

## Optimization of Control Rod Operation for Soluble-Boron Free SMPWR with Zircaloy Reflector

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### 1. Introduction

This paper suggests optimal control rod layout for soluble-boron free SMPWR with zircaloy reflector. The reactor with zircaloy reflector has advantage to extend the cycle length due to high scattering cross section of zirconium which compares to water [1].

The soluble boron-free pressurized water reactors have several advantages [2], such as efficient supply of the electricity at local and small grid country, reduction of the foot-print of reactor due to absence of Chemical Volume Control System (CVCS) and improvement of the structural integrity to prevent the reaction between boron and structural material [2].

Due to absence of boron, however, the reactor should solve the axial power distortion problem caused by control rods (CR) and burnable absorbers (BA) [1][3]. The target of the fuel cycle length is long-fuel cycle of 1,500 effective full power days (EFPDs). In order to ensure the safety, the dependency of control rods and burnable absorbers increases for excess reactivity control in the core. However, this situation leads the axial power shape distortion which affects to fuel melting. Therefore, to reduce power distortion, optimization of control rod operation is performed.

The optimization test has been performed by STREAM/RAST-K 2.0 code system [4][5]. The STREAM is a lattice code solving neutron transport equation and generates group constants for nodal calculation [5]. The RAST-K is a diffusion nodal code to analyze 3D whole core. Core simulation results conducted by the two-step approach has been verified by previous SMPWR model against with SERPENT and CASMO4e/SIMULATE3 [6].

### 2. Design parameters and limits

The Table 1 shows the target design parameters and design limits [1]. The thermal power of SMPWR is set as 180 MW with 37 number of 4.95 w/o enriched  $UO_2$  fuel assemblies. The active height is set as 200 cm and zirconium is used for reflector material. The zircaloy reflector gives the benefit to extend the cycle length due to high scattering cross section of zirconium, however, the excess reactivity is also increased. Therefore, the 80 w/o enriched  $HfB_2$  control rods are employed to control high reactivities.

Due to absence of boron, axial power distortion is one of important problem. Therefore, this paper focus on reducing axial shape index parameter. The other three design limits are also described at Table 1 [1][6]. ITC is isothermal temperature coefficient,  $F_q$  is three-dimensional power peaking factor. The shutdown margin is set referred mPower which is one of soluble-boron free SMPWR [2]. In addition, ASI limit is set as -0.4 to 0.4 according to previous soluble boron free SMPWR design [1][6].

**Table 1** Design parameter and design limit

Parameter	Value
Thermal power	180 MW
Target cycle length	~ 50 months (1,500 days)
Fuel assembly type	17X17 Westinghouse
Fuel assembly pitch	21.504 cm
Fuel enrichment	4.95 w/o U-235
Burnable absorber	1) Natural gadolinium R-BA
	2) Gadolinia (2 w/o $Gd_2O_3$ and 8 w/o $Gd_2O_3$ ) Integral Burnable Absorber (IBA)
	3) $Al_2O_3/B_4C$ Wet Annular Burnable Absorber (WABA)
Number of FAs	37
Active core height	2.0 m
Control rod material	80 w/o enriched $HfB_2$
Inlet/Outlet temperature	285 °C/306 °C
Flowrate	1,600 kg/sec
Pressure	155.1 bar
Reflector material	Zircaloy
Cladding material	Zircaloy
Boron concentration	0 ppm
ITC	ITC < 0 pcm/°C
$F_q$	$F_q < 5.09$
ASI	-0.4 < ASI < +0.4
Shutdown margin	> 3,000 pcm

### 3. Optimal conceptual design of SMPWR

This section presents the optimal conceptual design of SMPWR for using optimization progress of control rod operation. Fig. 1 presents the layout of six assemblies loaded in the core [1]. Pin 8 is natural gadolinium ring-type burnable absorber (R-BA). Ring

type burnable absorber is coated outside of cladding material, due to so, the lower conductivity of gadolinium does not affect to amount of uranium in contradistinction to gadolinia. Fig. 2 presents the loading pattern of optimal core [1]. There are 37 fuel assemblies are loaded and Fig. 3 presents the axial zoning of each assemblies [1].

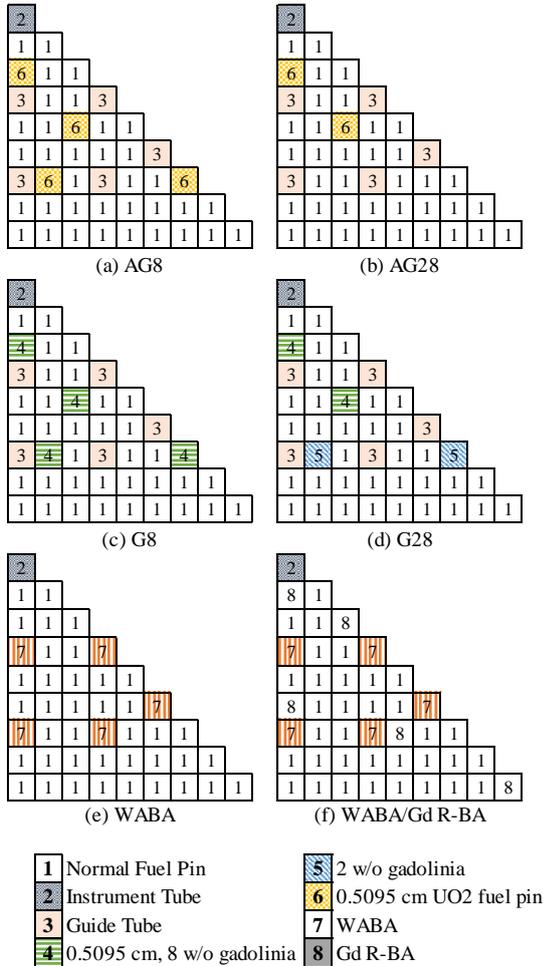


Fig. 1 Layout of assemblies loaded in core

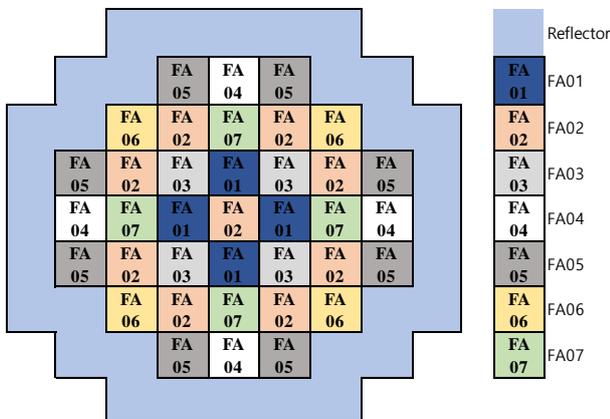


Fig. 2 Layout of optimal loading pattern

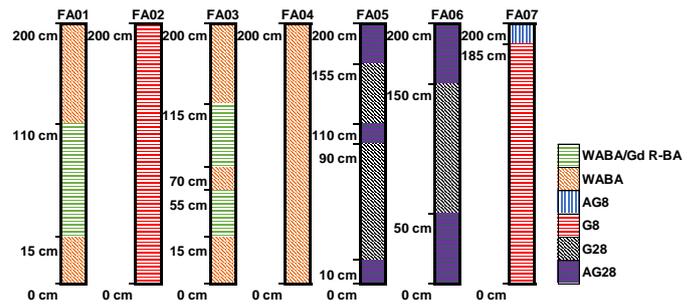


Fig. 3 Axial configuration of assemblies

### 3. Sensitivity study of control rod operation

This section presents the sensitivity study of control rod operation for SMPWR model introduced at section 2. Fig. 4 shows the radial layout of control rods and Fig. 5 presents the axial configuration of control rods. A is adjuster rod for controlling excess reactivities, R is regulating back for load following operation, P is ASI control rod for reducing the axial power distortion, S1 and S2 are shutdown rods. All rods are used 80 w/o enriched  $\text{HfB}_2$  for suppressing high amount of excess reactivity.  $\text{HfB}_2$  has  $55.0 \text{ cm}^{-1}$  macroscopic cross section and has been used in commercial PWRs [1][9][10]. Only P rod has axial heterogeneous configuration compared with other rods. The bottom of 140 cm height is composed of 80 w/o enriched  $\text{HfB}_2$  and the top of 60 cm height is employed stainless steel.

Fig. 6 presents the depletion characteristic of SMPWR with critical rod search calculation. The graph of ARO (all rod out condition) presents the excess reactivity of SMPWR. At the beginning of cycle (BOC), the SMPWR has highest excess reactivity as 5,186 pcm. The graphs of CR layout A, CR layout B and CR layout C, are drawn by critical rod search calculation and are shown the control rods could be controlled excess reactivity. Fig. 7 presents the axial shape index of three different control rod layouts. The black lines are design limits as -0.4 and 0.4. Only CR layout C satisfies the design limit. Fig. 8 shows the three-dimensional power peaking factor and three different CR layouts satisfy the design limit. Fig. 9, Fig. 10 and Fig. 11 present the control rod positions during the critical rod search calculation. The black line of A rod is positions of adjuster rods and the blue line of P rod is positions of ASI control rod.

In addition, the other import design parameter is cycle-length and this value is shown in Table 2. The cycle length is set as operating period of SMPWR under design limits. CR layout A only has 481 operating period, CR layout B has 107 cycle length and CR layout C has 1,577 EFPDs. CR layout C has at least 1,096 extra operating days compared with other two layouts. Therefore, the CR layout C is selected as

optimal control rod position for suggested SMPWR model.

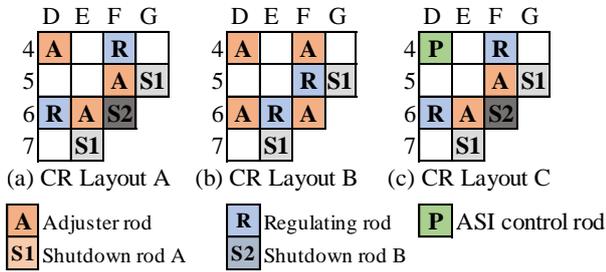


Fig. 4 Layouts of control rod positions

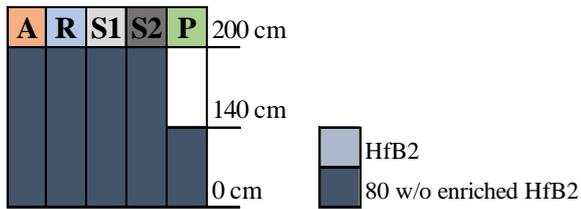


Fig. 5 Axial configuration of control rods

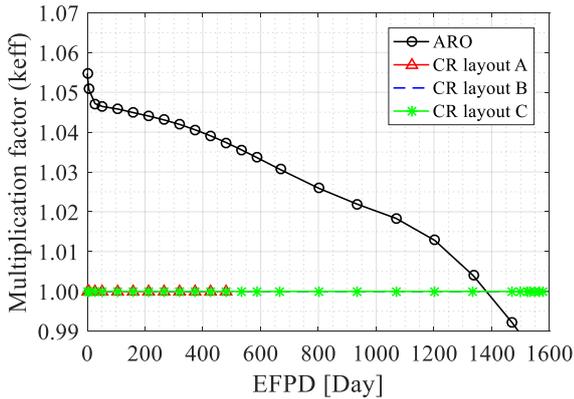


Fig. 6 Depletion characteristic of SMPWR with critical rod search calculation

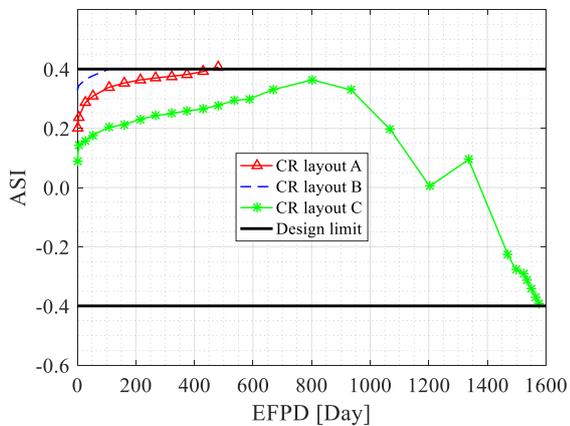


Fig. 7 Axial shape index with three different control rod layouts

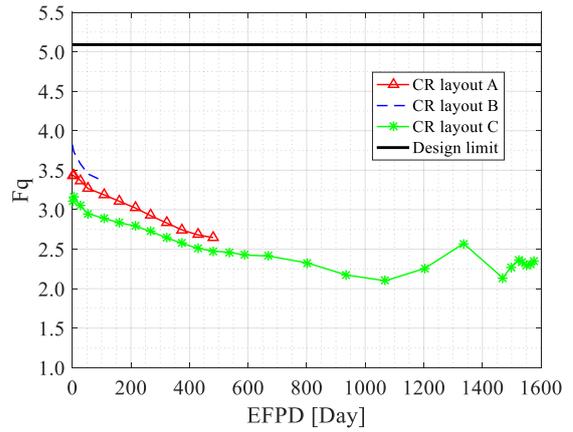


Fig. 8 Three-dimensional power peaking factor with three different control rod layouts

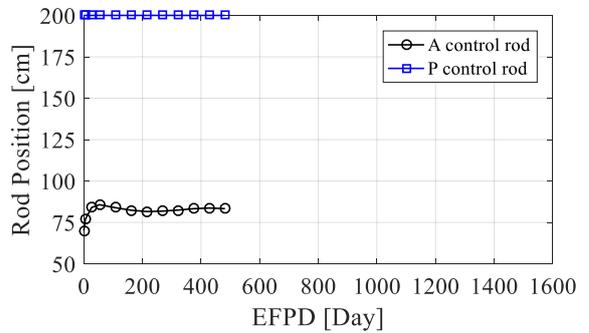


Fig. 9 Control rod position of CR layout A

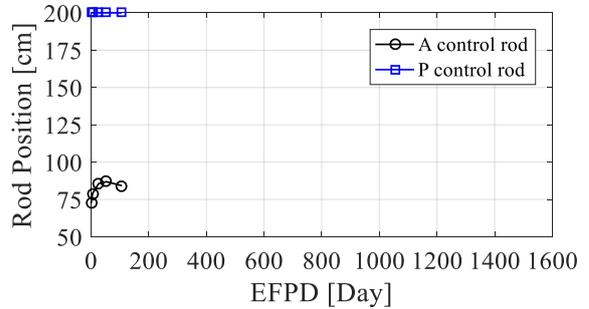


Fig. 10 Control rod position of CR layout B

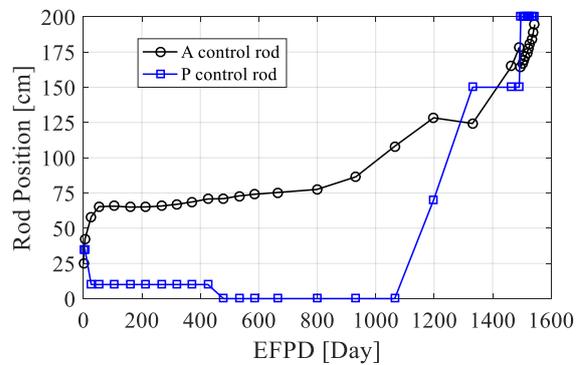


Fig. 11 Control rod position of CR layout C

**Table 2** Cycle length with three different control rod layouts

CASE	CR layout A	CR layout B
Cycle Length [EFPDs]	481	107
CASE	CR layout C	ARO
Cycle Length [EFPDs]	1,577	1,381

#### 4. Shutdown margin

To ensure the safety core operation, the shutdown margin is also important issue. When the core operation condition is changed to hot zero power from hot full power, the large excess reactivities caused by power defect are injected into the core. The shutdown margin is calculated the balance between this extra positive excess reactivities and negative reactivities produced by control rods. The design limit of shutdown margin is set as 3,000 pcm referred mPower [2]. While the shutdown margin calculation, stuck rod condition is considered to cover the conservative situation [1]. Table 3 presents the calculation results of shutdown margin with CR layout C. At the BOC, the shutdown margin is calculated as 3,223 pcm. Although middle of cycle (MOC) and end of cycle (EOC) results dose not mentioned at Table 3, two cases are also satisfied design limit as 3,700 pcm and 6,210 pcm, separately.

**Table 3** Shutdown margin with control rod with control rod layout C

State	BOC [0 GWd/MTU]
(1) = all-rod in worth – ASI Control rod worth	15,186
Stuck rod worth (2)	653
Uncertainty of rod worth (3) = (1) * 10%	1,519
Rod worth for criticality (4)	6,116
Engineering error (5)	100
Real worth (6) = (1) - [(5) + (4) + (3) + (2)]	6,798
Power defect from HFP to HZP (7)	3,475
Engineering error (8)	100
Total defect (9) = (7) + (8)	3,575
Shutdown margin (10) = (6) - (9)	3,223

#### 5. Conclusion

This paper suggests the optimal CR operation scenario for the SMPWR core with zircaloy reflector. The zircaloy reflector has an advantage to extend cycle length, however the excess reactivity also increases. In order to control large excess reactivity, it is necessary to use strong absorber material for control rods and to search optimized operation of control rods. HfB<sub>2</sub> with

B-10 enriched 80 w/o is utilized in this study and three different control rod layouts are suggested. To eliminate abnormal axial power shape during the operation, the control rod configuration which has different absorber materials axially is adopted at CR layout C. The CR layout C satisfies the design target with achieving the cycle length as 1,577 EFPDs and other two control rod configurations approach only 481 EFPDs and 107 EFPDs. To consider both design limit and target cycle length, the CR layout C is selected for optimal CR layout of SMPWR.

In perspectives, the different types of axial configurations for control rods will be tested to optimize the axial offset nearby 800 EFPDs.

#### ACKNOWLEDGEMENT

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