Optimization of Control Rod Positions for Long-cycle Soluble Boron-free SMPWR

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1. Introduction

This paper presents an optimization progress of control rods for a long-cycle soluble boron-free Small Modular Pressurized Water Reactor (SMPWR) core. The soluble boron free SMPWR has two main benefits. The first one is that it satisfies the national global requirements for clean, efficient, and consistent energy production [1][2]. The second one is that the soluble boron free reactor can remove the Chemical Volume Control System (CVCS), and therefore it will take much smaller footprint of the plant and improve economy [3].

The main feature of newly designed core is long-cycle operation without refueling. Therefore, it is important to suppress the initial excess reactivity with burnable absorbers and control rods. In this paper, the optimal control rod position is presented with a preliminary design of long-cycle SMPWR. This core loading pattern uses three different burnable absorber (BA) types: gadolinia, WABA and ring type burnable absorber (R-BA) [4][5].

Additionally, two-step approach is used for the optimal control rod position calculation. A neutron transport analysis code STREAM and a nodal code RAST-K 2.0 are used [6][7][8]. STREAM and RAST-K 2.0 codes are under development at the Computational Reactor physics and Experiment laboratory (CORE) group of Ulsan National Institute of Science and Technology (UNIST).

2. Design parameters and limitations

Table I presents the main design parameters and requirements of target soluble boron free SMPWR. The main feature of the new design of SMPWR is a long-cycle operation without refueling and no soluble boron. The target cycle length is 50 months (~ 1,500 EFPD) with 180 MW thermal power. The 37, 17X17 Westinghouse type fuel assemblies are used and fuels with 4.95 w/o contents of UO2 are utilized.

In order to ensure the safety of the reactor, the optimization process of control rod positions focuses on satisfying the three-dimensional (3D) peaking factor (Fq) limit which affects the Minimum Departure from Nucleate Boiling Ratio (MDNBR) and the axial shape index (ASI).

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	~ 50 months
Fuel Assembly Type	17X17 Westinghouse
Fuel Assembly Pitch	21.504 cm
Fuel enrichment	4.95 wt.% ^{235}U
BA material	Natural gadolinium, Gadolinia (2 wt.% and 8 wt.% 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
Boron concentration	0 ppm
Inlet/Outlet temperature	285/306°C
Flowrate	1600 kg/sec
Pressure	155.1 bar
Reflector material	Stainless steel
Cladding material	Zirlo
ITC	< 0 pcm/°C
Control Rod Material	HfB_2
Shutdown margin limit	> 3%

3. SMPWR Core Design

In the soluble boron free SMPWR, the initial excess reactivity should be suppressed by control rods and burnable absorbers. This section presents a preliminary design of core loading pattern of SMPWR to be used for the control rod optimization process. Fig. 1 shows the one-fourth layout of six fuel assemblies loaded in the core. Pin 1 is normal UO_2 fuel pin, pin 4 is 8 w/o gadolinia pin, pin 5 is 2 w/o gadolinia pin, pin 7 is WABA and pin 8 is gadolinium R-BA pin. There are three types of BAs: gadolinia, WABA, and R-BA. Especially, R-BA is a newly developed BA type to support the long-cycle operation feature [4][5]. R-BA geometry is presented in Fig. 2. In the figure, region 0 to 1 is fuel, 1 to 2 is air gap, 2 to 3 is cladding, 3 to 4 is R-BA and 4 to 5 is CrAl coating. R-BA is coated at outside of cladding material. Therefore, when R-BA is loaded in the core, it is possible to maintain the uranium enrichment and increase the amount of fission material without worrying the gadolinium heat conductivity.

Fig. 3 shows the radial composition of the preliminary core loading pattern design and Fig. 4 presents the axial composition. The 37 assemblies are loaded in the SMPWR and the preliminary design of core has 1,428 EFPD cycle length at all rod out condition.

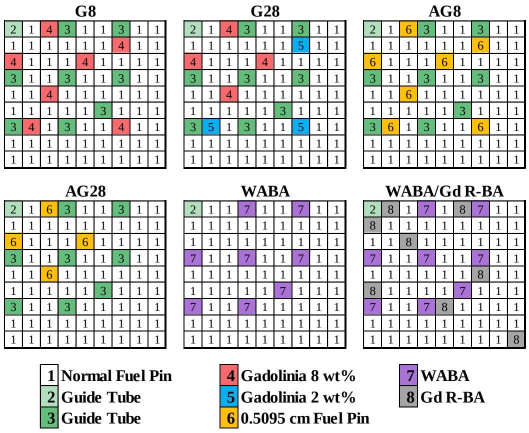
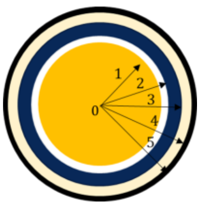


Fig. 1. One-fourth layout of fuel assembly



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. 2. R-BA geometry

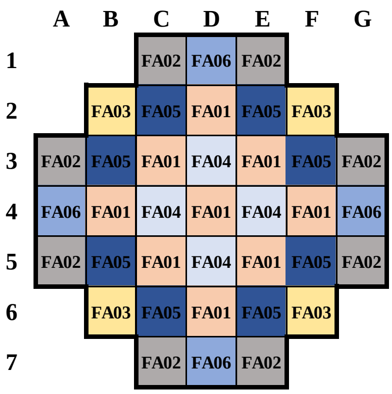


Fig. 3 Radial composition of preliminary core loading pattern

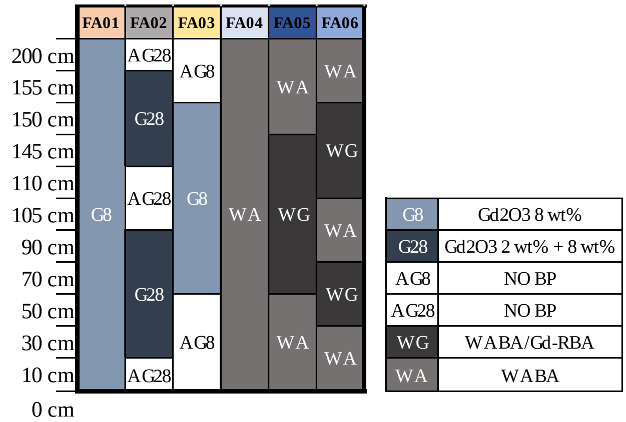
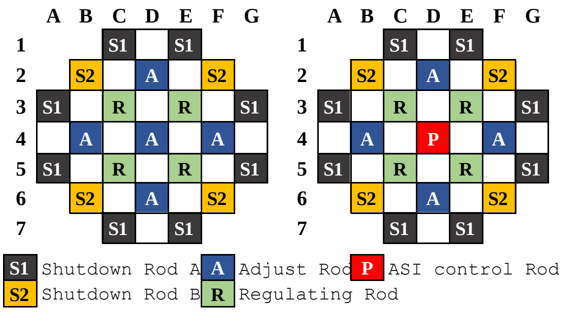


Fig. 4. Axial composition of preliminary core design.

4. Control rod sensitivity study

Fig. 4 shows the axial composition aiming at top skewed power distributions. In the preliminary design, the maximum ASI value is 0.0768, which suggests a possibility of violating the design limit when control rod inserted. In this section, the optimization process of control rod is presented. Fig. 5 shows two different rod bank positions for sensitivity study, CR layout A and B. Layout A has five adjust rods to control the reactivity, while layout B contains one rod for ASI control and four adjust rods to suppress the excess reactivity. In both control rod layouts, 21 control rods are used, where “A” is adjust control rod to control the excess reactivity, “R” is regulating bank to be used for load follow operation, “S1” and “S2” are shutdown rod banks and “P” is ASI control rod. The axial composition of control rods could be recognized in Fig. 6 which shows the height of each control rod. Adjust control rods, regulating rods, and shutdown rods adopt 200 cm height of HfB_2. The ASI control rod has 150 cm height of HfB_2 with 80% enriched B-10. CR material, HfB_2 has 55.0 cm^{-1} macroscopic cross section and has been used in US naval nuclear power reactors (submarine 571 Nautilus) and also commercial PWRs [5] [9].

Fig. 7 presents the multiplication factors as burnup proceeds. The graph also shows that the CR layout A and B as shown in Fig. 5 could be used to suppress the excess reactivity equivalent to 708 ppm soluble boron. Fig. 8 shows the Fq values with all rod out condition, CR layout A and B. The yellow line presents the limitation of Fq (4.42). Another safety parameter, ASI, is presented in Fig. 9 with the yellow limitation lines (-0.4 and +0.4). Fig. 10 and Fig. 11 shows the Adjust CR position and ASI CR positions during the critical rod search operation. The depletion results are summarized in Table II and Table III. Table III shows the cycle length increases to 1,544 days from 1,496 days by adding one ASI CR. Additionally, it is recognized the critical rod position search cases have larger cycle length than ARO, 1,428 days. Only CR layout B satisfies the target cycle length, 50 months (=1,500 EFPD). Besides, it produces ASI and Fq results which are always within the limitations and more conservative than CR layout A.



(a) CR layout A (b) CR layout B

Fig. 5. Radial control rod layout

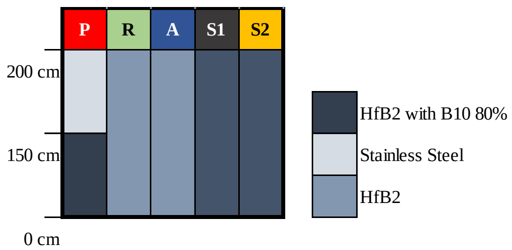


Fig. 6. Axial control rod composition

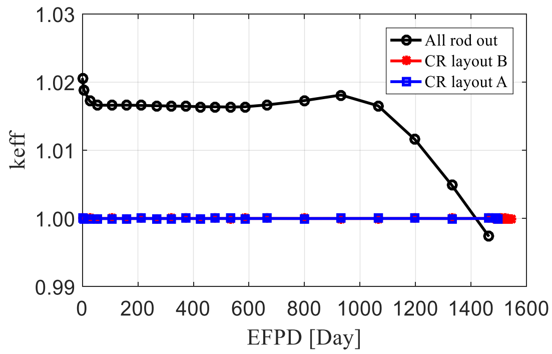


Fig. 7. Effective multiplication factor graph with all rod out, adjust control rod and ASI control rod

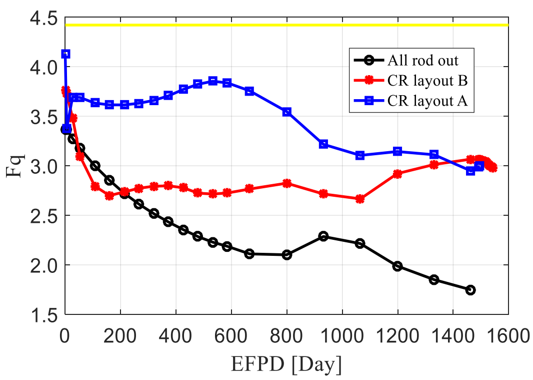


Fig. 8. 3D peaking factor with all rod out condition and control rod injection process

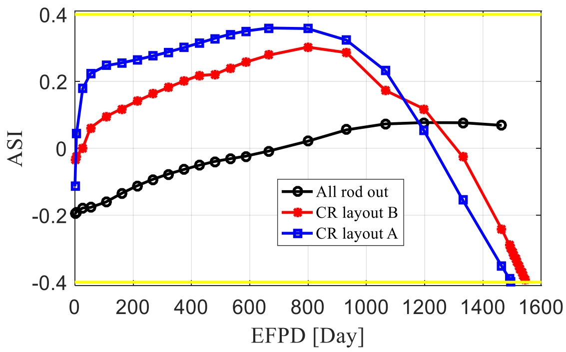


Fig. 9. Axial shape index with all rod out condition and control rod injection progress

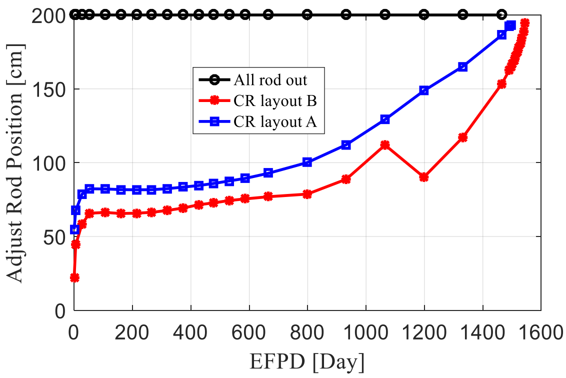


Fig. 10. Adjust CR position as EFPD proceeds

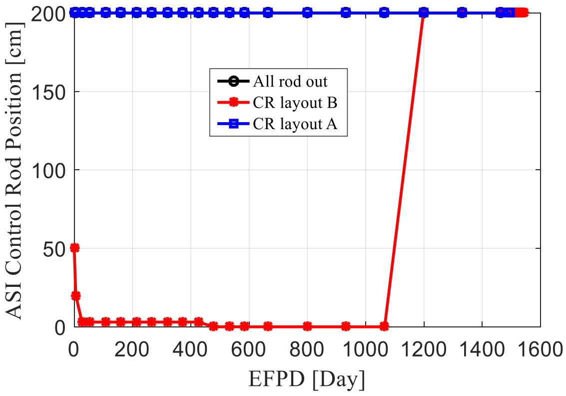


Fig. 11. ASI CR position as EFPD proceeds

Table II: ASI and power peaking factor with all rod out condition and CR layouts

CASE		ARO	CR layout A	CR layout B
ASI	Max	0.0768	0.3594	0.3022
	Min	-0.1963	-0.3976	-0.3921
	ASI_H	-0.0155	0.2193	0.1492
Fq	Max	3.3671	4.1301	3.7671
	Min	1.7484	2.9479	2.6662
	Fq_H	2.3333	3.4816	2.8432

* ASI_H, Fq_H: time integrated value.

Table III: Excess reactivity and cycle length with control rod position sensitivity test

CASE	Cycle Length [Day]	CBC at BOC, 0 GWd/MT [ppm]
NO BP	1,578	4,101
ARO	1,428	708
CR layout A	1,496	0
CR layout B	1,544	0

5. Shutdown margin

This is another important safety design issue. When the reactor core operation condition is changed to HZP from HFP, the positive reactivity is introduced into the core. Therefore, measures to provide the negative reactivity are needed to prevent the introduced excess reactivity for safety. This paper suggests the 3% shutdown margin referring to the mPower which is one of the soluble boron-free SMPWR designs. Fig. 5 shows the control rod layout to be used in shutdown margin calculation. CR layout A contains four different control rod banks: A, Adjust Rod; R, Regulating Rod; S1, Shutdown Rod A; S2, Shutdown Rod B. CR layout B contains five different control rod banks: A, Adjust Rod; R, Regulating Rod; S1, Shutdown Rod A; S2, Shutdown Rod B; P, ASI control rod.

Table IV presents the shutdown margin calculation results with CR layout A and B as shown in Fig. 5 at BOC condition. CR layout A and B have 7,634 pcm and 7,893 pcm shutdown margins separately. Those values have 4% additional margin comparing to the design limitation, 3 %.

Table IV: Shutdown margin with two different control rod position.

CASE	CR layout A	CR layout B
ARI (All rod in) worth	14,952	17,776
Highest CEA worth	969	714
Uncertainty of rod worth	1,495	1,778
Rod worth for criticality	4,839	3,957
Engineering error	100	100
Real Worth	7,548	11,228
HFP->HZP	3,235	3,235
Engineering error	100	100
Total Defect	3,335	3,335
Shutdown margin [pcm]	7,634	7,893

6. Conclusion

This paper presents the optimization results of CR position for preliminary design of SMPWR. The sensitivity test is performed with two different control rod layouts. One only uses five HfB_2 adjust control rods to suppress the excess reactivity and the other one uses four adjust control rods to control the excess reactivity and one HfB_2 control rod with 80% enriched B-10 for adjusting ASI. For safety evaluation, Fq, ASI and shutdown margin are calculated.

The core with CR layout A could operate for 1,496 EFPDs with all the design limitations satisfied. On the other hand, the CR layout B could make the core operate 48 days more than CR layout A, totally 1,544 EFPDs. In addition, the core design with CR layout B can give results that always satisfy the design requirements: Fq < 4.42; -0.4 < ASI < 0.4; cycle length ~ 50 months (~1,500 EFPDs).

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