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New Small LWR Core Designs using Particle Burnable Poisons for Low Boron Concentration

Ho Seong Yoo, DaeHee Hwang and Ser Gi Hong*
Department of Nuclear Engineering, Kyung Hee University
1732 Deokyoungdaero, Giheung-gu, Yongin, Gyeonggi-do, 446-701
**Corresponding author : sergihong@khu.ac.kr*

1. Introduction

The soluble boron has two major important roles in commercial PWR operations : 1) the control of the long-term reactivity to maintain criticality under normal operation, and 2) the shutdown of the reactor under accidents. However, the removal of the soluble boron gives several advantages in SMRs (Small Modular Reactor). These advantages resulted from the elimination of soluble boron include the significant simplification of nuclear power plant through the removal of pipes, pumps, and purification systems. Also, the use of soluble boron mitigates corrosion problems on the primary coolant loop. Furthermore, the soluble boron-free operation can remove an inadvertent boron dilution accident (BDA) which can lead to a significant insertion of positive reactivity. From the viewpoint of core physics, the removal of soluble boron or reduction of soluble boron concentration makes the moderator temperature coefficient (MTC) more negative. So, there have been many studies[1,2] to design the boron-free or low boron cores. Recently, we have suggested advanced fuel assemblies using new burnable poison rods containing BISO particles for achieving low boron concentration[3]. Originally, these particle type burnable poisons were considered in the several LWR reactor concept using FCM fuels[4,5,6,7].

In this paper, we designed two new small LWR cores using the new burnable poison rods that we have proposed in previous work[3]. In this work, the new small LWR cores employ the burnable poison rods containing B_4C burnable poison BISO particles or B_4C and Gd_2O_3 burnable poison BISO particles. Sec. 2 describes the computer codes and procedures used to design the fuel assemblies and the cores. The design and performance analysis of the fuel assemblies and cores are described in Sec. 3. Finally, the summary and conclusion are given in Sec. 4.

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[8] (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. This code uses 2D modular ray tracing to solve multi-group transport equation with MOC (Method of Characteristics) and subgroup method for resonance self-shielding treatment. 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[9] (Multi-purpose Analyzer for Static and Transient Effects of Reactors) code which is a 3D core depletion code developed by KAERI.

3. Design and Performance Analysis

3.1. Fuel Assembly Designs

Table I summarizes main design parameters for new fuel assemblies including specifications of new burnable poison rods. Fig. 1 shows the arrangements of fuel rods and the burnable poison pins including the BISO burnable poison particles for one fourth of the fuel assemblies. The new assemblies are designated by B1 and C1 types in Table I.

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	
Type	B1	C1
The number of BISO particle pins in whole assembly	36	32
Core Design A		
Burnable Absorber material	B_4C	B_4C
Packing fraction (%)	6.8	11.6 / 7.5
Kernel diameter (μm)	250	150 / 400
Core Design B		
Burnable Absorber material	B_4C	Gd_2O_3 / B_4C
Packing fraction (%)	6.8	11 / 12
Kernel diameter (μm)	250	100 / 400

These designations of the fuel assemblies are based only on the arrangement of fuel and burnable poison rods. It is noted that there are two different fuel assemblies for each fuel assembly type. That is to say, the C1 type fuel assembly used in Core Design A is different from the C1 type fuel assembly used in Core Design B. The descriptions of these cores are given in Sec. 3.2. On the other hand, there is a single fuel assembly for type B1. These fuel assemblies are based on the 17x17 Westinghouse fuel assembly which has 25 water holes for in-core instrumentation and for control rods. As shown in Fig. 1, the B1 type fuel assembly has 36 burnable poison rods where B_4C BISO particles are randomly distributed in SiC matrix. The central kernel of 250μm diameter contains B_4C and it is surrounded by two subsequent buffer layers to cope with the helium gases coupled with SiC matrix. The packing fraction of these BISO particles is 6.8%. On the other hand, there are two different fuel assemblies for C1 type. The fuel assembly of C1 type used in Core Design A consists of two different B_4C BISO particles having different packing fractions and kernel diameters. On the other hand, the fuel assembly of C1 type used in Core Design B consists of Gd_2O_3 and B_4C BISO particles of 11% and 12% packing fractions, respectively. The kernel diameters of these Gd_2O_3 and B_4C BISO particles used in the C1 type fuel assembly are 100 and 400 μm, respectively. The uranium enrichment of all the fuel rods is 4.95wt% U-235.

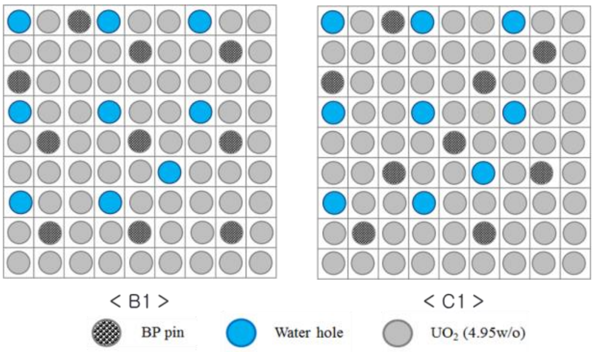

Fig. 1 Configuration of the new fuel assembly (1/4)

Fig. 2 compares the evolutions of the infinite multiplication factors over time for the fuel assemblies used in Core Design A. As shown in Fig. 2, these fuel assemblies have flat shape of evolutions of the infinite multiplication factor over 30MWD/kg.

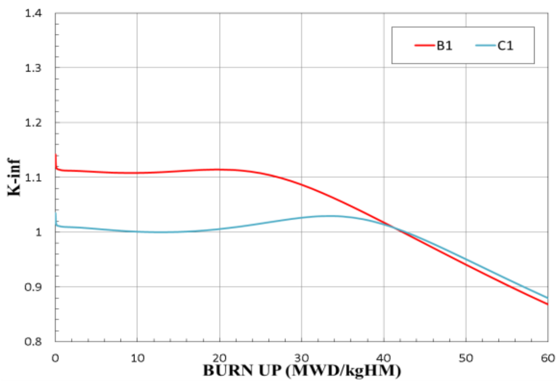

Fig. 2. Comparison of k_{inf} evolutions over time for the fuel assemblies used in Core Design A

In particular, the C1 type fuel assembly has much flatter change of the infinite multiplication factor than the B1 type one. Fig. 3 compares the evolutions of the infinite multiplication factors over time for the fuel assemblies used in Core Design B. As shown in Fig. 3, their trends of the evolutions of infinite multiplication factors are very similar to the corresponding fuel assemblies used in Core Design A. The basic purpose of using Gd_2O_2 BISO particles is to show the effects of the BISO particles having resonance absorption.

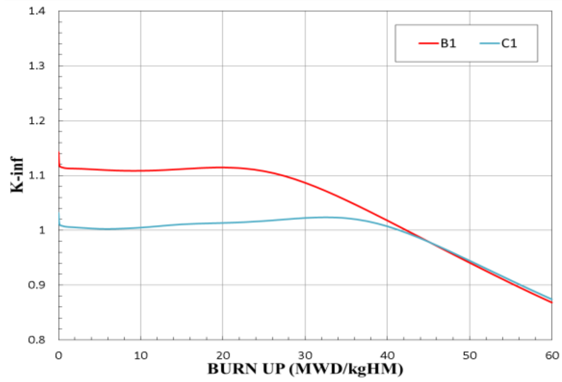

Fig. 3. Comparison of k_{inf} evolutions over time for the fuel assemblies used in Core Design B

3.2. Core Design and Performance Analysis

In this section, we describe the design specification and the results of core performances. In this work, two different small LWR cores are designed to have very small boron concentration by using the new fuel assemblies described in Sec. 3.1. Table II summarizes the major design parameters and core design targets for achieving low boron concentration cores.

Table II : Specification of the major core design parameters and design targets

Composition of core	
Electric power(MWe)	50
Thermal power(MWth)	180
Linear power density(W/cm)	110
Core height(cm)	168
Core design target	
Max. CBC(ppm)	500
Max. F_{xy} / F_{xyz}	1.7 / 2.2
Cycle length (EFPD/EFPY)	1095 / 3
Shutdown margin(pcm)	6500

The cores rate 180MWt and the active fuel height for these cores is 168cm. These cores have been designed to have relatively small power density whose the average linear heat generation rate is 110W/cm so as to have large thermal margin and long cycle length. These cores use one batch refueling scheme and so every fuel assembly is discharged at EOC (End of Cycle) and new fresh assemblies are re-loaded together at BOC

(Beginning of Cycle). The two cores designed in this work use the same loading pattern given in Fig. 4 while the C1 type fuel assemblies are different for two cores in spites of their same names as described in Sec. 3.1. The cores consist of 37 fuel assemblies. For power flattening, the assemblies with higher reactivity are placed in the outer core region. In this work, new reflector of 90wt% graphite and 10wt% SS303 is considered to reduce the neutron leakage which leads to a longer cycle length[9]. In Core Design B, the C1 type fuel assembly has the burnable poison rods that are comprised of B_4C BISO particles and Gd_2O_3 BISO particles.

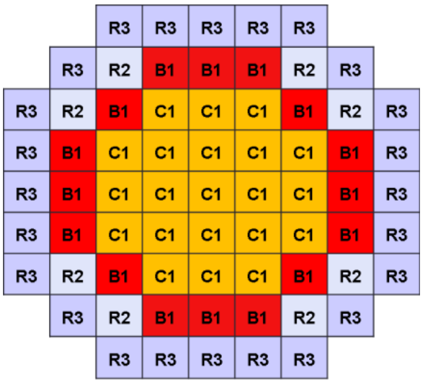

Fig. 4. Core loading pattern

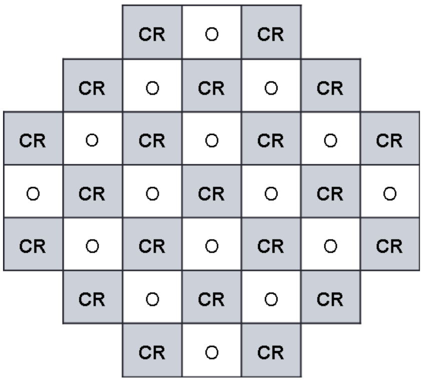

Fig. 5. Positions of the control rods in the designed cores

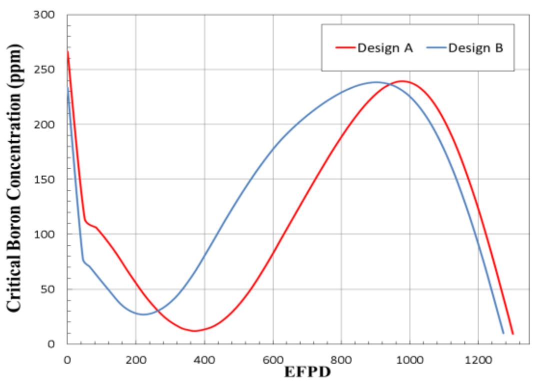

Fig. 6. Comparison of the evolutions of critical boron concentrations

Fig. 5 shows the positions of the control rod assemblies where the control rod assemblies are located with checkerboard pattern. Fig. 6 compares the evolutions of the critical boron concentrations of new cores. This figure shows our cores have very small maximum boron concentrations below 300ppm and the cycle lengths are about 1300 EFPDs (~3.5EFPYs). Core Design A has lightly longer cycle length by 28EFPDs than Core Design B. The evolutions of the 3D and 2D power peaking factors (F_{xyz}, F_{xy}) over time are compared in Fig. 7. It is shown in Fig. 7 that the 2D power peaking factors for two cores are nearly the same over the cycle and that Core Design B has lower 3D power peaking factor than Core Design B near the end of cycle. The 3D and 2D power peaking factors for both two cores satisfy the design targets.

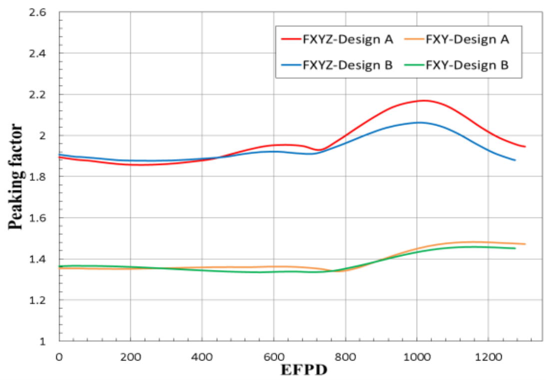

Fig. 7. Comparison of the evolutions of power peaking factors

The evolutions of the axial offsets are compared in Fig. 8. Fig. 8 shows that the axial power distributions are slightly tilt toward the core bottom at BOC. But the axial offsets are less in absolute value than 0.1. Figs. 9 and 10 compare the axial power distributions of the Core Designs A and B, respectively, at several time points. It is considered that the optimization of the axial power distribution will be possible by using axial cutback regions and it will be a future work.

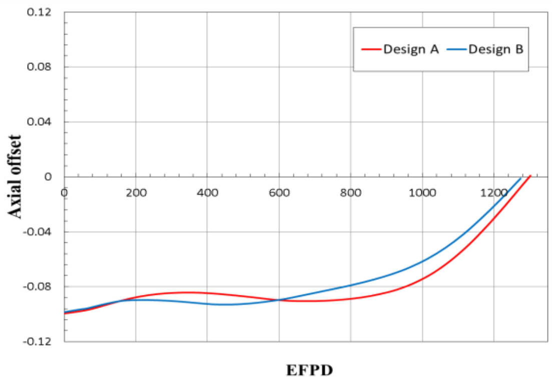

Fig. 8. Comparison of the evolutions of axial offsets (BOC)

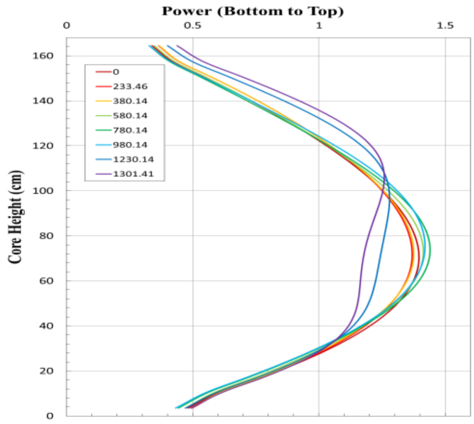

Fig. 9. Comparison of the axial power distributions (Core Design A)

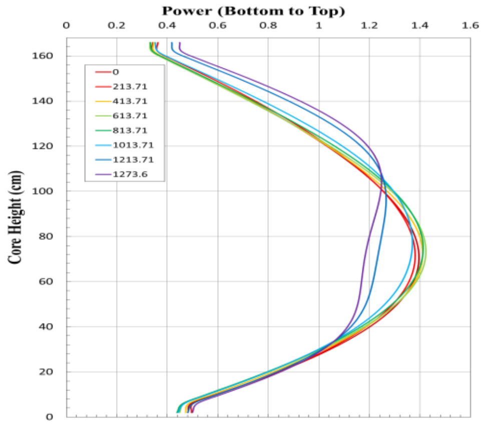

Fig. 10. Comparison of the axial power distributions (Core Design B)

The MTCs of the cores are compared in Fig. 11. Fig. 11 shows that new cores have strong negative MTCs over the cycle both at BOC and EOC due to the small critical boron concentrations.

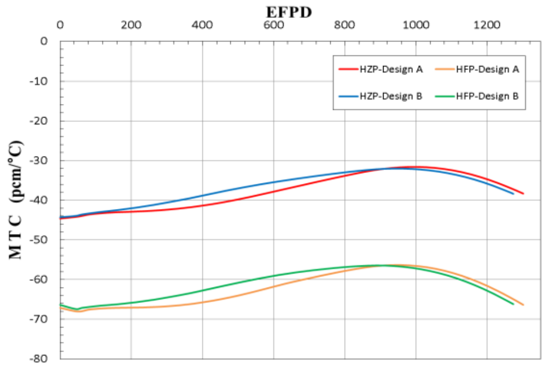

Fig. 11. Comparison of moderator temperature coefficients

The main core performance parameters of the cores are summarized in Table III. As shown in Table III, the cores have similar cycle length of ~3.5 EFPYs and satisfy all the design targets but they have small discharge burnup which leads to the degradation of fuel economic. The maximum critical boron concentrations for Core Design A and Core Design B are 266 ppm and 238 ppm over the cycles, respectively.

4. Summary and Conclusion

In this work, we proposed new fuel assemblies employing burnable poison rods having B_4C or B_4C and Gd_2O_3 BISO particles to achieve low soluble boron concentration and long cycle length in new small LWR cores. From the core design studies using new fuel assemblies, it is shown that the cores have very low critical soluble boron concentrations less than 500ppm, low peaking factors within the design targets, strong negative MTCs over cycles, and large enough shutdown margins both at BOC and EOC. However, the present cores have relatively low average discharge burnups of ~30MWD/kg leading to low fuel economy because the cores use lots of non-fuel burnable poison rods to achieve very low critical boron concentrations. So, in the future, we will perform the trade-off study between the fuel discharge burnup and the boron concentrations by changing fuel assembly design and the core loading pattern.

Table III : Summary of core performances for Core Designs A and B

	Design A	*Design B*
Max. CBC(ppm)	266	238
Cycle length(EFPD/EFPY)	1301 / 3.57	1273 / 3.49
Burnup (MWD/kgHM)	30.2	29.5
Power peaking factor		
Max. F_{xy}	1.482	1.4584
Max. F_{xyz}	2.169	2.0625
Axial offset	-0.10	-0.098
MTC		
HZP(Max./Min., pcm/°K)	-31.6/-44.6	-32.05/-44.31
HFP(Max./Min., pcm/°K)	-56.4/-68.0	-56.47/-67.43
Shutdown margin(BOC/EOC,pcm)	11547/12962	11466/12944

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