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Analysis of Nuclear Power Plant Load Follow Operation by Temperature Reduction Method

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냉각재 온도 감소 방식에 의한 원자력발전소 부하 추종 운전 해석

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Abstract

The inlet coolant temperature reduction technique has been used to extend the load follow operation further in the end-of-cycle-life(EOL). In order to simulate the technique and calculate the nuclear characteristics of a PWR core according to the load follow operation, the three dimensional computing system has been established. The analysis was performed in both MINB and SPINR modes of typical 12-3-6-3 locad follow operation for the EOL of KNU-1 plant. Moreover, the capability of return-to-power has been also tested for those two modes with the system analysis by the RETRAN-02 code. The results show that it has no difficulty to extend the load follow operation further in the EOL by applying the inlet coolant temprature reduction, and also the spinning reserve capacity(SRC) increases by 13% in MINB mode and 14% in SPINR mode more that used by control rods only, for 14°F drop in the inlet temperature.

요 약

보론 희석이 불충분한 주기말에서 부하추종 운전영역을 확장시키기 위해 냉각재 입구 온도 감소 방식을 사용하였으며, 이 방식을 모사하고 부하추종 운전시 가압경수로 노심의 핵적 특성을 해석하기 위해 3차원적 전산체제를 확립하였다. 해석은 고리 1호기 1주기말에서 12-3-6-3부하추종 운전에 대해 MINB 및 SPINR 모드로 수행되었으며, 부가적으로 이 두 방식에 대한 출력복귀능력도 RETRAN-02 코드를 사용한 계통해석과 더불어 시험하였다. 계산결과 냉각재 입구 온도를 감소시킴으로써 부하추종운전이 주기말에서도 가능함이 입증되었으며 14°F의 입구 온도 감소에 따라, SRC가 제어봉만 사용하는 방식보다 MINB 모드에서는 13%, SPINR 모드에서는 14%까지 증가됨을 보여주었다.

I. Introduction

As the nuclear portion of the utility's power generating capacity grows, it becomes necessary to operate some nuclear plants in a load follow mode, which is also the power system's operating requirements. Recently, extensive studies on the load follow capacities have been made in many countries.[1,2] However, the load follow operation is subjected to precise control rod manipulation and the interchange of soluble boron to compensate for the xenon behavior and meet the constant axial offset control (CAOC) strategy during power changes.

Especially, at the end-of-cycle-life (EOL) where the boron concentration is sufficiently low, the boron dilution capability will be limited. This decrease in dilution capabilities reduces the ability to override a xenon transient following a power reduction and, finally the ability of the plant to perform load follow operation proposed by the Westinghouse Electric Corporation. This method is based on a negative moderator temperature coefficient of reactivity. Hence a drop in moderator temperature, instead of boron dilution, produces the additional reactivity at EOL.

In this study, in order to simulate this technique and calculate the nuclear characteristics of core according to the load follow operation, the three-dimensional computing system has been established by using the KINS-2 code and other codes which provide input data for the KINS-2 code.

The analysis was performed with both MINB and SPINR modes of typical 12-3-6-3 (100-50-100% power) load cycle for the EOL of KNU-1 plant. MINB and SPINR mode are to minimize the role of boron system and to maximize the capability of return-to-power, respectively. Moreover the spinning reserve capacity (SRC) has been also tested for those two modes by the temperature reduction method and compared with that used by control rods only.

II. Computing System for Load-Follow Simulation

Generally the response of a PWR plant to network load demands depended largely on the ability of the mechanical control rod systems and chemical shim to change power in the reactor. Thus in order to precisely simulate the change of nuclear characteristics of core according to the control rod motion, it is important to perform the three-dimensional power calculation.

In this study, among the well-known and available computer codes, the most proper code for thd load follow simulation in each step of nuclear calculation was selected and analyzed. The KICC code[3] whose confidence has been already proved was selected for the cell calculation. The boron concentration change according to the core burnup was represented by the sawtooth shape from BOL (1,200ppm) to EOL (18,000MWD/MTU). However, since MASK could not be simulated with such sawtooth shape in actual generation of table-set, all isotope concentration in the sawtooth calculation were stored and only the boron concentration was varied linearly.

The FATAC code[4] was used to generate the group constants for BP rods, which was the neutron transport code using the collision probability method, and provided the microscopic cross-section of boron to the KIDD code. The KIDD code[5] was used for generating the assemblywise group constant by the color-set method. These group constants were collected in a table-set to be used in the three-dimensional KINS-2 code.

The KINS-2 code[5] is the nodal depletion code which uses the response matrix method for the calculation of transport probability parameters. This code has quite accurate models for xenon and thermal-hydraulic feedbacks to predict the xenon behavior during power changes and the coolant temperature effect, which are prerequisites for the load follow simulation. The flow chart of overall computing system is shown in Figure 1.

In order to prove the accuracy and the compatibility of KINS-2 code for this study, the

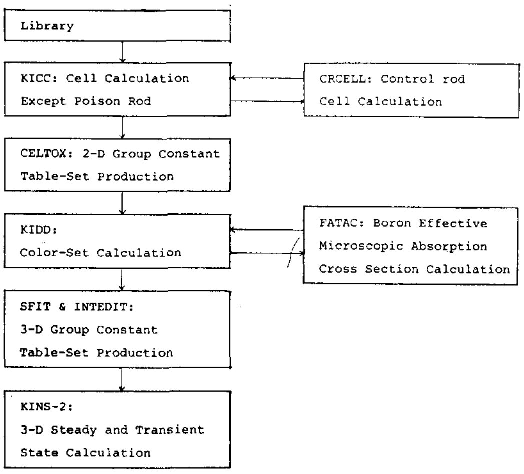

Fig. 1. Computing System for Load Follow Analysis

Table 1. Moderator Temperature Coefficient of Reactivity (pcm/°F)

Power	Programmed T_{av}	Design Report	Calculated
0%	547.0°F	−25.6	−20.47
20%	552.7°F	−26.5	−22.14
40%	558.4°F	−27.6	−24.06
60%	564.1°F	−28.9	−26.09
80%	569.8°F	−30.0	−28.11
100%	575.5°F	−31.1	−30.08

moderator temperature coefficient (MTC) of reactivity which was the basic parameter for the temperature reduction technique was tested for the EOL of KNU-1 core. In this study the coolant inlet temperature was perturbed with $\pm 5°F$ from the programmed inlet temperature and the effective multiplication factor was calculated for each temperature to obtain the MTC for various power level. The results were compared with those in the nuclear design report[7] and showed good agreements, as shown in Table 1.

III. Model Description

In the daily load follow operation, the xenon concentration suffers relatively severe damping due to the power changes before arrival at the equilibrium. The important characteristics of transient xenon in a reactor core can be represented as follows;

(1) A power change causes the xenon concentration to change in such a way that the power change will be accelerated in the short term.

(2) The xenon concentration change has a slow time constant.

Thus the accurate prediction of xenon transient is most important to keep the core axial offset (AO) in the target band by compensating its reactivity with the boron adjustment.

In this study, instead of the equilibrium xenon concentration in each time interval which was used in most depletion calculation, the time dependent non-equilibrium xenon concentration was calculated from the following rate equations;

$$\frac{dN_I}{dt}=Y_I-A_IN_I \tag{1}$$

$$\frac{dN_{Xe}}{dt}=Y_{Xe}-A_{Xe}N_{Xe}+\lambda_IN_I \tag{2}$$

where the disappearance rate is given by

$$A_n=\lambda_n+\sigma^n_{a1}\phi_1+\sigma^n_{a2}\phi_2 \tag{3}$$

and the yield rate is given by

$$Y_n=Y_n\left(\frac{1}{\nu}\right)(\nu\Sigma_{f1}\phi_1+\nu\Sigma_{f2}\phi_2) \tag{4}$$

where ϕ_1, ϕ_2=the absolute fluxes (n/bn-sec)

λ_n=the decy constant (sec^{-1}) for nuclide n

N_n=the number density of nuclide n (atoms/bn-cm)

Y_n=the yied fraction of nuclide n from fission

ν=the value of neutrons per fission

The above two coupled equations are generally not solved easily because the disappearance rate A_n and the yield rate Y_n are functions of time. However, if A_n and Y_n can be approximated to the step-wise constant at each time step Δt, those two equations will be the first order Bernoulli-type differential equations and can be solved analytically. This approximation will not introduce appreciable error because the core state was sufficiently slowly varying during the daily load follow operation and, moreover, the actual calculation time interval was divided by the sufficient number of subintervals just for the xenon calculation in this study.

The analytical form of concentation of each nuclide at the end of the subinterval can be expressed as;

$$N_I(\Delta t)=N_I(0)\exp(-A_I\Delta t) + \frac{Y_I}{A_I}(1-\exp(-A_I\Delta t)) \quad (5)$$

$$N_{Xe}(\Delta t)=N_{Xe}(0)\exp(-A_{Xe}\Delta t) + \left(\frac{Y_{Xe}}{A_{Xe}}+\frac{\lambda_I Y_I}{A_I A_{Xe}}\right)(1-\exp(-A_{Xe}\Delta t)) + \left(\frac{\lambda_I N_I(0)}{A_{Xe}-A_I}-\frac{\lambda_I Y_I}{A_I(A_{Xe}-A_I)}\right)(\exp(-A_I\Delta t)-\exp(-A_{Xe}\Delta t)) \quad (6)$$

where $N(0)$ is the nuclide concentration at the beginning of the subinterval. Those calculations have been propagated to the end of the actual time step and, according to the resulted xenon concentration the boron concentration was determined by the criticality search for the power level.

IV Load Follow Simulation by the Temperature Reduction Technique at EOL

To extend the nuclear plant operational flexibility, the capability of load follow operation is one of the foremost requirement for the reactor supplier. However, this enhancement in operational flexibility can be subject to the assurance of the safety limit, such as the LOCA envelope. Thus Westinghouse had suggested the constant axial offset control(CAOC) strategy[8] to minimize xenon redistribution and thus peak local power densities during operation while maintaining the necessary load change flexibility.

The basic principle of CAOC is to maintain the core axial offset within a band about a referance target value. According this strategy, two operational modes have been suggested[9] Mode A and Mode B which are operations without the use of part-length rods(PLR) and with the use of PLR, respectively. However, the latter is beyond our concern because the use of PLR has been prohibited in the KNU-1 plant.

For mode A the full-length rods(FLR) are used to control axial offset and to absorb part of the reactivity change associated with the power change. The balance of the reactivity change is controlled through changes in the boron concentration. Moreover, if the axial offset moves outside the band, the boron concentration is adjusted to bring the axial offset within the band.

However, as the core approaches the end-of-cycle-life, the boron concentration decreases and consequently the boron dilution becomes more difficult. The larger the power reduction, the larger the reactivity decrease becomes. Therefore, the amount of power change is more limited because the boron dilution capability is more limited as the core approaches the end-of-cycle-life. To overcome this problem, the temperature reduction technique[10] has been proposed by the Westinghouse Electric Corporation. This method is based on a negative moderator temperature coefficient of reactivity. Hence a drop in moderator temperature, instead of boron dilution, produce the additional reactivity at EOL.

In this study, the operational mode is based on the MINB mode,[1] which is to use only enough boron to keep the axial offset inside the target band and thus to minimize the boron sys tem duty. The calculational procedure in each time step is as follows;

(1) choose three locations of control rods with the position corresponding to reactivity change by the power defect as a center.

(2) calculate axial offset and the critical boron concentration for each location.

(3) check whether the axial offset is in the band and whether the change of critical boron

concentration satisfies the MINB mode.

(4) if the results of the third procedures is not satisfactory, adjust the location of rods dy interrelating axial offset and critical boron concentration. Thus choose new location and repeat the above procedures. Next, the other thing to be checked is the boron dilution rate which has a limit value corresponding to the original concentration. In KNU-1 plant, the rate of change is limited to 10 percent of the original concentration in one hour.[11] Thus if the calculated dilution rate exceeds to this limit value, the coolant inlet temperature should be dropped from the programmed value to compensate the boron dilution with holding axial offset as the same.

The calculations were performed for KNU-1 plant at 85%EOL(12450MWD/MTU). The load cycle has the 12-3-6-3(hour) pattern with 100-50-100(%) of power level. Results are shown in Figure2. As shown in Figure2. at 9 hour after the start of load follow, the boron dilution rate exceeded to the limit value and thus the temperature reduction was performed until 13 hour. As the result of this study. the maximum temperature drop was 9°F for the MINB mode.

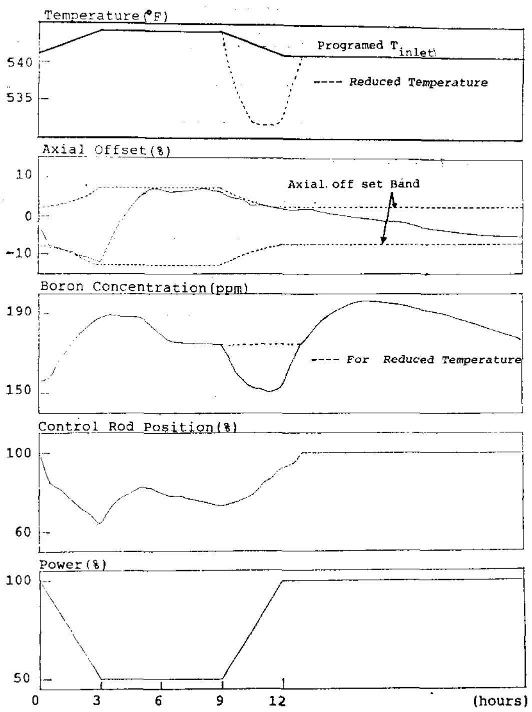

Fig. 2. 12-3-6-3 Load-Follow with MINB Mode (KNU-1, CY1, 85% EOL)

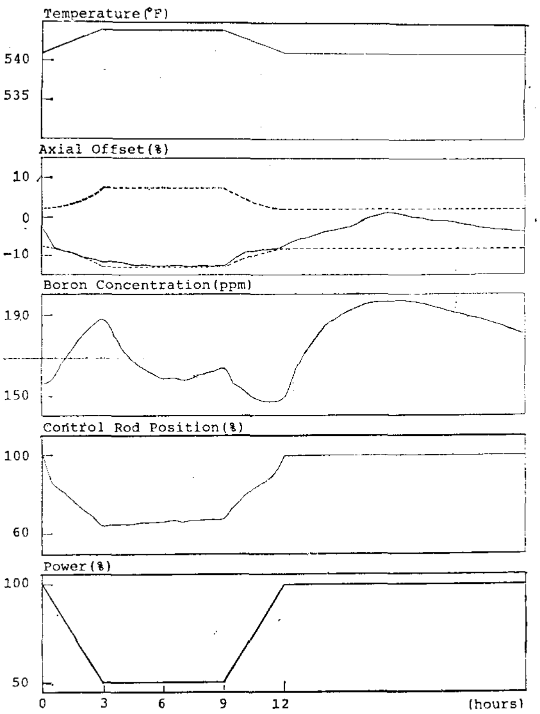

Fig. 3. 12-3-6-3 Load-Follow with SPINR Mode (KNU-1, CY1, 85% EOL)

V Return-to-Power Analysis

Another important parameter repuired during load follow operation is "spinning reserve capacity (SRC)". SRC refers to the ability to increase power at a rapid rate (5%/min) from some part-power operating during the daily load cycle to some higher power level in response to an unanticipated system demand.

At EOL where the boron concentration is not sufficient to override the xenon transient, the capability of return-to-power will be also limited and thus the temperature reduction technique will be attractive. In the previous section it was noted that under MINB constraints the control rods cannot be used for rapid load increase since either the rods are fully withdrawn or the rods cannot be withdrawn without violating CAOC limits from 9 hour after the initial power reduction. Thus in this study, the other strategy, which is named as "Maximum Spinning Reserve (SPINR)[1]" was simulated. The operational principle of this strategy can be summarized as follows;

(1) when operating above approximately 85 percent power maintains axial flux difference (ΔI) near the positive edge of the control band.

(2) when operating below approximately 85 percent power maintains ΔI near the negative edge of the control band.

The simulation of 12-3-6-3 load pattern for KNU-1, at EOL, with the SPINR mode is shown in Figure3. The procedure to test SRC with the temperature reduction method has three basic steps;

(1) use control rods to the maximum extent possible.

(2) force reactor coolant temperature to drop by continued turbine loading. until the low operation temperature limit is reached

(3) recover reactor coolant temperature by boron dilution. An example is shown is shown in Figure4.

Figure 5 shows the comparison of SRC with the temperature reduction to that used control rods only, for MINB mode. According to 14°F

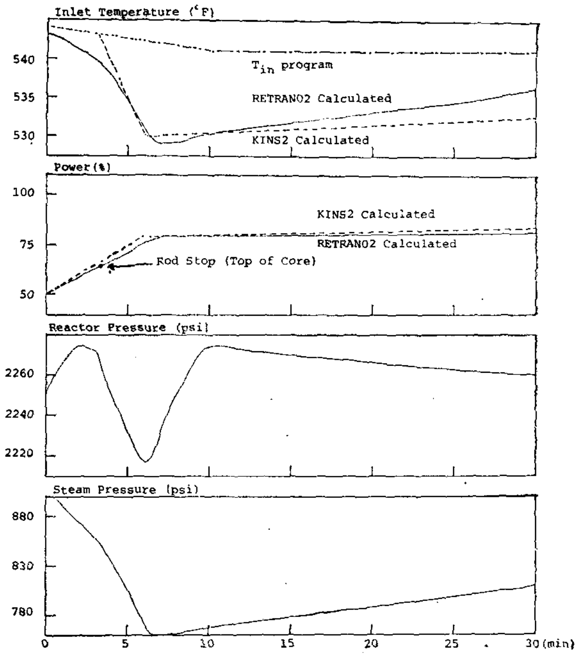

Fig. 4. Return-to Power with Reduced Temperature

drop in temperature, maximum increased SRC was 13% of power and, for the SPINR mode, maximum increased SRC was 14% of power as shown in Figure 6. Moreover it was already noted that the SPINR mode has greater SRC than MINB mode.

During the temperature reduction technique, it has two inherent system limits; throttle valve limits and steam generator moisture carryover. As a result of the temperature reduction the steam

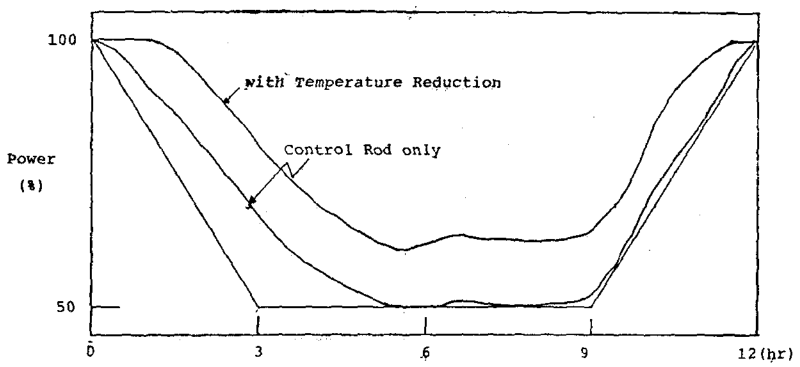

Fig. 5. Return-to Power Capability during 12-3-6-3 Load-Follow with MINB Mode (KNU-1, CY1, 85%EOL)

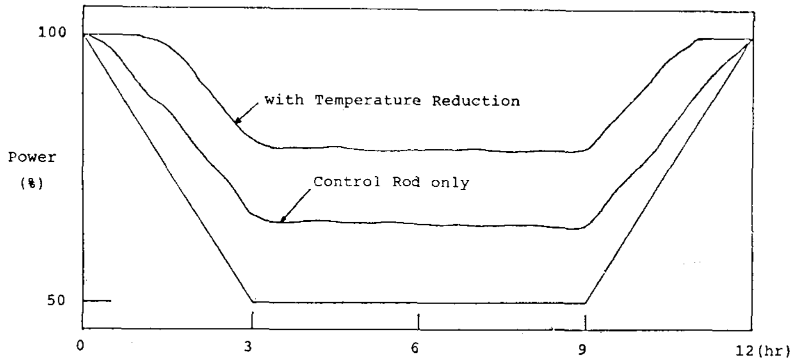

Fig. 6. Return-to-Power Capability during 12-3-6-3 Load-Follow with SPINR Mode(KNU-1, CY1, 85% EOL)

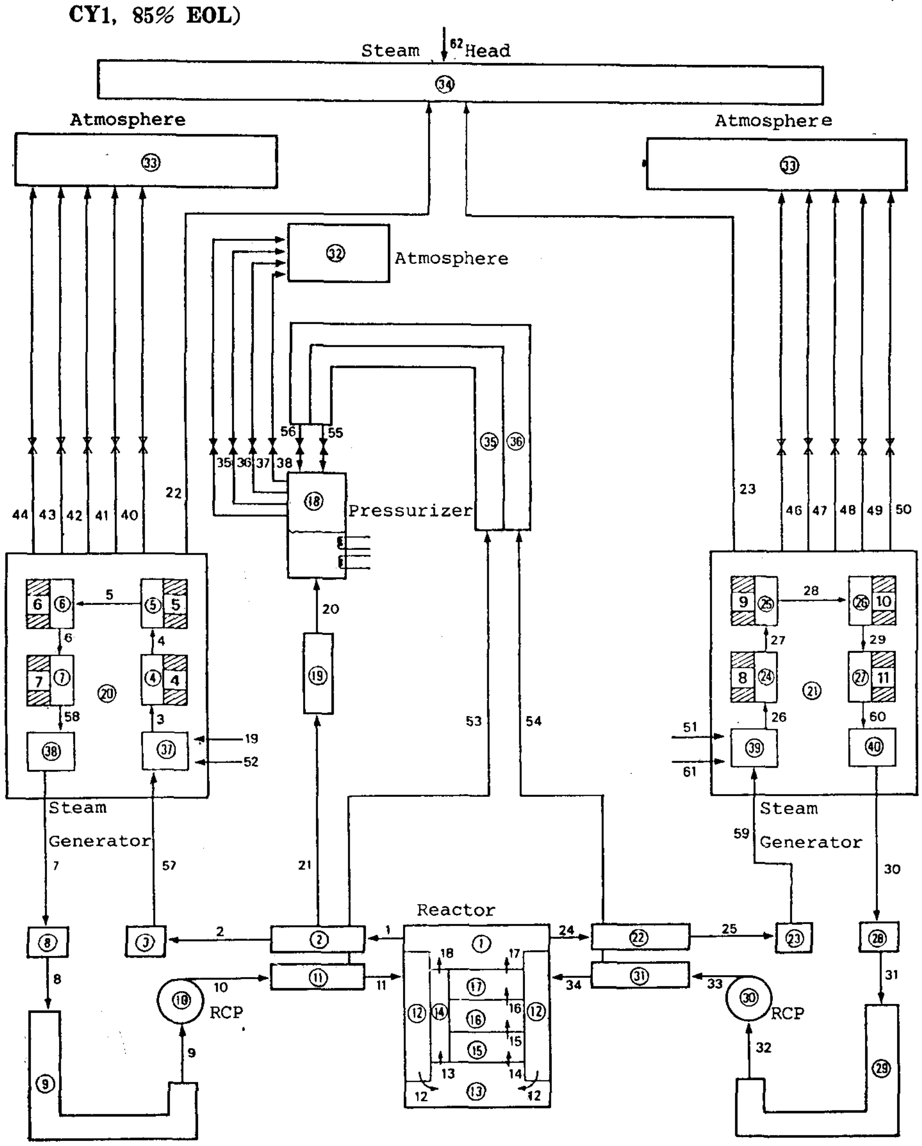

Fig. 7. System Nodalization for RETRAN-02 Calculation

pressure must decreases and consequently the turbine throttle valve must open to match the steam flow. At some point the steam preassure will become so low that the throttle valves are wide open. Also the reduced temperature operati on will increase the moisture carryover due to low steam pressure, which degrades the plant performance. In order to prevent such a violation, the control system provides interlock C-16 to prevent tempepature reduction of greater than 20°F. Therefore use of the inlet temperature reduction option must be compatible with the plant's secondary side characteristics and a plant system analysis is recommended prior to its utilization. In this study, the RETRAN-02 code[12] was used to simulate all essential primary and secondary operational parameters and control sys tems during the return-to-power. Initial conditions for the analysis were obtained from the core calculations described above and the plant nodalization was shown in Figure 7.

The simulations were performed with the reactivity control and the governer valve control to match the reactor power and the turbine load. The model analysis showed no abnormal performance of any plant controller, as shown in Figure 4, for 14°F drop in the inlet temperature which was sufficiently higher than the typical operational limit, 20°F.

VI Discussion and Conclusions

In this study, the extension of the load follow capability has been examined by the inlet temperature reduction technique at EOL of KNU-1, where the boron dilution capability is not sufficient to compensate the xenon transient. Thus in order to simulate the load follow operation, the three-dimensional computing system has been established by using the KINS-2 code. The analyses have been performed for both MINB and SPINR mode. The results showed that the required amount of temperature reduction to overcome the shortage of boron dilution at 9 hours after the start of power reduction was 9°F in MINB mode.

And the return-to-power capability was also tested for both of two modes with the system analysis by the RETRAN-02 code. In this SRC test, the maximum amounts of percent power increases are 13% and 14% in MINB and SPINR mode, respectively, for the 14°F drop in temperature. Moreover, it has been confirmed that the SPINR mode had more SRC than the MINB mode.

According to the results of this study, it has been conclusive that the load follow capability of KNU-1 plant was successfully extended at EOL by the temperature reduction method and also the SRC was remarkably increased without no abnormal performance of any plant controller.

References

1. Morita, T. and K.J. Dzikowski, "Nuclear Design Aspects of Load Following Capability in Westinghouse PWR's," WCAP-8598, Westinghouse Electric Corporation (1975).
2. "PWR towards Improved Maneuverability," Seminar Report in FRAMATOME (1984).
3. G.B. Lee, et al., "KICC: A Space-Dependant Cell Spectrum and Depletion Program for Analysis of LWR Lattices," KAERI/TR-48/83 (1983).
4. 문갑석외 "FATAC: Fuel Assembly Transport Analysis Code KAERI(발간예정)
5. S.G. Lee, et al., "KIDD: A KAERI Improved Diffusion-Depletion Program," KAERI(to be published)
6. S.G. Lee, et al., "KINS-2: A KAERI Improved Nodal Scheme Version 2," KAERI(to be published)
7. "Nuclear Design Report, KORI UNIT 1, CYCLE-1," Korea Electric Power Company(1979).
8. Sipush, P.J. et al., "Load-Follow Demonstrations Employing Constant Axial Offset Power Distrib-

ution Control Procedures," Nuclear Technology, Vol. **31** (1976).

9. Morita, T., et al., "Topical Report Power Distribution Control and Load Following Procedures," WCAP-8403, Westinghouse Electric Corporation (1974).

10. Meyer, C.E., C.L. Bernette, D.J. Hill and K.J. Dzikowski, "Improved Load Follow Strategy for Return-to Power Capability," Nuclear Technology, Vol. **41** (1978).

11. Final Facility Description and Safety Analysis Report of KORI Nuclear Power Plant Unit No. 1, Korea Electric Power Company

12. J.H. McFadden et al., "RETRAN-02 A Program for Transient Thermal-Hydraulic Analysis of Complex Fluid Flow Systems," EPRI NP-1850 CCM, Vol. 1, Electric Power Research Institute (1981).