Journal of the Korean Nuclear Society
Volume 14, Number 2, June, 1982

《Original》

PWR Core Stability Against Xenon-Induced Spatial Power Oscillation

Ho Ju Moon and Ki In Han

Advanced Energy Research Institute

(Received January 29. 1982)

경수로심의 제논진동 해석

문호주·한기인

한국에너지연구소

(1982. 1. 29 접수)

Abstract

Stability of a PWR core against xenon-induced axial power oscillation is studied using one-dimensional xenon transient analysis code, DD1D, that has been developed and verifed at KAERI. Analyzed by DD1D utilizing the Kori Unit 1 design and operating data is the sensitivity of axial stability in a PWR core to the changes in core physical parameters including core power level, moderator temperature coefficient, core inlet temperature, doppler power coefficient and core average burnup. Through the sensitivity study the Kori Unit 1 core is found to be stable against axial xenon oscillation at the beginning of cycle 1. But, it becomes less stable as burnup progresses, and unstable at the end of the cycle. Such a decrease in stability is mainly due to combined effect of changes in axial power distribution, moderator temperature coefficient and doppler power coefficient as core burnup progresses.

It is concluded from the stability analysis of the Kori Unit 1 core that design of a large PWR with high power density and increased dimension can not avoid xenon-induced axial power instabilities to some extents, especially at the end of cycle.

요 약

한국에너지연구소에서 개발한 1차원적 제논과도현상해석 코드 DD1D를 사용하여 가압경수로심의 축방향 제논진동에 대한 안정성을 조사하였다. 노심의 출력준위, 감속재온도계수, 노심입구온도, 도플러출력 계수 그리고 연소도의 변화가 노심의 축방향 안정성에 미치는 효과를 조사하기 위하여 고리 1호기의 설계 및 운전자료를 이용하였으며 본 민감도 분석을 통하여 고리 1호기의 노심은 주기 초에는 축방향 제논진동에 대하여 안정하나 연소도가 증가함에 따라 안정도가 차츰 감소하여 주기 말에는 불안정해진다는 것을 알았다. 이같이 연소도가 증가함에 따라 노심의 안정도가 감소하는 이유는 연소도 변화에 따라 축방향의 출력분포, 감속재온도 계수 및 도플러출력계수가 변하기 때문이다.

본 연구를 통하여 출력밀도가 높은 대형 가압 경수로의 경우 전 주기동안 축방향제논진동에 대하여 안정된 노심을 설계하기 힘들다는 결론에 도달하였다.

Nomenclature

D^1 : fast neutron diffusion coefficient

D^2 : thermal neutron diffusion coefficicnt

ϕ^1 : fast neutron flux

ϕ^2 : thermal neutron flux

$\Sigma_a{}^1$: macroscopic fast neutron absorption cross-section

$\Sigma_a{}^2$: macroscopic thermal neutron absorption cross-section

$\Sigma_f{}^1$: macroscopic fast neutron fission cross-section

$\Sigma_f{}^2$: macroscopic thermal neutron fission cross-section

Σ_r : macroscopic removal cross-section

K : effective multiplication factor

ν : average number of neutrons generated per fission

$I(t)$: atom number density of I-135 at time t

$X(t)$: atom number density of Xe-135 at time t

$P(t)$: atom number density of Pm-149 at time t

$S(t)$: atom number density of Sm-149 at time t

λ_I : decay constant of I-135

λ_X : decay constant of Xe-135

λ_P : decay constant of Pm-149

Y_I : yield fraction of I-135

Y_X : yield fraction of Xe-135

Y_P : yield fraction of Pm-149

$\sigma_x{}^a$: microscopic absorption cross-section of Xe-135

$\sigma_s{}^a$: microscopic absorption cross-section of Sm-149

ϕ : neutron flux

$\rho(h)$: enthalpy dependent water density

h : enthalpy

h_f : enthalpy of saturated fluid

h_{fg} : latent heat of vaporization

V_f : specific volume of saturated fluid

V_{fg} : specific volume change during evaporation

1. Introduction

The need for improved economics and efficiency of pressurized water reactors(PWRs) leads to the design of reactor cores with increased dimensions, high power densities and more uniform power distributions. Such improvements, however, make the cores inherently less stable against spatial power oscillations so called xenon-induced spatial power oscillations.

The interaction between xenon fission product buildup and the change in the neutron flux distribution that accompanies local changes in reactivity causes spatial oscillation of power distribution in a large PWR. Xenon-induced power oscillations usually occur with power level changes, but they can also take place with no corresponding changes in the power level of the core. The spatial oscillations may by caused by a power shift in the core which occurs rapidly in comparison with the xenon-iodine time constants. Such power oscillations can take place in both axial and radial direction of the core, however, recent design of the PWR cores and control system lead to the cores inherently stable against radial xenon oscillations.1) Therefore, xenon-induced spatial oscillation in axial direction of the core is treated a major concern in reactor control and stability analysis. Of course, it is generally suggested that xenon axial oscillations do not cause severe control problems due to the long period of oscillation relative to control mechanism or operator reaction time. But, if they are not detected with ease and carefully controlled by either control mechanism or operator, they may cause local power peaking of the core and eventual fuel damage. That is why it is necessary to understand xenon transient behavior of PWR and to find out the optimum control method of power distribution. It will be even more important when nuclear power plants are under load follow operation mode.

This paper deals with the research results on PWR core stability against xenon-induced axial oscillation carried out at the Korea Advanced Energy Research Institute(KAERI). The purposes of such research are

1) to investigate the stability of the Kori Unit 1 reactor core against free-running axial xenon oscillation,

2) to perform extensive sensitivity study on stability against axial xenon oscillation to various reactor core physical parameters,

3) to found a basis for further improvement in PWR core stability to xenon oscillation, and

4) to lay a milestone for future research on reactor power distribution control during base load and load follow operation.

Xenon transient analysis is performed utilizing one-dimensional steady-state and transient analysis computer code, DD1D[2] that is developed at KAERI based on two-group, steady-state neutron diffusion theory with time-dependent iodine and xenon depletion equations. The DD1D code undergoes an extensive verification process for its application to steady-state and transient calculations by comparing its calculation results with either experimental data or/and calculation results from other reliable computer codes.

Studies on PWR core stability against xenon-induced spatial oscillation are carried out by analyzing stability index and oscillation period of the Kori Unit 1, cycle 1. To be able to increase the accuracy and reliability of calculation by DD1D, parameters related to digital simulation such as spatial mesh size, time-step length and convergence criterion are investigated aimed at finding the most appropriate value, if not optimum. Finally, the effect of changes in reactor core physical parameters on axial stability in PWR is evaluated using the Kori Unit 1 reactor core data. Analyzed is the effect of changes in such parameters as core power level, moderator temperature coefficient core inlet temperature, doppler power coefficient and core average burnup. Through such sensitivity study, the stability of the Kori Unit 1 reactor core against axial xenon oscillation is analyzed.

2. DD1D; One-dimensional Xenon Transient Analysis Code

The development of the DD1D code at KAERI aims at mainly analyzing axial xenon transient behavior of a typical PWR. Development of the DD1D code is also accompanied by an extensive code verification process.

2.1 Description of the Code

DD1D is a one-dimensional, two-group, steady-state neutron diffusion theory code with time-dependent iodine and xenon depletion equations. Also, explicitly treated are space dependent feedback effects due to control rod movement, soluble boron concentration change and the changes in moderator density and fuel temperature.

The one-dimensional, two-group, steady-state neuron diffusion equations modeled in DD1D are written as

$$-\nabla D_1\phi_1+(\Sigma^1{}_a+\Sigma_r)\phi_1=\frac{1}{K}(\nu\Sigma^1{}_f\phi_1+\nu\Sigma^2{}_f\phi_2), \tag{2-1}$$

$$-\nabla D_2\nabla\phi_2+\Sigma^2{}_a\phi_2=\Sigma_r\phi_1. \tag{2-2}$$

The evolution of fission product poisons Xe-135 and Sm-149 and their precursors I-135 and Pm-149 are defined by the following equations:

$$\frac{dI(t)}{at}=-\lambda_I I(t)+Y_I\Sigma_f\phi, \tag{2-3}$$

$$\frac{dX(t)}{at}=\lambda_I I(t)+Y_X\Sigma_f\phi-\lambda_X X(t)-\sigma^a{}_x\phi X(t), \tag{2-4}$$

$$\frac{dP(t)}{dt}=-\lambda_p P(t)+Y_p\Sigma_f\phi, \tag{2-5}$$

$$\frac{dS(t)}{dt}=\lambda_p P(t)-\sigma^a{}_s\phi S(t). \tag{2-6}$$

The neutron diffusion equations are solved for each axial mesh interval using the variational finite difference method, while the fission product poison depletions are solved using θ-differencing method for each time step. The θ-differencing method is found to be an extremly useful tool for xenon transient analysis, for it reduces a significant amount of calculation time without losing much accuracy.[3] This method involves a two phase calculation of xenon depletion during a time step Δt. For the phase $(1-\theta)$ Δt, the xenon depletion is calculated using the previous flux distribution. For the remainder of the period, θ Δt, the xenon depletion calculation is updated each iteration by using the latest flux distribution. Experiences[4] say that a theta between 0.4 and 0.5 gives quite satisfactory results.

The feedback calculation models adopted in DD1D are rather simple and are based on the assumption of thermal hydraulic equilibrium with no slips and no cross flows between coolant channels. The interval-wise water density is calculated using a quadratic fit for density versus enthalpy, or

$$\rho(h)=a+bh+ch^2;h<h_f \qquad (2\text{-}7)$$

and

$$\rho(h)=\frac{1}{v_f+v_{fg}X};\ h\geq h_f \qquad (2\text{-}8)$$

where $X=(h-h_f)/h_{fg}$.

The coefficients a,b and c are fitted using standard steam table interpolation routines.

The interval-wise resonance effective fuel temperature can be determined by solving general steady-state heat transfer equations in radial direction of fuel pellet, once the interval-wise power is given. From the radial temperature distribution, the resonance effective fuel temperature is obtained through

$$T_{eff}=w\bar{T}+(1-w)T_s \qquad (2\text{-}9)$$

where

$\bar{T}$: pellet everage temperature,

T_s: pellet surface temperature,

w: statistical pellet weighting factor.[5]

The feedback effects obtained by solving feedback calculation models are accounted for in DD1D by correcting neutron cross sections as inputs to neutron equations. Such corrections are as follows:

1) boron and water density correction,
2) spectrum hardening correction,
3) fuel temperature correction,
4) control rod movement correction, and
5) xenon and samarium correction.

2.2. Verification of the Code

The verification of a code is actually a measure of how well the code can analyze problems of interest, and it involves comparisons of the calculation results with either experimental data or/and calculation results from other reliable computer codes. The DD1D code undergoes an extensive veirfication process for its application to steady-state and transient calculations.

For the verification of DD1D for its application to steady-state calculation, several parameters from Kori Unit 1 reactor core are calculated using the DD1D code and compared with those from either Kori Unit 1 FSAR (Final Safety Analysis Report) or calculations by other computer codes. The parameters stud-

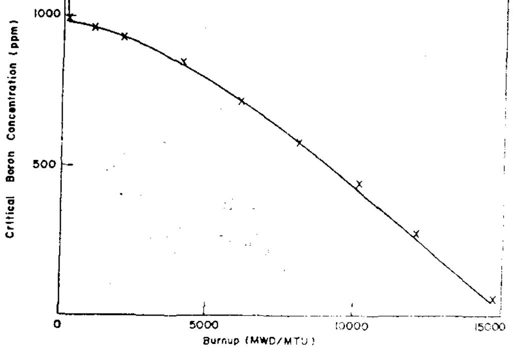

Fig. 1. Kori Unit 1, Cycle 1 Critical Boron Concentration vs. Burnup.

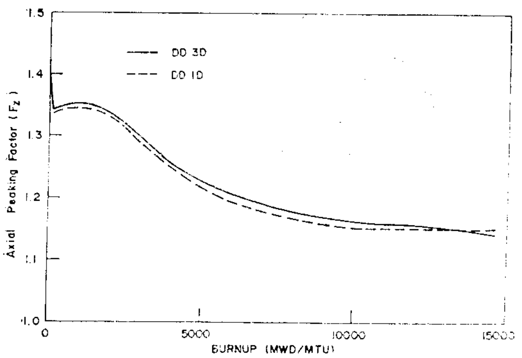

Fig. 2. Axial Power Peaking Factor vs. Burnup for Kori Unit 1, Cycle 1, HFP. ARO, EQ. Xenon.

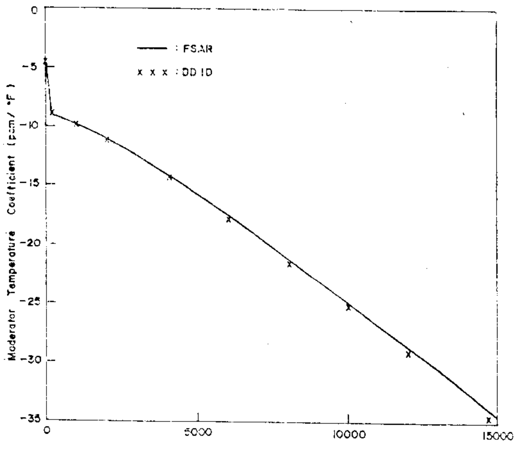

Fig. 3. Moderator Temperature Coefficient vs. Burnup for Kori Unit 1, Cycle 1, HFP, ARO, EQ. Xenon.

ied are critical boron concentration, axial power peaking factor, moderator, temperature coefficient, doppler only power coefficient and total power coefficient.

Shown in Figure 1 is the comparison between FSAR and DD1D predicted critical boron concentration vs burnup for the Kori Unit 1, cycle 1. Predicted values are in excellent agreement with those of FSAR. Also, shown in Figure 2 are the axial power peaking factors vs burnup calculated by DD1D and a three, dimensional steady-state neutronics code, DD3D,[6] for the Kori Unit 1, Cycle 1 at HFP and ARO, equilibrium xenon condition. Agreement between two values is also excellent. Figure 3 shows the comparison between FSAR and DD1D calculated moderator temperature coefficient vs burnup for Kori Unit 1, Cycle 1 at HFP and ARO, equilibrium xenon condition. Doppler only power coefficient and tota lpower coefficient vs reactor power level calculated through DD1D are compared with those from Kori Unit 1 FSAR in Figure 4 and 5, respectively. Again good agreements are noted from these Figures.

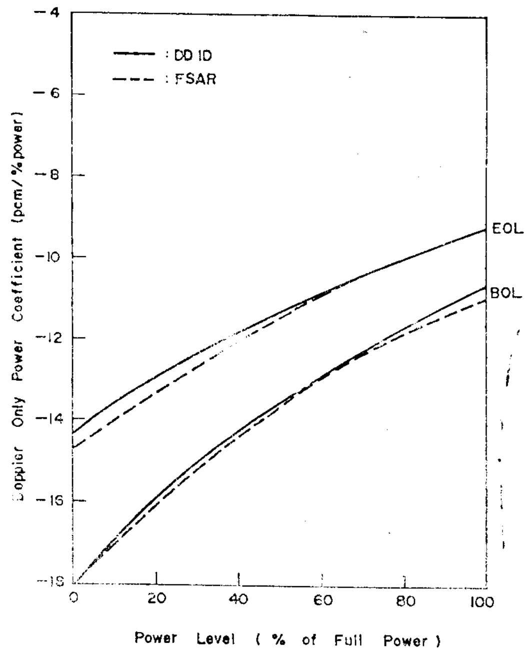

Fig. 4. Doppler Only Power Coefficient vs. Power Level for Kori Unit 1, Cycle 1 at BOL and EOL.

Verification of the DD1D code for xenon transient calculation is performed by comparing the calculation results with the measured values obtained during xenon transient experiment of the Kori Unit 1, cycle 1 at burnup 4000 MWD/MTU and 87% power. The purpose of the experiment was to study the xenon transient behavior of the Kori Unit 1 reactor core at BOL, and to assure the stability of the core against xenon oscillation. Simulation of the xenon transient test using DD1D is preceded by the close follow-up of core load history before the expe-

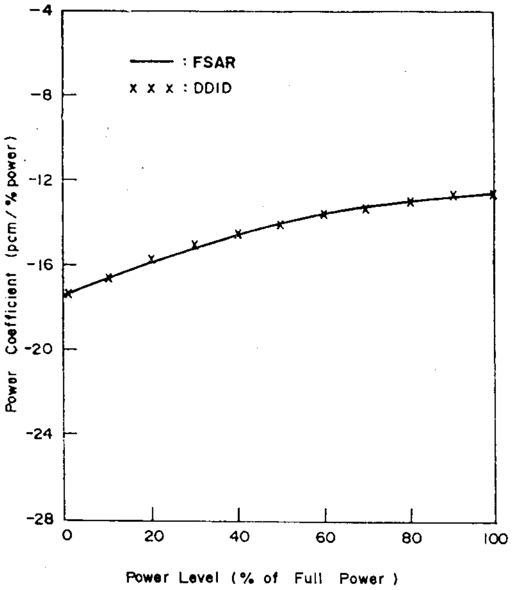

Fig. 5. **Total Power Coefficient vs. Power Level for Kori Unit 1, Cycle 1 at BOL.**

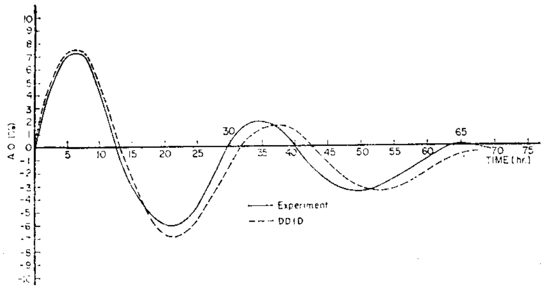

Fig. 6. **Axial Offset vs Time at Xenon Oscillation for Kori Unit 1, Cycle-1, Burnup-4000, 87% Power.**

riment. Experimental procedure should also be closely simulated. Shown in Figure 6 is the comparison between time dependent axial offset predicted by DD1D and experimental value obtained from xenon oscillation test for Kori Unit 1, cycle 1. As shown in this Figure reasonably good agreement is obtained.

From the above mentioned verification test results, the DD1D code is evaluated to be highly reliable not only for steady-steate neutronics calculation but also for xenon transient calculation.

3. Analysis of Reactor Core Sability Against Axial Xenon Oscillatilon

Studies on PWR core stability to axial xenon oscillation are proceeded in three steps. First of all, a parameter called stability index is defined that is usud as a measure of axial stability. Then various parameters related to DD1D digital simulation such as spatial mesh size, time-step length and convergence criterion are investigated to get optimal values for the purpose of improving the accuracy and reliability of calculation results. Finally, extensive studies on PWR core stability to axial xenon oscillation are performed through sensitivity analyses of the stability to reactor core physical parameters including core power level, moderator temperature coefficient, core inlet temperature, doppler power coefficient and core average burnup.

3.1. Definition of Stability Index

Whether a reactor core is stable or not against axial xenon oscillation is often undertood by inspecting the parameter called stability index. Usually, axial offset (AO) is used to represent the axial power distribution of the core and is defined as

$$AO(\%)=\frac{(P_T-P_B)}{(P_T+P_B)}\times 100(\%) \qquad (3\text{-}1)$$

where

P_T: average power of the upper core,

P_B: average power of the lower core.

When an axial offset changes in time as shown in Figure 7, it can be written as

$$AO(t)=A\ EXP\ (\rho t)+AO_0 \qquad (3\text{-}2)$$

where

$\rho=b+jw$,

$j=\sqrt{-1}$,

A: amplitude constant,

AO_0: equilibrium axial offset,

b: stability index,

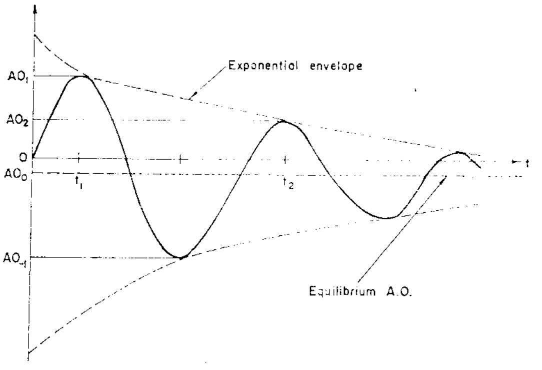

Fig. 7. Axial Offset vs Time at Typical Stable Xenon Oscillation.

w: oscillation frequency.

From the figure

$$AO_1 = AO(t_1) = A\ EXP(\rho t_1) + AO_0, \qquad (3\text{-}3)$$

$$AO_2 = AO(t_2) = A\ EXP(\rho t_2) + AO_0. \qquad (3\text{-}4)$$

Then

$$\frac{(AO_2 - AO_0)}{(AO_1 - AO_0)} = \mathrm{EXP}[\rho(t_2 - t_1)]$$

$$= \mathrm{EXP}[b(t_2 - t_1)]\cos[w(t_2 - t_1)]. \qquad (3\text{-}5)$$

When $(t_2 - t_1)$ is defined as oscillation period and noted as T, stability index b is expressed as

$$b = \frac{1}{T}\ln\frac{(AO_2 - AO_0)}{(AO_1 - AO_0)}. \qquad (3\text{-}6)$$

When b is negative as in Figure 7, the reactor core is stable, but the core becomes unstable when b turns to positive value.

3.2. Effect of Digital Simulation Parameters On Calculation Accuracy

Although simulation of a reactor core using a computer mathematical model is the most realistic method, errors are unavoidably introduced due to the descrete nature of the difference equations representing the system. Apart from the finiteness of the spatial and temporal mesh lengths, errors are incurred from the finite convergence criteria for the eigenvalue and flux shape. Sensitivity of the calculation accuracy to the above mentioned parameters is studied to find out the optimum or most appropriate values.

3.2.1. Spatial Mesh Size

To study the effect of spatial mesh size on the stability index calculated using the DDlD code, three different mesh sizes (23, 6 and 4.5 cm) are tried and their calculation results are shown in Table 1. From the Table it is observed that the accuracy of the calculation results (stability indices) is relatively insensitive to the variation of spatial mesh sizes within the range of investigation. However, mesh sizes of 6 and 4.5cm lead to better agreement and slight improvement in accuracy compared with 23cm long mesh size. The mesh size of 6cm is evaluated to be an appropriate value for the stability analysis of PWR core by the DDlD code.

3.2.2. Time-Step Length

Three different time-step lengths are tried to study the effect of time-step length variation and to find out an appropriate value in running the DDlD code. Table 2 and Figure 8 show changes in stability index vs time-step length, while Figure 9 shows time dependent axial offsets calculated using two different time-step lengths; 3 hour and 1 hour. Three is a significant change in stability index as the time-step length changes from 3 hour to 1 hour, but no significant improvement in accuracy from 1 hour to 0.5 hour. Therefore, a time-step length of 1 hour is selected for the rest of stability index

Table 1. Effect of Spatial Mesh Size (ΔZ) on Stability for Kori Unit 1, Cycle 1

BU (MWD/MTU)	POWER (%)	ΔZ (cm)	AO_0	AO_1	AO_2	b(hr^{-1})	T(hr)
6000	100	23	−5.53	0.41	−2.80	−0.01944	40
6000	100	6	−5.68	− .25	−3.48	−0.02177	41
6000	100	4.5	−5.65	− .11	−3.37	−0.02165	41

Table 2. Effect of Time-Step Length (ΔT) on Stability for Kori Unit 1, Cycle 1

BU (MWD/MTU)	POWER (%)	ΔT(hr)	AO_0	AO_1	AO_2	b(hr^{-1})	T(hr)
6000	100	3	−5.68	.59	−2.33	−0.02089	30
6000	100	1	−5.68	.76	−1.20	−0.01210	30
6000	100	0.5	−5.68	.80	− .99	−0.01060	30.5

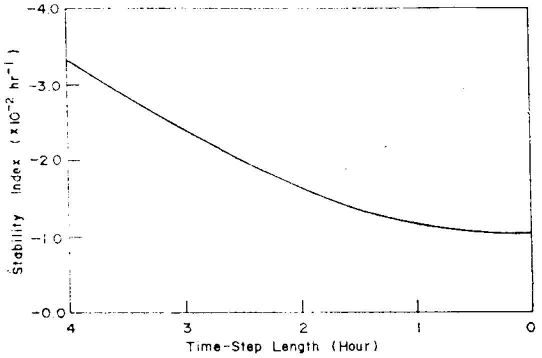

Fig. 8. Stability Index vs. Time-Step Length for Kori Unit 1, Cycle 1.

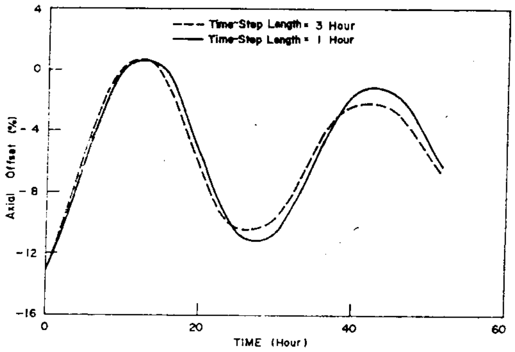

Fig. 9. Axial Offset vs. Time for Kori Unit 1, Cycle 1 at Burnup 6000 MWD/MTU Calculated Varying Time-Step Length.

calculations in this paper.

3.2.3. Convergence Criterion

Flux and eigenvalue convergence criteria are also important parameters that determine the accuracy of neutron flux and xenon distribution. In the DD1D code that utilizes EQUIPOISE method[7], the inner and outer iterations are accomplished at the same time, and the eigenvalue converges faster than the flux. Therefore, the flux convergence criterion is more limitng than the eigenvalue criterion.

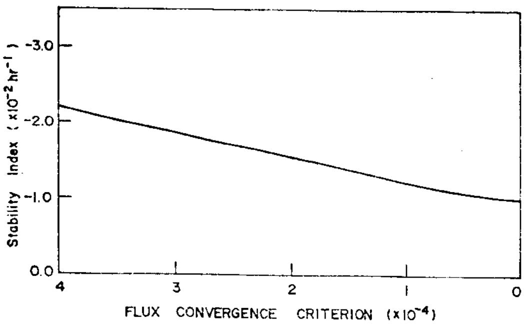

Fig. 10. Stability Index vs. Flux Convergence Criterion for Kori Unit 1, Cycle 1 at Burnup 6000 MWD/MTU.

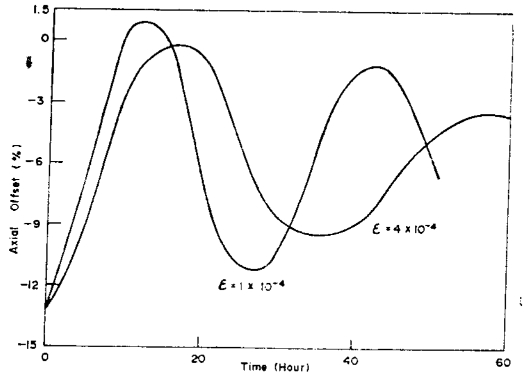

Fig. 11. Axial Offset vs. Time for Kori Unit 1, Cycle 1 at Burnup 6000 MWD/MTU Calculated with $\varepsilon = 1 \times 10^{-4}$ and 4×10^{-4}.

To study the effect of flux convergence criterion variation on stability, DD1D calculations with 4 different values are tried, and their results are depicted in Table 3 and Figure 10. Also, shown in Figure 11 are changes in axial offset vs time for ε(convergence criterion)$=1 \times 10^{-4}$ and 4×10^{-4}. It is concluded from the above results that for too large a convergence condition xenon oscillation tends to die out faster and stability index is quite sensitive to the convergence criterion. For the rest of DD1D

Table 3. Effect of Convergence Criterion on Stability for Kori Unit 1, Cycle 1

BU (MWD/MTU)	POWER (%)	$\varepsilon(\times 10^{-4})$	AO_0	AO_1	AO_2	$b(\mathrm{hr}^{-1})$	T(hr)
6000	100	4	−5.68	−.25	−3.48	−0.02177	41
6000	100	1	−5.68	.76	−1.20	−0.01210	30
6000	100	0.65	−5.68	.88	−.94	−0.01102	29.5
6000	100	0.35	−5.68	1.02	−.73	−0.01044	29

Table 4. Effect of Core Power Level on Stability for Kori Unit 1, Cycle 1

BU (MWD/MTU)	POWER (%)	AO_0	AO_1	AO_2	$b(\mathrm{hr}^{-1})$	T(hr)
6000	100	−5.68	.76	−1.20	−0.01210	30
6000	80	−2.39	3.68	1.09	−0.01661	33.5
6000	60	1.86	6.64	3.91	−0.02171	39

calculations, $\varepsilon=6.5\times10^{-5}$ is utilized with the understanding that the underestimate of true stability index at this convergence condition is within the acceptable level.

3.3. Sensitivity of Core Axial Stability to Core Physical Parameters

The effect of changes in core physical parameters on axial stability in PWR is evaluated using the Kori Unit 1 reactor core data. Analyzed is the effect of changes in such parameters as core power level, moderator temperature coefficient, core inlet temperature, doppler power coefficient and core average burnup.

3.3.1. Core Power Level

One of the known major influences affecting spatial stability is the core flux or power level. Three different power levels (100%, 80% and 60%) are selected to investigate the effect of core power level variation on axial core stability at burnup 6000MWD/MTU for Kori Unit 1, Cycle 1. Table 4 shows the effect of core power level variation on stability index and period, while Figure 12 shows axial offset vs time for 100% and 60% power level condition.

As shown in the Table an increase in power level leads to a decrease in core stability against xenon oscillation. Such a decrease in stability is due to the increased reactivity contribution by xenon poison resulting from the higher xenon concentration at increased power level.

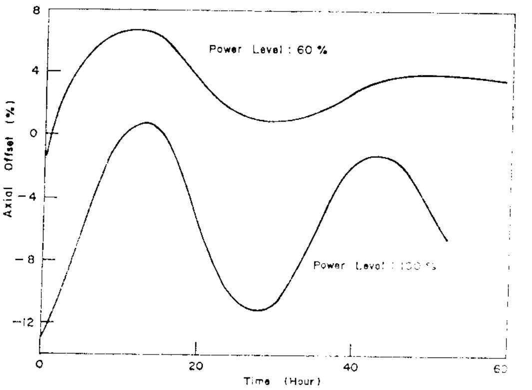

Fig. 12. Axial Offset vs. Time for Kori Unit 1, Cycle 1 at Burnup 6000 MWD/MTU Calculated Varying Power Level.

3.3.2. Moderator Temperature Coefficient

The effect of moderator temperature coefficient is studied indirectly by changing the corresponding moderator density coefficient as input to the DDID code. Two different cases are studied; one for converging oscillation and the other for diverging oscillation. The power level is fixed at 100%, but burnups of 6000 MWD/MTU and 10000 MWD/MTU are selected for converging and diverging oscillation cases, respectively. The calculation results are shown in Table 5; 3 calculations for converging oscillation and 2 for

Table 5. Effect of Modertor Temperature Coefficient on Stability for Kori Unit 1, Cycle 1

BU (MWD/MIU)	POWER (%)	$\Delta\rho/\Delta T$ (pcm/°F)	AO_0	AO_1	AO_2	$b(\mathrm{hr}^{-1})$	T(hr)
6000	100	−17.48	−5.57	1.02	−.89	−0.01122	30.5
6000	100	−17.90	−5.68	.76	−1.20	−0.01210	30
6000	100	−18.53	−5.77	.75	−1.32	−0.01273	30
10000	100	−25.80	−3.38	4.84	8.89	0.01369	28
10000	100	−26.64	−3.97	5.63	10.25	0.01403	28

Table 6. Effect of Core Inlet Temperature on Stability for Kori Unit 1, Cycle 1

BU (MWD/MTU)	POWER (%)	INLET T(°F)	AO_0	AO_1	AO_2	$b(\mathrm{hr}^{-1})$	T(hr)
10000	100	541.34	−3.83	4.84	8.89	0.01369	28
10000	100	540	−3.77	4.65	8.58	0.01368	28

diverging oscillation.

As shown in the Table, for a converging oscillation at the lower burnup axial stability increases as moderator temperature coefficient (absolute value) increases, that is, the absolute value of stability index increases as the absolute value for moderator temperator coefficient increases. However, for a diverging oscillation at the higher burnup the axial stability decreases as the moderator temperature coefficient (absolute value) increases. Such a decrease in stability for diverging oscillation with increased moderator temperature coefficient is due to the more negative slope of the coefficient that has a destabilizing effect on the first flux harmonic of the neutron flux shape.[8]

3.3.3. Core Inlet Temperature

Considering the fact that there exists a possibility of the increase in load-follow capability of PWR by reducing the core inlet temperature, it is of interest to study the effect of core inlet temperature change on core stability. However, the core inlet temperature change is directly related to the moderator temperature coefficient. Table 6 shows the stability index vs core inlet temperature (541.34°F and 540°F) for Kori Unit 1, Cycle 1 at burnup 10000 MWD/MTU and 100% power. In this Table it is noted that increase in inlet temperature results in decrease in stability. Such results are relevant to those from the sensitivity study of moderator temperature coefficient in previous section.

3.3.4. Doppler Power Coefficient

Doppler power coefficient of a typical PWR is negative and the negative doppler power coefficient around full power tends to decrease in magnitude as burnup progresses. To study the sensitivity of the core stability to doppler power coefficient, two different coefficients (−9.587 pcm/% power and −10.016 pcm/% power) are selected, and the calculation results are in Table

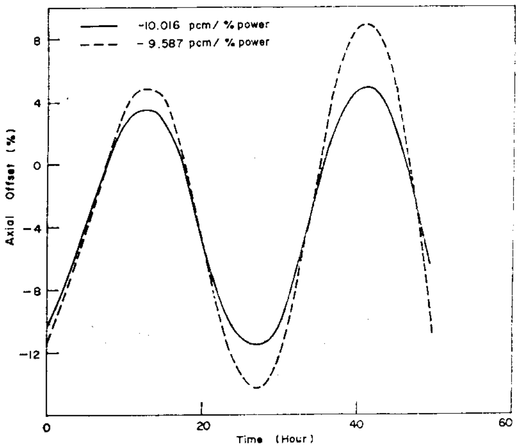

Fig. 13. Axial Offset vs. Time for Kori Unit 1, Cycle 1 at Burnup 10000 MWD/MTU Calculated Varying Doppler Power Coefficient.

Table 7. Effect of Doppler Power Coefficient on Stability for Kori Unit 1, Cycle 1

BU (MWD/MTU)	POWER (%)	$\Delta\rho/\Delta P$ (pcm/% power)	AO_0	AO_1	AO_2	b(hr^{-1})	T(hr)
10000	100	−9.587	−3.83	4.84	8.89	0.01369	28
10000	100	−10.016	−3.81	3.49	4.94	0.00647	28

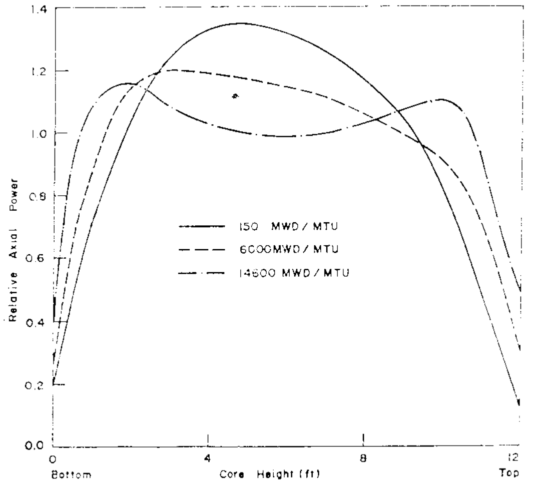

Fig. 14. Burnup Dependent Axial Power Profile for Kori Unit 1 Reactor Core.

7 and Figure 13. As expected a less negative coefficient leads to more unstable xenon oscillation.

3.3.5. Burnup

For a typical PWR, as fuel burnup progresses doppler coefficient becomes less negative, moderator temperature coefficient becomes more negative and axial power distribution becomes more flattened. Figure 14 shows a comparison among axial power distributions at BOL, MOL and EOL. The flattening of the power distribution reduces the coupling between upper and lower cores, and leads to less stable core against axial xenon oscillation. Combined effects of the above parameters affect the axial stable core against axial xenon oscillation. Combined effects of the above parameters affect the axial sitability as the burnup progresses. Shown Figure 15 is the change in stability index of the Kori Unit 1, Cycle 1 at 100% power and all rods out condition as fuel burnup increases. As shown in the Figure stability index becomes zero at the burnup of 7600 MWD/MTU beyond which the core becomes unstable against axial xenon oscillation.

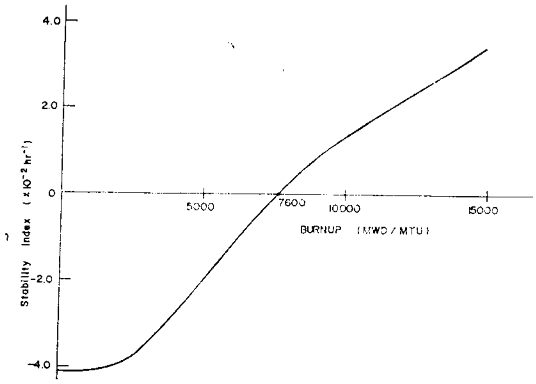

Fig. 15. Stability Index vs. Burnup for Kori Unit 1, Cycle 1 at HFP, ARO.

At this point, it is of interest to compare the calculation results as shown in Figure 15 to the results depicted in Chapter 4 of the Kori Unit 1 FSAR. The FSAR says that the axial stability index is essentially zero at 12000 MWD/MTU. Here, it should be noted that the values in FSAR are not from the actual calculation for Kori Unit 1 reactor core, but they are indeed taken from the calculated or experimental results for the RGE reactor of the United States.[8] The RGE reactor with design power of 490 MWe has the same core height (12ft) as the Kori Unit 1 reactor, but its power density is 74.35w/cc at full power while it is 107.9w/cc for Kori Unit 1. From the analysis results in previous section concerning sensitivity of power level variation, lower power level equivalent to lower power density in this case is found to lead to more stable core. Therefore, it is understandable for the RGE core to be more stable than the Kori Unit 1 core throughout the cycle. To validate the above arguement, a calculation of stability index is performed for the Kori Unit 1, first cycle at the burnup of 8,000MWD/MTU with the power density at 74.35w/cc and with the part length control rods at the core center. Such a condition is assumed to simulate the corresponding experiment performed at RGE reactor at the burnup of 7700MWD/MTU. The calculated stability index at this condition is -0.02hr^{-1} (still negative) while it is -0.014hr^{-1} for RGE reactor (this value is also quoted in the Kori Unit 1 FSAR, Chapter 4). Such a quantitative comparison supports the claim that the stability index in FSAR overestimates the axial stability of the Kori Unit 1 reactor core, and that the stability index of the Kori Unit 1 core is expected to become zero at the burnup of 7,600MWD/MTU rather than at 12,000 MWD/MTU.

4. Summary and Conclusions

Study on PWR core stability against axial xenon oscillation starts with the development of a one-dimensional xenon transient analysis computer code, DD1D. The DD1D code is proven to be highly reliable not only for xenon transient analysis but also for steady state analysis following extentive verification tests.

Investigated are the various digital simulation related parameters such as spatial mesh size, time-step length and convergence criterion for the purpose of selecting optimum values to assure the accuracy and reliability of calculation results. The calculated stability index is found to be insensitive to the variation of spatial mesh size between 4 and 23cm, but to be sensitive to time-step length and convergence oriterion. The time-step length shorter than 1 hour and flux convergence criterion less than 0.0001 are found to be acceptable.

Studied are the effects of changes in core physical parameters including core power level, moderator temperature coefficient, core inlet temperature, doppler power coefficient and core average burnup on the core stability against axial xenon oscillation. The Kori Unit 1 reactor core is found to be stable to axial xenon oscillation at the beginning of cycle, but becomes less stable as burnup progresses. Such a decrease in stability is due to the combination of the following reasons:

1) As burnup progresses, core axial power becomes flattened, and the coupling between upper and lower core is reduced leading to less stable core against xenon oscillation.

2) Moderator temperature coefficient becomes more negative as the burnup increases. This causes unstable core to be more unstable against axial xenon oscillation.

3) Doppler power coefficient becomes less negative that makes the core less stable against xenon oscillation.

It is calculated that the stability index for the Kori Unit 1 reactor core becomes zero at the burnup of 7,600MWD/MTU. This number does not match with that of FSAR of the Kori Unit 1. FSAR overestimates the axial stability of the core, and predicts that the stability index will be zero at the burnup of 12,000 MWD/MTU. Such a disagreement may be due to the fact that the cited value in FSAR does not come from the calculation for Kori Unit 1 but is indeed a calculated stability index for other reactor core with lower operating power density.

Through the researches on PWR core stability against axial xenon oscillation, it is concluded that design of a large PWR with high power density and increased dimensions can not avoid xenon—induced axial instabilities at EOL to some extents. Therefore, it is necessary to easily detect and carefully control such power oscillations that core local power peaking and eventual fuel damage may not occur. That is why it is most fundamental to understand xenon transient behavior of PWR, and to find out the optimum control method of power distribution.

A significant amount of insight into the xenon transient behavior and axial xenon stability of a PWR core has been gained through the researches performed for this paper. The results obtained in this work, however, are not to be considered as final ones, but they do provide the basis of future research for the establishment of an optimum power distribution control method of PWR.

References

1. FSAR for the Kori Nuclear Power Plant, Ch. 4, KECO (1977).
2. H.J. Moon, "DD1D, A One-Dimensional Two-Group Steady-State Neutron Diffusion Theory Program", KAERI/TR-31/81, Korea Advanced Energy Research Institute (1981).
3. K.I. Han et al., "Reactor Kinetics and Reactivity-Induced Accident Analysis" KAERI/RR-217/80, Korea Advanced Energy Research Institute (1981).
4. J.C. Lee, "Application of an Improved Time-Difference Method for Spatial Xenon Transient Analysis," Nucl. Sci. Eng. (1974).
5. Olhoeft, J.E., "Evaluation of Nuclear Effective Temperature in Thermal Power Reactor Fuel", Trans. Am. Nucl. Sci., 13, 306 (1970).
6. Y.W. Na, "DD3D (CORE3D), A Three-Dimensional Two-Group Neutron Diffusion Depletion Code", KAERI/449/RR-182/80, Korea Advanced Energy Research Institute (1980).
7. Tobias, M. and Fowler, T.B., "The EQUIPOISE Method-A Simple Procedure for Group Diffusion Calculations in 2 and 3 Dimensions", Nucl. Sci. Eng., 12, 513 (1962).
8. J.C. Lee at al., "Axial Xenon Transient Tests at the Rochester Gas and Electric Reactor", WCAP—7964, Westinghouse Electric Corporation (1971).