Rodded Daily Load-Follow Operation in APR1400 without Soluble Boron Adjustment Using Additional Part-Strength Control Element Assemblies

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1. Introduction

As the penetration of variable renewable energy sources grows, nuclear power plants are increasingly expected to operate flexibly [1]. Load-follow operation (LFO) in pressurized water reactors (PWRs) requires compensation for reactivity changes caused by power defect and xenon dynamics. Soluble boron adjustment is conventionally used together with control rod movement for reactivity control. Rodded LFO without soluble boron adjustment can reduce reliance on the chemical and volume control system, but places greater demand on control rod capability.

The APR1400 employs control element assemblies (CEAs), including full-strength CEAs (FSCEAs) and part-strength CEAs (PSCEAs). However, the limited number and worth of the conventional PSCEAs can restrict load-follow operation over a wide power range without soluble boron adjustment. Increasing the worth of individual PSCEAs can enhance reactivity control capability, but may also raise safety concerns associated with reactivity-initiated accidents (RIAs).

This study investigates rodded daily load-follow operation in the APR1400 with an increased number of available PSCEAs. Additional PSCEAs are considered through replacement of some FSCEAs when sufficient shutdown-margin allowance is available and through the use of spare CEAs. The resulting load-follow capability is examined through daily load-follow simulations without soluble boron adjustment.

2. Methods

2.1 Reactor Model

The APR1400 is a 3,983-MWt PWR with two reactor coolant loops and 241 fuel assemblies. The model uses the standard APR1400 initial core described in the Design Control Document (DCD) [2], including the core loading and major design parameters.

2.2 Increasing PSCEA Availability

The standard APR1400 CEA system consists of 81 FSCEAs and 12 PSCEAs, which use B4C and Inconel-625 absorbers, respectively [2]. To increase PSCEA availability, two options are considered: replacement of regulating FSCEAs and use of spare CEA locations. Figure 1 shows the standard CEA loading pattern and the candidate locations for additional PSCEAs.

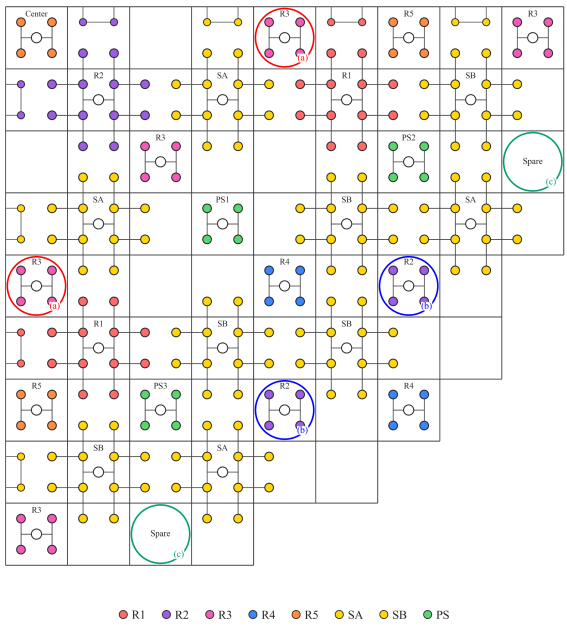


Figure 1 APR1400 CEA loading pattern and candidate locations for additional PSCEAs: (a) R3 replacement, (b) R2 replacement, and (c) use of spare CEA locations.

The first option considers replacing selected regulating FSCEAs with PSCEAs when sufficient shutdown margin (SDM) is available. APR1400 shutdown-margin evaluations under conservative assumptions have reported approximately 2,000 pcm of margin above the minimum requirement [3]. This margin allows limited FSCEA-to-PSCEA replacement to be considered while maintaining the required SDM. If additional shutdown worth is needed, it can be increased by enriching B-10 in the B4C shutdown absorbers [4]. B-10 enrichment therefore provides an additional option for securing sufficient SDM. Cases (a) and (b) apply this concept to four R3 CEAs and eight R2 CEAs in the full core, respectively.

The standard APR1400 design retains eight spare CEA locations, providing reserve positions for potential future control needs [2]. These locations are not assigned to the existing regulating, shutdown, or PSCEA banks

and can therefore be used to increase PSCEA availability without replacing existing FSCEAs. Case (c) utilizes all eight spare locations for additional PSCEAs.

2.3 PSCEA Absorber Configuration

In addition to the number and placement of PSCEAs, their individual worth is an important parameter for rodded LFO. The conventional Inconel-625 PSCEAs have very small worth, and previous work increased their control capability by replacing the absorber with Hf [5]. Changing the absorber material alone, however, offers limited control over the resulting PSCEA worth. The Hf absorber radius is therefore used as an additional degree of freedom for tuning the PSCEA worth. The remaining annular region is filled with Inconel-625 so that the overall absorber geometry remains unchanged. A Hf radius equal to 40% of the nominal absorber radius is denoted as Hf-0.4R and is used for all PSCEAs in the Hf-0.4R cases.

2.4 Mode-K+ Control Logic

Load-follow operation is controlled using the Mode-K+ algorithm, which determines CEA movement to control reactor power and axial power distribution [6]. The coolant average temperature and axial shape index (ASI) are used as the primary control variables. Reactor power control is based on the temperature mismatch, ΔT, between the current and target coolant average temperatures. A positive ΔT requires CEA insertion, whereas a negative ΔT requires CEA withdrawal. As shown in Fig. 2, separate thresholds are used for activating and deactivating the control flag, preventing frequent switching near the control boundary.

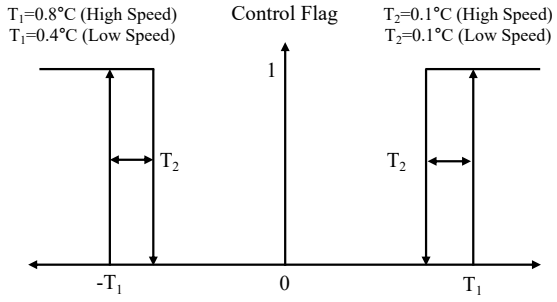


Figure 2 Temperature mismatch control flag

Axial power distribution is controlled according to the ASI deviation, ΔASI, between the current and target ASI values. As shown in Fig. 3, the Mode-K+ logic classifies the axial power shape into an acceptable ASI stage (AAS) and two ASI restoring stages (ARS+ and ARS−). When ΔASI exceeds the acceptable range, the control state changes to the corresponding restoring stage, and the CEA selection is adjusted to return the axial power shape toward the target. Separate thresholds are also used for activating and deactivating the ASI control, and their values vary with reactor power.

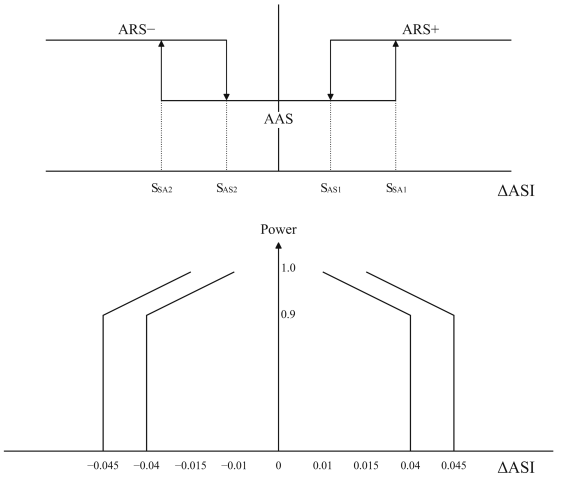


Figure 3 ASI mismatch control flag

In the rodded LFO simulations, the soluble boron concentration remains constant throughout the transient. Reactivity changes caused by power defect and xenon dynamics are therefore compensated by movement of the regulating banks and PSCEAs, with Mode-K+ determining the movement to follow the power demand while maintaining the axial power distribution.

2.5 Computational Code

The SERPENT/KANT two-step calculation scheme is used for the transient simulations. SERPENT 2 generates homogenized few-group constants [7] for KANT, which performs full-core transient calculations by solving the three-dimensional time-dependent neutron diffusion equations with neutronics–thermal-hydraulic coupling and xenon dynamics [8].

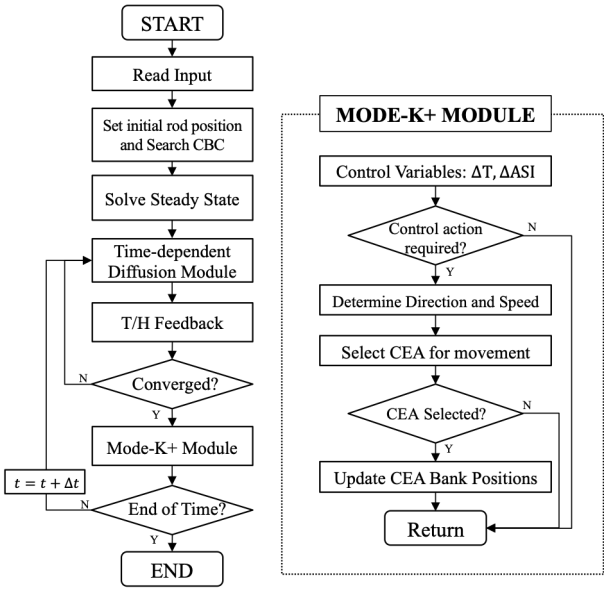


Figure 4 Flowchart of rodded daily load-follow operation

3. Results and Discussion

Rodded DLFO is evaluated at 90% EOC for 72 h under a repeated 14–2–6–2 h schedule. Each 24-h schedule consists of 14 h at full power, a 2-h power reduction to 50%, 6 h at 50% power, and a 2-h return to full power. For each configuration, the initial critical boron concentration is determined based on the initial rod positions and remains fixed throughout the transient. The three cases are evaluated independently as candidate configurations and are not intended to isolate the effects of PSCEA number or placement.

At 90% EOC, the Hf-0.4R absorber increases the PS1 bank worth from 95.7 to 156.8 pcm, or 1.64 times the conventional Inconel-625 value, as shown in Table 1. The three Hf-0.4R cases have four or five PSCEA banks, with their corresponding total PSCEA worths summarized in Table 2.

Table 1 PS1 bank worth at 90% EOC

Absorber	PS1 bank worth [pcm]	Normalized PS1 Bank Worth
Inconel-625	95.7	1.00
Hf-0.4R	156.8	1.64

Table 2 PSCEA availability and worth at 90% EOC

Case	Absorber	No. of PSCEA Banks	Total PSCEA Worth [pcm]
(a) R3 replacement	Hf-0.4R	4	643.5
(b) R2 replacement	Hf-0.4R	5	782.8
(c) Spare utilization	Hf-0.4R	5	624.0

Simulations with the conventional Inconel-625 PSCEAs fail to satisfy the required power and ASI control in all three cases. This indicates that increasing PSCEA availability alone is insufficient when control rods with relatively weak neutron absorption, such as Inconel-625 PSCEAs, are used. With Hf-0.4R, the PS1 bank worth increases from 95.7 to 156.8 pcm, corresponding to 1.64 times the conventional Inconel.

With Hf-0.4R PSCEAs, all three cases complete the 72-h 100–50–100% LFO. The maximum power-tracking error remains below 3%FP, and the ASI remains within the ±0.30 safety range throughout the simulations. The ASI also returns toward the target value of 0.1 following each power change, showing effective axial-shape control during the repeated load-follow cycles.

The results indicate that higher individual PSCEA worth and increased PSCEA bank availability together provide the control capability required for the present rodded DLFO. The standard three PSCEA banks are increased to four banks in case (a) and five banks in cases (b) and (c), giving Mode-K+ additional low-worth banks for reactivity and axial-shape control.

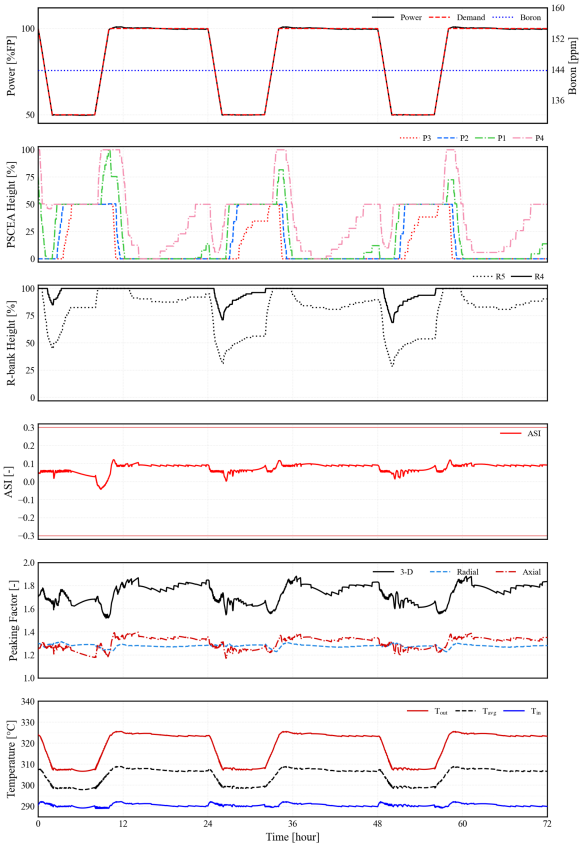


Figure 5 DLFO results for case (a) at 90% EOC.

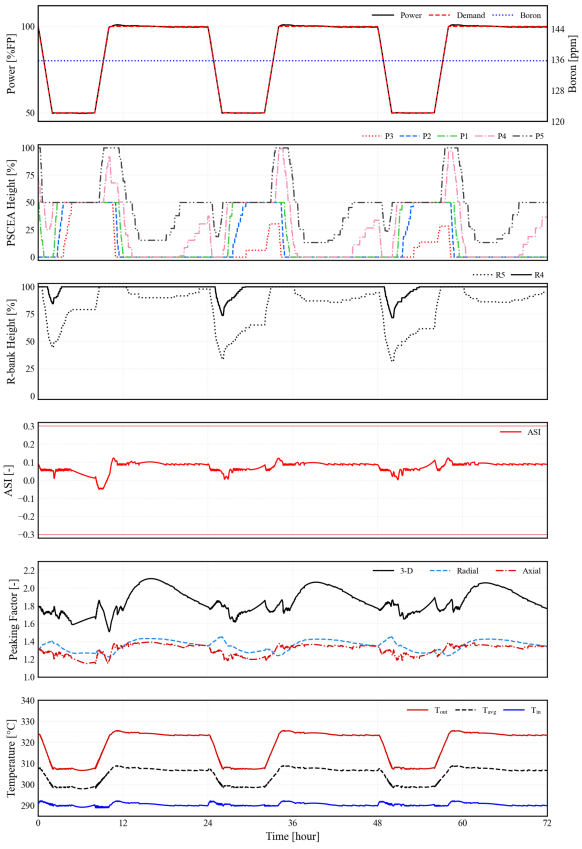


Figure 6 DLFO results for case (b) at 90% EOC.

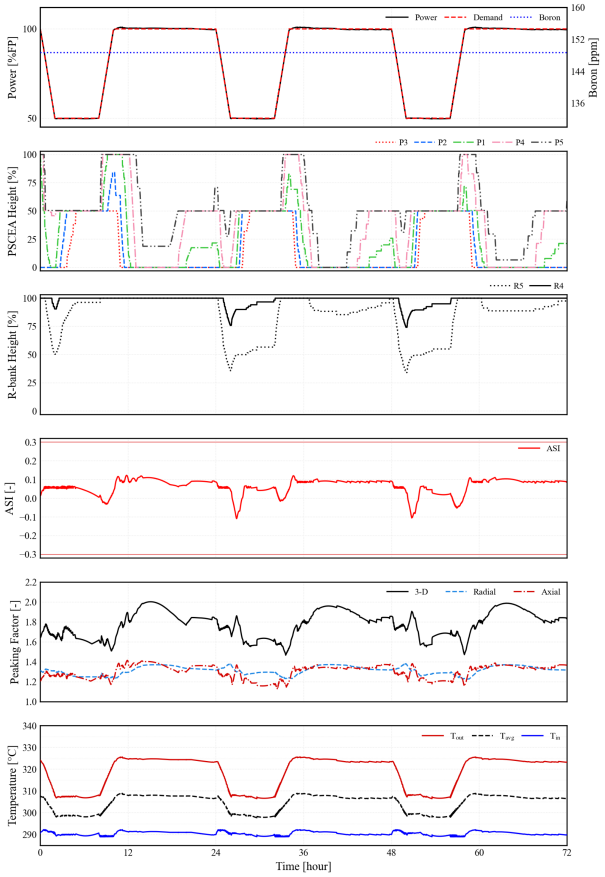


Figure 7 DLFO results for case (c) at 90% EOC.

Case (a) successfully follows the 72-h 100–50–100% load-follow schedule with one additional PSCEA bank, while case (c) demonstrates the same capability using two additional banks at the spare CEA locations without replacing existing FSCEAs. Together with case (b), these results show that several CEA configurations can support the present rodded DLFO.

4. Conclusions

This study investigated 100–50–100% rodded DLFO in APR1400 at 90% EOC without soluble boron adjustment by increasing PSCEA bank availability and using Hf-0.4R PSCEAs. The Hf-0.4R absorber increases the PS1 bank worth to 1.64 times the conventional Inconel-625 value, while the standard three PSCEA banks are increased to four or five banks depending on the CEA configuration. All three cases complete the 72-h load-follow schedule with a maximum power-tracking error below 3%FP, and the ASI remains within the ±0.30 safety range while returning toward the target value. These results show that sufficient individual PSCEA worth together with increased bank availability can provide the reactivity and axial-shape control required for wide-range rodded DLFO.

Increasing the availability of relatively low-worth PSCEA banks therefore provides a practical design option for extending the flexible operating capability of the APR1400 without soluble boron adjustment. Regulating FSCEAs can be replaced when sufficient shutdown margin is available, while the spare CEA locations provide another option without removing existing FSCEAs. The present work focuses on load-follow control feasibility; future work will directly quantify the shutdown margin of the FSCEA-replacement cases and evaluate the safety impact of the increased PSCEA worth.

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