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Xenon Initialization for Reactor Core Transient Simulation

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Abstract

The initial condition should be consistent with real reactor core state for the simulation of the core transient. The initial xenon distribution, which can not be measured in the core, has a significant effect on the transient with xenon dynamics of PWR. In the simulation of the transient starting from non-equilibrium xenon state, the accurate initialization of the non-equilibrium xenon distribution is essential to predict the core transient behavior. In this study, the xenon initialization method to predict the core transient more accurately was developed through the first-order perturbation theory of the relationship between simulated power and measured power distribution and verified by the application of the simulation for a startup test of Yonggwang Unit 3.

1. Introduction

The purpose of PWR core transient simulation is to predict the variation of the core behavior with xenon dynamics time scale due to the change of operating conditions such as power, control rod position and moderator temperature. The simulation of the core transient requires initial core conditions, not only measurable parameters (core burnup, control rod position, power distribution, moderator temperature etc.) but also non-measurable parameters (fuel temperature, xenon distributions, iodine distributions etc.). Difficulties in the core transient simulation or prediction are originated from the uncertainties in the parameters related with the initial conditions of core transient. The adaptive core simulation requires adjustments of several parameters which affect the core behavior. One of the most important and difficult parameters adjusted for the initialization is the xenon distribution, since it may affect the core behavior sustainedly. Furthermore, since the PWR reactor may have a xenon oscillation even though at equilibrium state, the exact prediction of the xenon distribution is almost impossible. In the direct initialization approach tried by Song[1][2], the existence of the pre-xenon-oscillation was identified by the variation of the core axial power shape before the transient. It has been found that the pre-xenon-oscillation was determined using the axial power shape variation before the transient. Song's method was assumed that the xenon and iodine changes due to power change are linear. The simulation of core transient with this method is reasonably accurate. However, the xenon distribution does not have exact linear relationship with the axial power shape. In this study, a simple method for the xenon initialization of the non-equilibrium state is developed through the first-order perturbation theory.

2. Xenon Initialization Using the First-Order Perturbation Theory

The existence of xenon oscillation is characterized by axial power shape variation. For the simple representation of the axial power shape variation, a parameter ASI (Axial Shape Index) is defined by

$$ASI=(P_B-P_T)\ /\ (P_B+P_T) \tag{1}$$

where P_B and P_T are the relative power of the bottom and top half of the core, respectively.

The iodine distribution can be reconstructed by Song's method[1][2].

$$\frac{N_I(z,t)-N_{eq.I}(z)}{\widetilde{N}} \propto \frac{\Phi(z,t)-\Phi_{eq.}(z)}{\widetilde{\Phi}} = \mu_I(P(z,t)-P_{eq.}(z)) \tag{2}$$

where

$N_{eq.I}(z), N_I(z,t)$ = the equilibrium and non-equilibrium axial iodine distribution

$\widetilde{N}$ = the core average iodine number density

$P_{eq.}(z), P(z,t)$ = the equilibrium and non-equilibrium power distribution

μ_I = constant to satisfies the following ASI condition

$$\left(\int_0^{\frac{1}{2}} N_I(z,t)\,dz-\int_{\frac{1}{2}}^{1} N_I(z,t)\,dz\right)\ /\ \widetilde{N}= ASI_I(t)=D_I(t)+ASI_{eq.I} \tag{3}$$

where

z = the normalized axial position whose values are 0 for the bottom and 1 for the top of the core

D_I = the ASI difference of iodine from the equilibrium state

$ASI_{eq,I}$ = the ASI of iodine at the equilibrium state

The transient xenon distribution is obtained as follows

$$N_{Xe}^{tr.} = N_{Xe}^{eq.} + \Delta N_{Xe}^{fx} \tag{4}$$

where

$N_{Xe}^{tr.}$ = the Xe^{135} number density at transient state

$N_{Xe}^{eq.}$ = the Xe^{135} number density at equilibrium state

$\Delta N_{Xe}^{fx} = f_X \times f_{norm}$ (f_{norm} = xenon normalized factor)

Xenon adaptation factor (f_X) on each node can be determined by utilizing the first-order perturbation theory. If there are I number of nodes, the relative power P_i of the i-th node are dependent on f_{X_i} which is the xenon adaptation factors of other nodes, i.e. $P_i = P_i(f_{X_1}, f_{X_2}, f_{X_3}, \cdots, f_{X_I})$.

ΔP_i can be determined by

$$\Delta P_i = \frac{\partial P_i}{\partial f_{X_1}} \Delta f_{X_1} + \frac{\partial P_i}{\partial f_{X_2}} \Delta f_{X_2} + \cdots + \frac{\partial P_i}{\partial f_{X_I}} \Delta f_{X_I} \tag{5}$$

where ΔP_i is defined by

$$\Delta P_i = P_i^{ref} - P_i \tag{6}$$

Substituting equation (6) for equation (5) gives

$$\frac{\partial P_i}{\partial f_{X_1}} \Delta f_{X_1} + \frac{\partial P_i}{\partial f_{X_2}} \Delta f_{X_2} + \cdots + \frac{\partial P_i}{\partial f_{X_I}} \Delta f_{X_I} = P_i^{ref} - P_i \ (i = 1, 2, \cdots, I) \tag{7}$$

The equation (7) gives the I number of equations whose coefficients, $\frac{\partial P_i}{\partial f_{X_I}}$, can be determined by the first-order perturbation theory. Thus, Δf_{X_i}'s can be obtained from the following matrix equation with pre-determined coefficient matrix.

$$\begin{bmatrix} \frac{\partial P_1}{\partial f_{X_1}} & \frac{\partial P_1}{\partial f_{X_2}} & \cdots & \frac{\partial P_1}{\partial f_{X_I}} \\ \frac{\partial P_2}{\partial f_{X_1}} & \frac{\partial P_2}{\partial f_{X_2}} & \cdots & \frac{\partial P_2}{\partial f_{X_I}} \\ \vdots & \vdots & & \vdots \\ \frac{\partial P_I}{\partial f_{X_1}} & \frac{\partial P_I}{\partial f_{X_2}} & \cdots & \frac{\partial P_I}{\partial f_{X_I}} \end{bmatrix} \begin{bmatrix} \Delta f_{X_1} \\ \Delta f_{X_2} \\ \vdots \\ \Delta f_{X_I} \end{bmatrix} = \begin{bmatrix} P_1^{ref} - P_1 \\ P_2^{ref} - P_2 \\ \vdots \\ P_I^{ref} - P_I \end{bmatrix} \tag{8}$$

3. Application for Core Transient Simulation

A core transient had been tested in Yonggwang Unit 3 Cycle 1 startup to verify the core power change capability to concur with turbine power change. The test was performed at 1900 MWD/MTU and started from ARO 95% power level with a step power change to 85%. About two and half hour later the core power was decreased to 70% by the ramp rate of -5% per minute. Then three hours after, the core power was increased to 85% by the ramp rate of 5% per minute. After another three hours core power returned to 95% by step change. Figure 1 shows the core power change in the transient. The boron concentration during the test was kept between 745 to 785 PPM. The major power control was performed by lead bank insertion and withdrawal. The boron concentration change and the lead bank movement during the test are shown in Figure 2. ASI variation was measured for the whole transient from the on-line monitoring system COLSS[3]. To simulate the tested core transient, ACE/ONED[4] code was used. ACE/ONED developed by KAERI is to replace the ABB-CE supplied XRBP(Xenon Reactivity Balance Program) that is one of the NSSS application program in PMS(Plant Monitoring System). ACE/ONED code is based on ONED90 code[5][6] which solves two group one-dimensional diffusion equation by ANM/NEM with adapted parameters. Figure 3 shows the comparison of measured ASI's with the ACE/ONED simulation results assuming the transient starts from the equilibrium xenon state. As shown in this figure, the simulation neglect ASI variation before the transient and thus the difference between measured ASI and ACE/ONED results increases as the transient proceeds with RMS difference of 1.8% in ASI predictions versus measurements. It can be seen that the four ASI measurement data before the transient of which power level is greater than 99%, were increasing slightly. It implies that the core has the xenon oscillation before the transient and the difference on transient core behavior appears by the difference between measured and simulated ASI's in Figure 3. In order to consider the xenon distribution difference due to xenon oscillation before the transient at the starting test point, xenon distribution is modified by Δf_X in Section 2. The transient test is simulated again by the modified xenon with the difference of xenon obtained from the power difference at the test starting point. And the result is shown in figure 4. It can be seen that the simulated ASI variation well agree with measured data. The RMS difference in ASI predictions versus measurements is 0.7%.

4. Conclusions

The core behavior represents the xenon status in the core as the variation of the axial power shape. The initial xenon distribution, which can not be measured, have a significant effect on the transient with xenon dynamics. If the simulation is required for the transient starting from the non-equilibrium xenon state, the accurate initialization of the iodine and xenon distribution is important. Because a fairly small xenon oscillation just before the test gives some effect on the test, the error gets greater. In order to reduce the error coming from xenon oscillation before the transient, the xenon initialization method using the first-order perturbation theory is employed in this study. The axial xenon distribution inferred from the measured power profile can easily be used in the simulation code such as ACE/ONED. The transient simulation shows that there is a good agreement with measurement. Therefore the core behavior is accurately predicted with this method only if measured power distribution is known.

References

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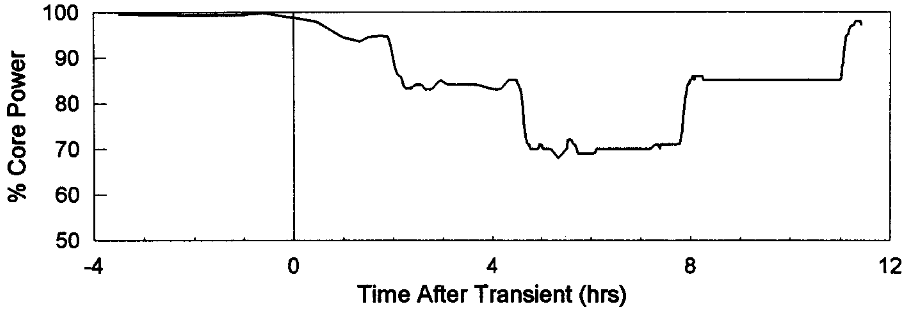

Figure 1. Core Power Change in Transient

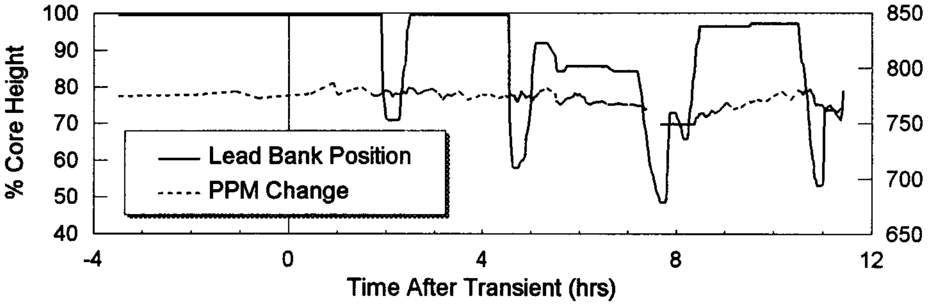

Figure 2. Lead Bank Position & PPM Change in Transient

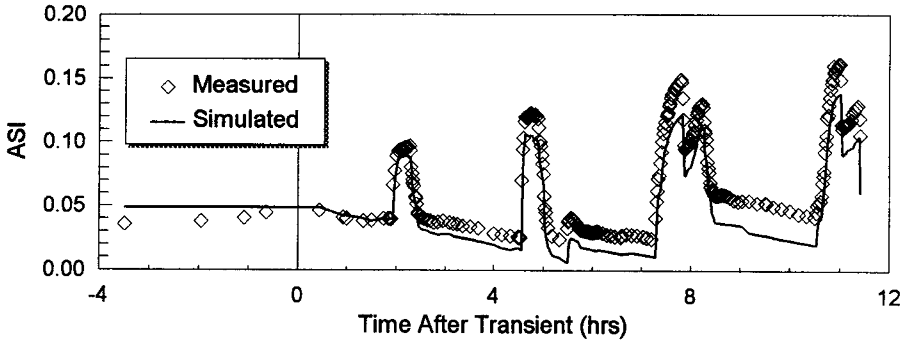

Figure 3. ASI Simulation of Transient with Eq. Xenon

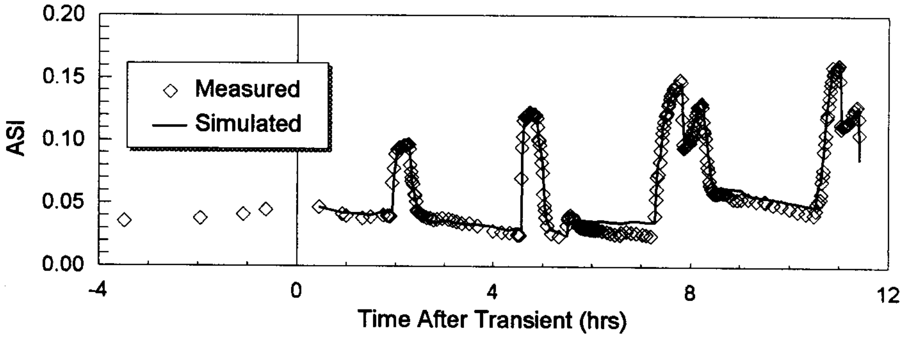

Figure 4. ASI Simulation of Transient with Modified Xenon