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Effects of Solid Reflectors for Water-Cooled Small Modular Reactor Core Design using FCM Fuels

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1. Introduction

The FCM fuel coupled with FeCrAl cladding has been conceived as one of the potential candidates for the Accident Tolerant Fuel (ATF) due to the excellent fission gas retention capability of TRISO fuel particle fuel and reduction of hydrogen gas production and low oxidation rate of FeCrAl cladding. In particular, the interests in the development of ATFs have been increased after the accident at Fukushima Dai-ichi. Recently, many countries including USA have launched projects to develop the accident tolerant fuels (ATF) [1,2] which can cope with the accidents such as LOCA (Loss of Coolant Accident). Recently, we have designed water-cooled small modular reactors using FCM fuels with uranium-nitride (UN) kernels and with Er_2O_3 burnable poison admixed with SiC matrix [3].

The objective of this work is to increase cycle length of the previous designed PWR small modular reactor [3] by employing two solid radial reflectors in order to improve the fuel economy by increasing fuel burnup and then to analyze the detailed performances of the new cores having solid reflectors. In particular, the core design including the generation of few group homogenized reflector cross section was performed with the DeCART2D [4] code and PROMARX [5].

2. Methods and Results

2.1 Review of Previous Fuel Assembly Designs

The previously designed SMR core rates the same power level of the SMART core (i.e., 330MWt) but 13x13 fuel assemblies having FCM TRISO particles whose UN kernel of 800μm diameter is surrounded by the four buffer layers. The thicknesses of the buffer layers and density of the UN kernel are determined through the discussion on the fabrication aspects with ORNL. Table I summaries the main parameters of the fuel and fuel assembly. The pitch of the fuel assembly is almost the same as that of the Westinghouse type 17x17 assembly. The active fuel length is 200 cm, the pellet diameter is 1.392 cm, and 400μm thick FeCrAl cladding was employed to reduce the hydrogen generation under the accidents associated with coolant losses.

Table I : Fuel and Assembly Design Parameters

Parameters	Value
Active fuel length (cm)	200
Fuel assembly pitch (cm)	21.50
Fuel pin pitch (cm)	1.651
Number of guide tubes	9
Guide tube inner radius (cm)	0.72235
Guide tube outer radius (cm)	0.76835
Kernel fuel material	UN
Kernel density (g/cm^3)	12.512
Fuel rod outer diameter (cm)	1.392
P/D ratio	1.1859
Fuel gap thickness (μm) for cladding	50
FeCrAl cladding thickness (μm)	400
Pellet diameter (cm)	1.302
Burnable absorber material	Er_2O_3
Matrix material	SiC
TRISO particle fuel dimensions	
Kernel diameter (μm)	800
Buffer layer thickness (μm)	80
Inner PyC layer thickness (μm)	20
SiC layer thickness (μm)	35
Outer PyC layer thickness (μm)	20

Fig.1 shows four different configurations of fuel assembly having different arrangements of BP rods. The configurations A, B, C, and D have 44, 48, 52, and 64 BP rods, respectively.

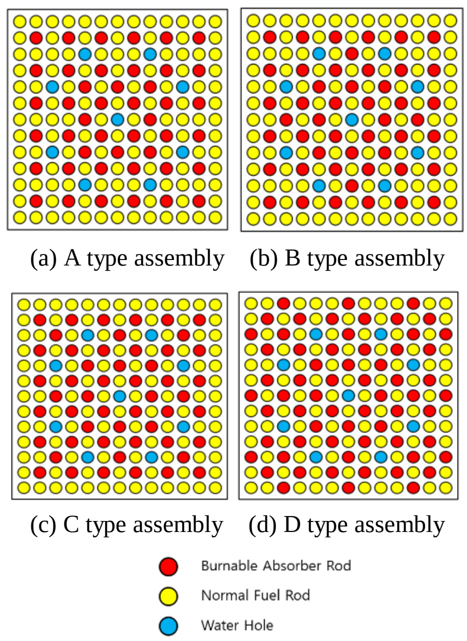


Fig. 1. Configuration of fuel assembly (FA)

Table II summarizes theses fuel assembly types. As shown in Table II, there are three different fuel assembly types of configuration A and they have same uranium enrichment of 17 % while they have different weight fractions of Er_2O_3 BP material in BP rods. The packing fraction of TRISO fuel particles is fixed to 40 %. In particular, the B1 type fuel assembly has the highest BP content of 24 wt% and lowest uranium enrichment of 14 % while the D1 type ones have the lowest BP content of 7 wt%, high uranium enrichment of 17 wt%, and the largest number of BP rods (i.e., 64 BP rods). Also, it is noted that the B1 and C1 type fuel assemblies have low uranium enrichment of 14 % and high BP contents of 24 and 22 wt%, respectively. The BP rods also include FCM fuels of 40% packing fraction of TRISO particles.

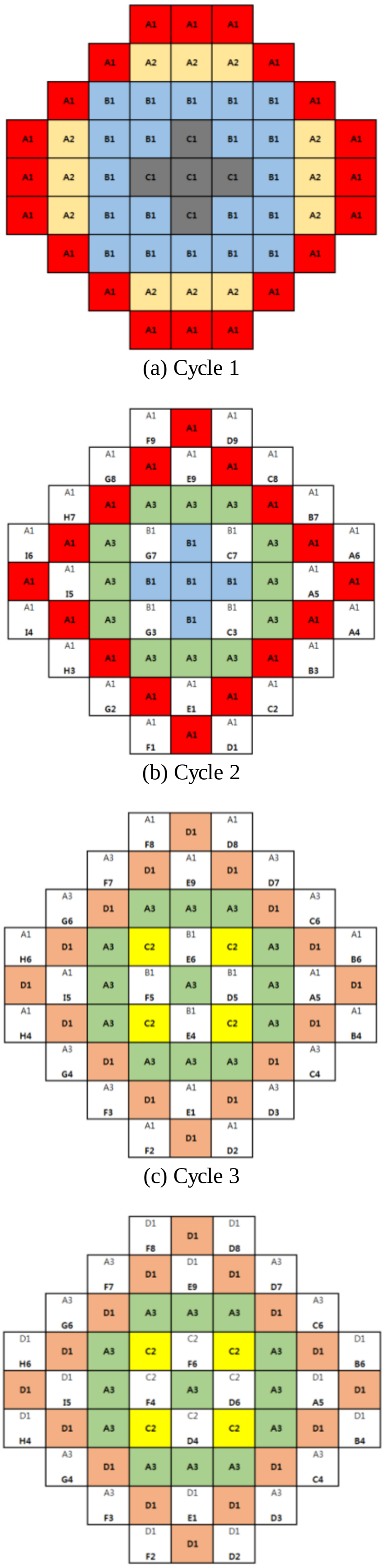
Table II : Design Parameters of Different FAs

FA Type	U Enrichment (wt%)	Number of BP rod per FA	TRISO Packing Fraction	Er_2O_3 Weight Fraction
A1	17	44	40	11
A2	17	44	40	22
A3	17	44	40	20
B1	14	48	40	24
C1	14	52	40	22
C2	17	52	40	21
D1	17	64	40	7

The depletion calculations for these fuel assemblies were performed with DeCART2D while the reflector homogenized two-group cross sections were calculated with DeCART2D whole core calculation and PROMARX program.

2.2 SMR Core Design

The core is comprised of 57 fuel assemblies. The loading patterns of the reload cores are shown in Fig. 2. We performed the cycle-by-cycle reload core analysis using the MASTER code [6]. We adopted a two-batch refueling scheme which discharges 33 fuel assemblies having high burnup at the end of cycle (EOC) for all the cycles. The fuel assemblies having white color represent the ones that are recycled from the previous cycle. We considered two additional solid reflectors (i.e., SS304 and graphited reflectors). The composition of SS304 solid reflector is 95% SS304 and 5% water while the one of the graphite-based reflector is 75% graphite, 20% SS304, and 5% water. The graphite-based reflector was considered to analyze the highly thermalized spectrum effects on the core performance by graphite near the reflector of the small reactor core.



(a) Cycle 1

(b) Cycle 2

(c) Cycle 3

(d) Cycle 4 and 5

Fig. 2. Loading patterns of the cycles 1, 2, 3, 4 and 5

The main performances of the reload cores from cycle 1 to cycle 5 are summarized in Tables III, IV, and V for the reference water, the SS304, and the graphite-based reflected cores. The comparison of Tables III and IV shows that the use of the SS304 reflector extends the cycle lengths by 45, 5, 18, 13, and 15 EFPDs for cycles 1, 2, 3, 4, and 5, respectively, in comparison with the reference water reflected core while the comparison of Tables III and V shows that the core having the graphite-based reflector extends the cycle lengths by 102, 1, 42, 27, and 32 EFPDs for the first five cycles in comparison with the reference core. In particular, it is noted that the first cycle lengths for the solid reflector cores are significantly extended by reducing radial neutron leakage while the second cycle length extensions are small due to the high burnup of the once burnt fuel assemblies. These extensions of the cycle lengths for the solid reflector cores led to the considerable increases of the maximum critical boron concentration and the discharge burnups. The peaking factors for the new cores having the solid reflectors are within the typical limit values.

Table III : Summary of the core performance parameters of the water reflector core

	CY-01	CY-02	CY-03	CY-04	CY-05
Cycle length (EFPDs)	681.21	740.78	706.82	732.53	724.65
Maximum CBC (ppm)	579.76	1644.81	1603.72	1735.07	1715.72
Maximum F_q	1.84	1.92	1.98	1.95	1.96
Maximum F_r	1.46	1.53	1.57	1.55	1.55
Cycle burnup (MWD/kgHM)	52.30	56.88	54.27	56.24	55.64
Average discharge burnup (MWD/kg)	59.07	82.33	93.64	95.91	96.50

Table IV : Summary of the core performance parameters of the SS304-based reflector core

	CY-01	CY-02	CY-03	CY-04	CY-05
Cycle length (EFPDs)	726.45	745.01	724.51	745.89	739.16
Maximum CBC (ppm)	703.74	1697.51	1668.10	1785.31	1769.33
Maximum F_q	1.88	1.89	1.95	1.91	1.92
Maximum F_r	1.45	1.51	1.54	1.52	1.53
Cycle burnup (MWD/kgHM)	55.77	57.20	55.63	57.27	56.75
Average discharge burnup (MWD/kg)	61.74	85.92	95.23	97.90	98.37

Table V: Summary of the core performance parameters of the graphite-based reflector core

	CY-01	CY-02	CY-03	CY-04	CY-05
Cycle length (EFPDs)	783.24	741.30	748.07	759.58	756.11
Maximum CBC (ppm)	853.61	1705.64	1731.58	1821.00	1814.35
Maximum F_q	1.92	1.86	1.92	1.88	1.88
Maximum F_r	1.49	1.50	1.52	1.50	1.50
Cycle burnup (MWD/kgHM)	60.14	56.92	57.44	58.32	58.05
Average discharge burnup (MWD/kg)	64.56	90.27	96.92	100.22	100.44

The MTCs (Moderator Temperature Coefficient) over the first and fifth cycles are compared in Figs. 3 and 4, respectively. In these figures, it is shown that the solid reflector cores have considerably less negative MTC values over the first and fifth cycles than the reference water reflector core.

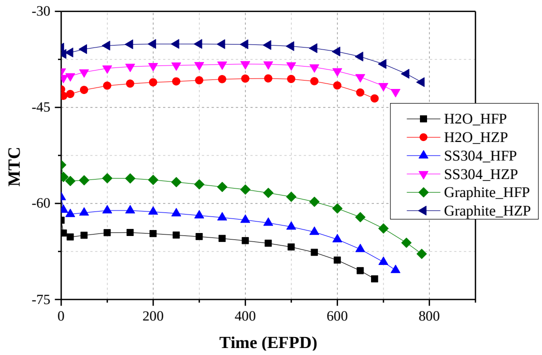


Fig. 3. Comparison of the MTC of cycle 1

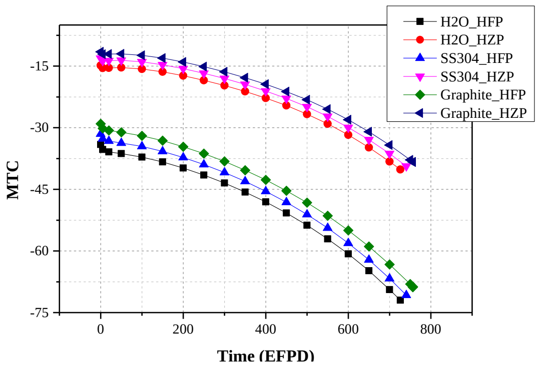


Fig. 4. Comparison of the MTC of cycle 5

3. Summary and Conclusions

In this work, the effects of the solid reflectors (SS304 and graphite-based reflectors) on performances of the small modular reactor core loaded FCM fuels having UN kernels are analyzed by designing and analyzing the reload cores. From the study, it was concluded that the SS304 and graphited reflectors are very effective to increase the cycle length and discharge burnup by reducing radial neutron leakage. In particular, the graphite-based reflector extended the first cycle and the fifth cycle (almost equilibrium cycle) by 102 and 32 EFPDs, respectively without the considerable degradation of the performance parameters.

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