Radial Optimum Design of Long-cycle Soluble Boron-free SMPWR

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1. Introduction

This paper suggests the conceptual design of a long-cycle soluble boron-free Small Modular Pressurized Water Reactor (SMPWR) core. The SMPWR possess inherent safety advantages and has the potential to supply the electricity in small grid country [1][2]. In addition, the soluble boron-free reactor could reduce the liquid spent nuclear wastes, eliminate the Chemical Volume Control System (CVCS) and reduce the reaction with structure materials [1][3].

The main feature of this newly designed core is long-cycle operation without refueling. Therefore, this paper is focused on suppression of the initial excess reactivity with burnable absorbers (BA). Especially, in the paper, the optimization analysis is performed with newly suggested BA type, ring type burnable absorber (R-BA). This is necessary to satisfy the long-cycle operation and to control the pin power peak [4][5].

On the other hand, the reflector sensitivity study is performed in this paper. The water reflector and metallic reflectors, stainless steel and zircaloy are investigated [6]. Compared with water reflector, if the same amount of fuel is loaded in the core, metallic reflectors give benefit of increased cycle length due to the increment of neutron scattering. However, the excess reactivity is also increased [6]. Therefore, in the paper, sensitivity study of reflector is focused on the excess reactivity and safety evaluation.

The optimization calculation of SMPWR core design is performed with STREAM and RAST-K 2.0 codes [7][8][9]. STREAM is a neutron transport analysis code and RAST-K 2.0 is a nodal code. These two codes are developed by the Computational Reactor physics and Experiment laboratory (CORE) of Ulsan National Institute of Science and Technology (UNIST).

2. Design parameters and limitations

Table I presents the design parameters and requirements of target soluble boron-free SMPWR. The main feature of target soluble boron-free SMPWR is long-cycle operation. The target cycle length is set as 44 months (~ 1,320 EFPDs) with 180 MW thermal power. In the SMPWR, 37 fuel assemblies of 17X17 Westinghouse type are loaded with UO_2 fuel of 4.95 w/o enrichment.

On the other hand, to ensure the safety of core operation condition, optimization of core loading pattern is focused on the the axial shape index (ASI) and 3D power peaking factor (Fq) that is associated with the Minimum Departure from Nucleate Boiling Ratio (MDNBR).

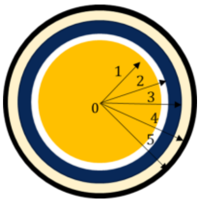
Table I: Design parameters and limitations

Parameter	Value
Thermal Power	180 MW
Power density	52.602 kW/L
Linear power density	9.21 kW/m
Target cycle length	44 months
Fuel Assembly Type	17X17 Westinghouse
Fuel Assembly Pitch	21.504 cm
Fuel enrichment	4.95 w/o ^{235}U
BA material	Natural gadolinium, Gadolinia (2 w/o and 8 w/o Gd_2O_3), Al_2O_3/B_4C
Shape of BA	R-BA, Integral Burnable Absorber (IBA), Wet Annular Burnable Absorber (WABA)
Number of FAs	37
Active core height	2.0 m
3D peaking factor (Fq) limit	4.42
ASI limit	-0.4 < ASI < +4.0
Inlet/Outlet temperature	285/306°C
Flowrate	1600 kg/sec
Pressure	155.1 bar
Cladding material	zircaloy
ITC	< 0 pcm/°C
Control Rod Material	HfB_2

3. Radial loading pattern optimization

In the boron-free SMPWR core operation with stainless steel reflector, the initial excess reactivity should be suppressed by BAs. This section presents the optimization of radial core loading pattern with three types of BAs: gadolinia, WABA and R-BA. The Fig. 1 presents the newly suggested R-BA geometry [4][5]. In the figure, 0 to 1 region is UO_2 fuel, 1 to 2 is air gap, 2 to 3 is cladding, 3 to 4 is gadolinium R-BA and 4 to 5 is CrAl coating. R-BA is coated outside of cladding material and that is different from IFBA. This geometry makes it possible to maintain and increase the amount of UO_2 fuel without consideration of gadolinium heat conductivity. The Fig. 2 presents the four types of fuel assemblies loaded in the core. Fig. 3. shows the layout of available WABA assembly positions and control rod positions. "A" is adjusting-power control rod to control the excess reactivity and "R" is regulating bank to be utilized for the load follow operation and "S1", "S2" are shutdown bank for pausing the core operation. The axial compositions of fuel assemblies are presented in right-side of Fig. 3.

Table II contains the core radial loading patterns and sensitivity test results. In the Table, P1 to P5 fuel assembly positions are presented in Fig. 3 and WABA assembly positions are fixed. According to those positions, 16 loading patterns are available. LP4 has the largest cycle length of 1,364 EFPDs. The second and third largest cycle length cases are LP10 and LP7 as 1,348 EFPDs and 1,331 EFPDs. Those three core loading patterns are shown in Fig. 4. Layout (a) is the LP4, layout (b) is the LP7 and layout (c) is the LP10. In the loading patterns, FA01 contains the 8 w/o enriched Gd_2O_3, FA02 has 2 w/o and 8 w/o enriched Gd_2O_3 and W contains the Al_2O_3/B_4C and natural gadolinium R-BA. Fig. 5 presents the multiplication factor, ASI and Fq of those three cases. As for the ASI, three cases satisfy the design limitation (-0.4 to 4.0). However, from the point of 3D peaking factor, only LP4 satisfies the limitation (4.42). The other two cases, LP7 and LP10, exceed the limitation as 9.587 and 45.4748.



Region	Radius [cm]	Material
0 – 1	0.4095	UO_2
1 – 2	0.4187	AIR
2 – 3	0.4500	ZIRLO
3 – 4	0.4760	Gadolinium R-BA
4 – 5	0.4810	CrAl

Fig. 1. R-BA geometry

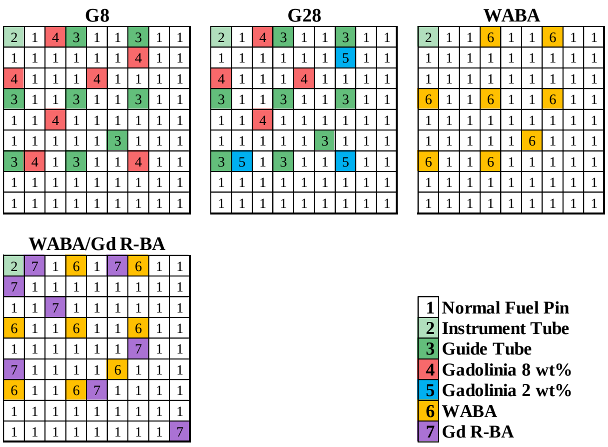


Fig. 2. Layout of fuel assembly

Table II: Core radial loading pattern sensitivity test results

LP (CR)	P1 (P)	P2 (A)	P3 (R)	P4 (S1)	P5 (S2)	Fuel Loading [MTU]	Cycle Length [Day]
LP1	FA01	FA01	FA01	FA01	FA01	9.629	1,223
LP2	FA01	FA01	FA01	FA01	FA02	9.611	1,271
LP3	FA01	FA01	FA01	FA02	FA01	9.593	1,327
LP4	FA01	FA01	FA01	FA02	FA02	9.574	1,364
LP5	FA01	FA01	FA02	FA01	FA01	9.611	1,225
LP6	FA01	FA01	FA02	FA01	FA02	9.593	1,274
LP7	FA01	FA01	FA02	FA02	FA01	9.574	1,331
LP8	FA01	FA02	FA01	FA01	FA01	9.611	1,250
LP9	FA01	FA02	FA01	FA01	FA02	9.593	1,297
LP10	FA01	FA02	FA01	FA02	FA01	9.574	1,348
LP11	FA01	FA02	FA02	FA01	FA01	9.593	1,255
LP12	FA02	FA01	FA01	FA01	FA01	9.625	1,216
LP13	FA02	FA01	FA01	FA01	FA02	9.606	1,266
LP14	FA02	FA01	FA01	FA02	FA01	9.588	1,322
LP15	FA02	FA01	FA02	FA01	FA01	9.606	1,219
LP16	FA02	FA02	FA01	FA01	FA01	9.606	1,244

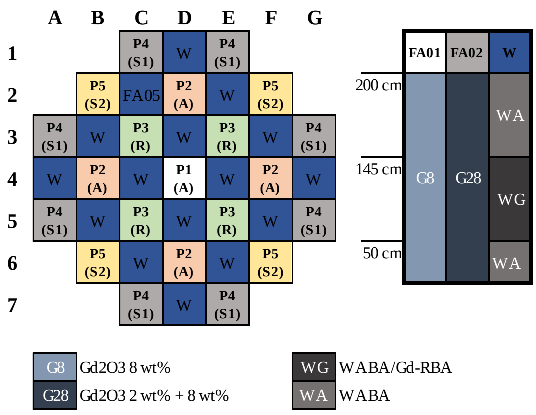


Fig. 3. Available assembly position in the core loading pattern and control rod position

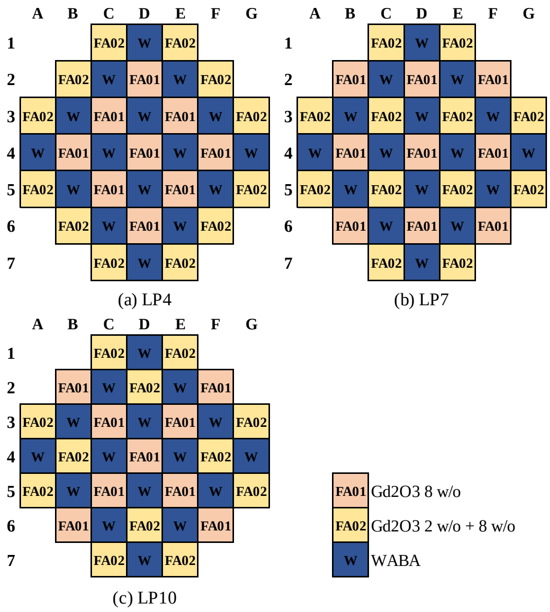


Fig. 4. LP4, LP7 and LP10 layout

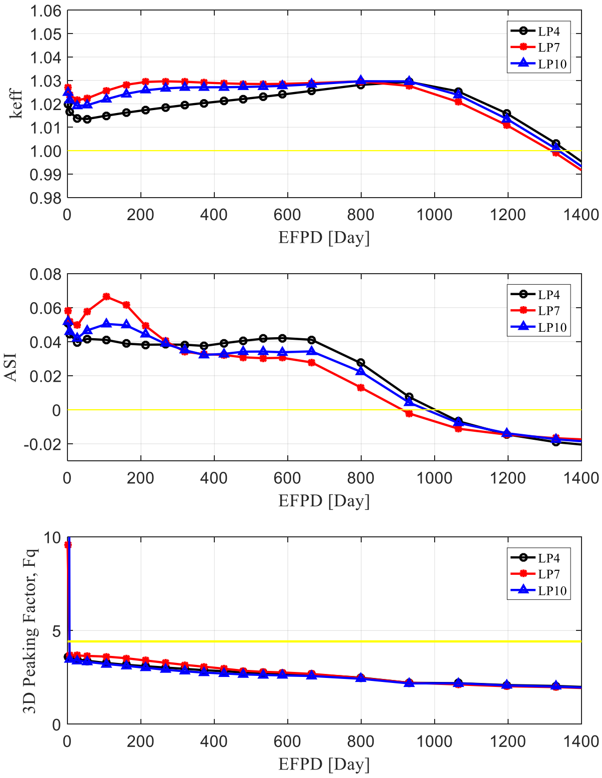


Fig. 5. k_{eff}, ASI, Fq of radial core loading pattern sensitivity study

4. Radial reflector sensitivity study

To improve the cycle length and safety margin for preventing accident, the radial reflector sensitivity study is performed with water, stainless steel and zircaloy reflectors. Stainless steel reflector has been used for all the PWRs in the Republic of Korea as thin-steel baffle and zircaloy reflector has been studied at several research centers [6]. The Fig. 6 layout based on LP4 pattern is used for sensitivity study. The fuel assembly loading pattern is the same as layout (a) shown in Fig. 4 and "REF" means the reflector region. In the sensitivity test, the reflector thickness is same as fuel assembly pitch, 21.504 cm. 32 reflector assemblies surround the reactor core. Fig. 7 presents the critical boron concentration with water and the other metallic reflectors, stainless steel and zircaloy. The NO BP case is calculated with stainless steel reflector and the yellow line is the design limitation (500 ppm). This limitation is set as considering the ability of excess reactivity suppression by control rods. The maximum critical boron concentration (CBC) is 551 ppm in zircaloy reflector case, 446 ppm in stainless steel reflector case and 315 ppm with water reflector case. Fig. 8 and Fig. 9 shows the Fq and ASI values as effective full power day proceeds. These two figures show that all cases can satisfy the limitation.

The depletion results are summarized in Table III. The table shows the zircaloy reflector case has the maximum cycle length as 1,495 EFPDs compared with the other two cases. This value is 21 EFPDs smaller than the NO BP case. In addition, stainless steel case satisfies the target cycle length, 44 months (~1,320 EFPDs). The initial excess reactivity of NO BP case is equal to 3,116 ppm soluble boron at beginning of cycle (BOC). The zircaloy case could substitute the 2,673 ppm and stainless steel could replace 2,781 ppm soluble boron to control the excess reactivity.

As a result, the zircaloy reflector has the maximum cycle length compared with the other cases. However, the limitation of CBC is not satisfied and the ability of controlling the excess reactivity is 107 ppm less than stainless steel case. On the other hand, stainless steel case can satisfy the limitation of CBC, ASI and Fq. In addition, the stainless steel case satisfies the cycle length design requirement and possesses the ability of controlling the excess reactivity equivalent to 2,781 ppm soluble boron at BOC.

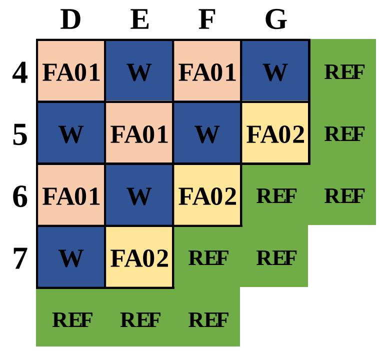


Fig. 6. One-fourth layout of radial core loading pattern

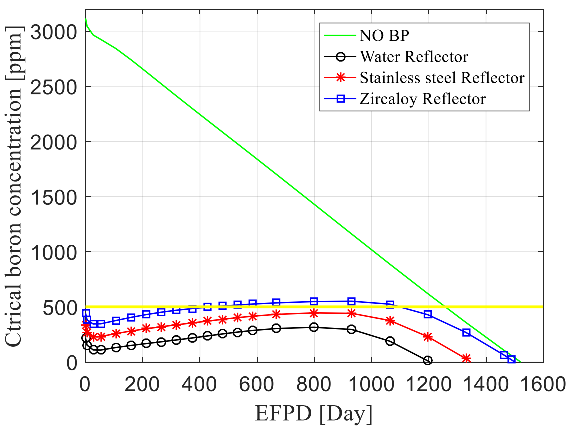


Fig. 7. Critical boron concentration with reflector sensitivity study

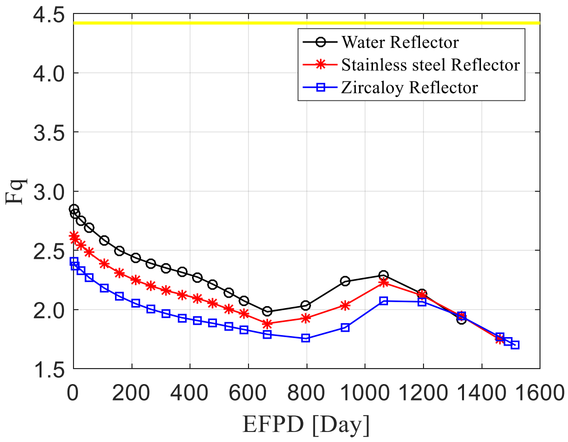


Fig. 8. Fq with reflector sensitivity study

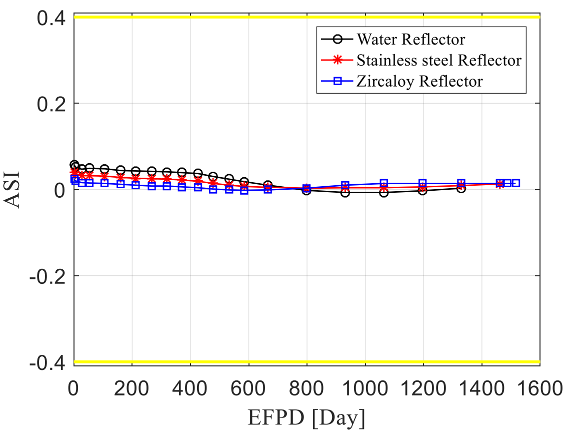


Fig. 9. ASI with reflector sensitivity study

Table III: Cycle length and BOC excess reactivity

	Cycle Length [EFPD]	Cycle Length difference [EFPD]	CBC at BOC, 0 GWd/MT [ppm]
NO BP	1,516	Reference	3,116
Water REF	1,197	-319	216
SS REF	1,341	-175	335
Zr REF	1,495	-21	442

5. Conclusion

This paper suggests the conceptual design of a long-cycle soluble boron-free SMPWR core. The main feature of the newly designed core is long-cycle operation without refueling. Therefore, this paper is focused on suppression of the initial excess reactivity with burnable absorbers (BA). In the paper, the optimization of the radial loading pattern and the reflector sensitivity study are performed to increase the cycle length and safety margin for preventing accidents.

In the radial loading pattern optimization, LP4, LP7 and LP10 have the longest cycle lengths of 1,364 EFPDs, 1,348 EFPDs and 1,331 EFPDs. Those three cases satisfy the ASI limitation (-0.4 to 4.0). However, from the point of Fq, only LP4 satisfies the limitation (4.42). The other two cases, LP7 and LP10, exceed the limitation as 9.587 and 45.4748.

The reflector sensitivity study is performed with LP4 radial loading pattern. The zircaloy reflector has the maximum cycle length while it does not satisfy the limitation of CBC. On the other hand, stainless steel case satisfies the limitation of CBC, ASI and Fq. In addition, the stainless steel satisfies the cycle length design requirement and possesses the ability of controlling the excess reactivity equivalent to 2,781 ppm soluble boron at the BOC.

In conclusion, this paper suggests the LP4 radial loading pattern with stainless steel reflector for the preliminary design of long-cycle soluble boron-free SMPWR.

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