Load follow operation Performance Analysis of 180MWt SMR core with GdN-CBA

Sung Hyun Cho [a], Woojin Lee [a], Ser Gi Hong [a, *]
[a] *Department of Nuclear Engineering, Hanyang University*
*Author: hyujsh99@hanyang.ac.kr, * Corresponding author: sergihong@hanyang.ac.kr*

***Keywords: Load-follow operation, Soluble boron free, SMR, GdN-CBA.**

1. Introduction

Demand control in nuclear power plants has become a critical issue due to the innate instability of renewable energy source in power generation. Achieving demand control is possible through implementing load-follow operations of thermal and nuclear power. However, the high operating costs and low fuel costs of nuclear power make load-follow operations economically less attractive. Small Modular Reactors (SMRs) have been suggested as a solution with its modularity, and to ensure the modularity, the soluble boron free (SBF) operation is suggested which eliminates Chemical Volume Control System (CVCS) [1].

Nevertheless, during SBF operation, excess reactivity is solely adjusted by control rods (CRs) and burnable absorbers (BAs). This leads to issues such as unfavorable power distribution or reduced cycle lengths due to the excessive use of burnable absorbers. Furthermore, potential safety problems including high peaking factors and xenon oscillation during load-follow operation may occur. To mitigate these disadvantages, burnable absorbers utilizing spatial self-shielding effect of gadolinium has been conducted, such as CSBA [2].

Following this trend, a novel BA leveraging gadolinium coating was designed, which named Gadolinium Nitride Coating Burnable Absorber (GdN-CBA) [3][4]. GdN-CBA possesses ability to the fine-tune the spatial self-shielding of gadolinium, therefore enables precise control over excess reactivity and gadolinium depletion time, while mitigating issues associated with traditional gadolinia, such as low thermal conductivity and decreased cycle length [3]. In this paper, GdN-CBA will be utilized for designing a 3-batch SBF SMR core of 180 MW_{th} and demonstrated for its feasibility in usual and unusual load following scenarios through quasi-steady-state calculations.

2. Methodologies

Figure 1 illustrates the configuration of GdN-CBA. Previous study examined the favorable material properties and neutronic characteristics of GdN-CBA [4]. The Minima-Maxima-Mixing method was adopted to achieve a flat reactivity profile. The detailed reactivity profile of fuel assemblies are shown in Figure 2, and the parameters of the fuel assemblies are listed in Table 1.

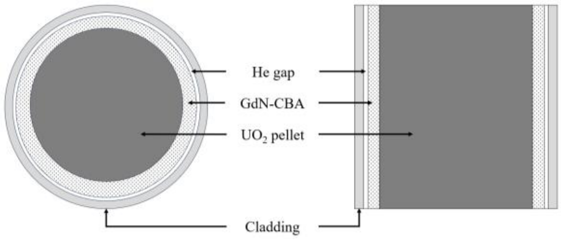

Figure 1. Configuration of GdN-CBA

Table 1. The major parameters of the fuel assembly

parameter	Value
Fuel array	17x17
Number of fuel pins	264
Number of guide tubes	24 / 1 instrument
Fuel assembly / rod pitch	21.5 cm / 1.26 cm
UO_2 Fuel pellet radius	0.4096 cm
Cladding inner radius	0.4178 cm
Cladding outer radius	0.4750 cm
Guide tube inside radius	0.5620 cm
Guide tube outside radius	0.6020 cm

The Type A assembly is considered as a special fuel assembly, which will be loaded at the core center, and burnt only single cycle. This Type A assembly implies relatively low uranium enrichment of 2.00 wt%, and the initial target k_{inf} value is approximately 1.05. The Type B assembly will be loaded around the core center and has a uranium enrichment of 4.95wt%, with an initial target k value of approximately 1.05. The Type C assembly, which will be loaded at the core periphery, has a uranium enrichment of 4.30 wt%, and its initial target k value is approximately 1.10. Figure 2 compares the evolutions of k_{inf} for these assemblies.

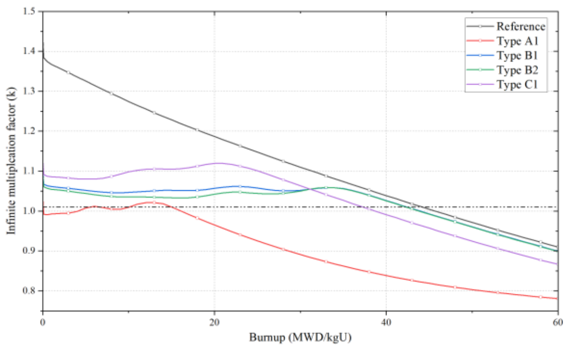

Figure 2. The infinite multiplication factors (k_{inf}) of the optimized fuel assemblies with respect to burnup

With the optimized fuel assemblies, a core with a 3-batch refueling scheme was designed. The core produces 180MW$_{th}$ of power, has an active height of 200cm, and a linear power density of 92.1 W/cm. Detailed parameters of the core are presented in Table 2. Since the SMR core utilizes only 37 fuel assemblies, the reactivity of each fuel assembly significantly influences the overall reactivity and power distribution of the core. Especially, the C type assemblies without sufficient burnup caused significant increase in radial peaking factor. As a result, each assembly within the core is designed to rotate in a triangular manner, gradually moving inward in a vortex-shape batch configuration. Figure 4 shows the detailed batch configuration.

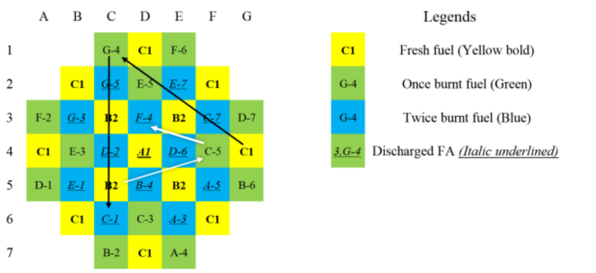

Figure 3. The 3-batch configuration of the core

Table 2. Major design and performance parameters of the core

Core parameters	
Core thermal output	180 MW$_{th}$
Core dimensions	200 cm (active height) 230cm (total height)
Linear power density	92.1 W/cm (per rod) 24.3 kW/cm (per FA)
Number of FA	37
Material density	10.220 g/cm^3 (UO_2 pellet) 8.645 g/cm^3 (GdN)
Fuel management	3-batch
Inlet/outlet temperature	288.0 ℃ (Inlet) 318.0 ℃ (Outlet)
Cycle length	1200 EFPDs (1st cycle) 600 EFPDs (Equ. cycle)
MTC	-57.2 pcm/℃ (1st cycle) -59.9 pcm/℃ (Equ. cycle)
Shutdown margin	20609 pcm (1st cycle) 18271 pcm (Equ. cycle)
k_{eff} under ARI (N-1)at CZP	0.93426 (1st cycle) 0.91791 (Equ. cycle)
Core target values	
Peaking factor limit	1.7 (2D) / 2.3 (3D)
Axial offset limit	-0.3 < A/O < 0.3
Xenon axial offset limit	-0.3 < Xe A/O < 0.3

To prevent rapid distortions in power during load follow operations, control rods are divided into regulation and shutdown banks. Regulation banks consist of 8 silver-indium-cadmium (Ag-In-Cd) rods, and 16 stainless steel 304 rods. Furthermore, regulation banks are inserted with overlap to alleviate negative axial offset issue. Figure 4 illustrates the position of regulation and shutdown banks in the core. The sliding T_{avg} mode was employed during load-follow operation, as shown in Figure 5, as the sliding T_{avg} mode is more frequently used than the constant T_{avg} mode for demand control in commercial PWRs.

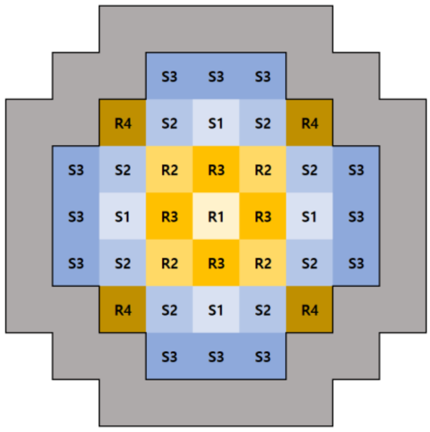

Figure 4. Configuration of the control rod banks

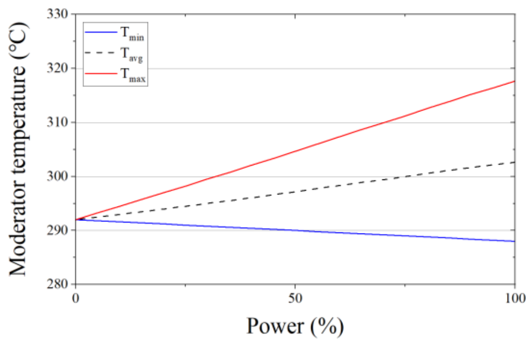

Figure 5. Change of moderator temperature with respect to the power output

The calculations for the fuel assemblies and the core were conducted using the Method of Characteristics (MOC) code DeCART2D and the nodal diffusion code MASTER, both developed by KAERI. During the MOC calculations, a ray interval of 0.01 cm was used, with 8 azimuthal angles and 3 polar angles per octant. The ENDF/B-VII.r0 was utilized as the cross-section library, with neutrons condensed into 47 groups and gamma rays into 18 groups. The group constants needed for nodal diffusion calculations were obtained through DeCART2D calculations and transferred to MASTER code via PROLOG and PROMARX coupling codes [5-6].

3. Results

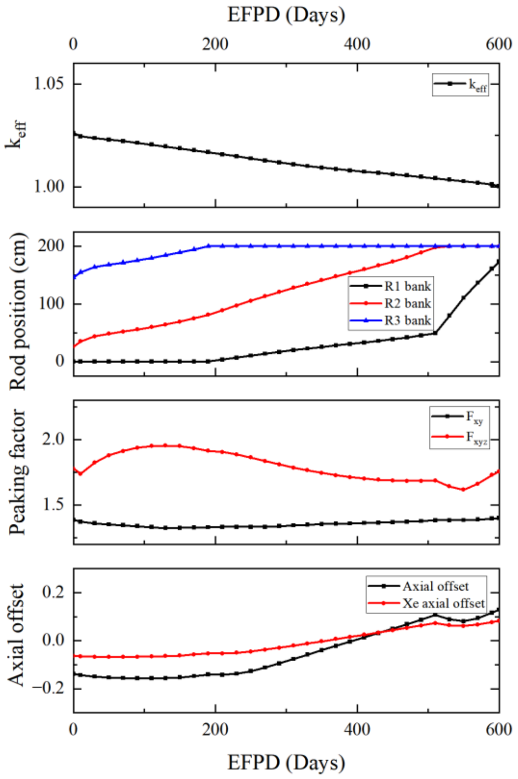

Figure 6. Changes of core parameters of the core at the equilibrium cycle

First, the steady-state calculation for the equilibrium cycle was carried out. The results are shown in Figure 6. Initially, the effective multiplication factor (k_{eff}) was approximately 1.03 at the Beginning of the Cycle (BOC) and decreased to the value of 1.0 by the end of the cycle (EOC). For control rods, the R1 and R2 banks remained inserted until the near end of the cycle, while the R3 bank was fully withdrawn around 200 EFPDs (Effective Full Power Days). The maximum 2D peaking factor was calculated to be 1.34, and the maximum 3D power peaking factor was observed to be 1.84 over the cycle. These values indicate a large margin compared to the design targets of 1.8 and 2.3, respectively. Due to the insertion of control rods, the axial power distribution is concentrated towards the bottom until reaching the Middle of Cycle (MOC). This is evident from the negative axial offset. Nonetheless, both the axial offset and the xenon axial offset were considered to have a substantial margin when compared to the target value of -0.3 < A/O < 0.3 and -0.3 < Xe A/O < 0.3.

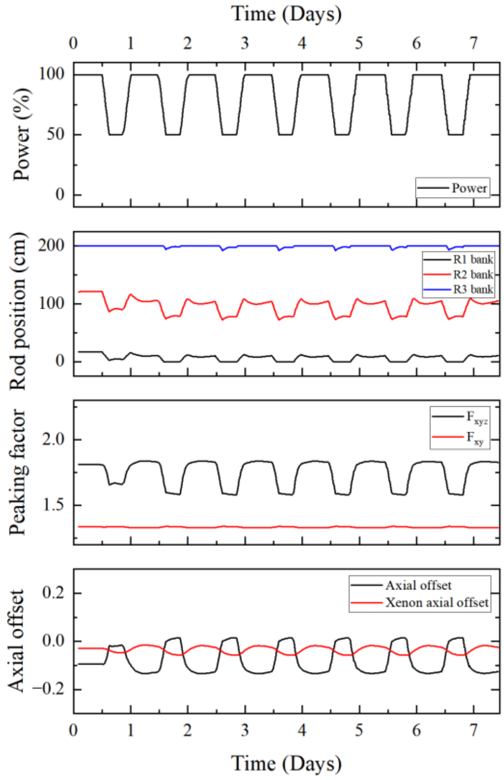

Figure 7. Changes of core parameters during usual load-following at the equilibrium cycle MOC

Next, calculations for the usual load-follow operation at MOC of the equilibrium cycle were conducted. The usual load-follow scenario was set according to European Utility Requirements (EUR) [7]. Specifically, it involved maintaining 100% rated power for 12 hours, reducing to 50% power over 3 hours, maintaining 50% power for 6 hours, and returning to 100% rated power over another 3 hours. This process was repeated a total of 7 times (approximately 7 days) and the changes in core parameters such as power peaking factor were observed. The results are presented in Figure 7. The calculations showed that the insertion and withdrawal of control rods were repeated to compensate the power defect caused by continuous power change. When rods were inserted, the peaking factor decreased as the overlapping strategy worked, while the axial offset became more negative. However, there were no instances where core parameters exceeded the target values during the 7 days of load-follow operation. The magnitude of xenon axial offset did not increase; therefore, xenon oscillation is considered not to be occurred.

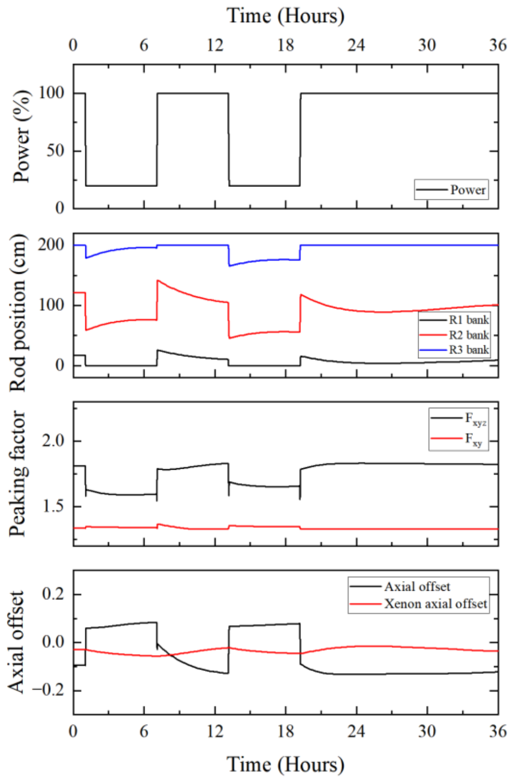

Figure 8. Changes of core parameters during unusual load-following at the equilibrium cycle MOC

Finally, calculations for the unusual load-follow operation at MOC of the equilibrium cycle were carried out. The unusual load-follow operation was also set according to the EUR standards. The power was changed by 20% of the rated power per minute, from 100% to 20% (and from 20% back to 100%). The results are depicted in figure 8. The calculations showed that control rods were rapidly inserted and withdrawn to compensate for the rapid power defect caused by the power changes. Nonetheless, similar to the usual load-follow operation, the power peaking factor, axial offset, and xenon axial offset remained within the target values. The maximum 2D peaking factor was 1.37, while the 3D peaking factor was 1.83 over the cycle. The absolute peak value of axial offset was 0.1321, which is considerably lower than the design target. Furthermore, it was observed that the magnitude of oscillation decreased progressively after the end of the unusual load-follow operation, returning to normal conditions after approximately 18 hours.

4. Conclusion

In this study, the feasibility GdN-CBA with a 3-batch SBF SMR core in load-follow operation was conducted. The GdN-CBA successfully controlled excess reactivity, effectively mitigating issues such as imbalance in axial power distribution or xenon oscillation. In both usual and unusual load-follow scenarios, critical core parameters, including power peaking factor and axial offset, were within the target. The power and xenon oscillation were not observed, even in the situation of rapid power change. Nonetheless, it is necessary to investigate further optimized fuel assemblies and the core in order to mitigate negative axial offset during load-follow operation across various cycles and conditions. In conclusion, the GdN-CBA has a potential to be used in SBF SMR core capable of load-follow operation and offers a better design for SMR with demand control ability.

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