Accident Tolerant Fuel Neutronics Analysis for Commercial PWR using Metallic Micro-cell UO_2–Mo (or Cr) Pellets with Cr-based Cladding Coating

Eun Jeong[a], Yunki Jo[a], Sooyoung Choi[a], Hyunsuk Lee[a], Ho Cheol Shin[b], Kwangho Lee[b], Deokjung Lee[a*]
[a]Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan 44919, Republic of Korea
[b]Core and Fuel Analysis Group, Korea Hydro and Nuclear Power Central Research Institute (KHNP-CRI), Daejeon, Korea
[*]Corresponding author: deokjung@unist.ac.kr

1. Introduction

This paper presents accident tolerant fuel (ATF) neutronics analysis for commercial PWR using metallic micro-cell UO_2–Mo (or Cr) Pellets with Cr-based cladding coating. In South Korea, the Korea Atomic Energy Research Institute (KAERI) has suggested and developed microcell UO_2 pellets with some additive materials such as Cr, Mo, and SiO_2-TiO_2 with coated claddings for an OPR-1000 reactor, which is the Korean standard reactor [1][2]. The DeCART2D/MASTER two-step code system has analyzed reactor core using Mo micro-cell type fuel. From that previous study, it is noted that the core using Mo micro-cell type has a shorter cycle length as amount of 105 EPFDs than the conventional UO_2 core [3]. Since the cycle length reduction amount cannot be ignored when using the fuel mixed with Mo material, the analysis of the neutronics effect was performed at previous research paper [4] . In this paper, as stated in the previous study, to analyze the effect of Mo material on the cycle length in more detail, ATF equilibrium core analysis is performed using a STREAM/RAST-K 2.0 two-step code system.

2. Methods and Results

2.1 Description of STREAM/RAST-K 2.0 ATF Core Design

In this section, STREAM/RAST-K 2.0 metallic micro-cell ATF equilibrium core design detail information is described. Table I shows candidate design of the ATF assemblies to compare the existing UO_2 core. Table II summarizes the five R types ATF assemblies information used for the STREAM/RAST-K 2.0 ATF equilibrium core design. For the ATF core analysis, core calculations are performed using ATF fuel rods instead of UO_2 fuel rods. The detail example design figure is shown at the Fig. 1. And axial design of reference UO_2 fuel and ATF fuel have same design shown as Fig. 2.

In the case of the OPR-1000 UO_2 reference equilibrium core is designed with a cycle length of 475EFPDs by increasing the fuel concentration to 4.60/4.10wt% based on the existing commercial OPR-1000 equilibrium core design.

Table I: ATF candidate fuel assembly list.

Core Type	Fuel Pellet	Coating Material
UO_2 (Reference)	UO_2	-
Mo Microcell (5 vol %)	UO_2-Mo (4.7wt%, 5vol%)	-
Cr Microcell (5 vol %)	UO_2-Cr (3.34wt%, 5vol%)	-
CrAl coting with Mo Microcell (5 vol %)	UO_2-Mo (4.7wt%, 5vol%)	CrAl 10micron

Table II: Fresh fuel description of the ATF equilibrium core.

Type	R0	R1	R2	R4	R6
U Enrichment (wt%)	4.60/ 4.10	4.60/ 4.10	4.60/ 4.10	4.60/ 4.10	4.60/ 4.10
U Enrichment in BP rod	-	2.0	2.0	2.0	2.0
Gd_2O_3 Content (wt%)	-	6.0	6.0	8.0	8.0
No. of BP rod per Assembly	0	8	12	16	12

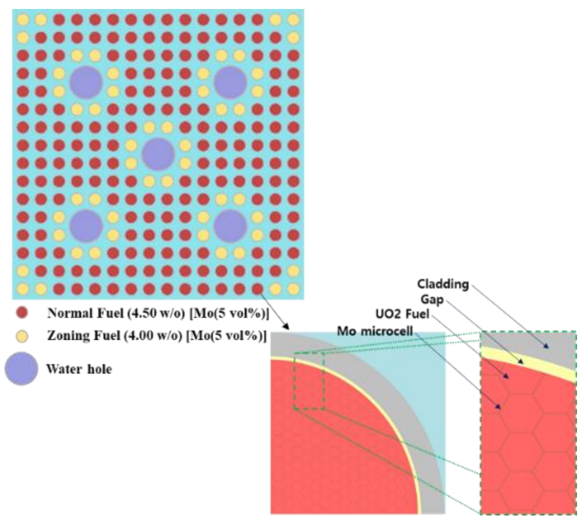

Fig. 1. Design of PLUS7 type fuel assembly with Mo micro-cell fuel pellet.

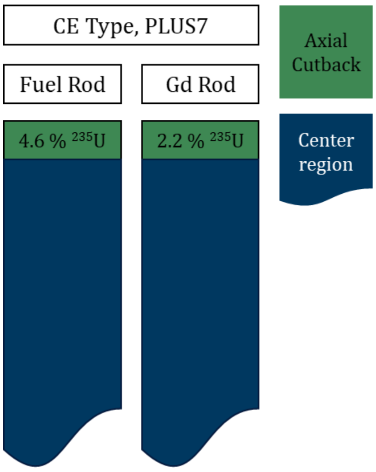

Fig. 2. Axial design of PLUS7 type fuel assembly.

2.2 STREAM/RAST-K 2.0 ATF Core Analysis with Thermal Conductivity Option

Table III: ATF thermal conductivity list.

Core Type	Thermal conductivity	etc.
UO_2 (Reference)	FRAPCON	Experiment Data [5]
Mo Microcell (5 vol %)	ATF (Mo Microcell 3vol%)	KAERI ATF Experiment Data [2]
Cr Microcell (5 vol %)	ATF (Cr Microcell 5vol%)	KAERI ATF Experiment Data [2]
CrAl coating with Mo Microcell (5 vol %)	ATF (Mo Microcell 3vol%)	KAERI ATF Experiment Data [2]

Table III summarizes the thermal conductivity functions used in each core calculation. For the reference core, the thermal conductivity function of the FRAPCON code is used, and for the core of the ATF, the thermal conductivity functions are constructed based on the data from KAERI. For the core calculation, assembly-wise thermal conductivity values are selected depending on the fuel type and burnup. The detail values of burnup-wise thermal conductivities are shown for 0Gwd/t burnup in Fig. 3 and 60Gwd/t burnup in Fig. 4, respectively. In the case of the core calculation graph legend, it is indicated as [candidate core type-thermal conductivity function type]. Table V shows the results of comparing the core cycle lengths without applying FA type and burnup-wise thermal conductivity calculations. Table V shows the result of applying FA type, burnup-wise thermal conductivity calculation.

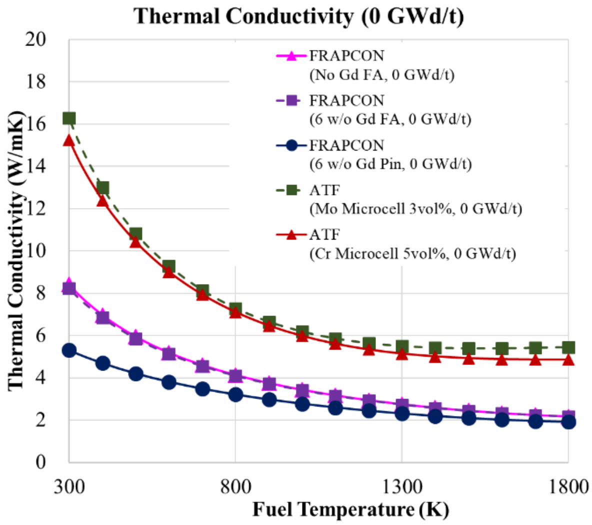

Fig. 3. Thermal conductivity function (0 GWd/t).

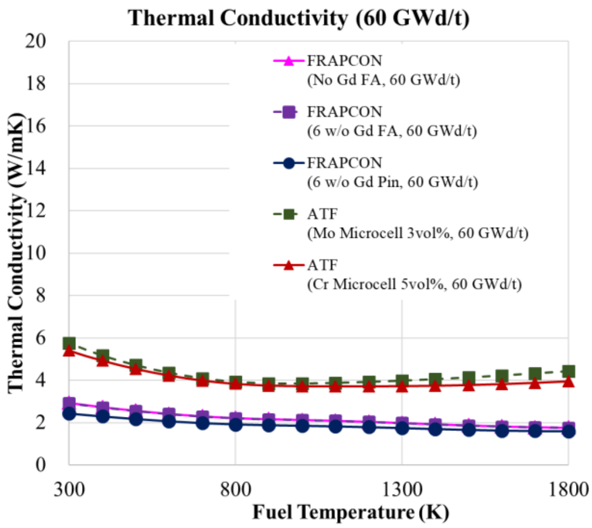

Fig. 4. Thermal conductivity function (60 GWd/t).

Table IV: Equilibrium core cycle length w/o thermal conductivity function.

Equilibrium Core	EFPD	Difference (day)
UO_2 (Reference)	419	-
Mo Microcell (5 vol %)	385	-34
Cr Microcell (5 vol %)	391	-29
CrAl coating with Mo Microcell (5 vol %)	383	-37

Table V: Equilibrium core cycle length with FA type and burnup-wise thermal conductivity.

Equilibrium Core	EFPD	Difference (day)
UO_2 (Reference)	475	-
Mo Microcell (5 vol %)	421	-61
Cr Microcell (5 vol %)	435	-44
CrAl coating with Mo Microcell (5 vol %)	418	-65

2.3 STREAM/RAST-K 2.0 ATF Core Analysis Results

Fig. 5 shows the results of comparing the critical boron concentration change. Table V compares the cycle length change for these core results. The cycle length is reduced by 61 EFPDs in the Mo Microcell core and 44 EFPDs in the Cr Microcell, These cycle length reductions come from decreasing of fission reactions because Mo and Cr microcell fuel assemblies are reduced of UO_2 amount by the 5 vol% Mo and Cr added to the existing UO_2 fuel, and the large neutron absorption of Mo and Cr. The characteristic of the equilibrium core calculation is that the thermal conductivity values are applied differently according to the burnup degree of each assembly as fresh fuel, once burned fuel, and twice burned fuel, so that the effect of reduction on cycle length is relatively low in the high burnup assembly. In aspect of these analyses, it is judged that the cycle length values are properly evaluated.

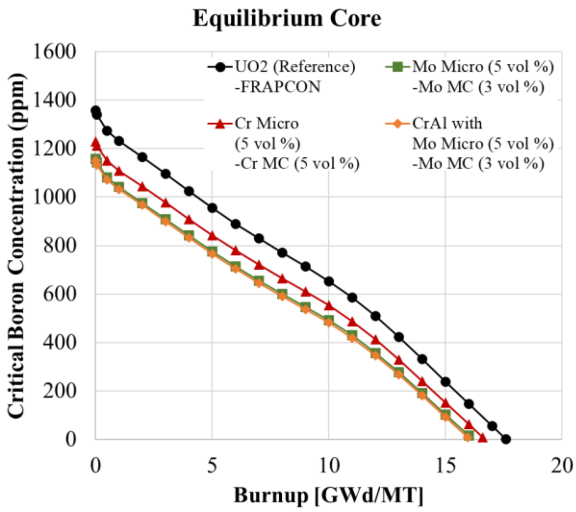

Fig. 5. Equilibrium core critical boron concentration results.

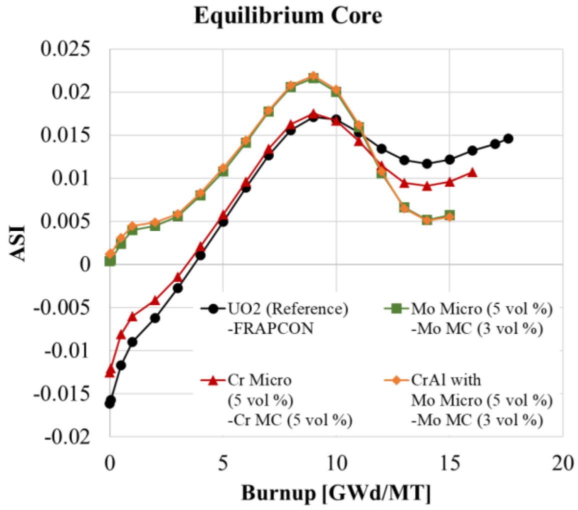

Fig. 6. Equilibrium core ASI results.

Fig. 6 shows the result of comparing the Axial Shape Index (ASI) with the reference core. At the beginning of the cycle, the ATF fuel core tends to lean upwards after 10 Gwd/MT, with the ASI biased more downward than the reference core. Fig. 7 shows the maximum Fxy change comparison in the equilibrium core using ATF and the reference core. Cores using ATF fuel tend to have lower values than the reference cores over the entire burnup cycle. In addition, in the case of the equilibrium core Fq change comparison shown in Fig. 8, the core using ATF fuel tended to have a lower value than the reference core. The overall core design parameters will be further researched based on the detailed analysis and calculation of the equilibrium core.

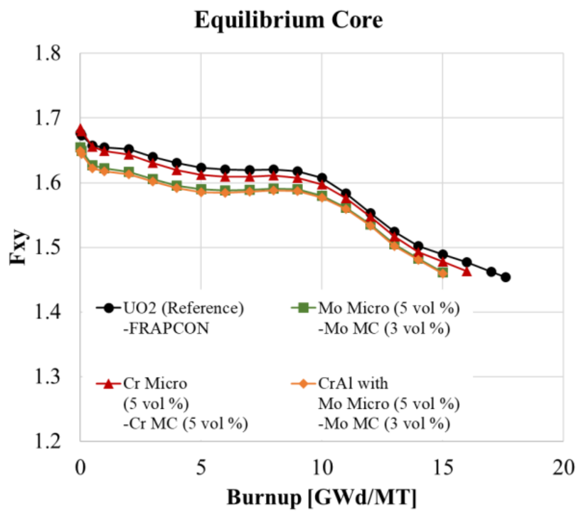

Fig. 7. Equilibrium core Fxy results.

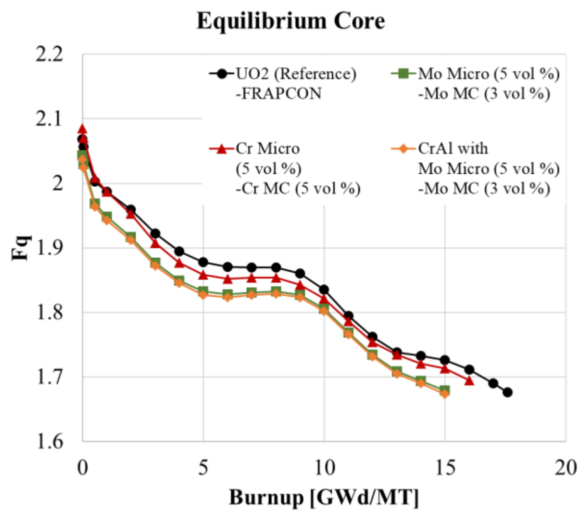

Fig. 8. Equilibrium core Fq results.

Fig. 9 is a graph comparing the maximum fuel centerline temperature between an ATF equilibrium core and the reference core. The fuel centerline temperature values, which are considered the most important in ATF fuel research, tend to be about 400 K lower than existing reference cores. The thermal conductivity of ATF fuel used as fresh fuel, once burned fuel, and twice burned fuel was designed to be lower than that of conventional fuels.

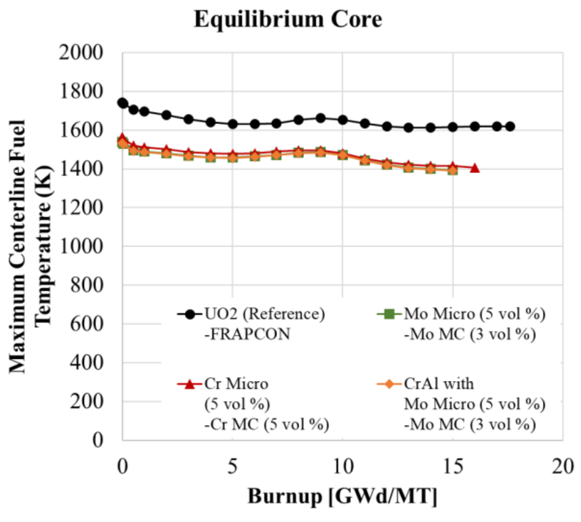

Fig. 9. Equilibrium core maximum centerline fuel temperature results.

3. Conclusions

In this paper, it was focused on the accident tolerant fuel (ATF) neutronics analysis for commercial PWR using metallic micro-cell UO_2–Mo (or Cr) Pellets with Cr-based cladding coating. In this study, ATF cores were compared with the existing UO_2 Core using STREAM / RAST-K 2.0 two-step code with FA type and burnup-wise thermal conductivity and It was confirmed that ATF core fuel performance aspect safety with fuel centerline temperature values.

As future work, based on the results of this preliminary ATF core study, it will be conducted that an optimized core design study that actually meets the commercial core design parameter limit.

REFERENCES

[1] H.G. Kim, I.H. Kim, Y.I. Jung, D.J. Park, J.Y. Park and Y.H. Koo, “Adhesion property and high-temperature oxidation behavior of Cr-coated Zircaloy-4 cladding tube prepared by 3D laser coating,” *Journal of Nuclear Materials*, 465, 2015.

[2] D.J. Kim, Y.W. Rhee, J.H. Kim, K.S. Kim, J.S. Oh, J.H. Yang, Y.H. Koo and K.W. Song, “Fabrication of micro-cell UO_2-Mo pellet with enhanced thermal conductivity,” *Journal of Nuclear Materials*, 462, 2015.

[3] D.H. Hwang, S.G. Hong and W.K. In, “Physical characteristics of a PWR core loaded with micro-cell UO_2 pellet fuels,” *Annals of Nuclear Energy*, 128, 2019.

[4] E. Jeong, Y. Jo, S. Choi, H. Lee, H.C. Shin, K. Lee and D. Lee, “Neutronics Effect to Reactor Core Analysis of Molybdenum Micro-cell Type Accident Tolerance Fuel,” *KNS 2019 spring meeting.*

[5] U.S.NRC Report, “FRAPCON-3.5: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup,” NUREG/CR-7022 Vol. 1, Rev. 1.