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Advanced Load Follow Operation Mode for Korean Standardized Nuclear Power Plants

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한국 표준 원전의 부하추종을 위한 운전 기법

최중인 · 오수열 · 송인호 · 하영준 · 구정의
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Abstract

An advanced load–follow operation mode, Mode K, is presented for the Korean Standardized Nuclear Power Plants. The Mode K utilizes a heavy worth bank dedicated to axial shape control independent of the existing regulating banks. In Mode K, the heavy bank provides a wide range of axial shape control and a monotonic relationship between its motion and the axial shape change, which makes it easy to automate axial shape control. The achievement of full automatic reactor power control both for the reactivity and power shape would reduce the burden due to load–follow operation on the operator. Also, it can accommodate the frequency control, which requires the plant to respond to the unexpected demand. The Mode K design concepts were tested using simulation responses of Yonggwang Units 3&4, the reference plants for the Korean Standardized Nuclear Power Plants. The results illustrate that the Mode K is an adequate operation mode to provide practical load–follow capabilities for the Korean Standardized Nuclear Power Plants.

요 약

한국 표준 원전의 부하추종운전 능력 향상을 위하여 노심 축 방향 출력분포 제어에 기존의 regulating bank와는 별개의 heavy bank를 사용하는 노심 제어 기법인 Mode K를 제시하였다. 이

경우 heavy bank는 제어할 수 있는 축방향 출력 변화의 범위가 크며, 또한 bank의 움직임과 축 방향 출력 변화가 단조적 관계를 항상 유지할 수 있으므로 운전을 용이하게 할 뿐 아니라 자동제어가 가능하도록 한다. Mode K 기법을 이용한 노심 제어 자동화는 부하추종운전에 대한 운전원의 부담을 경감시킬 수 있으며, 특히 주파수 제어 운전등 미리 예측되지 않은 부하변동에 응동할 수 있는 능력을 갖게 한다. 표준 원전의 참조 발전소인 영광 3,4호기의 운전을 모의 계산함으로써 Mode K의 설계 개념을 평가하였는데 그 결과를 통하여 한국 표준 원전의 실제적 부하추종운전을 위하여 Mode K 기법을 적절하게 사용할 수 있음을 입증하였다.

1. Introduction

Since the nuclear power generation has supplied more than 50% of the total electric power generation in Korea, nuclear power plants are required to have load–follow capabilities for effective management of the electric grid system. As the gap between the maximum and the minimum in electrical demand is getting increased in accordance with economic progress, it becomes more important for nuclear units to contribute to grid stability. Moreover, the participation of nuclear units into frequency control is needed to cope with the demand of high quality electricity required in the high technology industries. Accordingly, it is desirable that the Korean Standardized Nuclear Power Plants (KSNPPs) have the enhanced load–follow capabilities to meet grid requirements including frequency control.[1] The KSNPPs will refer to the Yonggwang Units 3&4 (YGN 3&4), which are under construction based on the Combustion Engineering Nuclear Steam Supply System (NSSS) design.

The YGN 3&4 NSSS is designed with a high degree of load–follow capability.[2] The NSSS can accommodate 10% steps or 5%/minute ramp rates in turbine load demand between 15% and 100% power without tripping the reactor. In addition, the NSSS can accommodate a load rejection of any magnitude (including turbine trip) without tripping the reactor or lifting primary or secondary safety valves. These load maneuvers are accomplished by the automatic and integrated operation of the Steam Bypass Control System (SBCS), Reactor Regulating System(RRS), and Reactor Power Cutback System (RPCS) in response to a change in turbine load demand. During these load maneuvers, reactivity control is accomplished with the automatic operation of the RRS to vary Control Element Assembly (CEA) reactivity. Because the use of CEA leads to power shape distortion, the RRS automatic operation may be severely limited in contributing to core power change. Accordingly, it was originally envisioned that the core power variation would be achieved through the manual change of boron concentration via the Chemical and Volume Control System (CVCS). The use of soluble boron, however, is subject to following problems :

- –slow compensation for short term reactivity change ;
- –increased liquid waste water generation ; and
- –limited capability near end of cycle.

To alleviate this situation, the use of "gray" control rods, called Part–Strength CEAs (PSCEAs), has been implemented in the YGN 3&4 design. The PSCEAs are designed to be used both for reactivity control and for axial power shape control. The PSCEAs may be effectively used to relax the problems of the use of soluble boron, maintaining power shape distortions within prescribed limits. However, the use of PSCEAs is too complicated by its coupled effects on reactivity and axial shape control to be automated. The manual control of PSCEAs would require the operator's expertise, experiences, and carefulness for the successful load–follow operations.

In this study, a new operating mode for the KSNPPs, called "Mode K", has been developed that promises practical load–follow capabilities to meet grid requirements by achieving high degree of automation and minimum use of soluble boron or maximum spinning reserve. The Mode K is based on the incorporation of a new power maneuvering model into the YGN 3&4 NSSS with taking advantage of its existing design features for load–follow operations such as on–line core operating and safety margin calculators (COLSS/CPC : Core Operating Limit Supervisory System and Core Protection Calculator) and limitation systems (RPCS/MDS : Reactor Power Cutback System and Megawatt Demand Setter).

2. Grid Requirements

In Korea, ever since the first commercial operation in 1978, the nuclear plants have been operating as base–load units, and have not been required to contribute to grid stability. Thus, the Utility has no specific grid requirements for nuclear power plants. Accordingly, the grid requirements for Mode K are determined based on the contractual load change warranty of YGN3 &4[3] and on the grid requirements practically imposed on the nuclear units in other countries such as France.[4]

Grid requirements are typically divided into power maneuvering, frequency control, and spinning reserve. Power maneuvering consists of those planned daily or weekend changes in unit power needed to maintain a balance between electricity generation and load demand. Based on the demand patterns in Korea, a typical daily maneuver might consist of a power reduction from 100 to 50% over a period of two hours, six hours at reduced power, and two hours for returning to full power (100–50–100%, 14–2–6–2 hr pattern). Weekend maneuvering is similar, but with a somewhat greater power reduction (for example, to 30%) and a longer duration.

Frequency control performs power changes when there is an imbalance between the electrical supply and demand which leads to a frequency deviation from its reference value (60Hz in Korea). Frequency control is typically characterized as being unplanned and being accomplished by frequent and fast changes in power but with small magnitude. In Korea, it is expected that the nuclear unit participation in frequency control with maximum magnitude of ±5% of the rated power will highly contribute to grid stability.

To support grid stability, the plants operating at part load are required to return to full power as quickly as possible. Both ±10% power steps (instantaneous spinning reserve) and ±5%/minute power ramps (delayed spinning reserve) are the basic design features of the YGN 3&4 NSSS. The spinning reserve capability would be ensured when the fast reactivity insertion means (the use of CEAs) is available. Thus, the spinning reserve requires the large use of soluble boron to maintain the CEAs in the core for the reservation of rapid power increase. Accordingly, there should be a trade–off between spinning reserve capability and utilization of soluble boron. The Mode K is designed to permit plant operation with the spinning reserve capability required by the grid until returning to full power, directed toward the minimum use of soluble boron.

3. Mode K Design Concepts

During load–follow operations, reactor power changes (to follow turbine load changes) can be accomplished by core reactivity compensation and power distribution control. Reactivity compensation is provided in the form of control rod position adjustment and/or boron concentration adjustment and/or primary average coolant temperature (T_{avg}) adjustment in order to account for reactivity associated with both changes in power level (power defect) and changes in transient xenon level (which result from the changes in power level).

Power distribution control is performed to maintain core thermal margin within operating and safety limits. Power distributions, usually axial shapes, are monitored and controlled during power maneuvers. Power shape control becomes somewhat complicated by the use of control rods because it is highly coupled with reactivity compensation. There have been some studies to develop a core control strategy which minimizes the effect due to shape control on the reactivity compensation.[5,6]

In Mode K strategy, the bank with high reactivity worth, HROD, is dedicated to axial power shape control while other regulating banks, RRODs, are used for reactivity compensation. They are designed to provide a monotonic relationship between the motion of HROD and the change of the axial power shape irrespective of the motion of RRODs for compensating for the core reactivity due to the HROD motion : i.e. as the HROD is inserted or withdrawn, the axial shape is bottom–shifted or top–shifted, respectively. When this relationship exists, automatic axial shape control can be achieved with the simple control logic. The core reactivity is balanced by the use of RRODs, soluble boron, and T_{avg} variation. The portion of each reactivity control methods can be optimized depending on the direction of load–follow operation toward the minimum use of boron or the maximum spinning reserve. In Mode K, the reactivity is balanced by RRODs primarily and by soluble boron if necessary. Practically, the boron concentration could be varied in a known manner for the expected load change by the operator and the RRODs would be used for fine tuning of the balance to keep T_{avg} to its programmed value in automatic mode. As mentioned above, automatic axial shape control can be achieved by the HROD. Thus, the reactor power can be automatically controlled for reactivity and for power shape. It is demonstrated schematically in Fig. 1.

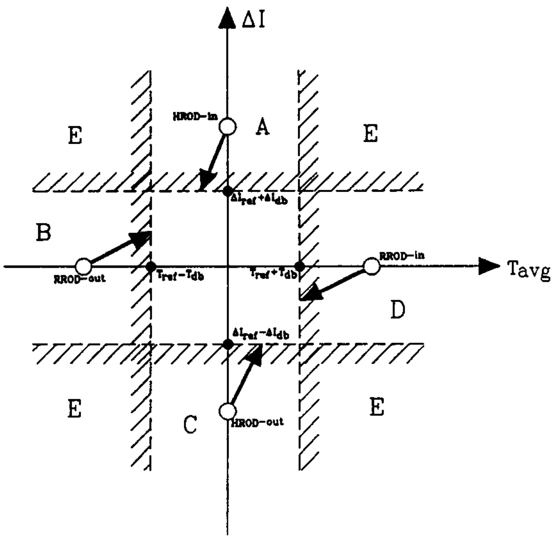


Fig. 1. Mode K Operation Diagram

4. Determination of Control Bank Pattern for Mode K

The target of this section is to determine the positions and materials of HROD and RRODs, so called CEA programming. The constraints are imposed on the CEA programming as follows :

- –there are only two types of neutron absorbing material (Inconel 625 and B_4C with fixed composition) ;
- –HROD and leading RROD bank cannot be positioned on the line between the core center and ex–core detectors ;
- –the fuel loading pattern is fixed and the shutdown margin is reserved as much as in the YGN 3&4 existing design.

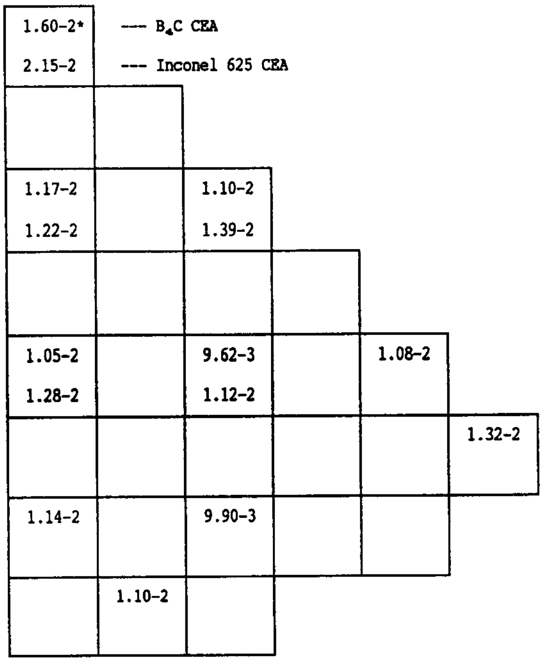
The quantitative index for CEA programming is the ratio of the change of reactivity to the change of Axial Shape Index (ASI) per unit motion of a single CEA in an octant core of YGN 3&4. As an index indicating axial power shape, the ASI is defined as follows :

$$ASI = \frac{P_B - P_T}{P_B + P_T}$$

where P_B : bottom half power, and

P_T : top half power.

The ratios are calculated at all positions which can accommodate a CEA except those for shutdown banks. The RRODs are assigned from the position with a larger ratio, and the HROD is assigned to the position with a minimum ratio. Figure 2 shows the ratios calculated at 2000 MWD/MTU, hot full power condition, and for a CEA inserted from 25% of the core height to 50%. Figure 3 shows a proposed control bank pattern based on the result in Fig. 2 with some engineering judgements. There are 5 RROD banks and 1 HROD bank, and shutdown banks are not shown in Fig. 3. The monotonic relationship of ASI to HROD motion can be observed in Fig. 4. At first, the steady state condition is established with 20% inserted HROD . Four plots in the figure are for 0, 20, 40, and 60% of initial lead RROD insertion, respectively, and the overlapping between RRODs is the fixed value of 40%. Then, the HROD is withdrawn step by step while the RRODs are inserted to maintain the criticality. It was assumed that the xenon reactivity is maintained in constant equilibrium level. Regardless of the initial RRODs position, the change of ASI shows a monotonic trend with HROD motion throughout the core life.



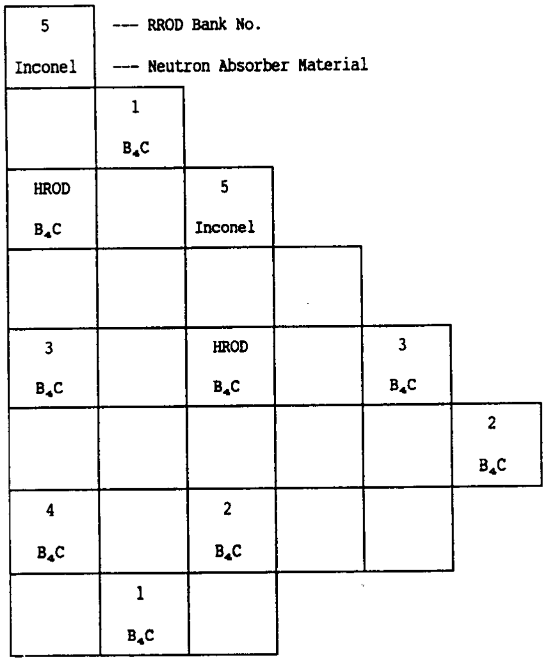
1.60-2* 2.15-2	— B_4C CEA --- Inconel 625 CEA

1.17-2 1.22-2		1.10-2 1.39-2			
1.05-2 1.28-2		9.62-3 1.12-2		1.08-2	
					1.32-2
1.14-2		9.90-3			
	1.10-2				

* 1.60E-02

Negative sign dropped for convenience

Fig. 2. Reactivity Change to ASI Change due to a CEA Insertion. (HFP, 2000 MWD/MTU, 25% to 50% insertion)



5 Inconel	— RROD Bank No. — Neutron Absorber Material

	1 B_4C				
HROD B_4C		5 Inconel			
3 B_4C		HROD B_4C		3 B_4C	
					2 B_4C
4 B_4C		2 B_4C			
	1 B_4C				

Fig. 3. Control Bank Pattern for Mode K

5. Mode K Evaluation

5.1 Daily Load-Follow Operation

A typical 100-50-100%, 14-2-6-2 hr pattern of load-follow daily power maneuver has been adopted to evaluate the Mode K strategy. The power varies from 100% to 50% in 2 hours, holds at 50% for 6 hours, then rises to 100% in 2 hours. As part of the evaluation performed, 3-day daily load maneuvers by mode K were simulated

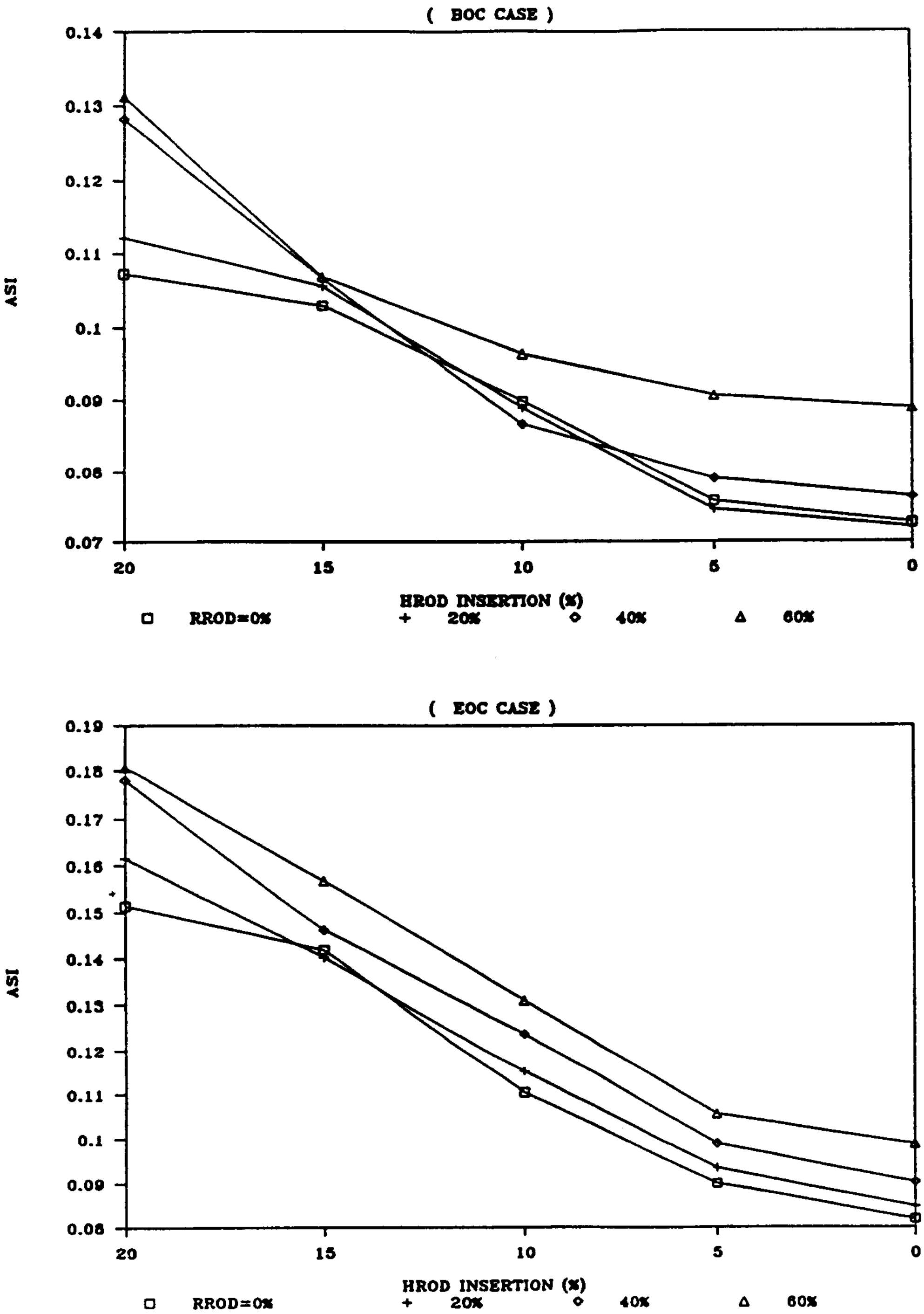


Fig. 4. Monotonic Relationship of ASI to HROD Insertion

based on a three dimensional nodal code, ROBUST[7] at three different burnup states; 15% BOC (beginning of cycle, 2 GWD/MTU), MOC (middle of cycle, 7 GWD/MTU), and 80% EOC (end of cycle, 11 GWD/MTU) of initial core of YGN 3&4 in the interim design stage.

The Power Dependent Insertion Limits (PDILs) for RRODs are same as those for YGN 3&4 and illustrated in Fig. 5. RROD banks are overlapped by 40% in sequence. Also, the RROD withdrawal limits are set at 30% in excess of PDIL for capability of frequency control and for the case where the power is increased to the level above the preset level of daily load–follow operation. The insertion limit of HROD is 25% of core height and HROD is initially inserted to 10% at full power before a ramp down maneuver begins at the first day of simulation. The target ΔI is the equilibrium ΔI at steady state condition with 10% inserted HROD and fully withdrawn RRODs. The ΔI is defined as follows :

$$\Delta I = P_T - P_B$$

where P_B, P_T are same as in ASI definition.

The target value of ΔI changes with the power level during the operation, as the equilibrium ΔI multiplied by the fractional power level. When the ΔI deviates more than 1% from the target value, HROD position will be adjusted.

The BOC results are shown in Fig. 6. These illustrate the behavior of a number of key core parameters : boron concentration, ΔI, RROD positions, HROD position, power operating and safety limits along with the power level. As shown, the boron concentration is varied in a known manner for the expected daily load maneuvering pattern by the operator. And the RRODs are used for fine tuning of the balance to keep T_{avg} within its programmed value in automatic mode. The axial power shape is controlled as close as possible to the target shape by using HROD. HROD is inserted to a certain height initially at full power in order to permit axial shape control in either way (toward top–shifting or bottom–shifting). When HROD is limited to one direction because it has already been fully withdrawn or inserted to its insertion limit, the shape is not controlled until it challenges the core operating limits. In this situation, the operator can use the boration/dilution to mitigate the axial shape distortion.

As shown in ΔI plot, the axial shape is controlled well within the target band. Thus, the margins to the power operating and safety limits are maintained well during the maneuver. The power operating limit, so called "POL", calculated by the on–line core monitoring system, COLSS, represents the alarm setpoint. According to the technical specification of YGN 3&4, if actual power output exceeds the POL, then the power output is required to be lowered within one hour to acceptable limit. The difference between the POL and the actual output is largest at low power while it is lowest after returning to full power and thereafter for about four hours. This implies that ΔI control can be relatively relaxed at low power level since the margin is large while caution may be neces-

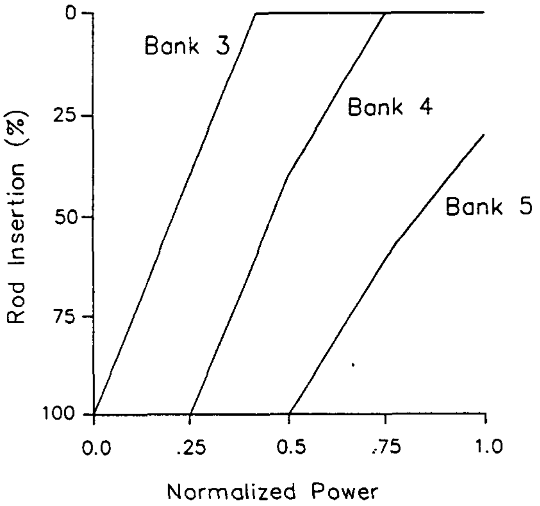


Fig. 5. Power Dependent Insertion Limits (PDILs) for RROD Banks

sary at high power level due to low margin. The POL is one of the main criteria in evaluating the Mode K strategy. As shown in the last figure in Fig. 6, the POL is always greater than the actual output such that power change can be maneuverd according to the plan. Therefore, the Mode K strategy can be verified. The safety limit that represents the trip setpoints was found to be always greater than the POL. The safety limit is calculated by the on-line core protection calculator, CPC.

The results of other burnup states (MOC, EOC) show similar trends. It implies that the Mode K is applied to the entire life of the core in a consistent manner. In addition, the trend and magnitude of parameters during the third day are almost identical to those for the second day. This indicates that the Mode K ia a stable strategy.

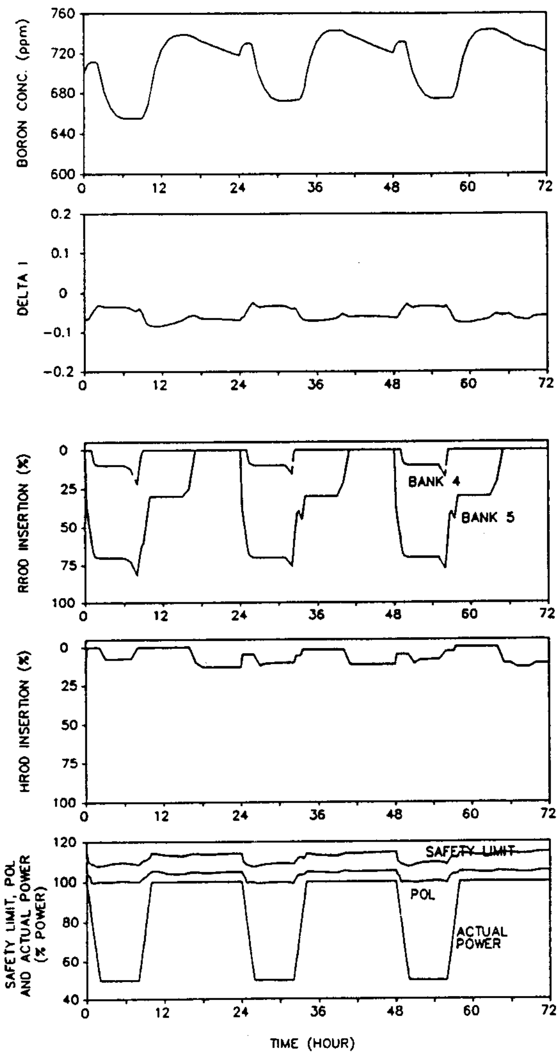


Fig. 6. Reactor Core Parameters during Daily Load Follow Operation(2000 MWD/MTU)

5.2 Frequency Control

Power changes during frequency control cannot easily be performed simply by adjusting the boron concentration of the reactor coolant system (they occur too frequently and are basically unpredictable). On the other hand, control rod movements directly affect the core power distribution, which must be carefully monitored and kept within operating limits.

For Mode K evaluation, the daily maneuvers accompanied with power variations due to frequency control are simulated. During a daily maneuver, the ±3% power variations with the period of 12 min are superimposed for 3hrs at 50% power and for 5 hrs after a return to 95% power (The additional ±2% power variations due to frequency control could be accommodated by T_{avg} variation). In such a case, boron concentration variations are identical to those of the daily load maneuver only. When the frequency control is performed, the ΔI is limited to ±5% from the target value and the PDIL and the PDWL are ignored. The reason for relaxing the ΔI control is that during the frequency control HROD movements are minimized such that the amount of control necessary by RRODs can be reduced. The PDIL is used when the power reduction is required and according to the technical specification of YGN 3&4, exceeding PDIL for 4 out of 24 hours is allowed. However, when continued low power operation is necessary such that the RROD will exceed the PDIL for more than 4 hours, then this unit loses capability to participate in the frequency control. In this case, the boration would need to make-up for the withdrawal of RRODs. The reactivity changes due to frequency control are adjusted by the RRODs and corresponding axial shape changes are controlled by the HROD. In Fig. 7, the one day maneuvering results are given.

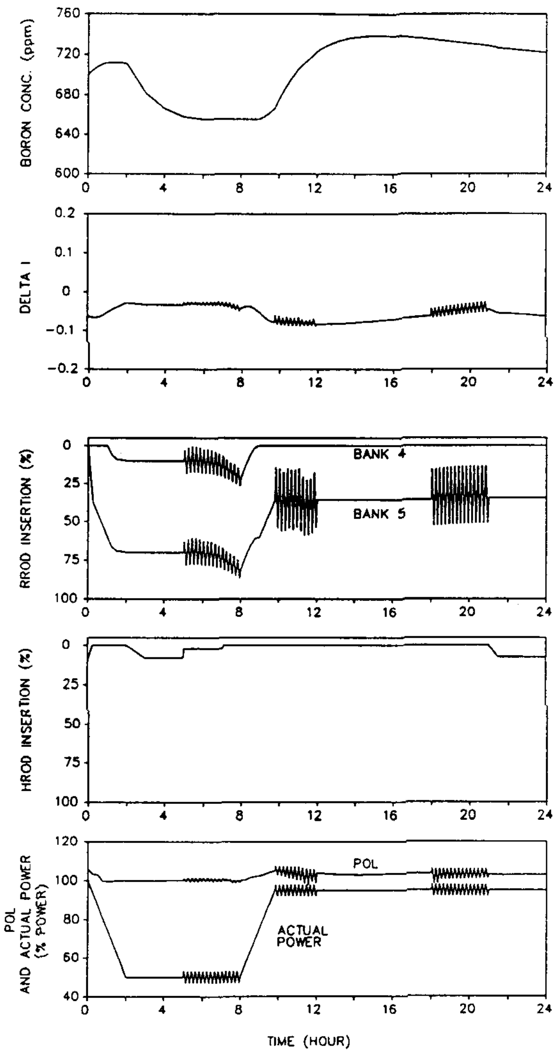


Fig. 7. Reactor Core Parameters during Daily Load Follow Operation with Frequency Control (2000 MWD/MTU)

The results indicate how the POLs are always maintained above the power levels during the frequency control. They illustrate that Mode K can be used to accomodate the load-follow operation with frequency control.

6. Conclusions

An advanced operation mode, Mode K, has been developed to enhance the load-follow capabilities for the KSNPPs. The Mode K strategies were evaluated based on the simulation of the YGN 3&4 plant responses. The simulation results demonstrated that the Mode K is a practical strategy for the load-follow operation including frequency control. It is recommended that the Mode K be incorperated into the KSNPPs as one of the Korean specific design features.

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