EVALUATION OF LOAD FOLLOW PERFORMANCE OF KOREAN NEXT GENERATION REACTOR (KNGR)

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ABSTRACT

The daily load follow capability of KNGR (Korean Next Generation Reactor), which is under development in Korea, is evaluated in this paper. During load maneuverings, in KNGR, the Mode-K control system controls the core power and the axial power distribution simultaneously with operator control of the boron concentration. Input signals to the Mode-K controller are measured values and they are the core temperature mismatch, the ASI (Axial Shape Index), and CEA (Control Element Assembly) positions. Given the input information, the Mode-K controller determines the direction of CEA movement and/or the CEA banks to be moved. The scenario of boron concentration is predetermined based on the power maneuvering strategy. The boron concentration is kept constant during power ramp-up and ramp-down and is subject to linear variations for simplicity and minimization of the waste water. The load follow performance of KNGR is analyzed using an NSSS (Nuclear Steam Supply System) analysis code, KISPAC-1D. Numerical simulations for an equilibrium core of the 18-month fuel cycle show that the Mode-K control system provides satisfactory performance for scheduled daily load follow operations, up to 90% EOC (End of Cycle). Core temperature as well as the ASI was successfully controlled and all the other NSSS systems worked as they were designed.

1. INTRODUCTION

During load maneuverings of power plants, the power output is controlled to correct for variations in grid frequency and to maintain reliability during various types of electrical system disturbances. Generally, nuclear power plants are utilized for base-load operation mainly due to their relatively low energy generation cost and partly due to the relatively poor load follow ability. However, if the nuclear capacity constitutes a large fraction of the total electric capacity in a country, the ability of nuclear units to perform load maneuverings is inevitable. In addition, improvement of load follow capability of nuclear power plants is required for better competitiveness of the nuclear units. It is well known that nuclear power plants are less effective in terms of load follow performance than the conventional fossil fuel units.

KNGR (Korean Next Generation Reactor) is an evolutionary PWR rated at 4,000 MW thermal power, which is currently under development in Korea[1]. One of top-tier requirements for KNGR is that it shall be able to do a wide range of load maneuverings including the daily load follow operation. Daily load maneuvering is to follow the relatively slow load variations during a day, and thus it is generally pre-planned and repetitive. With respect to load follow operations of KNGR, the bottomline of design requirements is that the load follow capability should be available throughout the whole lifetime (60 years) and the load follow operations could be performed from BOC (Beginning of Cycle) to 90% EOC (End of Cycle) in each fuel cycle.

Concerning the load follow performance, a key feature of the KNGR core design can be found in the CEA (Control Element Assembly) configuration[1]. The KNGR core has a total of 93 CEAs, which are grouped into 2 PSCEA (Part-Strength CEA) banks (P2, P1), 5 regulating banks (R5, R4, R3, R2, R1), and 2 shutdown banks. The absorber material for both regulating and shutdown banks is boron carbide (B_4C), while inconnel absorber is used in the two PSCEA banks. The shutdown banks are used only for shutdown, and power regulation is done using the regulating banks and PSCEAs. The five regulating banks are sequentially inserted (or withdrawn) in a fixed overlap mode. However, independent movement is allowed for the two PSCEAs banks. The two PSCEAs banks are introduced to enhance the load follow performance. Basically, the PSCEAs are gray rods and thus insertion or withdrawal of PSCEAs induces relatively small perturbations to the core power distribution, relative to the full-strength CEAs. Consequently, the PSCEAs can be effectively utilized to control the core axial power distribution during load maneuverings. Currently, the control of PSCEAs can be either manual or automatic in KNGR, depending on the operational mode.

To maximize the load maneuvering capability of KNGR, a robust automatic control logic, Mode-K, was developed and coupled with the conventional RRS (Reactor Regulating System). The Mode-K system controls the core power and the axial power distribution simultaneously with operator control of the boron concentration. The objectives of the present work are two-fold, one is to introduce the Mode-K control logic and the other one is to evaluate the daily load follow performance of KNGR. For evaluation of the load follow capability, the performance of the control system should be analyzed through integrated analyses of the NSSS (Nuclear Steam Supply System). In this paper, the load follow capability of KNGR is evaluated using an NSSS analysis code, KISPAC-1D[2]. KISAPC-1D was developed by extending the point core model of KISPAC[3] to a one-dimensional model.

II. Mode-K Control System

II.1 Overview

In most PWRs (Pressurized Water Reactors), the core power is only automatically controlled by a RRS (Reactor Regulating System). However, the RRS of KNGR can control automatically the core axial power distribution as well as the core power. In KNGR, the core axial power distribution is characterized by the so-called ASI (Axial Shape Index), which means the power difference between top and bottom halves of the core and is defined as: ASI = [Bottom Half Power - Top Half Power]/[Bottom Half Power + Top Half Power]]. In addition to successful control of core power, in daily load follow operations, adequate control of the core axial power distribution, i.e., ASI, is crucial from the viewpoint of fuel integrity and the repetitive load maneuverings. For this purpose, an automatic controller, called Mode-K, was developed and embodied in the RRS of KNGR. According to the interface with the conventional RRS, Mode-K is divided into two control logics, single-output and two-output. In the single-output application, introduced in section II.2, the direction of CEA movement is determined by the RRS using the core temperature mismatch, and the Mode-K logic selects only CEAs to be moved. Meanwhile, the two-output Mode-K controller can function independently, which is described in section II.3.

The Mode-K control system, for load follow operations of KNGR, has been developed on the basis of the following objectives and principles.

- The core temperature and ASI should be properly controlled.
- CEA movement is automatically controlled.
- Measurable quantities are used as input signals.
- All the CEAs should be fully withdrawn at the full power condition, if the ASI value is adequate.
- Core reactivity can be controlled by using CEAs and the boron concentration.
- Utilization of boron should be minimized.

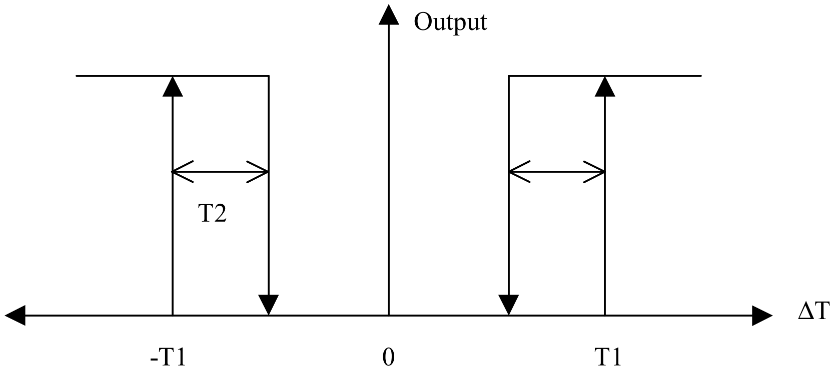
The second item means that the so-called rodded operation is excluded in the Mode-K logic. It goes without saying that the ASI control might be easier if a CEA bank is fully inserted in the core before starting load follow operations. Also, the rodded operations may lead to a significant reduction of the waste water since the boron dilution is not necessarily required at part power. In spite of potential several advantages of the rodded operation, it may result in CEA integrity problems and the current nuclear design procedures should be accordingly modified and the validity should be demonstrated. Thus, any initial preconditioning of CEA position is not considered in the current Mode-K. However, it should be noted that the Mode-K logics in the following sections are fundamentally compatible with the rodded operation concept.

It is well known that the control of ASI could be very successful, if adjustment of the boron concentration can be used as much as necessary and CEAs are introduced to control the ASI. However, the more the boron is used, the more volume of waste water. Also, the effect of the boration or dilution is very slow, and dilution of the boron concentration becomes difficult as the boron concentration decreases. Furthermore, the boron concentration is manually controlled in KNGR, repetitive control of the boron concentration is a big burden on the operators. Therefore, one of the major objectives is to minimize the dependency on the control of the boron concentration. Basically, Mode-K is concerned with the CEA movement. Meanwhile, the direction of CEA movement is directly affected by the change in the boron concentration. Consequently, boron scenario is important for successful load following operations.

II.2 Single-Output Mode-K Control Logic

The very objective of load follow operation is to control the core thermal output, i.e., the core temperature. Consequently, a better priority should be given to control of core temperature than that of the ASI, when the two parameter are the control variables. In the single-output Mode-K control logic, the direction and the speed of CEA movement is determined by the RRS using the core temperature mismatch between the core average temperature and the reference programmed temperature. Given the CEA direction, the Mode-K control logic selects the CEA bank (or banks) to be moved on the basis of the ASI deviation from a target ASI value, which is defined as ΔASI = Target ASI – Current ASI. In Mode-K, the target ASI is set to the equilibrium ASI (ESI) at the full power and is a function of the core burnup. This target ASI can be calculated in priori in the nuclear design stage for a fuel cycle. It is well known that the nuclear design codes for PWRs provide fairly accurate equilibrium ASI. The current ASI is from a core monitoring system COLSS[4] using the in-core detector information. COLSS calculates the core average axial power distribution on-line and monitors several important safety-related parameter such as DNBR (Departure from Nucleate Boiling Ratio), LHR (Linear Heat Rate), ASI, etc.

The selected CEA bank (or banks) is actually moved by the CEDMCS (Control Element Driving Mechanism Control System). CEDMCS drives CEAs at high (30 in/min) or low (3 in/min) speed, depending on the core temperature mismatch (ΔT). Figure 1 shows setpoints for the temperature dead band of the KNGR RRS. As shown in Figure 1, the KNGR RRS has a temperature dead band of 4 °F width. It should be noted that the single-output Mode-K controller does not generate any control output, i.e., no CEA movement, if the temperature mismatch is within the dead band. However, temperature mismatch in the dead band does not always mean that the ASI is acceptable. To resolve this problem, Mode-K generate control action using a different control logic, which is contained in section II.3, even when the core temperature mismatch is within the dead band.



[low speed : T1= 2 °F, T2=0.16 °F; high speed : T1=3.53 °F, T2=0.18 °F]

Figure 1. Setpoints for the RRS Temperature Dead Band in KNGR

During load maneuverings, the deviation of the core temperature determines the magnitude of the required positive or negative reactivity change. Meanwhile, the reactivity change can be compensated for by several types of CEA movements in the KNGR core since two PSCEAs can be independently driven. However, each type of CEA movement can be different in affecting the ASI. Therefore, the bank selection logic of the basic Mode-K controller depends on the magnitude of the ASI deviation. The ASI deviation from the target value is categorized into 3 state flags. The stage flag varies as the ASI deviation changes, as shown in Figure 2.

The ARS (ASI Restoring Stage)+ and ARS− stage flags mean bottom-shifted and top-shifted power distributions, respectively. For ARS± stage flags, Mode-K tries to select CEA banks to restore the ASI. SRS (Sequence Restoring Stage) basically denotes that the ASI deviation is small and acceptable. In the SRS stage, the Mode-K controller select CEA banks to restore the predetermined CEA sequence and overlaps between CEAs, regardless of the ASI change resulting from the CEA movement. When inserting CEA banks, P2 is the leading bank and follows P1, and then the regulating banks are inserted in a sequential, overlap mode.

Another factor affecting the CEA selection for SRS is the reference overlap between CEA banks. In KNGR, the 5 regulating banks should always be moved keeping 55% overlap between consecutive banks. Also, a 55% reference overlap is applied to the two bank pairs (P2, P1) and (P2, R5) in Mode-K for better controllability, even though variable overlap is allowed for those CEA banks. Of course, actual overlaps between the two pairs are generally far from the reference one since PSCEAs can be independently moved. However, in general, clustering of CEA positions are not favorable from the viewpoint of ASI control. Thus, CEA bank (or banks) to be moved is (or are) selected such that the selected CEA movement restore the overlaps when the stage flag is SRS.

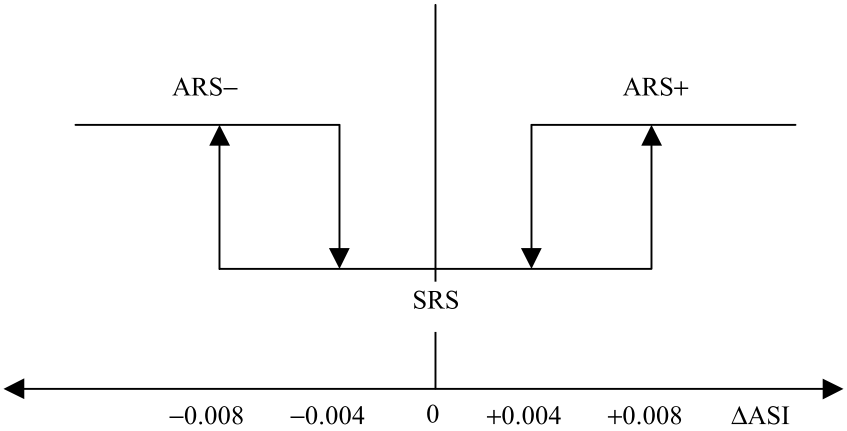


Figure 2. Hysteresis Curve of the Stage Flags for the Single-Output Mode-K Logic

In Figure 2, the setpoints for the hysteresis of the stage flags are determined via numerical simulations to maximize the performance of Mode-K. The setpoints in Figure 2 denote that Mode-K tries to control the ASI within the range −0.008 ~ +0.008 asiu (ASI Unit). During daily load follow of KNGR, the core operating guidelines (COGs) require that the ASI should be kept in the range −0.05 ~ +0.05 asiu.

Basically, the bank selection logic of Mode-K is based on a simple and general physical phenomena : insertion of a CEA in the top half of the core suppresses the top power, while CEA insertion in the bottom half decreases the bottom power, and thus increases the top power. On the contrary, withdrawal of a CEA in the top half of the core results in top-shift of the power distribution relative to the initial state, and a CEA withdrawal in the bottom half induces the bottom-shift of the axial power distribution. These effects of CEA movement generally hold for PWR cores. It should be noted that the boundary between upper and lower half cores may depend on the core condition and CEA worth. Usually, the boundary is very close to the center of the core, i.e., the mid-plane, if the initial ASI is not large and the CEA is not very strong. Numerical studies shows that the mid-plane can be safely treated as the boundary for the ASI range −0.3 ~ +0.3 asiu and for typical CEA worths of PWRs. It should be noted, however, that the separation point moves upward if the axial power distribution is highly top-skewed, and the point moves downward if the CEA worth is very large. These characteristics are attributed to the facts that the CEA worth depends on the core axial power distribution and CEA insertion (or withdrawal) itself changes the axial power distribution. In typical daily load follow of KNGR, the ASI variation is not so large as to affect the boundary plane between the upper and lower half core. Therefore, the boundary plane is assumed to be equal to the axial mid-plane of the core in Mode-K.

For a specific core condition, the Mode-K controller tries to select the optimal CEA bank (or banks), if any, depending on the CEA direction and the stage flag. If there is no proper CEA movement for the ASI control, the Mode-K controller selects CEA such that the adverse effect could be minimized. Table I shows of the detail logic table for the bank selection when the stage flag is ARS+ in the single-output Mode-K controller. For other stage flags, consistent logic tables are constructed based on the basic principles described above. As shown in Table I, the input signals to the single-output Mode-K controller are CEA directions and positions and the ASI deviation. In Table I, T, $B,$and H indicate the top and bottom of the core and the active core height, 381 cm, respectively, and W_X denotes the CEA withdrawal position of X bank. It should be noted that R5+ stand for the regulating banks.

The boron concentration plays an important role in the successful application of Mode-K. During load maneuverings, adjustment of the boron concentration is inevitable for the following reasons. First, dilution of the boron concentration is necessarily required to compensate for the xenon buildup due to the power reduction and to guarantee the return-to-full-power capability during the load follow operation. Secondly, the reactivity change of the core is essentially compensated by using the boron after the power is returned to the full power. This is due to the fundamental principle of Mode-K : all CEAs are fully withdrawn at full power, if the ASI is acceptable. Finally, the boron concentration should be controlled such that relevant CEA positions could be available as much as possible for the ARS± stage flags. In KNGR, the boron concentration is manually adjusted. Therefore, it is assumed that the boron scenarios for load follow operations are determined a priori by using a core simulation code. Meanwhile, in Mode-K, the boron concentration is kept constant during power ramp-up and ramp-down stages to simplify the boron scenario and thus to minimize the amount of waste water. In addition, it is assumed that the boron concentration is linearly varied.

Table I. CEA Bank Selection Logic Table for the Single-Output Mode-K Controller

Conditions			Selected CEA
Stage Flag	CEA Direction	CEA Position	
ARS+	Insertion	$W_{P2} > B$	P2
		$W_{P2} = B$, $W_{P1} > B$	P1
		$W_{P2} = B$, $W_{P1} = B$	R5+
	Withdrawal	*If* $(W_{P2} , W_{P1} , W_{R5}) \geq 350$ *then*	
		$W_{R5} < T$	R5+
		$W_{R5} = T$, $W_{P1} < T$	P1
		$W_{R5} = T$, $W_{P1} = T$, $W_{P2} < T$	P2
		Else	
		If $H / 2 < W_{R5} < T$	R5+
		Else If $(W_{P2} > H / 2 , W_{P1} > H / 2)$ *then*	
		$W_{P1} < T$	P1
		$W_{P1} = T$, $W_{P2} < T$	P2
		$W_{P1} = T$, $W_{P2} = T$	R5+
		Else If $(W_{P2} < H / 2 , H / 2 \leq W_{P1} < T)$ *then*	P1
		Else	
		If $W_{R5} < H / 2$ *then*	R5+
		Else	P1
		End If	
		End If	

II.3 Two-Output ASI control Logic

One of the major features of the single-output Mode-K control logic described in the previous section is that the CEA direction is determined by the RRS. Consequently, no control action is provided if the core average coolant temperature is within the temperature dead band (–2 ˚F < ΔT < +2 ˚F), no matter how large the ASI deviation is. This feature may lead to unfavorable ASI deviation during the load follow operations. Furthermore, due to such a drawback, Mode-K can be susceptible to the axial xenon oscillation taking place during a constant power level. To mitigate the defect of Mode-K and to maximize the load follow performance of KNGR, a two-output control logic has been developed, which functions in a standalone manner. This two-output Mode-K determines both CEA direction and CEAs to be moved for the ASI control even when the core average temperature is within the RRS temperature dead band.

As in the Mode-K logic in section II.2, 3 stage flags are defined as shown in Figure 3 for the CEA selection in the dead band ASI control logic. The AAS stage flag means that the ASI deviation is acceptable, thus, there is no control action in this case. UARS+ indicates that the power distribution is highly bottom-shifted and UARS- indicates the top-skewed axial power distribution. Setpoints for stage flag change are given in Figure 4. Figure 4 shows that the septoint depends on power level: a wider ΔASI band range (–0.045 asiu ~ 0.045 asiu) is allowed for low power level and fairly narrow ΔASI band (range –0.015 asiu ~ 0.015 asiu) is applied for the full power condition. This kind of setpoint is used in the dead-band controller (two-output Mode-K) for effective control of the xenon oscillation at full power. Generally, for successful load follow operations, it is important to control the ASI in a narrow range at the full power condition. On the one hand, the dead band controller essentially conflicts with the conventional RRS, since any CEA movement by the dead band controller changes the core temperature. Thus, too narrow ΔASI range might results in unnecessary, ineffective CEA movements.

In Figure 5, the logic diagram of the dead band ASI controller is given. First the stage flag is determined using the ASI deviation, and if the stage flag is UARS+ or UARS-, the ASI control is performed in the following strategies. If ΔT is positive, the effectiveness of the CEA insertion is checked. If there is a CEA (or CEAs) whose insertion can restore the ASI in the favorable direction, the CEA (or CEAs) is inserted. This kind of CEA insertion can reduce the ASI deviation well within the dead band. Otherwise, the CEA movement is decided in the direction of withdrawal. If there exists an effective CEA withdrawal and $\Delta T < 1.45$ ˚F, the selected CEA (or CEAs) is withdrawn. On the other hand, a similar CEA selection is performed in the case of negative ΔT. In this case, however, the effective CEA movement is searched in the direction of withdrawal first. It is worthwhile to note that the only effective CEA movement, from the viewpoint of ASI control, is accepted to avoid conflict with the temperature control of the RRS. Table II shows the CEA selection logic table for the temperature dead-band Mode-K controller.

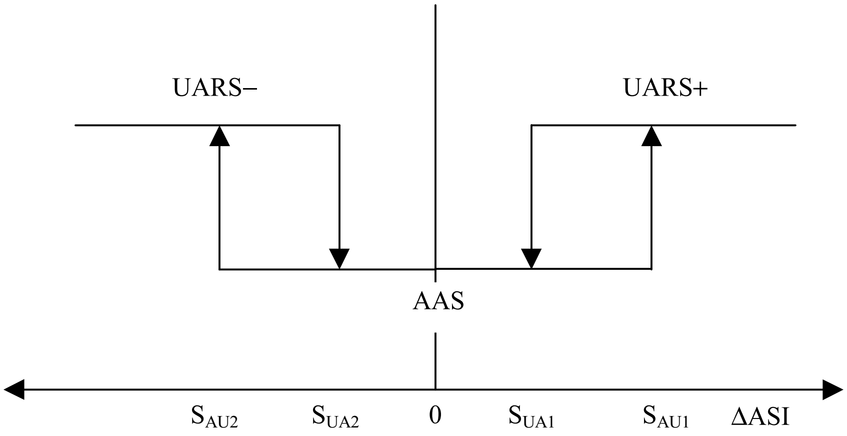


Figure 3. Stage Flag Change in the Two-Output Mode-K Control Logic

The objective of ASI control in the dead band is to keep the absolute value of ΔASI less than 0.045. The potential of the dead band control can be roughly estimated by evaluating the reactivity of the dead band. The MTC value of the equilibrium KNGR core is in the range −11.7 pcm/˚F (BOC) ~ −32 pcm/˚F (EOC) at the full power condition. Consequently, the total amount of reactivity contained in the dead band can be said to be equivalent to 46.8 pcm (BOC) ~ 128 pcm (EOC). This means that the ASI control, within the dead band, could be very effective if the CEA direction is consistent with mismatch of the core temperature. In the KNGR RRS, the rod speed depends on the core temperature mismatch. However, CEA is always driven at the low speed in the case of the dead-band ASI control, since the temperature mismatch is already small enough.

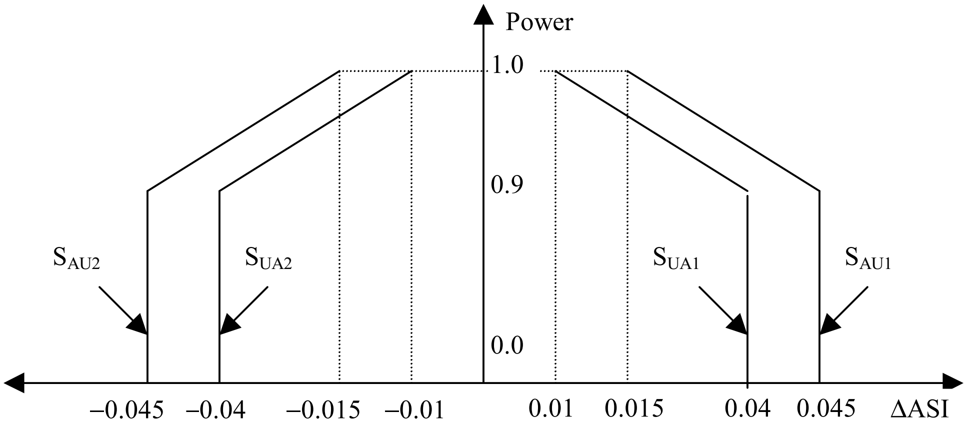


Figure 4. Setpoints for the Stage Flag Change in the Two-Output Mode-K Logic

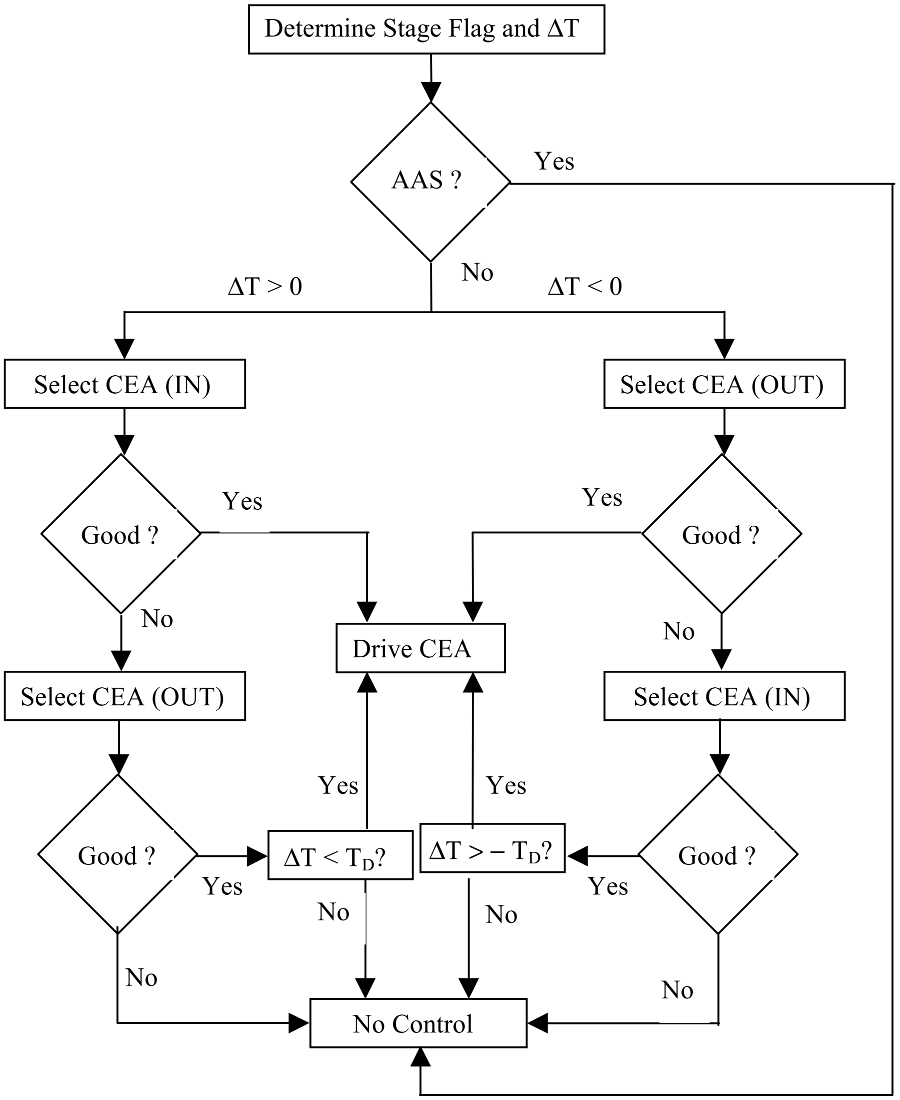


Figure 5. Two-Output Mode-K Logic for the Dead-Band ASI Control (T_D = 1.45 ˚F)

Table II. Logic Table for CEA Selection in the Dead-Band ASI Controller

Conditions			Selected CEA
Stage Flag	CEA Direction	CEA Position	
UARS+	Insertion	$W_{P2} > B$, $W_{P2} \le H/2$ $W_{P2} = B$, $W_{P1} > B$, $W_{P1} \le H/2$	P2 P1
	Withdrawal	$W_{R5} < T$, $W_{R5} \ge H/2$ ($W_{R5} = T$ or $W_{R5} \le H/2$), $W_{P1} < T$, $W_{P1} \ge H/2$ ($W_{R5} = T$ or $W_{R5} \le H/2$), $W_{P1} = T$, $W_{P2} \ge H/2$	R5+ P1 P2
UARS-	Insertion	$W_{P2} > H/2$ $W_{P2} \le H/2$, $W_{P1} < H/2$ $W_{P2} \le H/2$, $W_{P1} \le H/2$, $W_{R5} < W_{R5}^{IL}$, $W_{R5} > H/2$	P2 P1 R5+
	Withdrawal	$W_{P2} < H/2$ $W_{P2} < H/2$, $W_{P2} = W_{P1}$, $W_{P1} < H/2$	P2 P2 P1

W_X^{IL} : insertion limit of X CEA bank

III. Performance of Daily Load Follow Operations

To evaluate and demonstrate the daily load follow capability of KNGR using the Mode-K control logic, numerical simulations were performed with the KISPAC-1D code at MOC and 90% EOC of an equilibrium cycle (Cycle 6). In the equilibrium cycle, MOC and 90% EOC correspond to 12,000 MWD/MTU, 16,000 MWD/MTU, respectively. In general, successful load follow operations at high burnup states imply that the performance at BOC would be satisfactory. KISPAC-1D is based on a one-dimensional, time-dependent core model, which is collapsed from the three-dimensional ROCS[5] model. ROCS is a nuclear design code for the ABB-CE type reactors. For the core model of KISPAC-1D, several adaptation calculations are performed to minimize differences between the two core models. The adaptation procedures are applied to the axial power distributions, the CEA worth, the xenon worth, etc. In KISPAC-1D, 17 nodes and 23 flow paths are used to model the NSSS of KNGR, and the code provides thermal responses of all the NSSS components during various transients such as non-LOCA accidents, load maneuverings, reactor trip, etc.

Typical daily load maneuverings were simulated using the Mode-K control system, where the turbine power varies according to the 100-50-100%P pattern. Initially, the reactor is at the full power condition of equilibrium xenon and all CEAs are fully withdrawn. The power is reduced to 50% at a rate of 25%/hr and held at 50% for next 6 hours, which results in the maximum buildup of xenon reactivity. After the 6-hour hold at 50%, the power is ramped up to 100% power over 2 hours, and then kept at 100% power for the following 14 hours. It should be noted that the initial stage flag is SRS since the core is initially at an equilibrium condition.

III.1 Daily Load Follow at MOC

Figure 6 shows the simulation results for a 24-hour load maneuvering at MOC. In this case, the target ASI is 0.035 asiu, which is the equilibrium ASI at 100% power. It is worthwhile to note that the boron scenario is very simple. The initial concentration is kept for about 2.6 hours and linearly decreased to 489 ppm and remains constant until the power is returned to full power again, and then the concentration is varied to roughly compensate for the xenon reactivity change. This kind of adjustment of the boron concentration is a minimum production of the waste water in the sense that a boron dilution is inevitably required to guarantee the return-to-power capability and all CEAs should be withdrawn at the full power conditions.

It is observed that the ASI control is successful and the core power is also well controlled as is scheduled. The largest ASI deviation is about –0.03 asiu at 50% power level. Initially, the stage flag of the Mode-K controller is SRS and all CEA banks are fully out. Thus, the load maneuvering starts with insertion of the leading bank P2. While P2 is being inserted into the core, ΔASI shows a sharp upward peak, reaching ~0.017 asiu. This is mainly because only P2 can be inserted during the early stage of the ramp-down and partly because ΔASI tends to decrease as the core power decreases. As is well known, the power reduction induces the top-shifted axial power distribution, due to the moderator temperature effects and the axial burnup heterogeneity. Thus, one can note that ΔASI is controlled in the vicinity of –0.008 asiu during the ramp-down period. After the power is reduced to 50%, a deep valley is observed in ΔASI. This is because the core temperature mismatch is within the dead band for a while after the end of the power reduction and the stage flag for the dead-band ASI controller is AAS. Consequently, there is no control action for about 20 minutes after 2 hr. However, the core temperature mismatch exceeds the lower setpoint at about 2.3 hr since the xenon concentration increases. Then, Mode-K withdraws P2 to restore the ASI. At 50% power level, the ASI varies slowly and P2, P1, R5, and R4 banks are well positioned for the ASI control. Consequently, the ASI control is satisfactory while the power is ramp up to the 100% level.

When the core power reached again 100%, the position of P2 is 342 cm, not fully out. This is because the boron concentration is a little over diluted at 50% power. Partially inserted P2 induces a slightly bottom-shifted power distribution, and ΔASI touches the upper setpoint, 0.015 asiu, for the dead band ASI control logic, and then the dead band Mode-K controller withdraws P2 to restore ASI. It is important to note that this P2 withdrawal results in a very small temperature change. During the full power period, the core temperature is well controlled within the dead band by the boron adjustment. At the full power level, ΔASI has a tendency of very slow decrease due to a weak xenon oscillation. The ASI deviation exceeds the lower setpoint of the dead band control logic at about 22 hr, the Mode-K controller inserts P2 and increases the ASI up to –0.01 asiu. Finally, ΔASI is about 0.009 and the core is ready for the continuous load maneuverings.

In Figure 6, it is confirmed that both core inlet and average temperatures are well controlled by Mode-K, albeit fairly simple boron scenario. Although responses of the other NSSS systems were not provided in this paper, it was confirmed that they were also well controlled. The design inlet temperature of KNGR is 555 °F, and the maximum deviation of the inlet temperature is about 3.5 °F, occurring when P2 (or P1) is inserted or withdrawn alone. This is related to relatively small worth of P2 (164 pcm) and P1 (179 pcm) banks. Therefore, for better temperature control, the worth of PSCEAs needs to be a little increased.

III.2 Daily Load Follow at 90% EOC

In Figure 7, the daily load follow performance at 90% EOC is shown. As is well known, load follow operations near EOC is difficult due to large differences in the ESIs for power levels and also the xenon instability. The ESI at full power is 0.034 asiu, which is the target ASI, while the ESI is –20.2 asiu at 50% power level. Consequently, the axial power distribution has a very strong tendency to become top-shifted. Concerning the boron scenario, one can see that it is very similar to that of MOC in the pattern. Basically, in Mode-K, similar boron scenarios are used throughout a fuel cycle for simplicity.

It is clear that core power as well as inlet temperature is well controlled. Thus, all NSSS components worked as they designed as in the MOC simulation. Meanwhile, one can see that the core inlet temperature shows maximum deviation when PSCEA bank is driven alone as is observed in the simulation of load maneuvering at MOC. This also due to the relatively small worth of P2 and P1 banks. At 90% EOC, P2 and P1 have 176 pcm and 192 pcm, respectively.

As shown in Figure 7, ΔASI shows similar trend as in Figure 6. However, one can see that the maximum ΔASI is a little larger than that of Figure 6. In this case, the bottom-shifted power distribution is not observed when P2 is initially inserted. This is because the effect of power reduction overrides that of P2 insertion. After power reduced to 50%, ΔASI starts to decrease fairly fast, reaching –0.45 asiu, and turning on the dead-band control logic. To restore the ASI, Mode-K withdraws the deeply inserted P2. It is worth noting that withdrawal of P2 does not result in such an effective ASI change as in Figure 6. At 8 hr, P2 is placed at 120 cm and P1 and R5 are at the same position around the mid-plane of the core. Thus, P1 is initially withdrawn during the early stage of the power ramp-up, and the position of P2, P1, and R5 banks are coincided after a while. This kind of CEA configuration is not favorable for the ASI control during the ramp-up stage. Therefore, the axial power distribution has slightly top-skewed shape. When the core power returned to 100%, ΔASI is smaller than –0.015, thus the dead band controller inserts P2 bank. However, P2 is withdrawn again at 15.2 hr when ΔASI becomes larger 0.015 asiu due to the xenon oscillation. Finally, ΔASI continues to decrease, reaching –0.009 asiu at 24 hr. It should be noted that dasi would be very large during 50% power if the dead band control logic is not introduced. And large dasi at part load will incur a significant xenon oscillation after returning to full power.

IV. CONCLUSIONS

An efficient and robust control logic, named Mode-K, has been developed for the load follow operation of KNGR, an advanced PWR. The performance for a typical daily load maneuvering of KNGR was evaluated by using an NSSS performance analysis code. Numerical simulations shows that the Mode-K control logic controls both core power and ASI successfully, even up to the 90% EOC condition of an equilibrium cycle, in spite of very simple boron scenarios. Also, all the NSSS components were well controlled during the daily load maneuverings.

In Mode-K, the boron concentration is kept constant during power maneuvering stages and linear variations are only utilized, resulting in minimization of the waste water. One of the important features of the Mode-K control logic is that it provides control output even when that core temperature is within a dead ban. Therefore, the Mode-K controller is not sensitive to the boron scenarios and effectively controls the xenon oscillation.

In order to further improve the load maneuvering capability of KNGR, the followings are identified from the present works. An increase of the worth of PSCEAs (P2, P1) would provide better temperature control. Increased PSCEA worth would also improve the ASI controllability of the Mode-K controller. Better load follow performance would be available through an optimization of the worth of the regulating banks.

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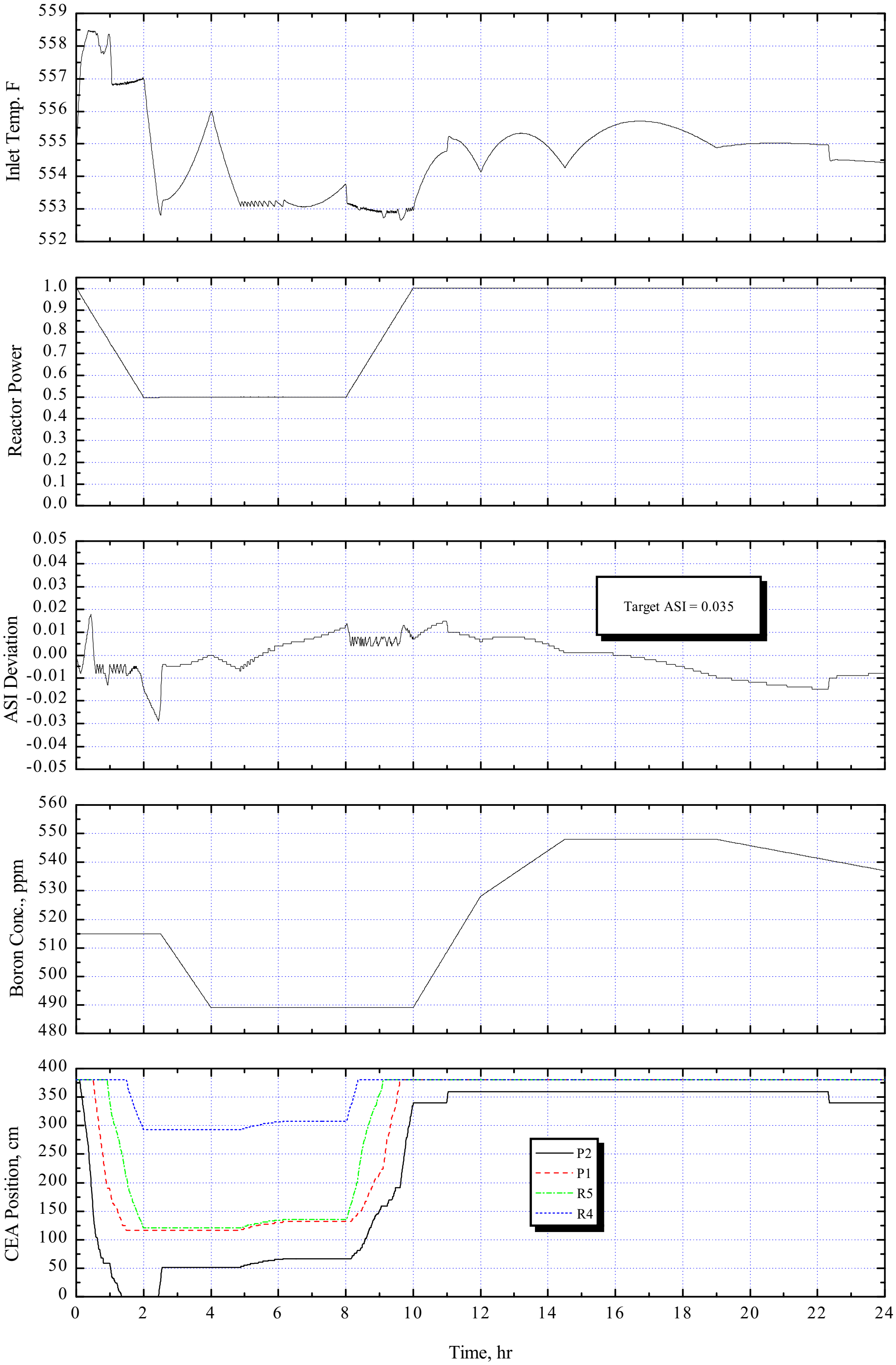

Figure 6. Daily Load Follow Operation at MOC of KNGR

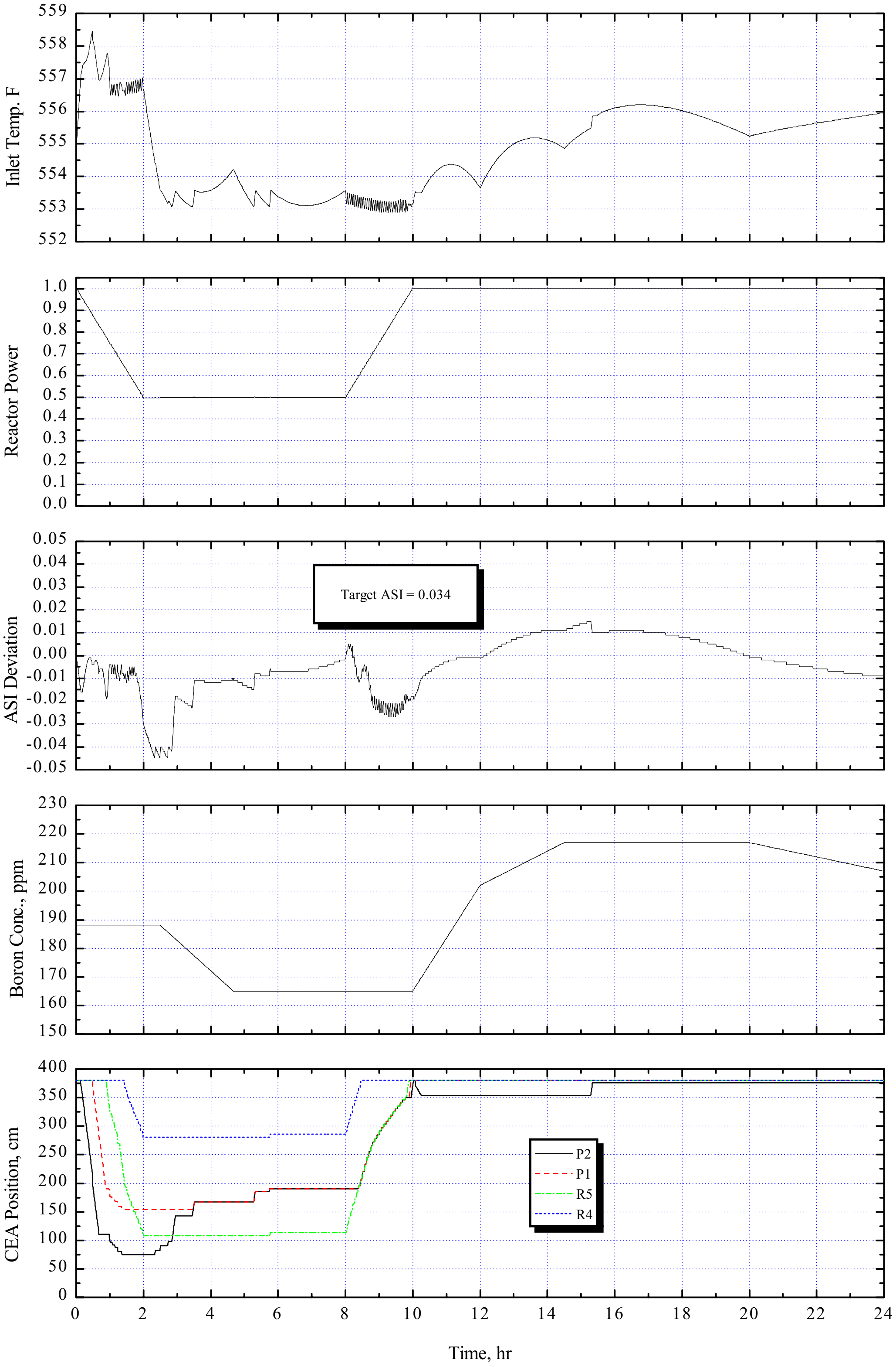

Figure 7. Daily Load Follow Operation at 90% EOC of KNGR