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A Comparative Physics Study on Low Boron Concentration Small PWR Core Designs using Different Reflectors

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1. Introduction

Recently, the small modular reactors (SMR) have taken interests in nuclear industry and research by a desire to reduce the risk of the high capital costs on commercial PWRs and to provide power away from large grid systems. In particular, the SMRs have been designed to simplify the system components so as to improve passive safety by integrating the main system components into reactor vessel with the removal of valves and pipes. Korea also has supported a project for designing the light water cooled SMR which can be operated without soluble boron or low boron concentration.[1,2] As a part of this project, we have designed an advanced light water cooled SMR core with new Fully Ceramic Micro-encapsulated(FCM) burnable poison rods (BPR) which can be operated over 4 EFPYs with low boron concentration (<350 ppm).[3,4,5]

The objective of this work is to analyze the effects of different radial reflector materials on the performances of our SMR core having FCM BPRs because it is considered interesting to know how long we can extend the cycle length of the SMR core by optimizing the reflector design.[5] Also, to improve the accuracy of the reflector homogenized two-group cross sections, we performed two-dimensional whole core transport calculations with DeCART2D to obtain the detailed spectrum of the reflector and used it in producing the reflector homogenized two-group cross sections. In this work, we considered not only water reflector but also several different solid reflectors for this purpose.

2. Computer Codes and Design Procedure

We employed the typical two step procedure for LWR core design and analysis which is comprised of the fuel assembly depletion calculation using two-dimensional lattice transport code and the core depletion calculation using nodal diffusion codes. The fuel assembly depletion calculations were performed by using DeCART2D[6] (Deterministic Core Analysis based on Ray Tracing for 2-Dimensional Core) code which were developed in KAERI (Korea Atomic Energy Research Institute) to generate the homogenized group constants for core nodal diffusion calculations. In particular, in this work, a whole core modeling with DeCART2D was used to accurately produce the homogenized two group cross sections of the reflectors and the discontinuity factors of the reflector assemblies for core analysis using nodal diffusion calculation. In particular, DeCART2D provides an excellent capability for treating particle fuels and particle burnable poisons by using the Sanchez's method for resonance treatment for double heterogeneities.

The core depletion calculations including core physics parameter evaluations were performed by using the MASTER[7] (Multi-purpose Analyzer for Static and Transient Effects of Reactors) code which is a 3D core depletion code developed by KAERI.

3. Core Design and Performance Analysis

Table I summarizes main design parameters for new fuel assemblies including specifications of FCM BPRs. Fig. 1 shows the arrangements of fuel rods and the burnable poison rods for one fourth of the fuel assemblies. Actually we designed two new assemblies with FCM BPRs that are designated by B1 and C1 types in Table I. As shown in Fig. 1, the 17x17 fuel assembly has 32 FCM BPRs. In the FCM BPR, the BISO BP particles of which the central kernel is B_4C with natural boron are distributed in SiC matrix. For the B1 type fuel assembly, a single type BISO particle with 150μm kernel diameter and 8% packing fraction is used while the two different types of BISO BP particles are used in the C1 type fuel assembly. These two BP particles used in the C1 type fuel assemblies have the same packing fraction of 10% but they have different kernel diameters of 100μm and 400μm. The uranium enrichment for all the fuel rods is maximized up to 4.95wt% to extend the cycle length. In this work, the axial cutbacks are not used in the FCM BPRs. The evolutions of the infinite multiplication factors (k-inf) over time for these two fuel assemblies are compared with that of the reference fuel assembly having no FCM BPRs in Fig. 2.

Table I. Design Specifications of Fuel Assemblies, Fuel Rods, and Burnable Poison Rods

Composition of assembly	
Enrichment	4.95%
Fuel pellet radius	0.4096 cm
Fuel cladding outer radius	0.4759 cm
Fuel pins spacing	1.2658 cm
The number of FCM BPRs per FA	32
Burnable Absorber Material	B_4C

Type	B1	C1
Packing fraction (%)	8	10 / 10
Kernel diameter (μm)	150	100 / 400

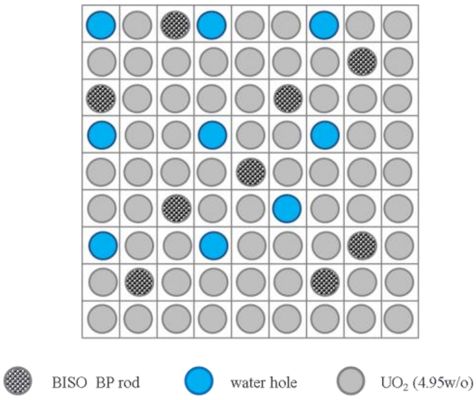


Fig. 1. Configuration of the new fuel assembly (1/4)

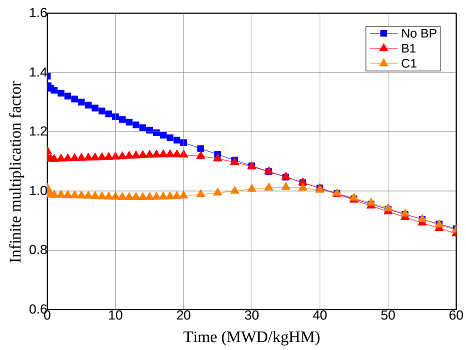


Fig. 2. Comparison of the evolutions of k-infs for new fuel assemblies

Fig. 2 shows that our new fuel assemblies have no loss of fuel cycle length even if they have less number of fuel rods and the C1 type fuel assembly has very flat change of k-inf evolution curve.

As in the previous work, the core rates 180MWt which corresponds to 50MWe with 27.8% efficiency.[4,5] The active core is 200cm tall and the core consists of 37 fuel assemblies. The core loading pattern is shown in Fig. 3.

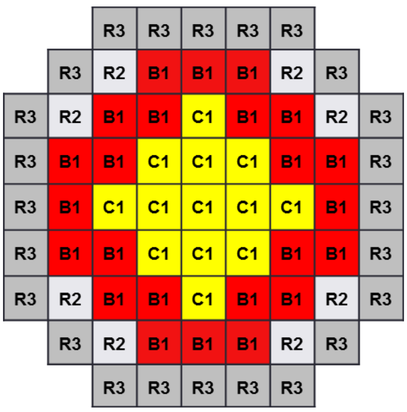


Fig. 3. Radial configuration of the new core

The average heat generation rate is 105W/cm which is lower than the SMART core. This low power density is selected to achieve long cycle length and large thermal margin. The core uses one-batch refueling scheme and its target cycle length is 4 EFPYs. In Fig. 3, the reflector assemblies are denoted as R2 and R3. In this work, we designed a reference core with water reflector to achieve low boron concentration and to have low power peaking factors over the cycle. Then, we performed comparative study only by replacing the water reflector with the following reflectors : 1) SS303, 2) beryllium, 3) graphite, and 4) 90wt% graphite+10wt% SS303. Fig. 4 compares the evolutions of the critical boron concentrations (CBC) over time. This figure shows that the replacements of water reflector with solid reflectors lead to the large extensions of the cycle length but the increases of the maximum CBC. The graphite reflector was found to have the longest cycle length but the highest maximum CBC of ~1050ppm. The main performance parameters of the cores having different reflectors are compared in Table II.

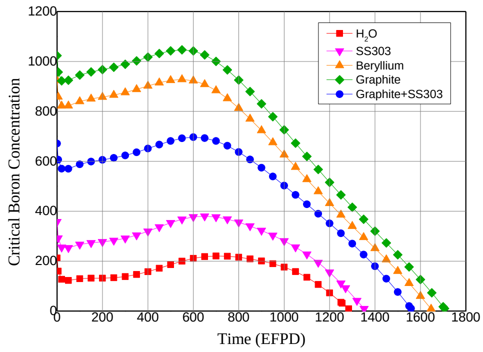


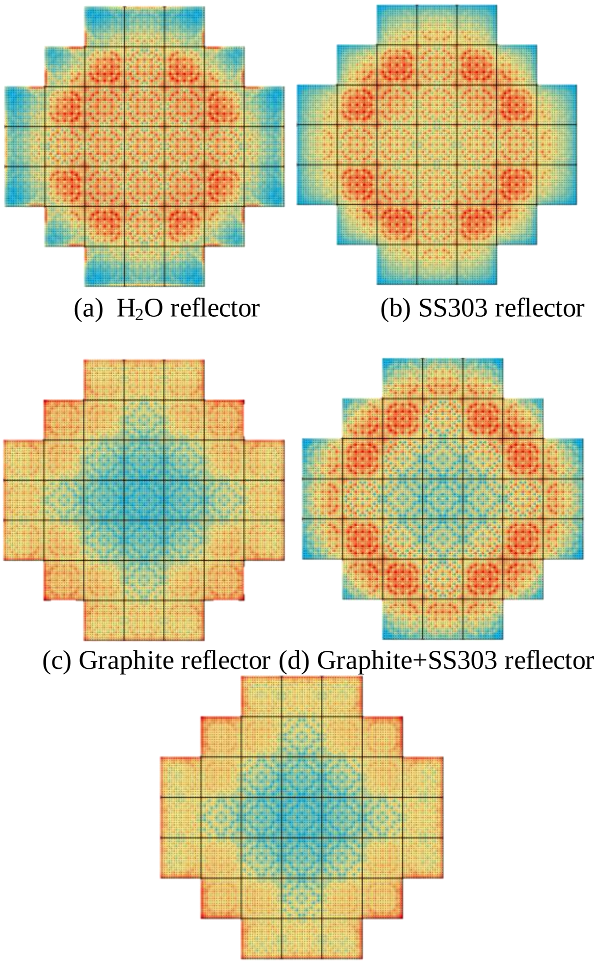
Fig. 4. Comparison of the evolutions of CBC over time for different radial reflectors

Table II : Summary of core performances

Reflector	H_2O	SS303	Graphite	Graphite + SS303	Beryllium
Cycle length (EFPD/EFPY)	1284 / 3.52	1352 / 3.70	1706 / 4.67	1558 / 4.27	1647 / 4.51
Burnup (MWD/kg)	28.13	29.63	37.43	34.19	36.13
Max. CBC (ppm)	220.58	379.89	1046.65	696.59	927.81
Maximum F_q	2.2195	2.2315	2.5067	2.0878	2.8672
Maximum F_r	1.5388	1.5587	1.7754	1.5204	2.0299
Leakage fuel region (neutrons/sec)	1.08E+18	8.68E+17	5.35E+17	7.08E+17	6.49E+17
MTC					
HFP (Max./Min., pcm/°K)	-59.78 / -70.87	-39.41 / -53.45	-24.65 / -58.63	-40.02 / -62.96	-27.45 / -59.34
HZP (Max./Min., pcm/°K)	-35.7 / -48.49	-18.97 / -30.82	-7.3 / -33.29	-19.35 / -36.2	-9.92 / 33.71

As shown in Table II, the SS303, graphite, and beryllium solid reflector extends the cycle length by 68, 422, and 363 EFPDs, respectively but they have larger maximum CBCs of 380, 1047, and 928ppm, respectively. Of course, it is possible to redesign the core having the solid reflectors to reduce the maximum CBC but we did not try it at present because the purpose of this work is to show the overall effects of the reflectors for the reference core. The 90wt% graphite+10wt% SS303 reflector which was used in our previous low boron core has cycle length of 4.2 EFPYs, maximum CBC of 697ppm, and the smallest power peaking factors. Table II also compares the neutron leakage rate through the active core region, which shows that the cycle length is closely related with the neutron leakage rate. The graphite reflected core has the smallest neutron leakage rate while the water reflected core has the highest neutron rate.

The thermal flux distributions at the beginning of the cycle are compared in Fig. 5.



(a) H_2O reflector (b) SS303 reflector

(c) Graphite reflector (d) Graphite+SS303 reflector

(e) beryllium reflector

Fig. 5. Comparison of the fuel pin-wise thermal fluxes

Fig. 5 shows that the reference water reflected core have very low level of thermal fluxes in the outermost fuel assemblies while the outermost fuel assemblies have higher thermal fluxes than in the inner central fuel assemblies for the graphite and beryllium reflectors. These thermal flux distributions explain why the graphite reflected and beryllium reflected cores have longer cycle length than the water reflected core.

The evolutions of the moderator temperature coefficients (MTC) at HFP (Hot Full Power) and HZP (Hot Zero Power) are compared in Fig. 6 and Fig. 7, respectively. These figures show that all the cores have negative MTCs over their cycles both at HFP and HZP. In particular, it is noted that the reference water reflected core has very strong negative MTC up to ~-70 pcm/^{o}C which might be resulted from the lowest boron concentration in the primary coolant. However, these strong negative MTC can be problematic under the SLB (Steam Line Break) accidents because the inflow of cold water can be led to the large positive reactivity insertion.

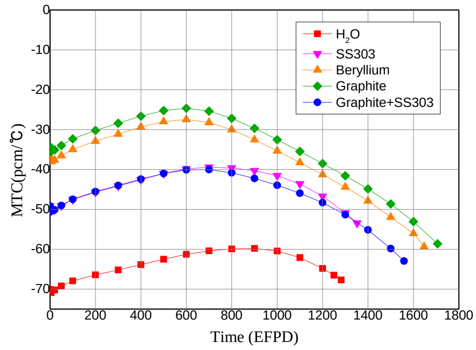


Fig. 6. Comparison of the MTC evolutions (HFP)

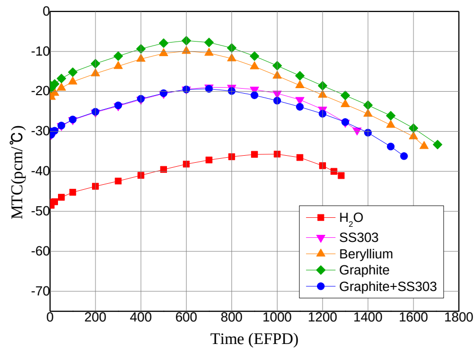


Fig. 7. Comparison of the MTC evolutions (HZP)

4. Summary and Conclusion

In this work, we performed the comparative physics study on the long cycle small PWR core with the several different reflector assemblies. A reference core having water reflector was designed to have low boron concentration by using new FCM burnable poison rods with B_4C kernel BISO particles. Then, the comparative study was performed by replacing the water reflector with the candidate reflector compositions in the reference core. The study showed that the reference water reflected core has the shortest cycle length of 3.5 EFPYs and the lowest boron concentration of 221ppm while the other solid reflected cores have significantly longer cycle lengths but higher boron concentrations. Of the cores, the graphite reflected core has the longest cycle length of 4.6 EFPYs but the highest boron concentration of 1046ppm. Also, this core has the highest peaking factors due to the high thermal flux in the outer fuel assemblies. In particular, it was shown that the 90wt% graphite+10wt% SS303 reflected core has good features such as long cycle length of ~4.3 EFPYs, the smallest power peaking factors, and the low boron concentration of 697ppm.

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