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Feasibility of Daily Load-Follow Operations without Soluble Boron Adjustment in APR1400

Husam Khalefih, Yunseok Jeong, and Yonghee Kim
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea
husam.khalefih@kaist.ac.kr, yongheekim@kaist.ac.kr

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1. Introduction

During the Daily Load Follow Operation (DLFO) in standard Pressurized Water Reactors (PWRs), various reactivity feedback mechanisms occur due to changes in core power. Factors such as fuel temperature, coolant temperature, and xenon concentration introduce different reactivity effects that must be managed through the Control Element Assembly (CEA) or adjustments in the concentration of soluble boron [1].

Soluble boron concentration adjustments offer effective reactivity control within the reactor core. Since the boron is uniformly distributed, these adjustments minimize the impact on the radial and axial power profile distribution that typically results from CEA movement. Moreover, adjusting soluble boron has a negligible effect on the Axial Power Index (ASI). However, using soluble boron during DLFO presents unavoidable challenges. The processes of boration and dilution are inherently slow, particularly dilution, making it impractical to rely solely on soluble boron for DLFO when rapid power adjustments are required [2].

The Chemical and Volume Control System (CVCS) in PWRs is responsible for controlling boron concentration within the reactor system. During the dilution process, clean demineralized water is introduced into the system to reduce boron concentration, which subsequently increases the volume of liquid radioactive waste produced by reactor operations. Under DLFO conditions, unlike in base load operations, the daily power ramp-up and ramp-down processes would significantly increase liquid radioactive waste due to the repeated boration and dilution cycles [3].

One straightforward solution is to conduct DLFO without altering the soluble boron concentration. However, this approach presents several challenges. In the CPR1000 reactor, Li Wang studied the feasibility of performing DLFO without adjusting soluble boron, focusing on modifying the original control logic to enhance DLFO capacity [4]. Similarly, Yawei proposed adjusting CEA locations and groupings to address the difficulties of DLFO without soluble boron adjustments [5].

Another example of DLFO without soluble boron adjustment is found in Soluble Boron Free (SBF) PWRs. Ahmad developed a control logic to perform DLFO in the SBF reactor design ATOM [6]. The primary challenge in this study was the highly negative Moderator Temperature Coefficient (MTC), which necessitated a very high CEA worth to manage the large power defect. However, due to the small core size, axial power control during DLFO was less problematic.

This study investigates a soluble boron adjustment-free DLFO in the standard APR1400 initial cycle. The Mode-K+ control logic has been employed, and the CEA design modified to enhance DLFO performance. The analysis was conducted using the in-house 3D time-dependent diffusion code KANT [7]. Two-group cross-sections were generated using the Serpent 2.2.0 Monte Carlo code with the ENDF/B-VII.1 data library [8].

2. Reactor Description

The APR1400 reactor comprises 241 fuel assemblies with varying fuel enrichments for the initial cycle. The core has an active height of 3.81 meters and operates at a rated thermal power of 3.981 GW. For reactivity and power control, the Reactor Regulating System (RRS) utilizes three Partial Strength Control Element Assemblies (PSCEA) containing Inconel neutron absorbers, alongside three Full Strength Control Element Assemblies (FSCEA) regulating banks equipped with B_4C absorbers. Figure 1 illustrates the CEA loading pattern in the APR1400 [9]. According to the standard operation technical specifications for the APR1400, the three PSCEA banks can be configured into various groupings based on operational status and operator requirements.

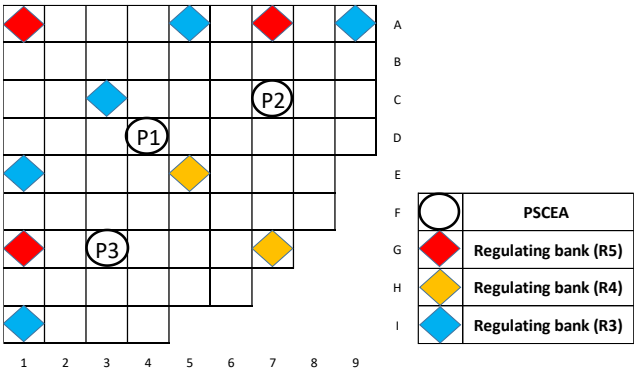

Figure 1 APR1400 CEA configuration.

3. Mode-K+ Control Logic

Mode-K+ controls reactor power during LFO by utilizing the average coolant temperature (T_{avg}) and the ASI signals. Figure 2 illustrates the input and output signal flow within Mode-K+. The target average coolant temperature, based on the demanded power, is calculated using the inlet temperature sensor data, as reactor power (P) can be defined by Equation (1):

$$P = h(T_{exit} - T_{inlet}) \quad (1)$$

where h represents enthalpy, and T_{inlet} and T_{exit} are the inlet and exit coolant temperatures, respectively.

The difference between the demanded average coolant temperature and the measured coolant temperature determines the necessary CEA movement. A positive difference indicates the need for CEA insertion, while a negative difference requires CEA withdrawal [1].

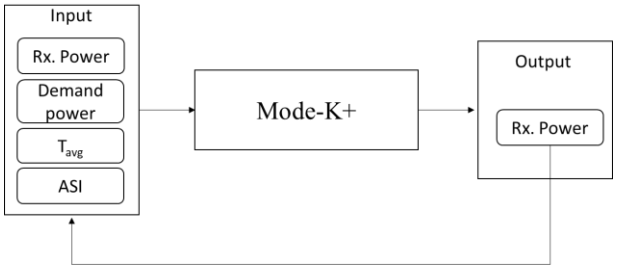

Figure 2 Schematic presentation of input/output in Mode-K+.

CEA selection is based on the anticipated effect of its movement on the ASI, defined by Equation (2):

$$ASI = \frac{P_{bottom} - P_{top}}{P_{bottom} + P_{top}} \quad (2)$$

The effect of CEA movement on the axial power profile depends on the initial CEA position. Insertion of the CEA in the upper half of the core reduces power in the top half and increases power in the bottom half, resulting in a more positive ASI [10].

Using KANT simulations, the required direction and magnitude of CEA movement are determined by the Mode-K+ module. The node-wise cross-sections are then updated at each timestep to reflect the new core configuration. Subsequently, the neutronic and thermal-hydraulic coupled time-dependent 3D diffusion equation is solved using the NEM-CMFD accelerated scheme to calculate the updated reactor status.

4. Soluble Boron Adjustment-Free Simulation

without soluble boron adjustment was evaluated for the initial cycle of the APR1400 at a burnup condition of 0.0 GWD/MTU. In this clean core configuration, using soluble boron during DLFO typically allows for effective control of both power and the ASI, as demonstrated by previous studies [11]. However, Figure 3 presents a 96-hour DLFO simulation at the Beginning of Cycle (BOC) in the APR1400 without soluble boron adjustment. While power control was executed with high accuracy, the ASI control failed to stay within the operational limits of ±0.3 due to the deep insertion of the strong regulating banks, as illustrated in Figure 4. [9]

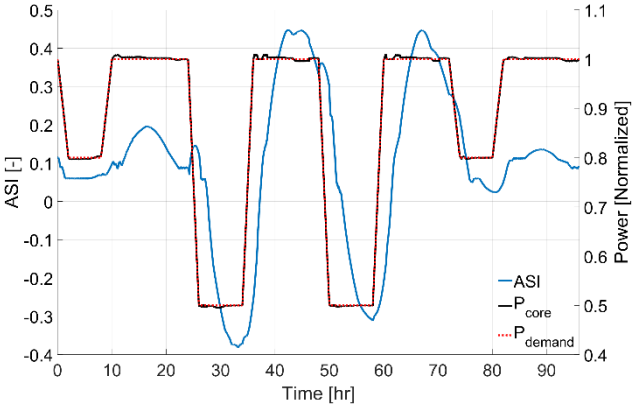

Figure 3 Soluble boron adjustment-free DLFO at the BOC condition in APR1400.

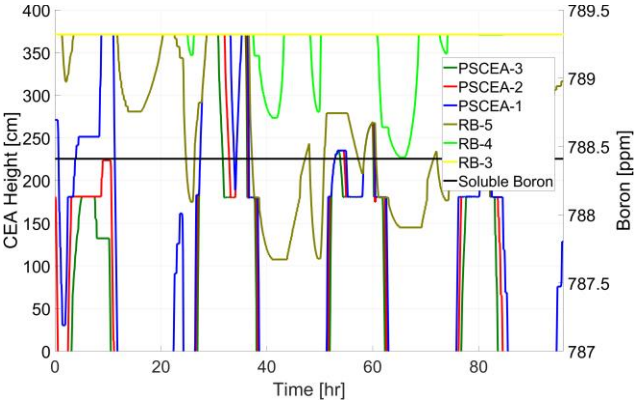

Figure 4 Simulation shows CEA position during 96-hours DLFO in standard APR1400.

To address this issue, a modification of the PSCEA design is required to achieve a slightly higher reactivity worth. One proposed solution is to replace the current Inconel neutron absorber with Hafnium (Hf). Hafnium has a long history of use in the nuclear industry, particularly in research reactors, where it is effectively utilized for reactor power control [12]. In both PWRs and BWRs, Hf has demonstrated its suitability for high operational temperatures due to its high melting point, which surpasses that of the commonly used Ag-In-Cd alloy [13]. Additionally, Hf's application in PWRs is notable for its resistance to swelling during irradiation. Figure 5 and Table 1 provide details on the standard PSCEA design parameters

used in the APR1400. In the proposed modified design, the absorber material would be replaced with Hafnium while maintaining the same dimensions. The Inconel cladding surrounding the absorber will ensure that there is no interaction between the coolant and the Hafnium, thereby safeguarding the absorber from wear and hydriding [13].

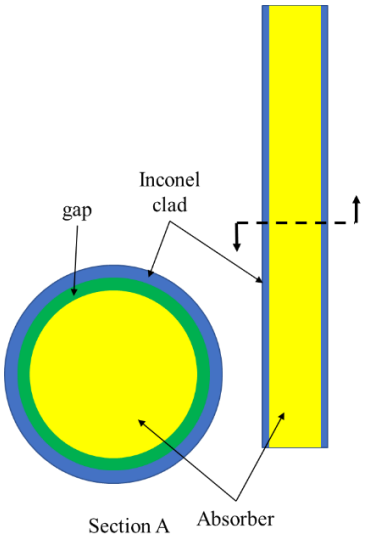

Figure 5 Schematic representation of the APR1400 PSCEA configuration.

Table 1 Standard APR1400 PSCEA design parameters [9].

Clad thickness (cm)	0.089
Clad outer radius (cm)	1.0365
Gap thickness (cm)	0.0115
Absorber radius (cm)	0.936
Absorber length (cm)	378.5

Replacing the Inconel absorber with Hafnium resulted in an increase in the total worth of the three PSCEA banks from approximately 200 pcm to 660 pcm at the BOC condition. This tripling of the PSCEA worth is expected to reduce the need for deep insertion of the regulating banks during DLFO, thereby improving ASI control.

5. Results and Discussion

To compare the performance of the new Hf-PSCEA with the standard configuration, a similar DLFO scenario was simulated. Figure 6 illustrates the 96-hour DLFO at the BOC with Hf-PSCEA. In this scenario, reactor power was reduced to 80% of full power on the first day and to 50% on the second and third days. On the final day, power was inserted back to 80% of full power. Compared to the results shown in Figure 3, the ASI demonstrated significantly better control, staying within operational limits throughout the four-day DLFO simulation. As anticipated, the insertion of strong regulating banks was minimized, particularly during the first and last days when the power was reduced to 80% of full power.

Similarly, during the second and third days, there was almost no insertion from regulating bank RB-4, which is significantly stronger than RB-5.

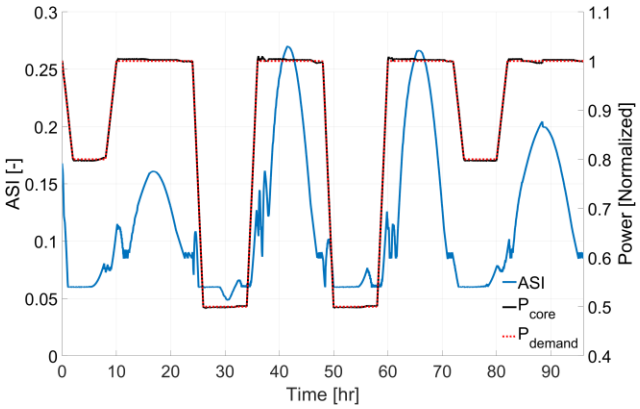

Figure 6 Soluble boron adjustment-free DLFO in APR1400 using Hf PSCEA.

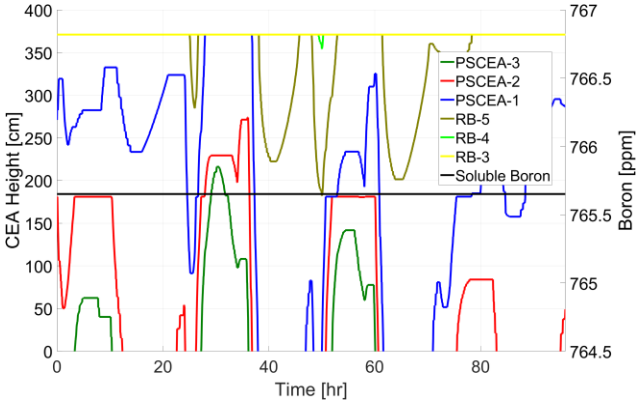

Figure 7 Simulation shows CEA position during 96-hours DLFO using Hf PSCEA in APR1400.

Another crucial safety factor to consider is the power peaking factor. Figure 8 presents the axial, assembly-wise radial, and 3D power peaking factors during the 96-hour DLFO scenario using the Hf-PSCEA. The simulation shows that the 3D power peaking factor remained below 2.0 throughout the entire simulation, assuming a conservative pin power peaking factor of 1.1. However, for a more accurate estimation of the 3D power peaking, pin-by-pin power reconstruction should be considered in future research.

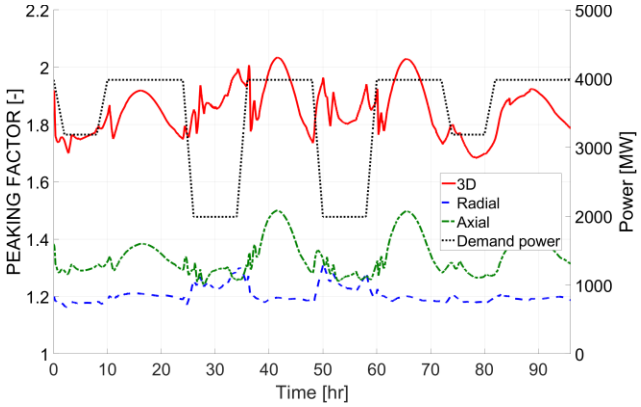

Figure 8 Radial, Axial, and 3D power peaking factor during DLFO using Hf PSCEA.

6. Conclusions and Future Work

Soluble boron adjustments during Daily Load-Follow Operation (DLFO) offer several advantages, such as minimizing radial and axial power peaking and exerting a negligible effect on the axial power profile. However, due to the slow speed of the boration and dilution processes, this method is ineffective for rapid power insertions. Additionally, the dilution process generates a substantial volume of liquid radioactive waste, as clean water must be introduced into the system.

In this study, the capability of the standard APR1400 to perform DLFO without soluble boron adjustment was investigated. It was found that with the standard design, which includes weak Partial Strength Control Element Assemblies (PSCEA), the Axial Shape Index (ASI) control fails, particularly during significant power reductions, such as down to 50% of full power. To address this issue, Hafnium (Hf) was proposed as a replacement for the Inconel used in the standard PSCEA design. This substitution, without modifying the dimensions, increased the total worth of all PSCEAs from 200 pcm to approximately 660 pcm.

With the implementation of Hf-PSCEA, both power and ASI control demonstrated improved performance compared to the standard design. This improvement is primarily due to the reduced need for deep insertion of strong regulating banks. The Mode-K+ control algorithm was utilized in this simulation, using the in-house 3D time-dependent diffusion code KANT, with two-group cross-sections generated via the Serpent 2.2.0 Monte Carlo code.

For future research, the performance of the Hf-PSCEA design during DLFO at higher burnup levels will be investigated. This further study will help to determine the robustness and effectiveness of the proposed design under more advanced operational conditions.

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