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Load Follow Performance of KNGR Using an Extended Mode-K Control Logic

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Abstract

The load-following capability of KNGR (Korean Next Generation Reactor) is evaluated in this paper. During load maneuverings, in KNGR, an extended 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 logic are the measured core temperature mismatch and the ASI (Axial Shape Index). The load follow performance of KNGR is evaluated by using an NSSS (Nuclear Steam Supply System) analysis code, KISPAC-1D. Numerical simulations for an equilibrium cycle show that the Mode-K control system provides satisfactory performance for both scheduled daily load follow and grid follow operations. Core temperature as well as ASI was successfully controlled and all the NSSS systems worked as they were designed.

1. Introduction

During the load maneuvering, the power output of electric supply system is controlled to correct for variations in grid frequency and to maintain reliability during various types of electrical system disturbances. In general, nuclear power plants are utilized for base-load operation due to their relatively low energy generation cost. However, if the nuclear capacity constitutes a large fraction of the total electric capacity, 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 nuclear units[1].

KNGR (Korean Next Generation Reactor) is an evolutionary PWR rated at 4000 MWth, which is currently under development in Korea[2]. One of the top-tier requirements of KNGR is that it shall be able to do a wide range of load maneuverings including the scheduled daily load following and the general frequency control operations[3]. In this paper, the load follow capability of KNGR is evaluated for both daily load follow and general grid follow operations.

For evaluation of the load follow capability, the performance of the control logic should be analyzed through integrated analyses of NSSS (Nuclear Steam Supply System). In the present work, the load follow performance of KNGR is evaluated by using the KISPAC-1D[4] code, which is a best estimate NSSS performance analysis code, KISPAC-1D was developed by extending the point core model of KISPAC[5] to a one-dimensional model in order to incorporate Mode-K[6], which is the control strategy for KNGR load follow operations.

2. KNGR Design Features for Load-Following Operations

Load follow operations are typically divided into daily or weekly power maneuverings and grid frequency regulation including the primary and remote frequency controls. Daily or weekend power maneuvering is to follow the relatively slow load variations during a day or weekend, and thus it is generally pre-planned and repetitive. In contrast, the objective of frequency control operations is to regulate the grid frequency against unexpected fairly fast external disturbances.

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 and load follow operations could be performed from BOC (Beginning of Cycle) to 90% EOC (End of Cycle) of each core cycle. Table 1 shows the specific design requirements for load follow operations of KNGR[3].

Table 1. Load follow requirements of KNGR

Operation Mode	Requirement
Daily Load Follow	o 100-50-100 %P [(10 ~ 16)-2-(10 ~ 4)-2 hr] power cycle over a 24-hour period
Frequency Control	o ±2.5 %P load change for local frequency control o ±10 %P load change for remote frequency control o maximum load change rate : 0.5 %P/sec for local control : 2 %P/min for remote control
Unexpected Load Change	o 100% load rejection without reactor trip o ±10 %P step load change
Ramp Change	o ±5%/min load change

One of key features of the KNGR core design, to improve the load follow performance, is the CEA (Control Element Assembly) configuration[2]. 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 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 maximize the load follow performance. Basically, the PSCEAs are gray rods and thus insertion or withdrawal of PSCEAs induces small perturbations to the core power distribution, relative to the full-strength CEAs. Currently, the control of PSCEAs can be either manual or automatic, depending on the operational mode. For normal full power operations, the PSCEAs are manually operated, while they are automatically controlled during load maneuverings.

3. Load Follow Control Logic

3.1 The Mode-K Control System

For improved load follow performance of KNGR, the Mode-K control logic has been originally developed by KAERI. The basic objective of Mode-K is to control automatically the axial power distribution as well as the core power, i.e., the core average temperature. Specifically, the Mode-K control system is designed to provide the reactivity control and the axial power profile control simultaneously and automatically by mainly using the CEAs, with operator control of the soluble boron concentration, during the load maneuvering. The 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 the Mode-K control system, the direction and the speed of CEA movement is determined by the current RRS (Reactor Regulating System) using the core temperature mismatch between the core average temperature and the reference programmed temperature. Given the CEA direction and speed, the Mode-K control logic selects the CEA bank (or banks) to be moved on the basis of the ASI deviation from the target ASI value, and the selected CEA bank (or banks) is actually moved by the CEDMCS (Control Element Driving Mechanism Control System).

The bank selection logic of Mode-K depends on the magnitue of the ASI deviation ($\Delta ASI \equiv$ ASI - target ASI) which is categorized by 5 stage flags. The stage flag varies as the ASI deviation changes as shown in Fig. 1. The ARS (ASI Restoring Stage)+ and ARS- stage flag mean bottom-shifted and top-shifted power distributions, respectively. For ARS ± stage flags, Mode-K tries to select CEA banks to restore the ASI. FOS (Fixed Overlap Stage)+ denotes slightly bottom-shifted power profile, while FOS- slightly top-shifted profile. During FOS ±, the ASI deviation is considered as acceptable and thus all CEA banks are moved simultaneously in the fixed overlap mode to control the core reactivity. When the ASI mismatch is very small, the stage flag is ORS (Overlap Restoring Stage). The ORS stage flag indicates that the CEA movement should be done such that the reference overlap between CEA banks could be restored, regardless of the ASI change resulting from the CEA movement.

For a specific core condition, the Mode-K logic selects the optimal CEA bank (or banks), if any, depending on the CEA direction and the stage flag. Detail logic tables for the stage flag change and the CEA selection can be found in Refs. 6, 7. The setpoints in Fig. 1 for the hysteresis of the stage flag are determined via numerical simulations to maximize the performance of Mode-K.

In the Mode-K logic, the CEA banks are sequentially inserted, starting with P2, then P1, and then the regulating banks. As previously stated, the PSCEA groups can be moved independently, i.e., variable overlap is allowed between P2, P1 and R5. However, the regulating banks should be moved keeping the fixed reference overlap. For self-consistency and simplicity of the Mode-K control logic, several constraints for the PSCEA movement are imposed on the CEA selection and movement: P1 (or R5) cannot be inserted more than P2 (or P1) and P2 (or P1) cannot be withdrawn more than P1 (or R5).

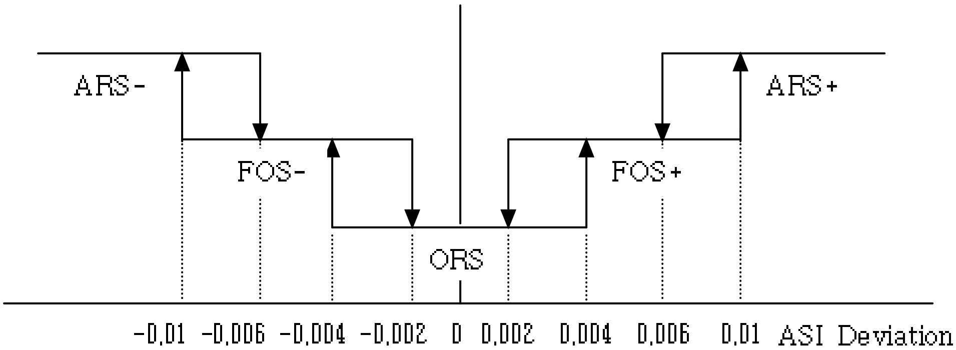

Fig. 1. Concept of Mode-K stage flag change

Basically, the bank selection logic of Mode-K is based on a simple, well-known 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, 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 CEA withdrawal in the bottom half induces the bottom-shift of the power distribution.

The boron concentration plays an important role in the successful application of Mode-K. Control of the boron concentration is inevitable for the following reason. 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-power capability during the load follow operation. Secondly, 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 a priori determined 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 boron scenario and thus to minimize the amount of waste water.

3.2 The ASI Control Logic for RRS Dead Band

One of the major features of the 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, 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 dead band ASI control logic was developed, which controls the

ASI even when the core average temperature is within the RRS temperature dead band[7]. The KNGR RRS has a symmetric dead band of 4 °F width, in other words, RRS requires no CEA movement when -2 °F < ΔT (temperature mismatch) < 2 °F.

As in the previous Mode-K logic, a new stage flag is defined, as in Fig. 2, 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. As shown in Fig. 2, the dead band ASI control is actuated if the ASI deviation exceeds 0.05. The setpoint 0.05 for the ASI control is from the current COG (Core Operating Guideline) of KSNP. The KNGR COG should be determined in the future, consistently to the Mode-K control logic.

In Fig. 3, the logic diagram of the dead band ASI control 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 $\Delta T < 1.75$ °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 only effective CEA movement, from the viewpoint of ASI control, is accepted to avoid conflict with the temperature control of the RRS. Ref. 7 contains more detail informations for the dead band ASI control logic.

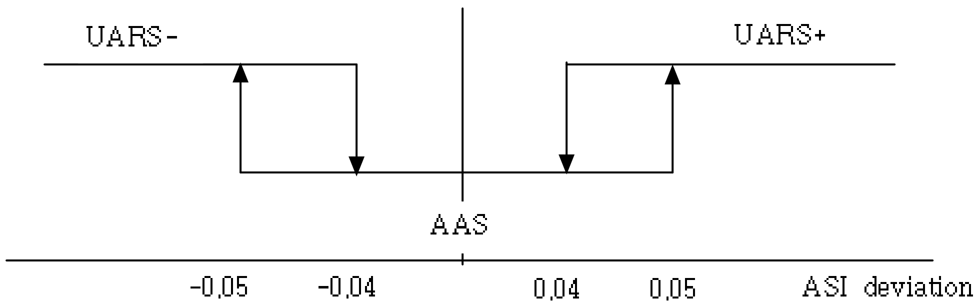

Fig. 2. Stage Flag change in the dead band ASI control Logic

The objective of ASI control in the dead band is to keep the absolute value of ΔASI less than 0.05. 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 within 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, high (30 inch/min) or low (3 inch/min) speed. However, CEA is always driven at the low speed in the case of the dead band ASI control, since the temperature mismatch is small enough.

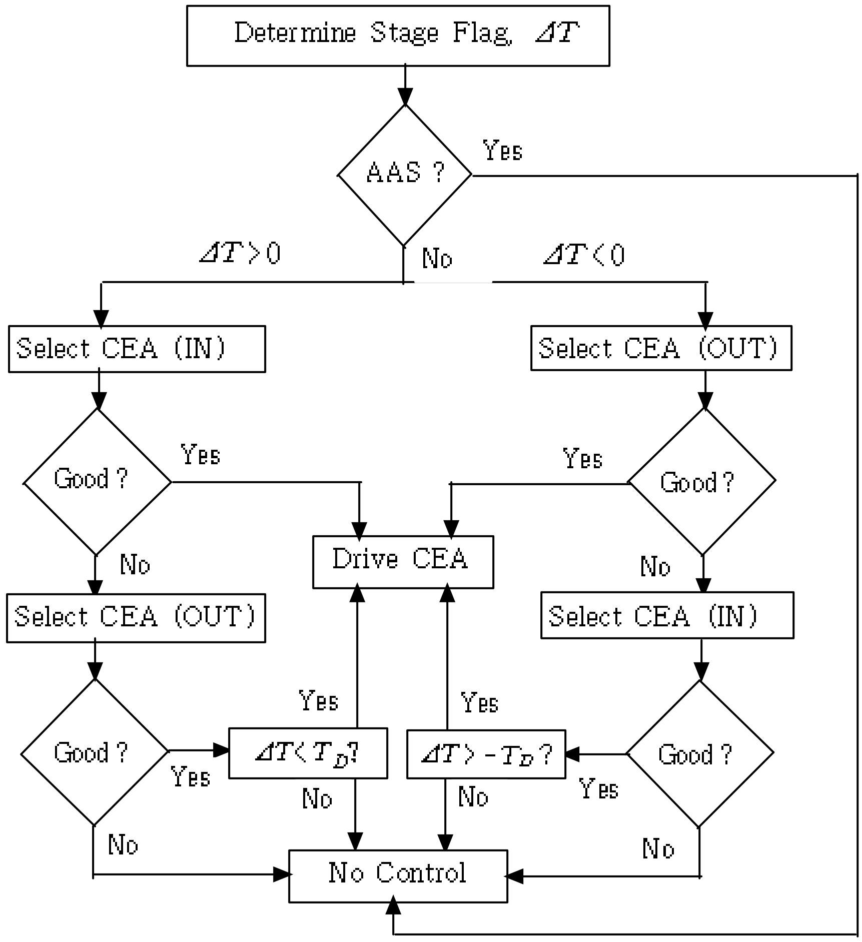

Fig. 3. Diagram of the dead band ASI control logic (T_D = 1.75 °F)

4. Simulation Results

To demonstrate the load follow capability of KNGR, numerical simulations were performed with the KISPAC-1D code at 90% EOC of an equilibrium cycle (Cycle 6). In general, successful load follow operations at EOC imply that the load follow performance at BOC or MOC would be acceptable.

KISPAC-1D is based on a one-dimensional core model, which is collapsed from the three-dimensional ROCS[8] model. In the KISPAC-1D model, several adaptation calculations are performed to make major core parameters close to those of ROCS as much as possible and to minimize the difference between these two models. The adaptation procedures are applied to axial power distribution, the CEA worth, the xenon worth, etc. Table 2 compares core characteristics of KISPAC-1D with those of ROCS. In Table 2, ESI means the equilibrium shape index, and this is the target ASI in the load follow simulations.

Table 2. Core model comparison of KISPAC-1D and ROCS

Parameter	BOX (500 MWD/T)		MOC (12000 MWD/T)		90%EOC (16000 MWD/T)	
	ROCS	1-D	ROCS	1-D	ROCS	1-D
ESI (x100)						
100 %P	-1.3	-1.3	3.5	3.5	3.4	3.4
50 %P	-11.9	-11.6	-13.6	-13.2	-20.2	-19.3
Xe worth (pcm)						
100 %P	2460	2460	2647	2647	2712	2712
50 %P	NA*	1798	NA	2142	NA	2206
CBC (ppm)						
100 %P	1125	1125	515	515	188	188
50 %P	1295	1295	676	677	351	352
CEA worth (HFP, pcm)						
P2	144	144	164	164	177	176
P1	166	166	180	179	193	192
R5	220	220	281	281	294	294
R4	303	306	311	310	333	333
R3	939	941	985	986	1043	1042
Boron worth (pcm/ppm)						
100 %P	7.2	7.18	8.1	8.16	8.7	8.72
50 %P	7.3	7.26	8.2	8.19	8.6	8.71
Power Defect (100-50%P, pcm)	605	604	802	853	997	952

* Not Available

In the current design of KNGR, the overlap between regulating banks are 60%, i.e., 228.6 cm. The overlap is defined as the distance between the rod tip of a preceding CEA and that of the following CEA. Load follow simulations with 60% overlap showed that the load-following performance of KNGR is fairly poor at MOC and EOC[7, 9, 10]. To improve the performance of KNGR load follow operations, in this work, the overlap between regulating banks was changed to 40%, i.e., 152.4 cm.

4.1 Daily Load Follow Operation

Typical daily load maneuverings were simulated at 90% EOC 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 next 14 hours. In this case, the target ASI is 0.034, i.e., the ESI at 100% power, thus the initial Mode-K stage flag is ORS.

In Fig. 4, simulation results for two cases of daily load maneuverings are given. The two power maneuverings are different in the boron scenarios. One is the reference boron scenario, where the amount of boron dilution is determined to adequately compensate for the xenon buildup during the part load. With the reference boron scenario, the dead band ASI control logic is not used. The other case corresponds to a 5 ppm overdilution relative to the reference one. In this case, the extended Mode-K logic including the dead band control scheme is applied to control the ASI. The uncertainty of the boronometer to be used for KNGR is known to be $\pm$(2% of reading + 5 ppm). Thus, the 5 ppm overdilution is well within the uncertainty range of measurements of the boron concentration.

For the reference boron scenario, it is observed that both the core temperature and ASI are well controlled. The maximum ASI deviation is about -0.054 asiu at 50% power and ΔASI during full power is less than 0.025 asiu. As shown in Fig. 4, the ASI deviation tends to increase during the ramp-down stage. This is due to quite a large difference in the ESI values of 100% and 50% power levels. After power reached 50% power, ΔASI starts to decrease, reaching -0.054 asiu at 2.69 hr. During this period (2 hr ~ 2.69 hr), in spite of relatively large ASI deviation, there is no CEA movement to control the ASI, since the core temperature mismatch is within the RRS dead band. However, after 2.69 hr, the temperature mismatch become larger than the dead band because of the xenon buildup, thus RRS requires a CEA withdrawal. In this situation, the Mode-K logic select P2 bank since the stage flag is ARS-, i.e., top-shifted power distribution. Withdrawal of P2 continues, depending on the RRS signal, until P2's position coincides with those of P1 and R5. Afterward, P2, P1, and R5 banks are intermittently withdrawn like a single CEA until 8 hr.

In the case of the 5 ppm overdilution of the boron concentration, one can notice that ΔASI is controlled within $\pm$0.05 asiu over the whole time. During the power ramp-down, the ΔASI behavior is very similar to that of the reference boron scenario. In this case, the overdilution keeps the core temperature mismatch within the dead band during the part load stage. As in the previous case, ΔASI decreases almost linearly after reaching 50% power, becoming smaller than -0.05 asiu at 2.72 hr. At that time, the dead band control logic starts to work. In this case, the stage flag of the dead band control logic is UARS-, thus P2 bank is withdrawn until ΔASI is larger than -0.04 asiu. While the core power stays at 50%, the ASI is likely to reach the ESI of 50% power, consequently, ΔASI tends to decrease continuously during the part load. Therefore, similar dead band ASI control is repeated until 8 hr. When the core power is increased back to full power at 10 hr, P2 is 316 cm withdrawn and other banks are fully withdrawn. A relatively large insertion of P2 at 100% power is due to the 5 ppm overdiluation at 50% power. Over the next two hours, P2 is slowly withdrawn to the top of the core. During full power, the reactivity change due to xenon behavior is wholly compensated via the boron concentration control. At 24 hr, the ASI deviation is about -0.018 and the core is ready to repeat subsequent daily load follow operation.

It should be noted that ΔASI would be very large during 50% power if the dead band control logic is not introduced. And large ΔASI at part load will incur a significant xenon oscillation after returning to full power. Unfortunately, behavior of the other NSSS systems are not provided due to the lack of space in this paper. However, it was confirmed that all NSSS systems were successfully controlled.

4.2 Grid Follow Operation

A grid follow operation was simulated for KNGR, where both remote and local frequency controls were superposed on the typical daily load maneuver. In this simulation, maximum power increase and decrease rate are 1.%/min and 1.7%/min, respectively. The power maneuvering pattern is typical of the French PWR grid follow operations[9]. Turbine load changes (P_{LOCAL}) due to the local frequency control are determined by using the following formula:

$$P_{LOCAL} = 0.02 f_{rand} \sin\left(\frac{2\pi}{20(1+f_{rand})} t\right),$$

where f_{rand} is a random number.

Fig. 5 shows the simulation results for the grid follow operation. One can see that ΔASI is controlled within ±0.05 asiu most of the time except short period during a power increasing range around 9.5 hr. The maximum ΔASI is -0.059 at 9.5 hr. During the part load (0 hr ~9 hr), the ASI control is slightly better, compared with the daily load maneuverings of the previous section. This is mainly because the power maneuvering range is a little smaller in grid follow operation, and also turbine power repeats increase and decrease. On the one hand, bottom-shifted power distributions are observed during the remote frequency control at full power. This phenomenon is because the ESI at low power is much smaller than that of full power.

It is also observed that the core inlet temperature is well controlled within the range, 552 °F ~ 558 °F. Although not shown here, it is emphasized that all the other NSSS systems were also successfully controlled. Especially, the pressurizer spray valve was not opened over the whole time, despite that the turbine power varies fairly fast and largely.

Concerning grid follow operations in nuclear power plants, one of the critical issues is the control rod stepping. Table 3 shows the traveling distances of CEA banks in the grid follow operation. As is expected, the PSCEA's traveling distances are much longer than those of regulating banks. It should be noted that the dead band ASI control results in a marginal increase in the traveling distance of P2 bank. The design lifetime of the current CEDM (Control Element Driving Mechanism) is about 80,000 ft. Therefore, the lifetime of CEDM should be significantly extended in order to perform usual grid follow operations during the lifetime of KNGR.

Table 3. CEA traveling distance in grid follow operation

CEA Bank	P2	P1	R5	R4	R3
Traveling Distance (m)	55.2 (51.2)*	30.2 (29.9)	15.2 (15.4)	7.46 (7.46)	0 (0)

* without dead band ASI control

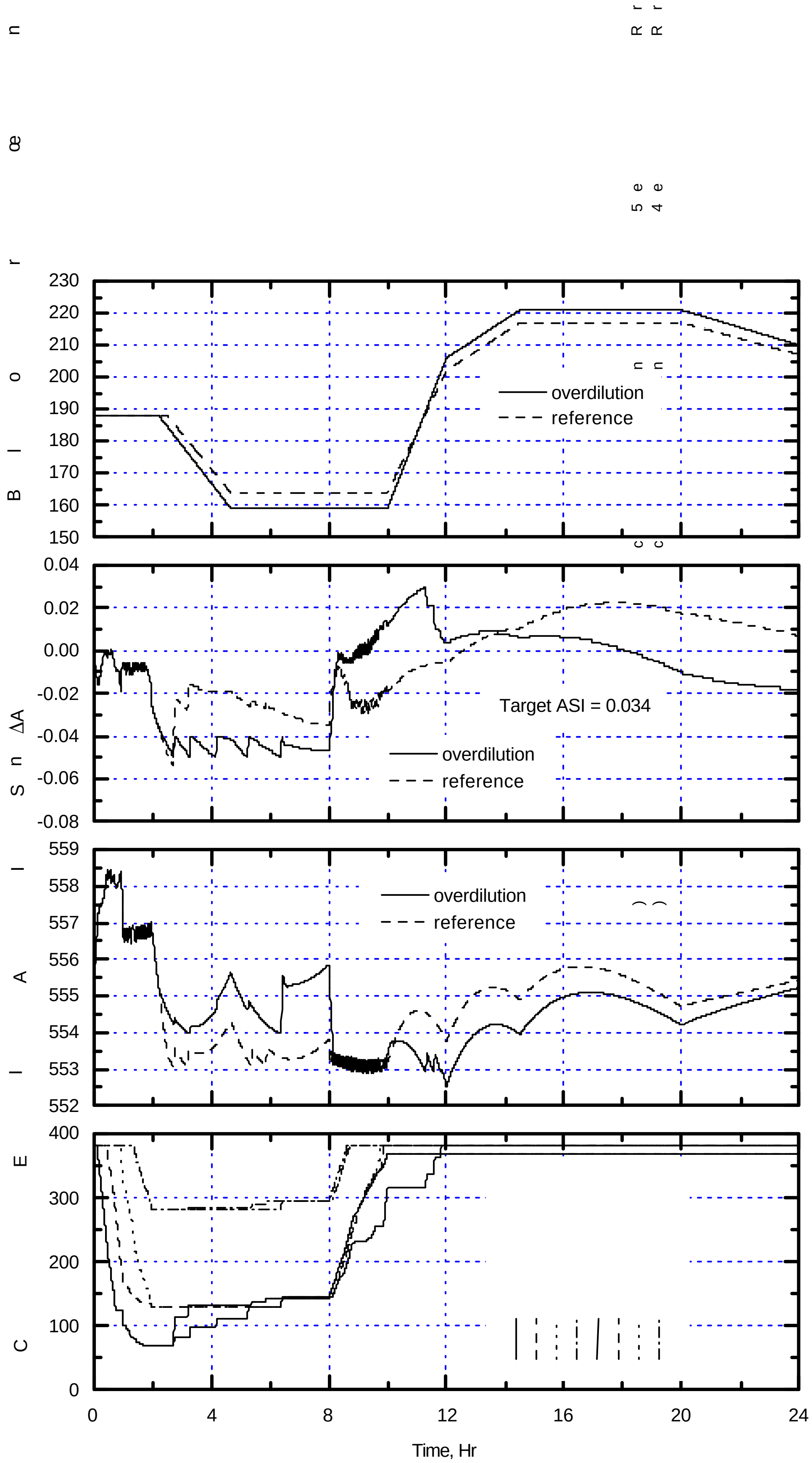

Fig. 4. Daily load follow operation at 90% EOC

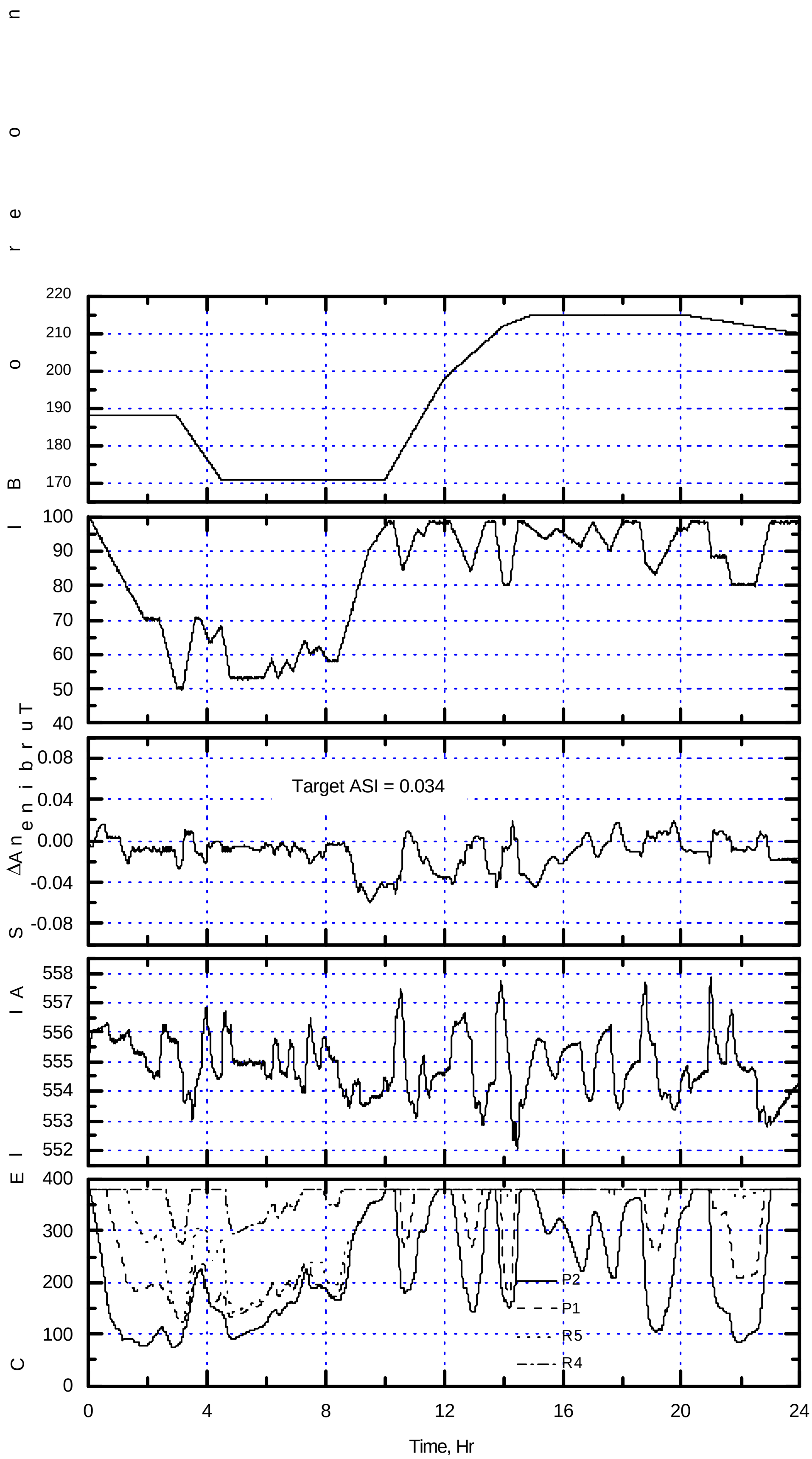

Fig. 5. Grid follow operation at 90% EOC

5. Summary and Conclusions

For improvement of load follow performance of KNGR, an automatic control logic named Mode-K was developed, where both core temperature and axial power distribution are simultaneously controlled with manual control of the boron concentration. In the original Mode-K logic, the CEA movement is wholly determined by the RRS, thus the logic is fairly sensitive to the boron scenario. To resolve the drawback of Mode-K, a temperature dead band ASI control logic was introduced. The load maneuvering performance of KNGR was analyzed for daily load follow and grid follow operations using an NSSS analysis code, KISPAC-1D. Load follow simulations at 90% EOC of an equilibrium cycle identified the following characteristics of KNGR.

- With 60% overlap between regulating CEA banks, load follow performance of KNGR is not satisfactory. However, the core power and ASI are successfully controlled when the overlap is changed to 40%.
- With introduction of the temperature dead band ASI control logic, flexibility of the boron scenario is significantly improved, and also the control logic can be robust with respect to the axial xenon oscillation.
- During daily load follow and grid follow operations, all NSSS systems are well controlled.
- Lifetime of CEDM should be significantly extended to perform usual grid follow operation based on the Mode-K control logic.

It is recommended, for further improvement of load maneuvering capability of KNGR, that the PSCEA worth should be increased and the worth of regulating banks should be optimized. Optimized CEA worth is expected to improve the load follow performance and also reduce the CEA traveling distance.

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