A Comparative Physics Study of Commercial PWR Cores using Metallic Micro-cell UO_2–Cr (or Mo) Pellets with Cr-based Cladding Coating

Dae Hee Hwang [a], Ser Gi Hong [a*], and Wang Kee In [b]
[a]*Department of Nuclear Engineering, Kyung Hee University*
1732 Deogyeong-daero, Giheung-gu, Yongin-si, Hyeonggi-do, 446-701,Korea
[b]*Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-Gu, Daejeon 34057*
[*]*Corresponding author: sergihong@khu.ac.kr*

1. Introduction

Commercial PWR power plants have been proven to be a reliable and cost-effective source of stable large scale electricity. However, there are still lots of research and development issues to improve safety under normal and transient conditions. In particular, after the events at Fukushima Dai-ichi nuclear power plant in 2011, ATFs (Accident Tolerant Fuel) have been actively developed to provide improved performance in DBA (Design Basis Accident) or BDBA (Beyond Design Basis Accident) by mitigating the detrimental process with reduction of high temperature oxidation rate and delay of the ballooning and burst of cladding under transients. The ATF concepts studied in this work are the metallic micro-cell UO_2 pellets containing Cr or Mo with cladding outer coating composed of Cr-based alloy which have been suggested as the ATF concepts in KAERI (Korea Atomic Energy Research Institute) [1, 2]. The metallic micro-cell pellets and Cr-based alloy coating can enhance thermal conductivity of fuel and reduce the production of hydrogen from the reaction of cladding with coolant, respectively. The objective of this work is to compare neutronic characteristics of commercial PWR equilibrium cores utilizing the different variations of metallic micro-cell UO_2 pellets with cladding coating composed of Cr-based alloy.

2. Methods and Results

2.1 Computational Methods

DeCART2D (Deterministic Core Analysis based on Ray Tracing for 2-Dimensional Core) code was used for fuel assembly calculations. The DeCART2D code has been developed in KAERI to generate few group homogenized neutron cross section data for nodal diffusion core analysis code [3]. Then, the table sets which include functionalized group constants are produced by using the PROLOG program and HGC file prepared with DeCART2D. The calculations for core analysis are performed by using MASTER (Multi-purpose Analyzer for Static and Transient Effects of Reactors) code which has been developed in KAERI. The MASTER code is a nuclear analysis and design code which can simulate the PWR or BWR cores in 1-, 2-, or 3-dimensional Cartesian or Hexagonal geometry with the advanced nodal diffusion methods [4].

2.2 Assembly and Core Design

In this study, we compared four different cases which have same uranium enrichments as shown in Table I. CASE 1 is the reference case which uses conventional UO_2 pellet with enrichments of 4.60/4.10 (normal/zoning) wt% and no Cr-based alloy coating. As in our previous study [6, 7], the uranium enrichments of 4.60/4.10 wt% were determined to satisfy the cycle length of 480 EFPDs [6]. CASE 2 has the same design data as reference case except for 0.005cm thick coating on cladding in order to evaluate the effect of the cladding coating composed of Cr-based alloy. The Cr-based alloy coating on claddings was considered to reduce the oxidation and corrosion rate, and to improve ballooning and rupture resistance in comparison with the zircaloy-4 cladding under high temperature accident conditions. CASE 3 and 4 use metallic micro-cell UO_2 pellets including small amount of Cr or Mo and the weight percentage of each material in pellets was determined to have same amount of initial heavy metal. These both cases have Cr-based alloy coating on cladding. The illustration of fuel rods for reference case and the other cases is depicted in Fig. 1

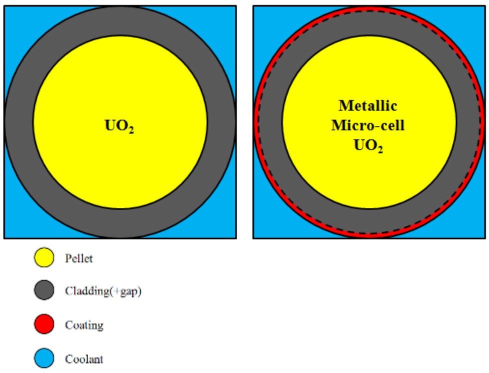

Fig. 1. Illustration of fuel pellet and cladding for reference fuel case and ATF cases

Table I. Comparison of data for each case such as design parameters, average discharge burnup, and cycle length

	CASE 1	CASE 2	CASE 3	CASE 4
U enrichment (wt%)	4.60/4.10	4.60/4.10	4.60/4.10	4.60/4.10
Fuel pellet	UO_2	UO_2	UO_2-Cr	UO_2-Mo
Pellet density (g/cc)	10.430 (96 %TD)	10.430 (96 %TD)	10.249 (96 %TD)	10.392 (96 %TD)
Pellet radius (cm)	0.4095	0.4095	0.4095	0.4095
Initial HM (g)	1143.0	1143.0	1085.7	1085.4
Cladding material	Zircaloy-4	Zircaloy-4	Zircaloy-4	Zircaloy-4
Cladding thickness+gap (cm)	0.0655	0.0605	0.0605	0.0605
Coating material	-	Cr-based alloy	Cr-based alloy	Cr-based alloy
Coating thickness (cm)	-	0.005	0.005	0.005
Rod radius (cm)	0.4750	0.4750	0.4750	0.4750
Pin pitch (cm)	1.2882	1.2882	1.2882	1.2882
Assembly pitch (cm)	20.879	20.879	20.879	20.879
Avg. discharge BU (MWD/kg)	48.9	47.7	45.0	40.1
Cycle length (EFPD)	482.5	471.1	422.5	376.8

All of fuel assemblies employed an enrichment zoning to reduce the pin power peaking, which places low uranium enrichment fuel rods around the water holes [6, 7]. Burnable absorber (BA) rods were used to reduce initial excess reactivity [6, 7]. The BA rods included the cutbacks on the top and bottom of the rods in order to flatten axial power distribution as shown in Fig. 2. As shown in Table I, the additions of the Cr and Mo into the fuel pellet decrease heavy metal inventories by ~5% but the use of the Cr coating does not lead to the reduction of initial heavy metal because the addition of Cr coating led to the reduction of cladding thickness without the reduction of pellet.

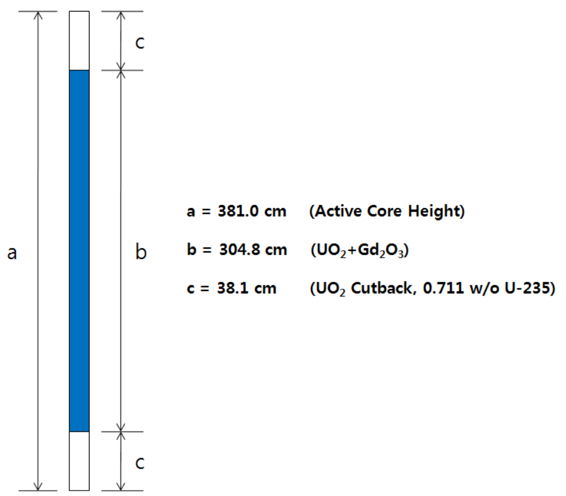

Fig. 2. Axial cutback configuration of burnable absorber rod

The ATF assemblies were loaded from the 8th cycle core of Hanbit-3 nuclear power plant because its detailed design data from 1st to 7th cycles was available for us. The loading pattern of 7th cycle was simplified to find equilibrium cycle as soon as possible. The low-leakage loading pattern coupled with the concept of three batch refueling scheme was considered [5] and there were no fresh fuel assemblies in the center of the core in order to mitigate power peaking [6, 7]. Figure 3 shows the core loading pattern of 12th cycle for all cases. Cycle 12 was chosen as the equilibrium design since the core burnup characteristics converge beyond this cycle.

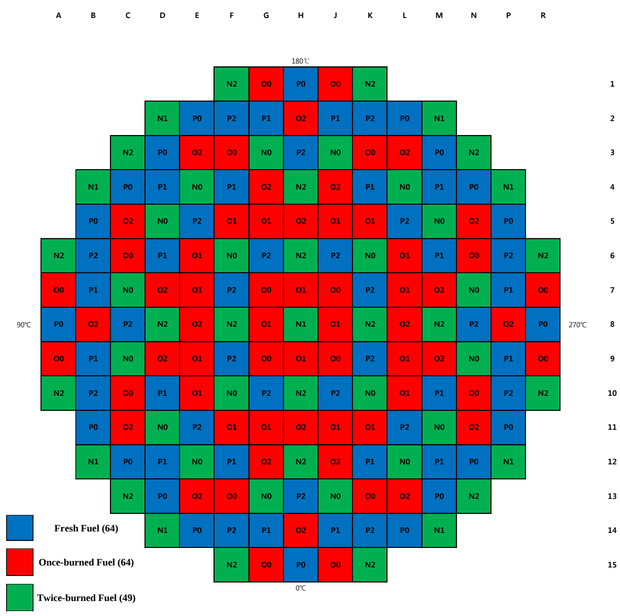

Fig. 3. Low-leakage loading pattern coupled with the concept of three batch refueling scheme of 12th cycle for all cases

2.3 Results and Analysis

Figure 4 shows the comparison of critical boron concentrations (CBC) of 12th cycles for all the cases. The cycle length of the reference case is 482 EFPDs. In CASE 2 using conventional UO_2 pellet and Cr-based alloy coating, the cycle length is decreased by 11.4 EFPDs in comparison with the reference case because of the higher capture cross section of Cr-52 than that of Zr-90. Figure 5 compares the capture cross sections of Zr-90, Cr-52, and Mo-98 versus neutron energy. They are most abundant isotopes in their natural materials. As shown in Fig. 5, Cr-52 has much higher capture cross section than Zr-90. The cycle lengths of CASE 3 and 4 are further reduced by 60 and 106 EFPDs, respectively because of their lower amount of initial heavy metal as shown in Table I. These shorter cycle lengths are also due to high capture cross sections of the Mo and Cr isotopes. In particular, it is noted that Mo-98 has high thermal capture resonances. The average discharge burnups compared in Table I show that the use of the considered ATFs leads to the reduction of the discharge burnup due to the shortening of cycle length.

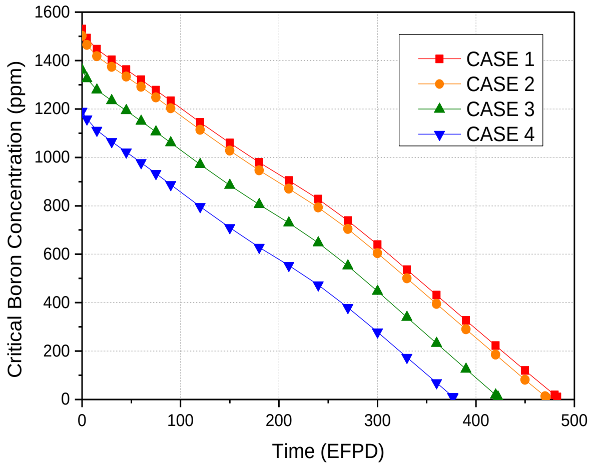

Fig. 4. Comparison of critical boron concentrations of 12th cycles for all cases

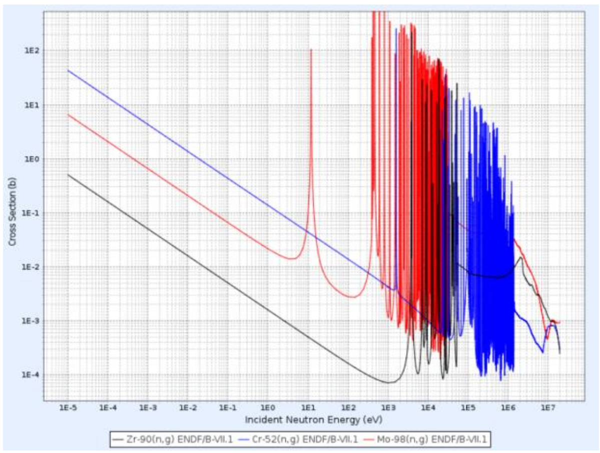

Fig. 5. Comparison of capture cross section of Zr-90 (black line), Cr-52 (blue line), and Mo-98 (red line) which are most dominant isotopes for each material [8]

Figure 6 shows the 3-dimensional peaking factors of 12th cycles for all the cases. The peaking factors for all cases are within typical limit of 2.5. The axial offsets of 12th cycles for all cases are depicted in Fig. 7. The axial offset for all cases are within -4.1 to 7.2 %. It is notable that the axial power distribution of CASE 4 using the micro-cell UO_2-Mo pellet and Cr-based alloy coating moves towards the core bottom at beginning of the cycle (BOC), which is resulted from the strong negative MTC of this core. We estimated the axial burnup distributions of the cores at EOC of 11th cycle but there were no significant differences as shown in Fig. 9. Therefore, it is considered that the small axial offset of CASE 4 at BOC can be understood with the significantly more negative MTC of this core (See Fig. 10).

Figure 8 shows the cycle burnups of 12th cycles for all cases. CASE 3 and 4 have large cycle burnups at the same time step because their small amounts of initial heavy metal but their burnups at EOC are lower than those of the reference case due to their shorter cycle lengths.

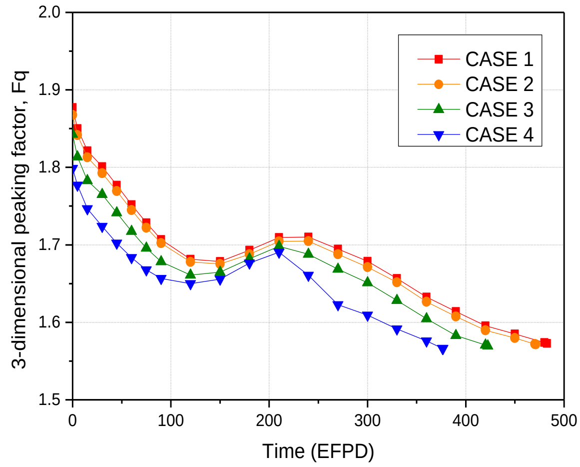

Fig. 6. Comparison of 3-dimensional peaking factors of 12th cycles for all cases

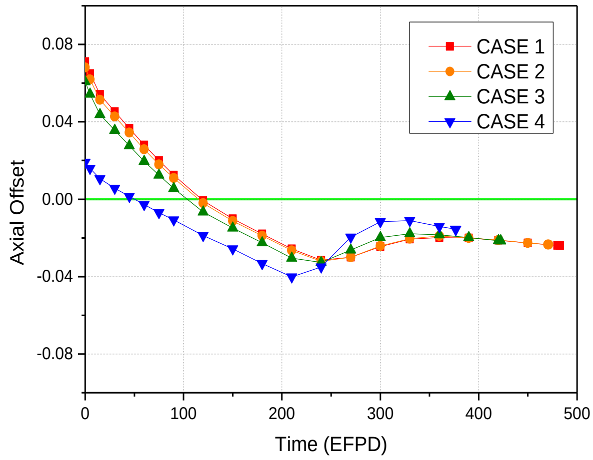

Fig. 7. Comparison of axial offsets of 12th cycles for all cases

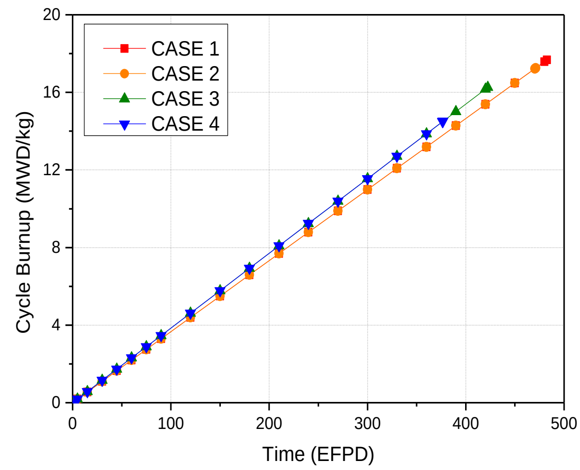

Fig. 8. Comparison of cycle burnups of 12th cycle for all cases

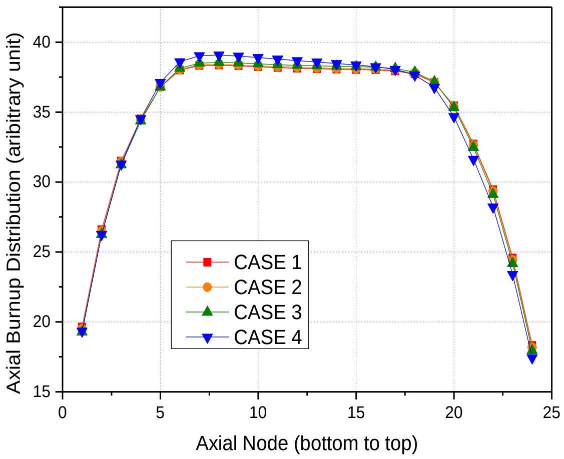

Fig. 9. Normalized axial burnup distributions for all of cases

Figure 10 and 11 show the moderator temperature coefficients (MTC) for core and assembly calculations respectively. These figures show that CASE 4 using UO_2-Mo pellets and Cr-based alloy coating has the most negative MTC because of strong resonance absorption cross section of Mo as shown in Fig. 5 and the resulted hardest neutron spectrum compared in Fig. 12. In particular, in case of core calculation, the significant more negative MTC of CASE 4 is also contributed from its lowest CBC. Figure 12 compares the neutron spectra of the fuel assemblies which have different fuels. These fuel assembly-level analyses are useful to understand the differences on the reactivity coefficients with the same condition (i.e., same temperature and boron concentration). Figure 10 shows that CASE 3 using UO_2-Cr pellets and Cr-based alloy coating has more negative MTC than those of CASE 1 and 2 in core calculation, which is resulted from its lower CBC than those of CASE 1 and 2. On the other hand, CASE 3 has less negative MTC than those of CASE 1 and 2 in assembly calculation as shown in Fig. 11. This fact may be resulted from the fact that Cr isotopes have smaller resonance cross sections than U-238. Figure 13 shows the fuel temperature coefficients (FTC) of the fuel assemblies which have different fuels. We did not give the core level FTCs because we could not estimate accurate fuel temperature in core calculation performed by using MASTER code. At present, we did not consider the differences in thermal conductivities of the different fuels because our main concern is on the core neutronics but we have plans to consider the effect of thermal conductivity by using COBRA-CP module in MASTER. As shown in Fig. 13, the micro-cell UO_2-Mo and UO_2-Cr pellets have slightly more negative FTCs. It should be noted that these differences in FTC are partially due to the burnup and so these differences will be reduced if the FTCs are compared at the same burnup.

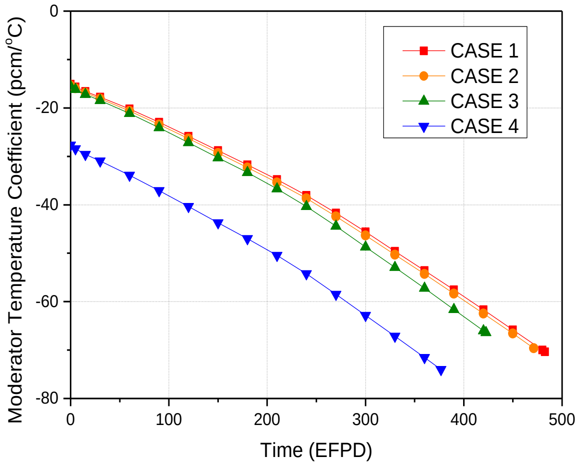

Fig. 10. Comparison of moderator temperature coefficients of 12th cycles for all cases (Core calculation)

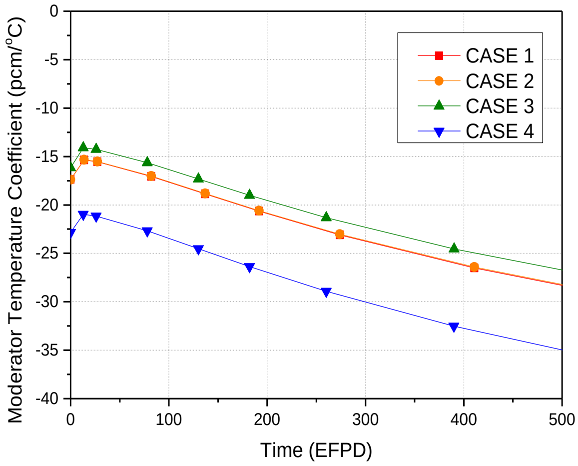

Fig. 11. Comparison of moderator temperature coefficients of the fuel assemblies having different fuels

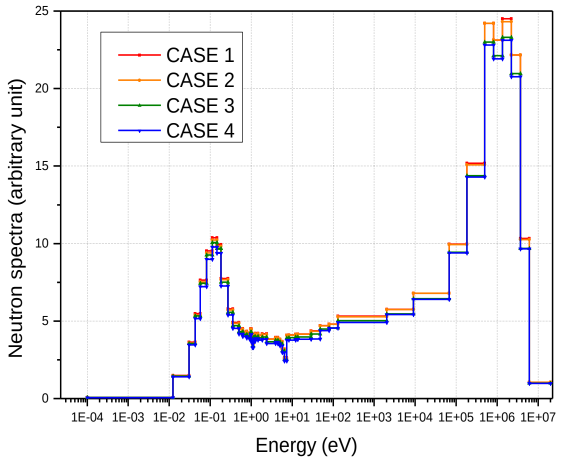

Fig. 12. Comparison of the neutron spectra of the fuel assemblies having different fuels

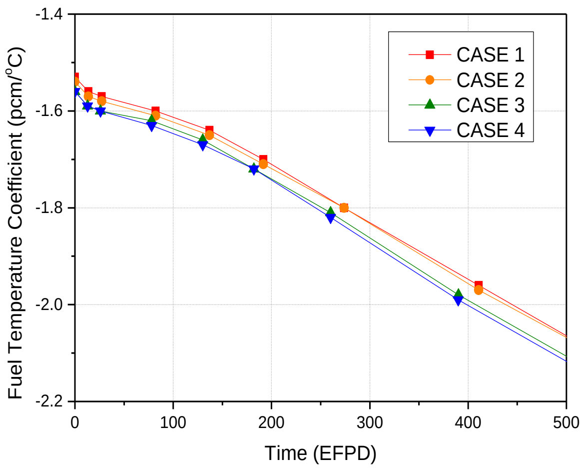

Fig. 13. Comparison of fuel temperature coefficients of the fuel assemblies having different fuels

3. Conclusions

In this work, a comparative neutronic analysis of the cores using ATFs which include metallic micro-cell UO_2-Cr, UO_2-Mo pellets and Cr-based alloy coating on cladding was performed to show the effects of the ATF fuels on the core performance. In this study, the cores having different ATFs use the same initial uranium enrichments. The results showed that the cores using UO_2-Cr and UO_2-Mo pellets with Cr-based alloy coating on cladding have reduced cycle lengths by 60 and 106 EFPDs, respectively, in comparison with the reference UO_2 fueled core due to the reduced heavy metal inventories and large thermal absorption cross section but they do not have any significant differences in the core performances parameters. However, it is notable that the core fueled the micro-cell UO_2-Mo pellet and Cr-based alloy coating has considerably more negative MTC and slightly more negative FTC than the other cases. These characteristics of the core using micro-cell UO_2-Mo pellet and Cr-based alloy coating is due to the hard neutron spectrum and large capture resonance cross section of Mo isotopes. However, our present study did not consider the fuel temperature differences resulted from thermal conductivity and so this topic will be studied in the future work.

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