs. 5 and 6. As shown in Fig. 6, the power distribution of 20 μm Cr coated assembly was similar with the base assembly having no Cr coating.

Table IV : Multiplication Factor [A0 Assembly]

Cr [μm]	Separated Cr Cell	
	k_∞	diff.
Ref.	1.23362	N/A
10	1.22850	-0.00512
20	1.22411	-0.00951
30	1.21938	-0.01424
40	1.21467	-0.01895

Fig. 5. Power Distribution with 20 μm coated A0 Assembly

Fig. 6. Power Distribution Error between 20 μm coated and base Assembly [A0 Assembly]

3.2.2 B2 Assembly

The changes in k_∞ according to Cr coating thickness are summarized in Table V. In both cases, it was confirmed that the reactivity value decreased by about 650 pcm when the Cr coating thickness was 20 μm. The power distribution was shown in Figs. 7 and 8. As shown in Fig. 8, the power distribution of 20 μm coated assembly was similar with base assembly which was not coated with Cr.

Table V : Multiplication Factor [B2 Assembly]

Cr [μm]	Separated Cr Cell	
	k_∞	diff.
Ref.	1.21463	N/A
10	1.21138	-0.00325
20	1.20814	-0.00649
30	1.20490	-0.00973
40	1.20167	-0.01296

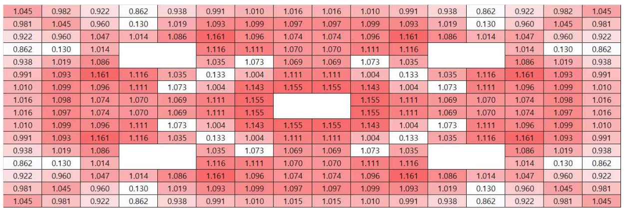

Fig. 7. Power Distribution with 20 μm coated B2 Assembly

Fig. 8. Power Distribution Error between 20 μm coated and base Assembly [B2 Assembly]

3.2.3 C3 Assembly

The changes in k_∞ according to Cr coating thickness are summarized in Table VI. In both cases, it was confirmed that the reactivity value decreased by about 580 pcm when the Cr coating thickness was 20 μm. The power distribution is shown in Figs. 9 and 10. As shown in Fig. 10, the power distribution of 20 μm coated assembly was similar with base assembly which was not coated with Cr.

Table VI : Multiplication Factor [C3 Assembly]

Cr [μm]	Separated Cr Cell	
	k_∞	diff.
Ref.	1.21139	N/A
10	1.20848	-0.00291
20	1.20558	-0.00581
30	1.20267	-0.00872
40	1.19977	-0.01162

1.113	1.045	0.983	0.920	0.992	1.039	1.053	1.056	1.056	1.053	1.039	0.992	0.920	0.983	1.044	1.113
1.045	1.087	1.002	0.130	1.052	1.115	1.111	1.106	1.106	1.111	1.115	1.052	0.130	1.002	1.087	1.044
0.983	1.002	1.093	1.086	1.151	1.174	1.084	1.059	1.059	1.084	1.175	1.151	1.086	1.093	1.002	0.983
0.920	0.130	1.086			1.144	1.014	1.003	1.003	1.015	1.146			1.086	0.130	0.920
0.992	1.052	1.151			1.082	0.130	0.938	0.939	0.130	1.087			1.151	1.052	0.992
1.039	1.115	1.175	1.144	1.082	1.093	1.005	1.069	1.070	1.011	0.984	1.087	1.146	1.175	1.115	1.039
1.053	1.111	1.084	1.015	0.130	1.005	1.161	1.192	1.192	1.164	1.011	0.130	1.015	1.084	1.111	1.052
1.056	1.106	1.059	1.003	0.938	1.069	1.191			1.192	1.070	0.939	1.003	1.059	1.106	1.056
1.056	1.106	1.059	1.003	0.938	1.069	1.191			1.192	1.069	0.938	1.003	1.059	1.106	1.056
1.053	1.111	1.084	1.015	0.130	1.005	1.160	1.191	1.191	1.160	1.005	0.130	1.014	1.084	1.111	1.053
1.039	1.115	1.175	1.144	1.082	1.093	1.005	1.069	1.069	1.005	1.093	1.082	1.144	1.174	1.115	1.039
0.992	1.052	1.151			1.082	0.130	0.938	0.938	0.130	1.082			1.151	1.052	0.992
0.921	0.130	1.087			1.144	1.015	1.003	1.003	1.014	1.144			1.086	0.130	0.920
0.983	1.003	1.093	1.087	1.151	1.175	1.084	1.059	1.059	1.084	1.175	1.151	1.086	1.093	1.002	0.983
1.045	1.087	1.003	0.130	1.052	1.115	1.111	1.106	1.106	1.111	1.115	1.052	0.130	1.002	1.087	1.045
1.113	1.045	0.983	0.921	0.992	1.039	1.053	1.056	1.056	1.053	1.039	0.992	0.920	0.983	1.045	1.113

Fig. 9. Power Distribution with 20 μm coated C3 Assembly

0.037%	0.048%	0.027%	0.016%	0.029%	0.058%	0.072%	0.078%	0.079%	0.072%	0.057%	0.029%	0.016%	0.028%	0.048%	0.037%
0.048%	0.041%	0.002%	-0.719%	-0.008%	0.045%	0.066%	0.075%	0.075%	0.066%	0.045%	-0.008%	-0.720%	0.002%	0.041%	0.048%
0.028%	0.001%	-0.037%	-0.094%	-0.073%	0.004%	0.044%	0.058%	0.059%	0.044%	0.005%	-0.072%	-0.093%	-0.036%	0.002%	0.028%
0.015%	-0.727%	-0.093%			-0.074%	-0.010%	0.024%	0.024%	-0.010%	-0.073%			-0.093%	-0.720%	0.016%
0.029%	-0.008%	-0.071%			-0.097%	-0.731%	0.002%	0.002%	-0.723%	-0.094%			-0.071%	-0.008%	0.029%
0.057%	0.045%	0.005%	-0.075%	-0.098%	-0.045%	-0.022%	-0.012%	-0.013%	-0.020%	-0.029%	-0.094%	-0.074%	0.005%	0.045%	0.057%
0.072%	0.067%	0.043%	-0.012%	-0.723%	-0.023%	-0.009%	-0.061%	-0.060%	-0.008%	-0.019%	-0.723%	-0.011%	0.044%	0.067%	0.072%
0.079%	0.075%	0.058%	0.024%	0.002%	-0.013%	-0.060%			-0.060%	-0.012%	0.002%	0.025%	0.058%	0.075%	0.079%
0.079%	0.075%	0.058%	0.024%	0.001%	-0.013%	-0.060%			-0.060%	-0.013%	0.001%	0.025%	0.059%	0.075%	0.079%
0.072%	0.067%	0.043%	-0.012%	-0.723%	-0.022%	-0.009%	-0.060%	-0.060%	-0.009%	-0.022%	-0.731%	-0.012%	0.044%	0.066%	0.072%
0.058%	0.045%	0.004%	-0.074%	-0.098%	-0.045%	-0.022%	-0.012%	-0.012%	-0.021%	-0.044%	-0.097%	-0.074%	0.005%	0.046%	0.057%
0.028%	-0.008%	-0.072%			-0.097%	-0.723%	0.003%	0.003%	-0.723%	-0.096%			-0.072%	-0.008%	0.029%
0.016%	-0.719%	-0.093%			-0.073%	-0.010%	0.025%	0.025%	-0.011%	-0.073%			-0.093%	-0.719%	0.016%
0.028%	0.001%	-0.036%	-0.094%	-0.072%	0.004%	0.044%	0.058%	0.059%	0.044%	0.004%	-0.073%	-0.093%	-0.036%	0.001%	0.028%
0.048%	0.041%	0.002%	-0.727%	-0.008%	0.045%	0.067%	0.075%	0.075%	0.067%	0.045%	-0.008%	-0.719%	0.002%	0.041%	0.048%
0.037%	0.048%	0.028%	0.015%	0.028%	0.057%	0.072%	0.079%	0.079%	0.073%	0.057%	0.029%	0.016%	0.028%	0.049%	0.037%

Fig. 10. Power Distribution Error between 20 μm coated and base Assembly [C3 Assembly]

4. Conclusion

It was confirmed that the current methodology utilized for the analysis of PWR cores loaded with zirconium-based alloy cladding fuels are still valid for the analysis of the Cr-coated ATF loaded cores since the effects on the key neutronics parameters due to the thin chromium coatings are minimal. Also, it was confirmed that the Cr coating and its thickness had an insignificant effect on the neutron energy spectrum. Any thin Cr coating on the existing cladding, however, results in reducing the assembly multiplication factor. From the point view of reactor fuel management, this reduction in the assembly multiplication factor can affect the cycle length and subsequently requiring additional study on the reactor core cycle analysis.

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