Preliminary Analysis of Daily Load-Following Operation for OPR 1000 and Soluble Boron-Free SMR using DeCART2D/MASTER Two-Step Code System

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1. Introduction

In Rep. of Korea, according to the 11th basic plan for long-term electricity supply and demand, a 700 MW-class small modular reactor (SMR) is scheduled to be built by 2038. With the advancement of global carbon neutrality policy, the share of renewable energy in the domestic energy mix will unavoidably increase significantly. As a result, it will become difficult to maintain grid frequency (i.e., 60 Hz) within the target range with the existing power plants responsible for base-load generation. From the 2030s onward, SMR nuclear power plants will likely be required to perform load-following operations.

Leading nuclear countries are already promoting flexible operation of nuclear power plants in response to such global changes. International standards, such as the European Utility Requirements (EUR) and the Electric Power Research Institute Utility Requirements Document (EPRI URD), also specify performance requirements for flexible operation. Therefore, flexible operation technology is necessary not only to adapt to carbon-neutral policies but also to enhance competitiveness in nuclear power exports [1].

A soluble boron-free (SBF) SMR, unlike conventional pressurized water reactors (PWRs), can control the reactivity in the core without adjustments in soluble boron concentration, solely through the insertion and withdrawal of control rods. In conventional commercial PWRs, adjusting the soluble boron concentration for power level control took several hours. In contrast, SBF SMR allows for more flexible power control compared to conventional reactors, enabling it to respond more effectively to power fluctuations.

In this study, daily load-follow operation (DLFO) simulations for the equilibrium core of the Hanbit unit 3 OPR-1000 and the SBF SMR system were conducted by the DeCART2D/MASTER [2-3] two-step code system. For the OPR-1000, it will be confirmed that flexible operation is possible through the adjustment of regulating banks, boron concentration, and part strength control element assembly (PSCEA).

2. Daily Load Following Operation for OPR-1000

2.1 Daily Load Follow Operation (DLFO) Scenario

In this study, the DLFO with a typical load variation scenario for Hanbit unit 3 were simulated by the DeCART2D/MASTER code system. The 24-hour load variation scenario adopted from the OPR-1000 assumes the following typical power profiles: 50% power operation during low electricity demand hours from 3:00 to 9:00, gradual ramp-up to 100% power from 9:00 to 12:00, full power operation from 12:00 to 24:00 during peak demand hours, and a gradual ramp-down to 50% power from 0:00 to 3:00. Figure 1 shows the typical load variation scenario (12-3-6-3) in OPR-1000.

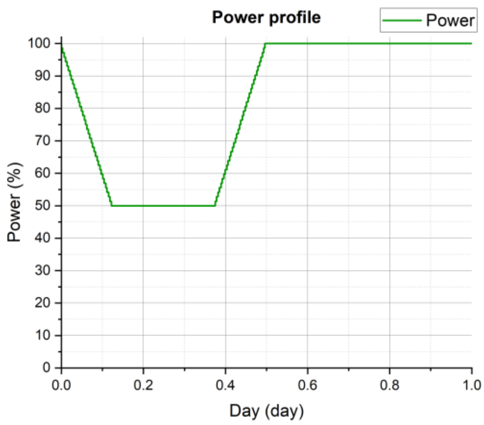

Fig. 1. Daily load following operation power profile (12-3-6-3)

2.2 Methods for DLFO

In simulating DLFO, three control mechanisms were employed to regulate reactor power: regulating banks (i.e., R1~R5), manual boron concentration adjustment, and PSCEA [4,5]. The DLFO simulations was performed at near BOC (40 EFPD) of the equilibrium cycle in the Hanbit Unit 3.

For the OPR-1000, power-dependent insertion limits (PDIL) are enforced on control rod movement to ensure sufficient shutdown margin (SDM) at various power levels. These limits shall be satisfied to ensure safe reactor operation. And operational parameters such as Axial Offset (AO) and power peaking factor (F_r and F_q) must remain within specified limits for the reactor to be considered in normal operation.

To achieve this, Regulating Banks 5 and 4 (R5 and R4) are primarily used to achieve criticality at the desired power level. In this process, the CRS command card in the MASTER code is utilized to define the control rod operation strategy [3]. To avoid violating the PDIL, boron concentration is manually adjusted. Furthermore, the PSCEA is used to manage the axial power distribution and ensure that AO and related parameters remain within acceptable operational limits.

2.3 OPR-1000 DLFO Results

At the beginning of DLFO, the R5 regulating bank was initially inserted 10% prior to initiating the load-follow sequence, with the regulating banks then adjusted to maintain an overlap distance of 228.6 cm. Figures 2 shows the critical rod position corresponding to power variations at the BOC. As power rises, the xenon concentration decreases, adding positive reactivity to the core, which must be suppressed by inserting control rods. Taking this into account, the regulating banks were adjusted in accordance with the PDIL of the OPR-1000.

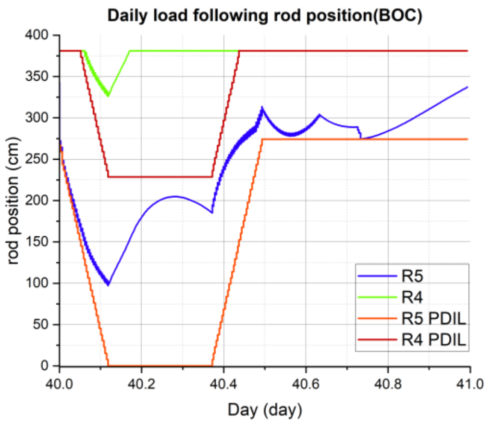

Fig. 2. Daily load following rod position and PDIL at BOC

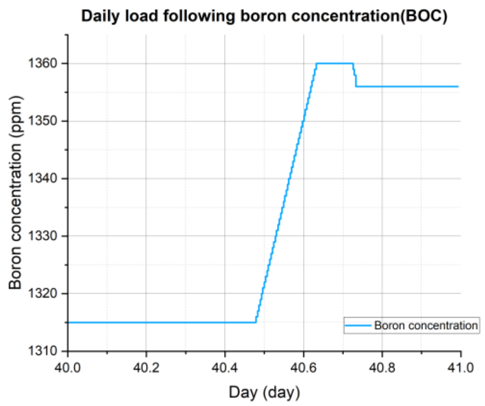

Fig. 3. Daily load following boron concentration at BOC

For the boron concentration at BOC, 1315 ppm of boron was injected at the start of load-following operation, and in order to maintain the regulating bank PDIL limit, the boron concentration was increased when the power returned to 100 % to offset the positive reactivity. It was then reduced to 1356 ppm for reactivity stabilization. Figure 3 shows the variation of boron concentration over time. After reactivity control through regulating bank movement and boron concentration adjustment, the PSCEA positions were adjusted to bring the axial power distribution within the allowable limit. The PSCEA started at a 20% insertion level. Figure 4 shows the time-dependent position changes of the PSCEA.

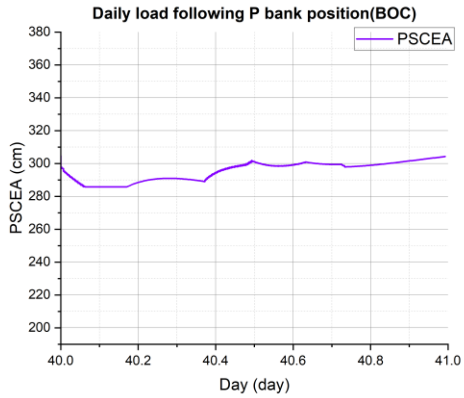

Fig. 4. Daily load following PSCEA position at BOC

The AO resulting from control rod adjustments, boron concentration control, and PSCEA position adjustments, are shown in Figure 5, and the F_q values are shown in Figure 6, respectively.

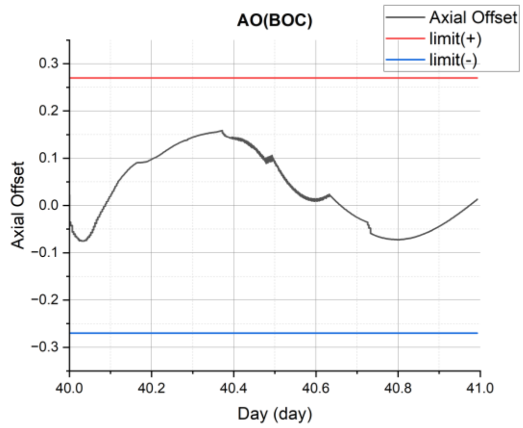

Fig. 5. Daily load following Axial offset variation at BOC

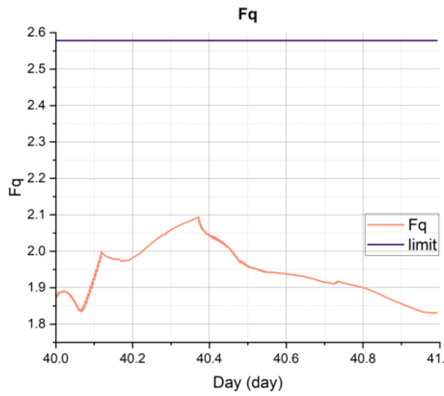

Fig. 6. Daily load following Peaking factor variation at BOC

3. Daily Load Following Operation for SBF SMR

3.1 Methods for DLFO

The same scenario as used previously for the OPR-1000 was adopted. Unlike the OPR-1000, the SBF SMR[6] does not control reactivity through boron, so the reactivity must be adjusted solely with control rods. Therefore, the CRS card in MASTER was used to create an input deck in which the regulating banks were inserted sequentially from R4 to R1, maintaining a 50% overlap interval. This approach was used to determine the critical control rod positions and adjust the reactivity accordingly.

3.2 SBF SMR DLFO Results

For the SBF SMR, burnup was carried out in DLFO mode at three burnup points; 40 EFPD, 230 EFPD and 330 EFPD. The critical control rod positions were determined using the MASTER code, and the time-dependent positions of each control rod are shown in Figure 7,8,9, respectively.

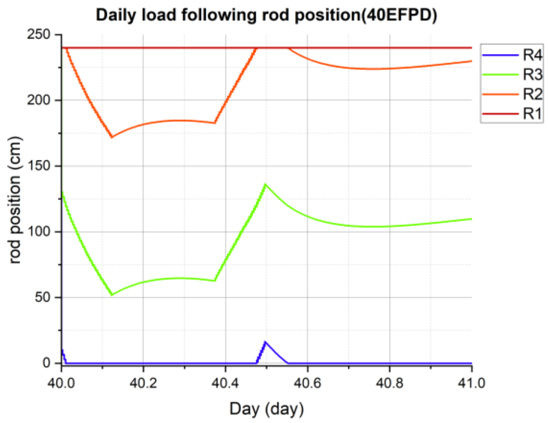

Fig. 7. Rod positions during daily load following operation in SBF SMR at 40EFPD

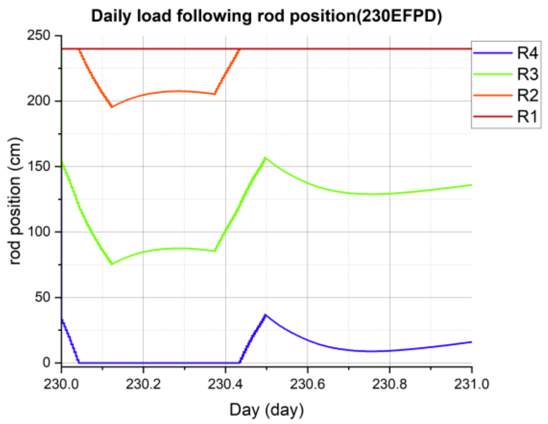

Fig. 8. Rod positions during daily load following operation in SBF SMR at 230EFPD

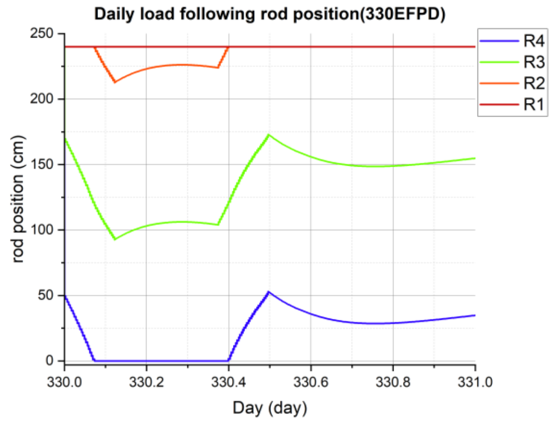

Fig. 9. Rod positions during daily load following operation in SBF SMR at 330EFPD

For the AO, at 40EFPD, maximum value is −0.1073 and minimum is −0.3541; at 230EFPD, maximum value is −0.0738 and minimum is −0.3024; and at 330EFPD, maximum value is −0.0878 and minimum is −0.2751.

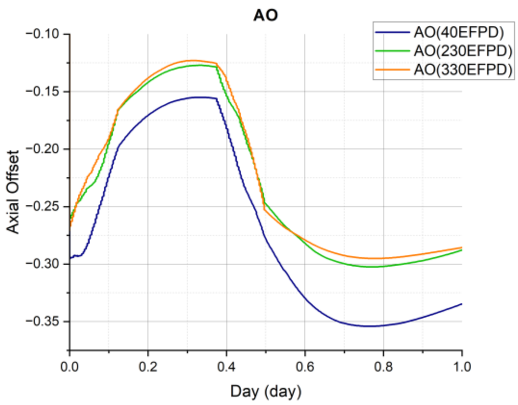

Fig. 10. Axial offset variation during daily load following operation in SBF SMR at three burnup points

For Fq, at 40EFPD, maximum value is 2.4501 and minimum is 1.8770; at 230EFPD, maximum value is 2.2710 and minimum is 1.7733; and at 330EFPD, maximum value is 2.2010 and minimum is 1.7877.

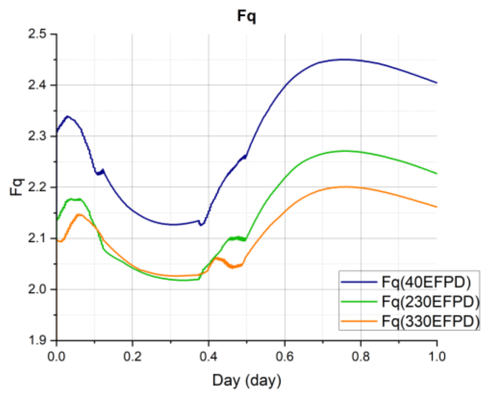

Fig. 11. Peaking factor variation during daily load following operation in SBF SMR at three burnup points

4. Conclusions

In this study, preliminary DLFO analysis were performed for both the OPR-1000 Hanbit Unit 3 and the SBF SMR using the DeCART2D/MASTER two-step code system. For the OPR-1000 equilibrium cycle, it was noted that the reactivity in the core was successfully controlled through adjustments of regulating bank, PSCEA, and boron concentration. Moreover, the axial power distribution was stabilized by regulating the PSCEA. It was confirmed that the operations of the DLFO for OPR-1000 meet the AO (-0.3 ~ 0.3) and F_q limits (< 2.55).

For the SBF SMR, which operates without soluble boron, reactivity is only controlled through regulating bank adjustments. As in the case of the OPR-1000, a stepwise control rod operation strategy was applied using the CRS card to determine the critical control rod positions. It was confirmed that the operations of DLFO for SBF SMR meet the AO (-0.3 ~0.3) and F_q (<2.55) limits which is the conventional limit for commercial PWRs as burnup progressed.

Acknowledgment

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