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A Study on Rodded Load Follow Operation Without Soluble Boron Adjustment in APR1400

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1. Introduction

With the global increase in the share of renewable energy sources, the demand for flexible operation of nuclear power plants (NPPs) has become increasingly important. To maintain the stability of the electric power grid, NPPs are now required to perform load follow (LFO) operations, shifting away from their traditional role as strictly base-load providers.

Traditional load follow operations rely on adjusting soluble boron concentrations, which generates large amounts of liquid radioactive waste and increases the operational complexity of the Chemical and Volume Control System. Furthermore, as the reactor approaches the end of the cycle (EOC), the effectiveness of boron adjustment becomes limited because the boron concentration is already low.

To address these drawbacks, rodded load-follow operation, which utilizes control rod movements without soluble boron adjustment, has been proposed as an alternative [1]. This study investigates boron-adjustment-free rodded LFO in the APR1400 under the Mode-K+ control logic. In particular, this study examines how the initial bank configuration affects power tracking and axial power distribution during a 100-80-100% load follow cycle at 90% EOC.

2. Methods

2.1 Reactor description

The analysis is conducted for the APR1400 initial core, a 1,400 MWe pressurized water reactor. Figure 1 illustrates the fuel assembly (FA) and control element assembly (CEA) loading pattern of the core. The control rod materials are as follows: Part Strength CEAs (PSCEA) are made of Inconel-625, while the Regulating Banks utilize B_4C with natural boron as the absorber material. The other design parameters and core specifications are consistent with the standard APR1400 design [2].

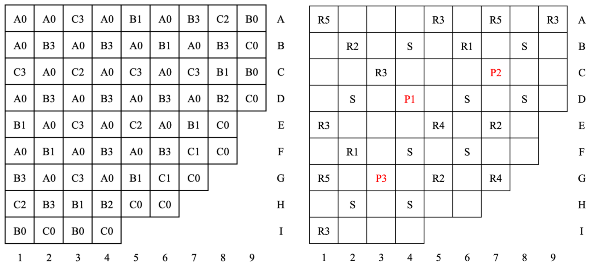

Figure 1 Fuel assembly and CEA loading pattern

2.2 Mode-K+ control logic

Mode-K+ is an automatic control algorithm designed to manage reactor power and axial power distribution during LFO [3]. It primarily utilizes the coolant average temperature and the Axial Shape Index (ASI) as control variables. The reactor power is controlled based on the temperature mismatch (ΔT), defined as the difference between the measured and the target coolant average temperature. As shown in Figure 2, the control logic evaluates ΔT against predefined deadbands to determine the CEA movement flag. Here, T_1 defines the ΔT condition for activating the control flag, whereas T_2 defines the condition for deactivating it. A positive ΔT requires rod insertion, while a negative ΔT requires rod withdrawal. Once the control flag is activated at T_1, it remains active until ΔT returns to T_2, thereby preventing frequent switching near the control boundary.

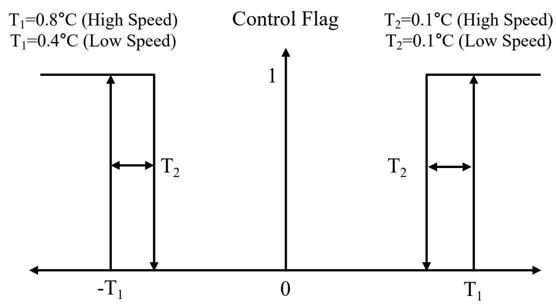

Figure 2 Temperature mismatch control flag

Simultaneously, Mode-K+ controls the axial power distribution from the ASI signal, ΔASI ($ASI^{current} - ASI^{target}$). As illustrated in Figure 3, the control state is classified into three stages: Acceptable ASI Stage (AAS), ASI Restoring Stage for a bottom-skewed shape (ARS+), and ASI Restoring Stage for a top-skewed shape (ARS−). Here, S_2 denotes the ΔASI limit for activating the ASI control flag, whereas S_1 denotes the limit for deactivating it. When ΔASI exceeds $+S_2$ or falls below -S_2, the control state changes from AAS to ARS+ or ARS−, respectively. Once activated, the ASI control remains active until ΔASI returns within $+S_1$ and -S_1, which avoids frequent switching near the setpoint. The values of S_1 and S_2 are power dependent, as shown in the bottom of Figure 3.

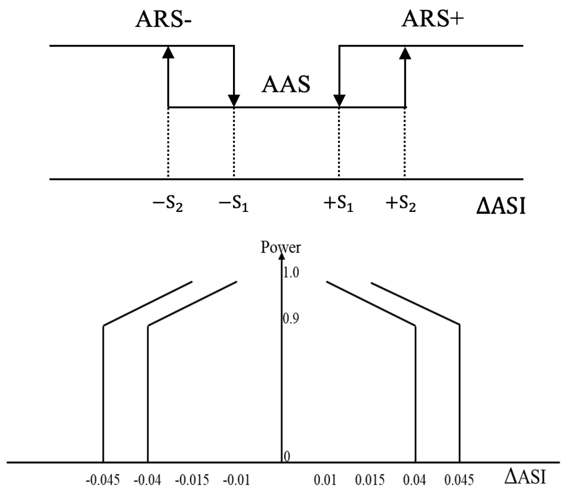

Figure 3 ASI deviation control flag

While the Mode-K+ algorithm can integrate soluble boron, this study employs a boron adjustment-free mode for rodded LFO. In this strategy, the boron concentration is kept constant throughout the transient, and the entire reactivity burden including the compensation for xenon dynamics and power defects is managed solely through the coordinated movement of the PSCEA and Regulating Banks.

2.3 Computational code

The analyses are performed using a conventional two-step method based on the SERPENT/KANT code. The homogenized group constants are generated using the SERPENT 2 continuous-energy Monte Carlo code with the ENDF/B-VII.1 library [4]. For the 3D whole-core calculation, the in-house nodal diffusion code KANT is employed, which solves the multi-dimensional neutron diffusion equations based on the NEM/CMFD scheme [5].

The transient calculations are performed by solving the time-dependent diffusion equations at each time step. The neutronics module provides power distributions, which are coupled with a thermal-hydraulic module to update the TH parameters. After convergence, the Mode-K+ module is invoked to determine appropriate control rod adjustments based on the temperature and ASI signals. This entire computational procedure is repeated throughout the LFO scenario [3].

3. Numerical Results

The simulations are performed for a 48-hour load follow operation at 90% EOC under a 100-80-100% power cycle, consisting of 14 hours at full power, a 2-hour ramp-down, 6 hours at low power, and a 2-hour ramp-up. In the boron-adjustment-free mode, the soluble boron concentration was fixed at the critical value corresponding to the initial CEA positions and remained unchanged throughout the transient. Under this condition, control rod movement becomes the only available means of accommodating the transient core behavior, making the initial bank configuration an important factor in the load follow operation. The PSCEAs move independently without overlap, while a 55% overlap is applied between adjacent regulating banks. In addition, the power-dependent insertion limits of the regulating banks are disabled in this study to enable rodded operation.

Table 1 summarizes the simulation cases considered in this study. The cases were constructed by varying the initial PSCEA positions so that different insertion configurations, from the lower region to the upper region of the core, could be systematically examined. In this way, the influence of the initial PSCEA locations on the subsequent load follow behavior and ASI control could be compared. In all cases, R5 was maintained at the ARO condition. Table 2 presents the reactivity worth of each control bank at 90% EOC, showing the very low worth of the Inconel PSCEAs.

Table 1 Initial bank positions for simulation cases

Bank Positions from the bottom (%)				
Case	P3	P2	P1	R5
1	0	100	100	100
2	0	50	100	100
3	0	0	100	100
4	0	0	50	100
5	0	0	0	100

Table 2 CEA worth at 90% EOC (unit: pcm)

	P3	P2	P1	R5	R4
CEA worth	92.5	92.5	88.8	432.3	509.8

Under the present 100-80-100% scenario, all cases show stable power tracking because the xenon oscillation remains within a relatively narrow range. Accordingly, the main differences among the cases appear not in the overall power-following capability but in the rod movement pattern and the ASI response. In all cases, the ASI remains generally bottom-skewed, which is an inherent feature of the present rodded load follow operation.

During the low-power period, ARS− control requires PSCEAs located in the lower core region. Since xenon increases after the ramp-down, rod withdrawal is unavoidable, and withdrawal of lower-core PSCEAs helps mitigate the top-skewed axial power shape. This behavior is observed in Cases 1-4. On the second day in Figure 4, however, the xenon concentration has not yet returned to the full-power equilibrium concentration, so the xenon change during the subsequent ramp-down becomes larger. As a result, the bank positions differ from those on the first day, and the rods become more biased toward the upper core, leading to a larger ASI increase during the following full-power period.

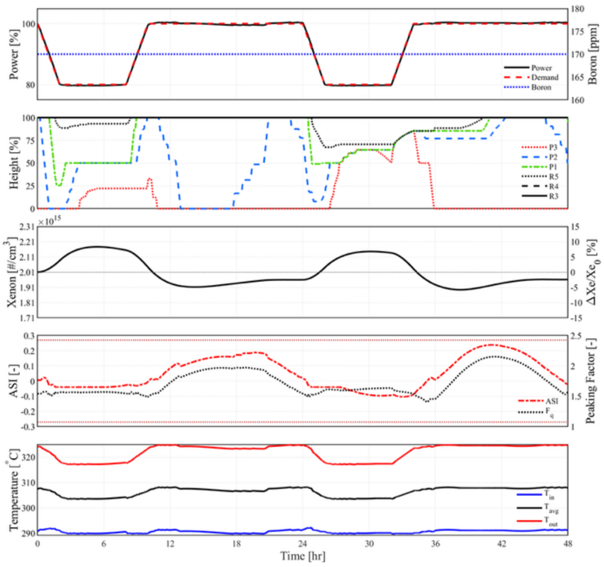

Figure 4. Simulation results for case 1

After the return to full power, ARS+ control becomes important because the xenon concentration starts to decrease and rod insertion is therefore required. Since the ASI remains generally bottom-skewed under the present rodded load-follow operation, effective insertion into the lower core region is needed during this period. The most favorable configuration for ARS+ control is for the PSCEAs to be located near the core mid-plane at the beginning of the full-power recovery period, so that they can be inserted into the lower core region and reduce the lower-core power. A representative example is Case 2 in Figure 5, where P2 and P1 are inserted into the lower core region and ARS+ control is achieved effectively. In contrast, in Cases 4 and 5 shown in Figures 7 and 8, most PSCEAs are already deeply inserted at the initial state, leaving few PSCEAs in a usable position for further insertion. As a result, effective ARS+ control is not achieved in these cases. Nevertheless, the ASI remains within the operating limit in the present 100-80-100% scenario because the xenon fluctuation is not large. However, this limitation may become more significant in a deeper load-reduction scenario such as 100-50-100%.

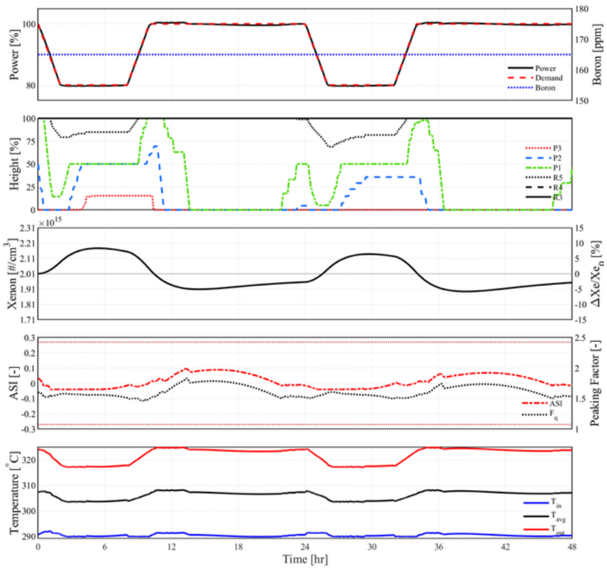

Figure 5 Simulation results for case 2

In repeated LFO cycles after the first day, the xenon concentration has not yet returned to its full-power equilibrium level. The xenon change during the second ramp-down is larger than that during the first cycle. Nevertheless, Cases 2 and 3 in Figures 5 and 6 show nearly identical CEA positions at 24 and 48 hours. This indicates that these cases develop a repeatable rod movement pattern during consecutive LFO cycles and maintain stable load follow behavior even under the larger xenon fluctuation of the later cycle. Although fuel depletion is not considered in the present 48-hour simulations, this is still reasonable because such load follow operation is not typically sustained continuously for a very long period, and the reactivity loss due to fuel depletion can be compensated by gradually reducing the boron concentration, as in base-load operation.

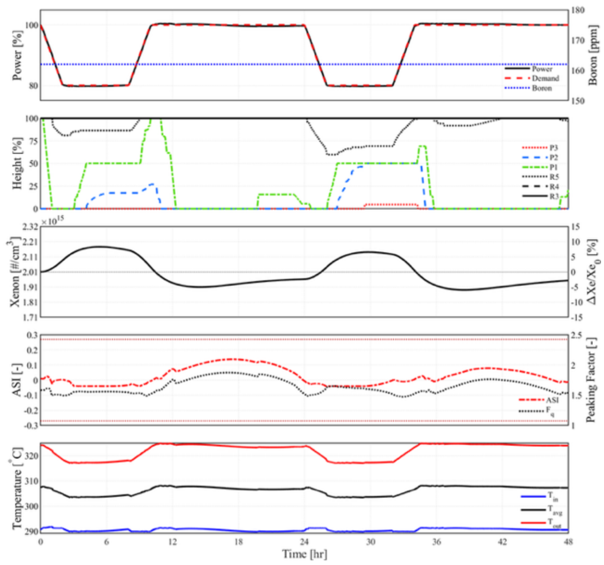

Figure 6 Simulation results for case 3

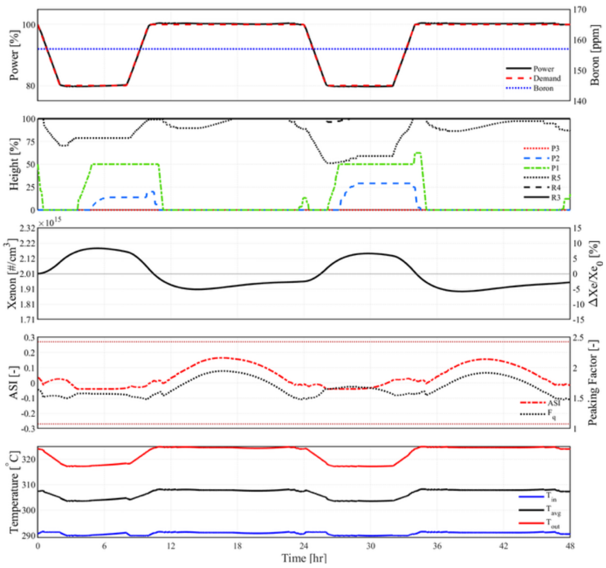

Figure 7 Simulation results for case 4

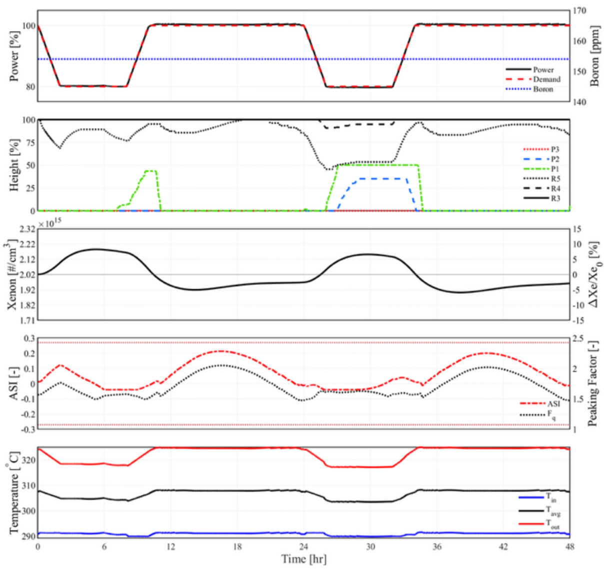

Figure 8 Simulation results for case 5

4. Conclusions

This study investigated boron-adjustment-free 100-80-100% rodded load follow operation in the standard APR1400 without design modifications. Under the present scenario, stable power tracking was achieved, while the main differences among the cases appeared in the rod movement pattern and the ASI response. The results indicate that the initial PSCEA configuration strongly affects the ASI control behavior. In particular, lower-core PSCEAs are favorable for ARS− control during the low-power period, whereas PSCEAs located near the core mid-plane are favorable for ARS+ control after the return to full power. In addition, some cases showed a nearly repeatable rod movement pattern over consecutive LFO cycles, suggesting that short-term repeated operation may be feasible under suitable initial configurations.

The present analysis is limited to the 100-80-100% scenario over 48 hours. Although this scope is reasonable for the present purpose, deeper load follow scenarios such as 100-50-100% may be more challenging because of the larger xenon fluctuation and the low worth of the current Inconel PSCEAs. These issues should be addressed in future work.

Acknowledgements

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