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A Study on Daily Load-follow Operation in the APR1400 Reactor using Manganese-Based Partial Strength Control Element Assembly

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1. Introduction

In many countries, the Nuclear Power Plant (NPP) is required to be able to perform load variation, this process can be classified into two categories, the first one is the frequency operation, in which the power may fluctuate within 5% from the nominal power. The second scheme is called daily Load Follow Operation (LFO), in this scheme, the power plant shall be able to operate at two different power levels within 24 hours. Usually, power variation from 100% of rated power to 50% is considered a minimum requirement in the reactor design [1]. The motivation for such a requirement is to follow the power demand, which is varying depending on the season and the time of the day.

In this study, the performance of APR1400 during the daily load follow operation is investigated and the operation logic called Mode-K+ is utilized to perform the simulation [2]. The APR1400 control rod design has been modified to enhance the LFO capability, originally the Partial Strength Control Element Assembly (PSCEA) is made of Inconel alloy, which has a weak neutron absorption cross-section, in the modified design the Manganese PSCEA is introduced [3]. This modification enhanced the Control Element Assembly (CEA) worth which lead to less control rod insertion and then enhanced the power peaking factor and axial power distribution.

This simulation was performed using KANT (KAIST Advanced Nuclear Tachygraphy) code, which is an in-house 3D diffusion-based code. The time-dependent diffusion equation solution was utilized. Meanwhile, the cross-sections for the initial core were generated using the Monte Carlo code SERPENT 2, and ENDF VII.1 date library was adapted [4].

2. Methods and Design

2.1 Control Logic

The constant inlet coolant temperature design is utilized in the APR1400 steam generator, in this concept, the average core temperature between the cold and hot legs is controlled to match the power demand. In general, the targeted average temperature is determined based on the demanded core power, as described in figure 1. The inlet coolant temperature remains almost constant during the LFO. However, according to the technical specification, the cold leg temperature shall be maintained smaller than 293.3 ℃, and larger than 286.7 ℃ at thermal power smaller than 90 % of the full power, while the minimum value is 289.4 ℃ if the power is larger than 90% full power.

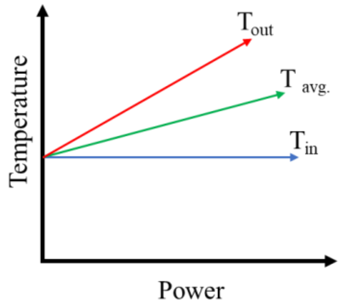

Fig. 1. APR1400 programmed coolant temperature as a function of the reactor power.

Using the Mode-K+ control logic, the Temperature mismatch (ΔT) which is defined as the difference between the targeted average temperature and the core average temperature is controlled, in this logic, there are two set points for the temperature mismatch to determine the speed of control rod movement. Figure. 2 describes the temperature control logic. Based on the control logic, if ΔT exceeds T1 then the control rods will move to recover the coolant temperature, the speed is determined based on the ΔT value, so if ΔT exceeds 0.4 K then the Reactor Regulating System (RRS) will drive the CEA with the minimum speed (0.127 cm/s), while if ΔT exceeds 0.8 K, RRS will move the CEA with a maximum speed (1.27 cm/s).To prevent frequency control when ΔT is close to the setpoint value, T2 was introduced as a latch condition so that the control flag will be activated until the ΔT is 0.1 K lower than T1. Similarly, the direction of the CEA movement is determined based on the ΔT sign. If ΔT is negative, CEA withdrawal is determined, while positive ΔT indicates CEA insertion is required.

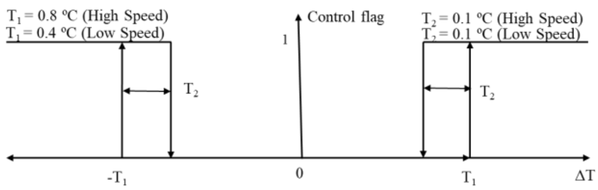

Fig. 2. RRS temperature control setpoint for Mode-K+.

In large size PWR, the temperature control only is not enough. Since there are different CEAs, there should be a selection criterion for the CEA movement, also the Axial Shape Index (ASI) should be properly controlled during the reactor operation. The ASI value can be controlled using a simple physical concept, which is that control rod insertion in the top half of the reactor core will increase the lower half's power, while the CEA withdrawal from the upper half will reduce the ASI compared to the initial status. The same thing happens in the lower half. A control rod insertion will reduce the lower half power, which means less bottom skewness while the withdrawal from the bottom half will lead to more bottom skewed axial power profile. From that, we define the ASI as the bottom half power minus the top half power divided by the total halves power.

To control the ASI, the ΔASI is defined as ($ASI_{current}$ - ASI_{target}). Based on the ΔASI value and sign, the ASI control flag is determined. Figure 3 shows the ASI control flag set points used in Mode-K+. ASI control is activated when the ΔASI value exceeds 0.015 at full power and it is deactivated when it is lower than 0.01, this setpoint value linearly changes up to 90% of the full power, while the setpoints are fixed at 0.045 and 0.04 when core power is less than or equal 90% of the full power.

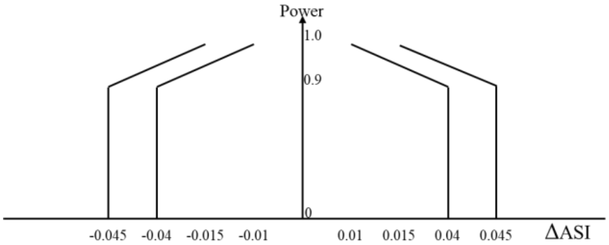

Fig. 3. The ASI control flag used in Mode-K+ control algorithm.

Mode-K+ has three stage flags, UARS+, UARS-, and AAS. In this case, UARS+ indicates that the power distribution is more bottom skewed than the target one, while the opposite is with UARS-. The AAS indicates Acceptable ASI, which means that the ASI is within the deadband. Tables 1 illustrate the CEA selection logic based on the ΔASI flag and the required movement direction.

Table 1. CEA selection logic based on ΔASI state flag. (W_{XX} = CEA XX position, B= bottom, H= active core height).

Condition			Selected CEA
Stage flag	**CEA direction**	**CEA Position**	
ΔASI+	Insertion	$W_{P3} > B$, $W_{P3} <= H/2$	**P3**
		$W_{P3} = B$,$W_{P2} > B$, $W_{P2} <= H/2$	**P2**
		$W_{P3} = B$,$W_{P2} = B$, $W_{P1} > B$, $W_{P1} <= H/2$	**P1**
		$W_{P3} = B$,$W_{P2} = B$, $W_{P1} = B$, $W_{R5+} > B$, $W_{R5+} <= H/2$	**R5+**
	Withdrawal	$W_{R5} < T$, $W_{R5} >= H/2$	**R5+**
		($W_{R5} = T$ or $W_{R5} <= H/2$), $W_{P1} < T$, $W_{P1} >= H/2$	**P1**
		($W_{R5} = T$ or $W_{R5} <= H/2$), ($W_{P1} = T$ or $W_{p1} <= H/2$), $W_{P2} >= H/2$	**P2**
		($W_{R5} = T$ or $W_{R5} <= H/2$),($W_{P1} = T$ or $W_{p1} <= H/2$), ($W_{P2} = T$ or $W_{p2} <= H/2$),$W_{P3} >= H/2$	**P3**
ΔASI-	Insertion	$W_{P3} > H/2$	**P3**
		$W_{P3} <= H/2$, $W_{P2} > H/2$	**P2**
		$W_{P2} <= H/2$, $W_{P3} <= H/2$, $W_{P1} > H/2$	**P1**
		$W_{P2} <= H/2$, $W_{P3} <= H/2$, $W_{P1} <= H/2$, $W_{R5} > H/2$	**R5+**
	Withdrawal	$W_{R5} > B$, $W_{R5} < H/2$	**R5+**
		($W_{R5} = T$ or $W_{R5} >= H/2$), $W_{P1} < H/2$	**P1**
		($W_{R5} = T$ or $W_{R5} >= H/2$), ($W_{p1} = T$ or $W_{p1} >= H/2$), $W_{P2} < H/2$	**P2**
		($W_{R5} = T$ or $W_{R5} >= H/2$), ($W_{p1} = T$ or $W_{p1} >= H/2$), ($W_{p2} = T$ or $W_{p2} >= H/2$), $W_{P3} < H/2$	**P3**

During the reactor operation, the temperature mismatch might be within the deadband. However, the ASI could be deviating from the target value, so an ASI control shall be performed. Figure 4 shows the control logic when the temperature is within the deadband, in this case, the CEA movement direction will be selected based on the sign of the ΔT, then the logic will search for a CEA movement that is favorable in terms of ASI control. If the CEA movement will enhance the ASI value, then the CEA will move, otherwise, the logic will search for a favorable CEA movement in the other direction, but two conditions shall be met. The first one is that CEA movement will lead to a favorable ASI value, and the second one is that the temperature is smaller than some deadband value T_d, this value shall be selected smaller than the temperature mismatch to guarantee that the CEA movement will not cause core temperature to exceed the limits.

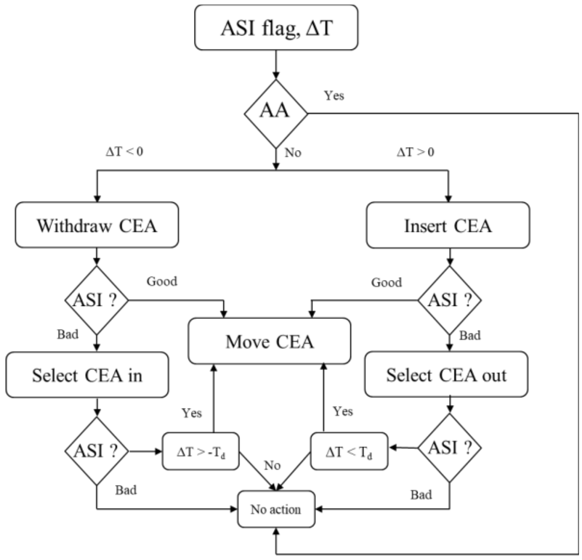

Fig. 4. ASI control logic when the temperature mismatch within the deadband.

2.2 Modified CEA Design

In this research the original PSCEA design has been modified to enhance the CEA worth, a Manganese-based PSCEA is introduced instead of Inconel one. Figure 5 shows the modified PSCEA control rod design, an Mn absorber with an Inconel clad is introduced. This cladding layer is very important to prevent any interaction with the coolant, which will eliminate the corrosion and help incontaining any radioactive material during the irradiation.

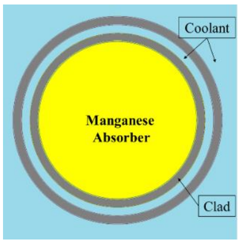

Fig. 5. Modified PSCEA control rod design using Manganese as absorber material.

Figure 6 shows the reactor core control rod loading pattern. Three PSCEA banks can be moving independently, which provides flexibility in terms of ASI control, while the regulating bank insertion is constrained with overlap, a 55% overlap is considered in the simulation between the regulating banks. PSCEA-3 is the leading bank, which means no other bank can be inserted in the core more than P3. Also, the PSCEAs have the priority in insertion, though the regulating banks have the priority in withdrawal.

R5				R3		R5		R3
	R2		S		R1		S	
		R3				P2		
	S		P1		S		S	
R3				R4		R2		
	R1		S		S			
R5		P3		R2		R4		
	S		S					
R3								

Fig. 6. APR1400 Control Element Assemblies (CEA) loading pattern (P = PSCEA, R = Regulating, and S = Shutdown bank).

3. Results

The replacement of the Inconel with Mn-PSCEA increases the total worth of the 12-PSCEA from 194 pcm to 344 pcm. With stronger PSCEA the control rod insertion was reduced, providing a better radial power profile and enhancing the ASI control. Meanwhile, a stronger control rod worth leads to better temperature control. In this simulation, the power changes from 100% of Full Power (FP) to 50% FP in 2 hours and stays at 50% for 6 hours before ramping up again to full power in another 2 hours. Figure 7 shows the 24-hour LFO simulation scenario using the Inconel PSCEA, it shows a well-matching between the core power and demand power.

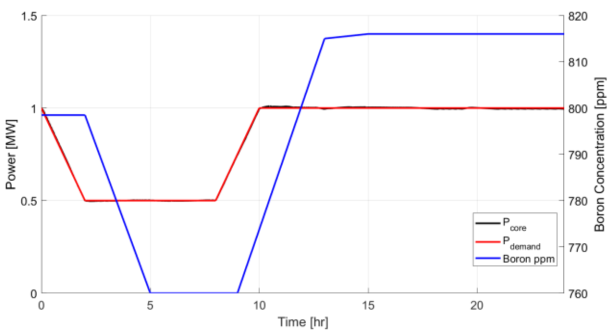

Fig. 7. Power and boron scenario for Inconel PSCEA LFO.

Figure 8 shows the ASI behavior with the Inconel PSCEA, given the initial ASI value which is around 0.1 ASIu, the control was well maintained below the operational limits.

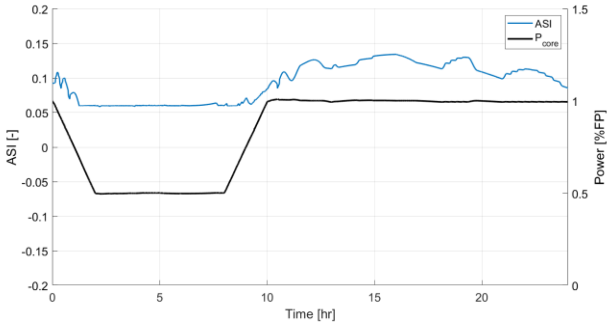

Fig. 8. ASI value for 24-hour LFO simulation using Inconel PSCEA.

Figure 9 shows the CEA movement during the LFO, it can be noticed that the leading regulating bank R5 was inserted into the core during the 50% power level, simply due to the weak worth for the PSCEA.

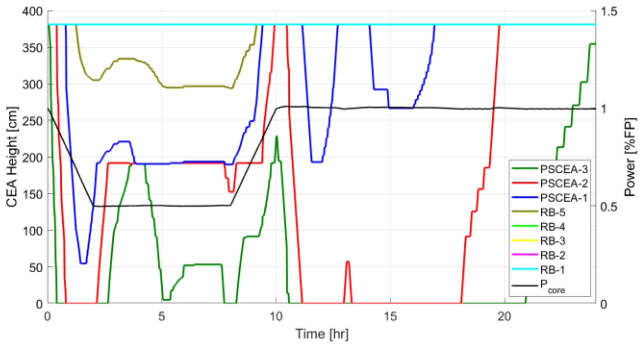

Fig. 9. 24-hour LFO simulation at BOC for Inconel PSCE

Figure 10 shows the power variation with the pre-determined boron scenario using the Mn-PSCEA, The boron scenario was chosen to be simple and linearly changing to minimize the volume of the liquid radioactive waste similar to the Inconel-PSCEA scenario.

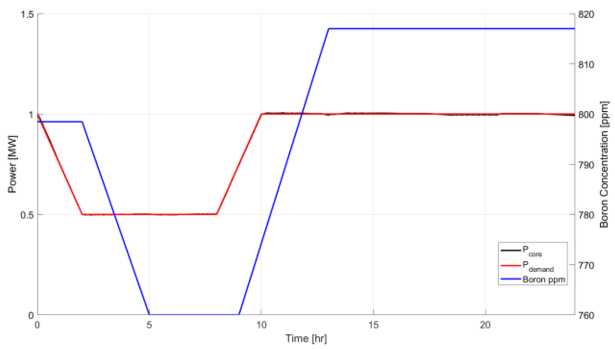

Fig. 10. 24-hour LFO scenario and core power using Mn-PSCEA.

Figure 11 represents the reactor core temperature variation during the LFO, the variation in the inlet coolant temperature was well maintained within the reactor Limiting Condition of Operation (LCO).

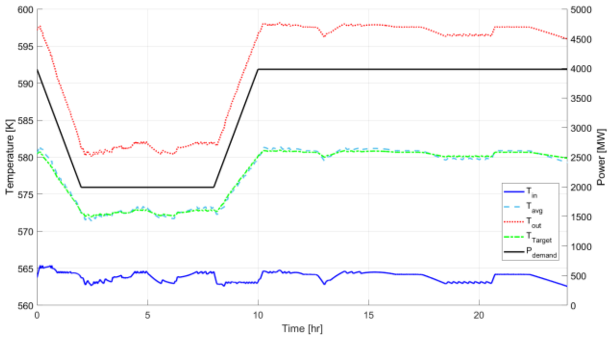

Fig. 11. Reactor temperature variation during 24-hour LFO using Mn-PSCEA.

Figure 12 provides a demonstration of the ASI value during the LFO, it was well maintained within the design limits (±0.27) all through the 24-hours simulation time.

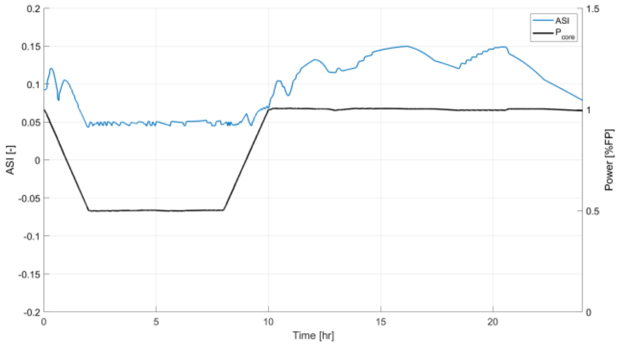

Fig. 12. ASI value during the 24-hour LFO using Mn-PSCEA.

Figure 13 shows the CEA movement; the simulation began with All-Rod-Out (ARO) condition. since the worth of the PSCEA is higher, the insertion of the regulating rods was minimized, also the CEA were all fully withdrawn near the end of the 24-hour to prepare the reactor for the next day's LFO.

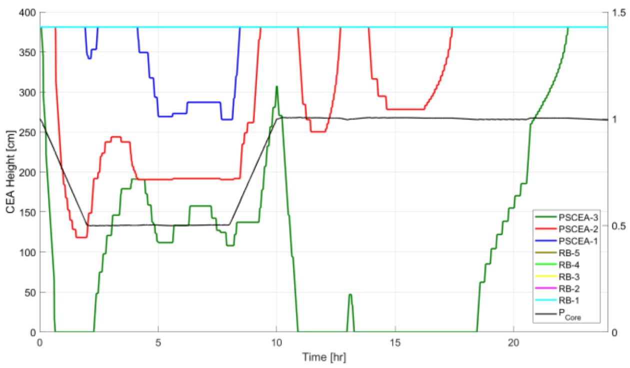

Fig. 13. CEA movement during the 24-hour LFO using Mn-PSCEA.

The xenon behavior was also investigated in this simulation. Figure 14 shows two xenon peaks at 6 and 15 hours. On the next day LFO, the xenon peaks are expected to be in some lower level, which means a higher boron level shall be considered to compensate for the xenon concentration changes.

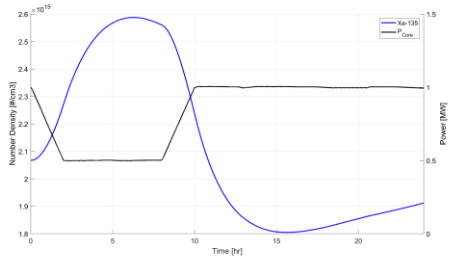

Fig. 14. Xenon concentration change during the LFO.

In this simulation, the maximum radial peaking is 1.22 with the Mn-PSCEA compared to 1.24 observed in the Inconel-PSCEA as shown in figure 15.

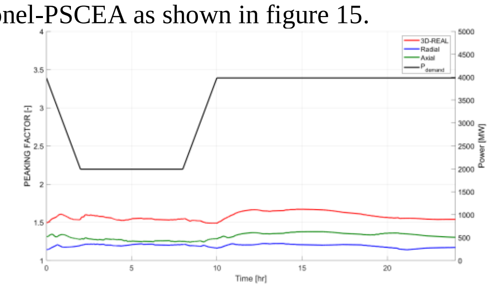

Fig. 15. Reactor core power peaking using Mn-PSCEA.

4. Conclusion and Future Work

Load-Follow Operation (LFO) was performed to APR1400 initial cycle, Mode-K+ control logic was also utilized in this simulation. Using the time-dependent deterministic code KANT, the analysis shows that ASI and temperature were successfully controlled during the 24-hour Beginning of Cycle (BOC) condition.

For future work, a more realistic simulation of the inlet coolant temperature change shall be simulated by coupling the steam generator. The capability to perform the LFO near the End-of-Cycle (EOC) shall also be investigated. However, since the Mn-PSCEA total worth is larger than the Inconel-PSCEA, its expected that at EOC the LFO performance will be enhanced.

ACKNOWLEDGMENT

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4. Reference

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