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Development of Integrated Boration and Dilution Model for Boron Concentration Behavior Analysis

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붕산농도 거동분석을 위한 종합적 붕산주입 및 희석모델 개발

지성구 · 최한권 · 구정의
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Abstract

In this study, an integrated boration and dilution (INBAD) model is proposed to predict the required makeup flowrate for RCS boron concentration change and to analyze the boron concentration behavior at each subsystem within the RCS including CVCS during boration and dilution operation. The INBAD model is constructed by integrating an existing neutronic code and a boration and dilution model. The boration and dilution model has been developed for our specific purpose using the one-cell model and multi-cell model. In addition, in order to assess the boron concentration behavior more realistically, two important features such as variable pressurizer heater output and optional makeup mode (either direct or indirect injection) are implemented in this model.

In order to demonstrate the usefulness of this model, the boron concentration behavior analysis at each subsystem were performed for both direct and indirect injection mode using YGN 3 and 4 design data. Also, the effect of pressurizer heater output on the primary loop boron concentration was investigated. The results showed that the boron concentration changes can be predicted accurately at each subsystem during boration and dilution operation.

요 약

본 연구에서는 붕산주입 및 희석운전동안에 노심의 붕산농도를 변화시키기 위한 보충수 유량을 예측하고 화학 및 체적제어계통을 포함한 원자로 냉각재계통내에 있는 각종 계통에서 붕산농도 거동분석을 위한 종합적 붕산주입 및 희석모델(INBAD)이 제안되었다. 이 모델은 기존의 노심코드와 새로 개발된 붕산주입 및 희석모델로 구성되어 있으며 붕산주입 및 희석모델은 단일 cell 모델 및 다중 cell 모델을 이용하여 본 연구목적에 맞게 개발되었다. 또한, 본 모델에서는 보다 실제적인 붕산농도 거동분석을 위하여 가변적 가압기 가열기 출력 및 선택적인 보충수 운전형태 (직접주입 또는 간접주입)가 모사되었다.

이 모델의 유용성을 증명하기 위하여 영광 3,4호기 설계자료를 이용하여 각종 계통에서 직접주입 및 간접주입운전에 대한 붕산농도 거동분석을 수행하였고, 노심의 붕산농도에 대한 가압기 가열기의 영향을 검토하였다. 그 결과 본 모델은 붕산주입 및 희석운전시에 각종 계통에서 붕산농도 변화를 정확히 예측할 수 있음을 보여 주었다.

1. Introduction

During nuclear power plant operation, reactivity may be changed resulting from changes in reactor coolant temperature, fuel burnup and xenon concentration. Control rods and soluble boron are used for reactivity control. However, the use of control rod is restricted during power maneuvering due to the limitations on rod insertion and axial power distribution. The boron control system is used to provide reactivity compensation for fuel burnup. Additionally, it can be and is used to compensate for some or all of the reactivity effects that are resulted from power maneuvering situations such as startup operation, shutdown operation and load following operation.

Adjustment of the reactor coolant system (RCS) boron concentration is basically made through the "feed and bleed" operation. For normal dilution or boration, the makeup water, either boric acid and/or demineralized water, is introduced into the volume control tank (VCT). The makeup water is mixed with letdown water in the VCT and is injected to the RCS through the charging pumps. For emergency dilution or boration, the makeup water is injected directly to the RCS through the charging pumps.

Several models have been proposed to investigate the behavior of RCS boron concentration during nuclear power plant operation in pressurized water reactor (PWR). One-cell mode[1], which treats the RCS including CVCS with a single diffusion cell, has been used to derive boration and dilution chart. This chart is generally used by operator in commercial PWR to calculate the required makeup flowrate in changing RCS boron concentration. Mathieu and Distexhe[2] presented a multiple-cell model that took into account primary loop, pressurizer, and VCT as an instantaneous diffusion cell and connecting pipes as a time lag line. They showed that this model can predict more accurately the required makeup flowrate as a function of time to achieve the primary loop boron concentration predicted by neutronic code. However, Mathieu and Distexhe model requires that reactor operator should control the makeup flowrate very frequently in order to achieve the required boron concentration in the primary loop.

In this study, an integrated boration and dilution model is proposed, which utilizes one-cell model to predict the required makeup flowrate in changing RCS boron concentration and multi-cell model to analyze the boron concentration behavior at each subsystem within RCS including CVCS. This new integrated boration and dilution model allows the reactor operator not only to realistically and quickly determine the amounts of makeup water but also to easily and accurately predict the boron concentration behavior at each subsystem during RCS boration and dilution operation.

2. Integrated Boration and Dilution (INBAD) Model

The INBAD model is constructed by integrating an existing neutronic code and a boration and dilution model. The boration and dilution model has been developed for our specific purpose. In addition, in order to assess the boron concentration behavior more realistically, two important features are implemented in our model. They are variable pressurizer heater output and optional makeup mode (either direct or indirect injection). Figure 1 illustrates the overall calculation sequence for the analysis of boron concentration behavior in the various subsystem within the RCS including CVCS.

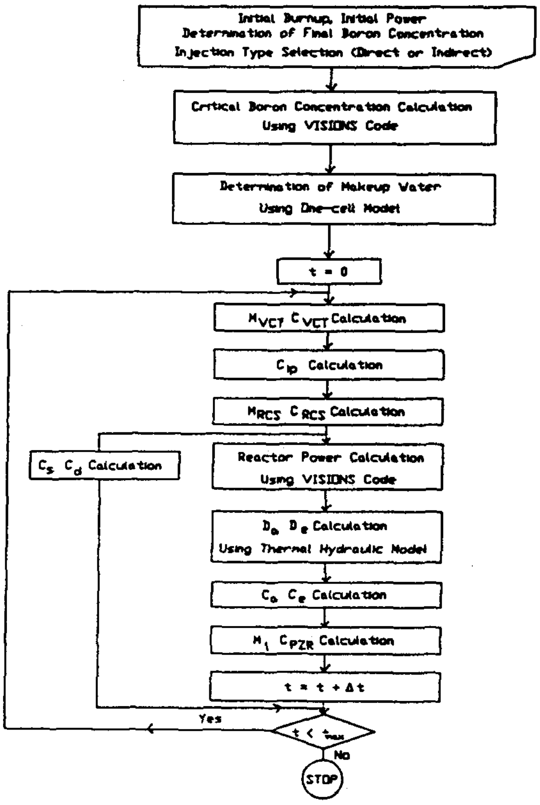

Fig. 1. Overall Calculation Sequence

2.1. Neutronic Model

For a given initial burnup and reactor power, a critical boron concentration is calculated using the VISIONS code[3,4]. In this code, power distribution is calculated in 3–dimensions using a neutronic coarse mesh model based on the modified one group diffusion theory. Appropriate feedback contribution due to moderator temperature, fuel temperature and xenon concentration changes are included. In addition, the xenon–iodine equations are explicitly solved during xenon time stepping calculation. Also, the VISIONS code is used in order to calculate the reactor power for the different RCS boron concentration predicted by the multi–cell model.

2.2. Boration and Dilution Model

2.2.1. One–cell Model

The one–cell model is used to determine the total amount of boric acid or demineralized water that must be added to the RCS for the purpose of changing the boron concentration by assuming the RCS including CVCS as a single control volume. Employing the boron balance around the control volume, the following first–order linear differential equation is derived as

$$W_{RCS}\frac{dC_{RCS}}{dt}=\dot{m}_{in}C_{in}-\dot{m}_{out}C_{RCS} \tag{1}$$

where,

W_{RCS} : total reactor coolant mass including the CVCS

C_{RCS} : RCS boron concentration

C_{in} : makeup boron concentration to be injected to the control volume

$\dot{m}_{in}$: makeup flowrate to be injected to the control volume

$\dot{m}_{out}$: ejected flowrate from the control volume

Solving Eq.(1) by assuming that the injected flowrate is equal to the ejected flowrate (that is, $\dot{m}_{in}=\dot{m}_{out}=\dot{m}$), the RCS boron concentration is expressed as

$$C_{RCS}=(C_O-C_{in})\exp(-\dot{m}t/W_{RCS})+C_{in} \tag{2}$$

where, C_O : initial boron concentration

From Eq.(2), the required total makeup volume to change the RCS boron concentration is expressed as

$$V_{in}=k\ W_{RCS}\ln(\frac{C_{in}-C_O}{C_{in}-C_f}) \tag{3}$$

where, C_f : final boron concentration

k : unit conversion constant

2.2.2. Multi-cell Model

When the makeup water determined by one-cell model is injected into the RCS, the diffusion process of the makeup water in the various subsystem can be simulated by the multi-cell model. In this model, primary loop, pressurizer and VCT are modeled as an instantaneous diffusion cell and connecting pipes as a time lag line as shown in Figure 2.

In the time lag line, if the boron concentration at the inlet of the pipe is known, the boron concentration at outlet can be determined by the following relationship.

$$C_{out}(t) = C_{in}[t - \gamma(t)] \quad \text{with } \gamma(t) = W(t)/D(t) \tag{4}$$

The above equation means that the boron concentration at the outlet is simply delayed by a lag time $\gamma(t)$ with respect to the inlet boron concentration.

In the diffusion cell, the mass balance equation and the boron balance equation around the control volume can be written as follows.

$$\frac{dM(t)}{dt} = D_{in}(t) - D_{out}(t) \tag{5}$$

$$\frac{d}{dt}[M(t)C(t)] = D_{in}(t)C_{in}(t) - D_{out}(t)C_{out}(t) \tag{6}$$

By assuming that water mass and boron concentration within the control volume are constant during time interval Δt, Eqs.(5) and (6) can be derived as follows.

$$M^{n+1} = M^n + (D_{in}^n - D_{out}^n)\Delta t \tag{7}$$

$$C^{n+1} = \frac{[(D_{in}^n C_{in}^n - D_{out}^n C_{out}^n) - C^n(D_{in}^n - D_{out}^n)]\Delta t + M_l^{n+1}C^n}{M^{n+1}} \tag{8}$$

The solution of Eqs.(7) and (8) represents the boron concentration at each subsystem.

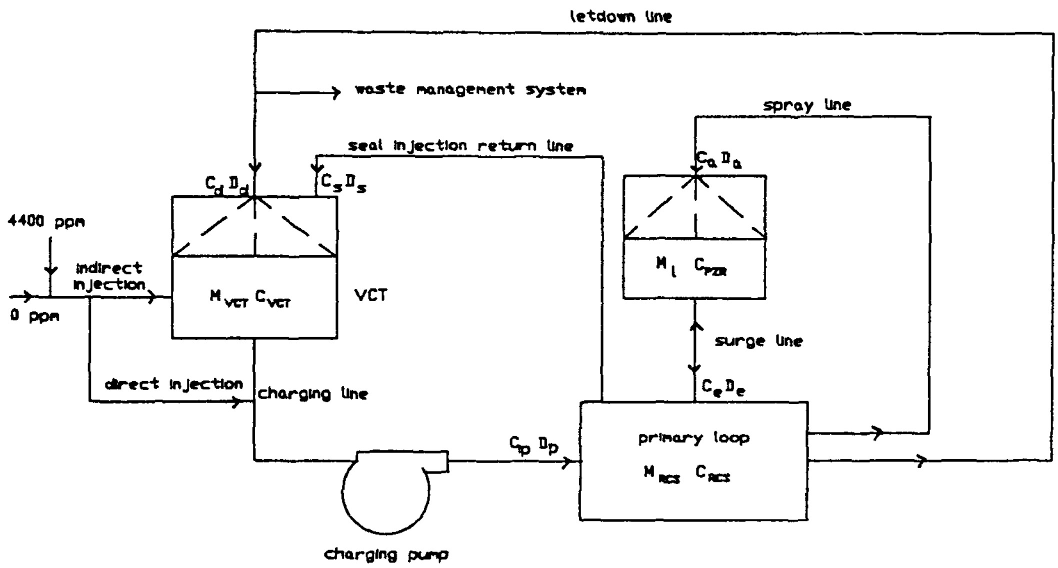

Fig. 2. Geometrical Multi-cell Model

2.2.2.1. Pressurizer Thermal Hydraulic Model

A simple pressurizer model is employed as shown in Figure 3 in order to calculate the flowrate at the spray line and the surge line, which will be used in the diffusion model (see Section 2.2.2.2). In this model, the vapor phase of mass M_v is in equilibrium with a liquid phase of mass M_l. The total mass of both phases is

$$M_t=M_l+M_v \tag{9}$$

The total enthalpy is

$$H_t=M_lh_e+M_vh_v, \tag{10}$$

where h_l and h_v are enthalpies of liquid and vapor at a saturated state. The total volume is

$$V_t=\frac{M_l}{\rho_l}+\frac{M_v}{\rho_v}=\text{Constant}, \tag{11}$$

where ρ_l and ρ_v are mass densities of liquid and vapor at a saturated state. From Eqs. (9), (10) and (11),

$$\frac{dM_t}{dt}=(1-\frac{\rho_v}{\rho_l})\frac{dM_l}{dt}=\frac{1}{r}\frac{dM_l}{dt}$$
$$\text{with } r=\frac{\rho_l}{\rho_l-\rho_v} \tag{12}$$

and

$$\frac{dH_t}{dt}=(h_l-\frac{\rho_v}{\rho_l}h_v)\frac{dM_l}{dt}=h^*\frac{dM_l}{dt}$$
$$\text{with } h^*=h_l-\frac{\rho_v}{\rho_l}h_v \tag{13}$$

For an isobaric process, the mass balance equation and the thermal balance equation in the pressurizer can be expressed as

$$\frac{1}{r}\frac{dM_l}{dt}=D_a-D_e \tag{14}$$

$$h^*\frac{dM_l}{dt}=Q_H-Q_L+D_ah_a-D_eh_l. \tag{15}$$

where,

Q_H : total heating output of the pressurizer heater

Q_L : heat loss rate from the pressurizer

h_a : enthalpy of liquid at the pressurizer spray line

From Eqs.(14) and (15), the flowrates at the surge line and the spray line are derived as follows.

$$D_e=\frac{Q_H-Q_L-h^{**}dM_l/dt}{h_l-h_a}$$
$$\text{with } h^{**}=h^*-\frac{1}{r}h_a \tag{16}$$

$$D_a=D_e+\frac{1}{r}\frac{dM_l}{dt} \tag{17}$$

By assuming that the pressurizer water level is maintained at its programmed level at any time, the dM_l/dt can be calculated using the relationship between the average RCS temperature and the reactor power as follows.

$$T_{avg}(t)=T_c+(T_h-T_c)\times Power(t)/100 \tag{18}$$

$$M_l(t)=M_{lo}+\frac{M_{ln}-M_{lo}}{T_h-T_c}[T_{avg}(t)-T_c] \tag{19}$$

$$\frac{dM_l}{dt}=\frac{M_l^{n+1}-M_l^n}{\Delta t} \tag{20}$$

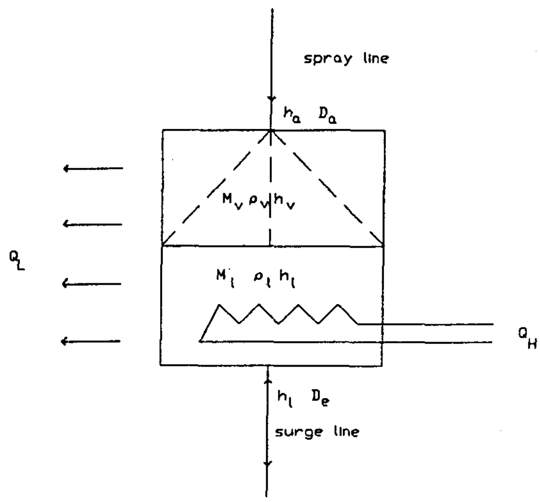

Fig. 3. Pressurizer Model

where,

T_c, T_h : average RCS temperatures at zero power and full power, respectively

M_{lo}, M_{ln} : pressurizer liquid masses at zero power and full power, respectively

$T_{avg}(t)$: average RCS temperature at time t

2.2.2.2. Diffusion Model

A. VCT

The VCT is modeled as an instantaneous diffusion cell containing a water mass $M_{VCT}(t)$ and a boron concentration $C_{VCT}(t)$. In the case of indirect injection, the mass balance equation and the boron balance equation can be expressed as

$$\frac{dM_{VCT}(t)}{dt} = D_d(t) + D_s(t) + D_m(t) - D_p(t) \quad (21)$$

$$\frac{d}{dt}[M_{VCT}(t)C_{VCT}(t)]$$

$$= D_d(t)C_d(t) + D_s(t)C_s(t)$$

$$+ D_m(t)C_m(t) - D_pC_{VCT}(t). \quad (22)$$

By assuming that M_{VCT} and C_{VCT} are constant during time interval Δt, Eqs.(21) and (22) can be derived as follows.

$$M^{n+1}_{VCT} = M^n_{VCT} + (D^n_d + D^n_s + D^n_m - D^n_p)\Delta t \quad (23)$$

$$C^{n+1}_{VCT} = \frac{(D^n_dC^n_d + D^n_sC^n_s + D^n_mC^n_m)\Delta t + M^{n+1}_{VCT}C^n_{VCT}}{M^{n+1}_{VCT} + (D^n_d + D^n_s + D^n_m)\Delta t} \quad (24)$$

In the case of direct injection to the charging pump, above equations can be expressed as follows.

$$M^{n+1}_{VCT} = M^n_{VCT} + (D^n_d + D^n_s)\Delta t \quad (25)$$

$$C^{n+1}_{VCT} = \frac{(D^n_dC^n_d + D^n_sC^n_s)\Delta t + M^{n+1}_{VCT}C^n_{VCT}}{M^{n+1}_{VCT} + (D^n_d + D^n_s)\Delta t} \quad (26)$$

B. Charging Line

The charging line is modeled as a single time lag line containing a constant water mass. The boron concentration at the primary loop inlet can be expressed as follows.

In the case of indirect injection,

$$C_{ip}(t) = C_{VCT}[t - \gamma_{ip}(t)]$$
$$\text{with } \gamma_{ip}(t) = W_{ip}/D_p(t) \quad (27)$$

In the case of direct injection to the charging pump,

$$C_{ip}(t) = C_m[t - \gamma_{ip}(t)]$$
$$\text{with } \gamma_{ip}(t) = W_{ip}/D_p(t) \quad (27)$$

C. Primary Loop

The reactor vessel and the RCS loops are modeled as a single instantaneous diffusion cell. This cell contains a water mass $M_{RCS}(t)$, which is a function of average RCS temperature, and has a uniform boron concentration $C_{RCS}(t)$. This modeling can be justified, since the lag time of RCS loop is relatively small (about 3 seconds for reactor vessel and about 6.2 seconds for RCS loop in the case of YGN 3 and 4) compared with other time lag lines (an order of several minutes) and the injected water into the RCS is fully mixed in the upper support structures of the core. The mass balance equation and the boron balance equation can be expressed as follows.

$$\frac{dM_{RCS}(t)}{dt} = D_p(t) + D_e(t)$$
$$- [D_d(t) + D_s(t) + D_a(t)] \quad (29)$$

$$\frac{d}{dt}[M_{RCS}(t)\ C_{RCS}(t)]$$
$$= D_p(t)C_{ip}(t) + D_e(t)C_e(t) \quad (30)$$
$$- [D_d(t) + D_s(t) + D_a(t)]\ C_{RCS}(t)$$

By assuming that M_{RCS} and C_{RCS} are constant during time interval Δt, Eqs.(29) and (30) can be derived as follows.

$$M^{n+1}_{RCS} = M^n_{RCS} + (D^n_p + D^n_e - D^n_d - D^n_s - D^n_a)\Delta t \quad (31)$$

$$C^{n+1}_{RCS} = \frac{(D^n_pC^n_{ip} + D^n_eC^n_e)\Delta t + M^{n+1}_{RCS}C^n_{RCS}}{M^{n+1}_{RCS} + (D^n_p + D^n_e)\Delta t} \quad (32)$$

D. Pressurizer

The pressurizer is modeled as an instantaneous diffusion cell containing a saturated vapor of mass $M_v(t)$ and zero boron concentration. The saturated vapor is in equilibrium with a saturated liquid of mass $M_l(t)$ at a uniform boron concentration $C_{PZR}(t)$. The mass balance equation and the boron balance equation can be expressed as follows.

$$\frac{dM_l(t)}{dt}=D_a(t)-D_e(t) \tag{33}$$

$$\frac{d}{dt}[M_l(t)C_{PZR}(t)] = D_a(t)C_a(t)-D_e(t)C_e(t) \tag{34}$$

By assuming that M_l and C_{PZR} are constant during time interval Δt, Eqs.(33) and (34) can be derived as follows.

$$M_l^{n+1}=M_l^n+(D_a^n-D_e^n)\Delta t \tag{35}$$

$$C^{n+1}_{PZR}= \frac{[(D_a^nC_a^n-D_e^nC_e^n)-C_{PZR}^n(D_a^n-D_e^n)]\Delta t+M_l^{n+1}C_{PZR}^n}{M_l^{n+1}} \tag{36}$$

E. Spray Line

The two spray pipes are modeled as a single time lag line containing a constant water mass. The boron concentration at the pressurizer inlet can be expressed as follow.

$$C_a(t)=C_{RCS}[t-\gamma_a(t)] \quad \text{with } \gamma_a(t)=W_a/D_a(t) \tag{37}$$

F. Surge Line

The surge line is modeled as a time lag line containing a constant water mass. The boron concentration at the surge line can be expressed as follow.

$$C_e(t)=C_{PZR}[t-\gamma_e(t)] \quad \text{with } \gamma_e(t)=W_e/D_a(t) \tag{38}$$

G. Letdown Line

The letdown line is modeled as a time lag line containing a constant water mass. The boron concentration at the VCT inlet can be expressed as follow.

$$C_d(t)=C_{RCS}[t-\gamma_d(t)] \quad \text{with } \gamma_d(t)=W_d/D_d(t) \tag{39}$$

Also, when the VCT water level is increased above the level setpoint, the letdown line is modeled to divert the letdown flow to the waste management system.

H. Seal Injection Return Line

The seal injection line is modeled as a time lag line containing a constant water mass. The boron concentration at the VCT inlet can be expressed as follow.

$$C_s(t)=C_{RCS}[t-\gamma_s(t)] \quad \text{with } \gamma_s(t)=W_s/D_s(t) \tag{40}$$

3. Calculation Results

The boron concentration behavior at each subsystem was analyzed for both direct and indirect mode by an integrated boration and dilution model using YGN 3 and 4 design data[5]. Also, the effect of pressurizer heater output on the primary loop boron concentration was investigated.

3.1. Indirect Mode

As an initial condition, critical boron concentration at 50% power, middle of cycle (MOC) and all rod out (ARO) condition was calculated using the VISIONS code. The calculated critical boron concentration was 579.8ppm in this case. The total makeup volume required for the dilution of 10 ppm was calculated using one-cell model as

1010.5 gallon. When the demineralized water was injected through the VCT at a rate of 16.84 gpm for 1 hour, our model predicted the boron concentration changes at each subsystems as shown in Figures 4 and 5.

As shown in Figure 4, the boron concentration at VCT is rapidly decreased at the beginning. However, after 1 hour, it starts increasing due to the higher borated flow returning from letdown line and seal injection return line, and reaches to the equilibrium condition approximately after 4 hours. At the inlet of the primary loop, the boron concentration changes with 2 minutes lag time with respect to the VCT.

Figure 5 shows the boron concentration changes at the primary loop, the pressurizer and the VCT inlet. At the primary loop, the boron concentration initially decreases and reaches 570.03 ppm at equilibrium condition, which is in a good agreement with the anticipated boron concentration from one-cell model, 569.8ppm. The boron concentration at the pressurizer was calculated with the maximum heater output (1800KW) as shown in Figure 5. The boron concentration at the surge line changes with 2.3 minutes lag time with respect to the pressurizer. The lag time of letdown line, seal injection return line and spray line are 12.2, 4.8, and 2.5 minutes with respect to the primary loop, respectively.

Figures 6 and 7 show the boron concentration

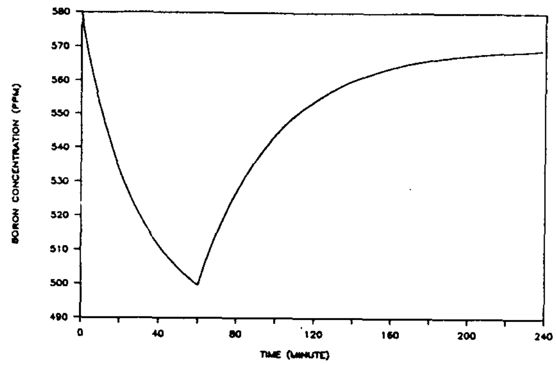

Fig. 4. Boron Concentration Change at VCT for Indirect Dilution

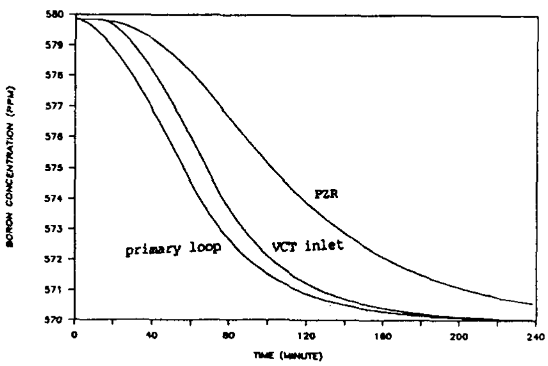

Fig. 5. Boron Concentration Changes at Primary Loop, Pressurizer and VCT Inlet for Indirect Dilution

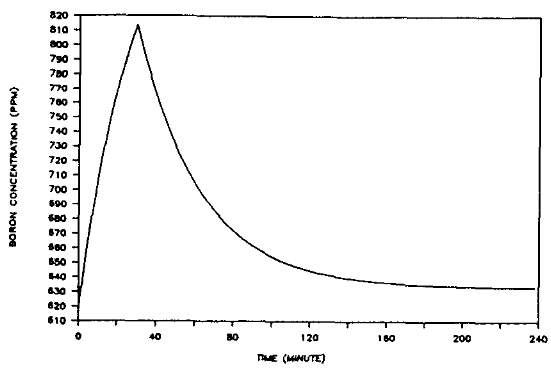

Fig. 6. Boron Concentration Change at VCT for Indirect Boration

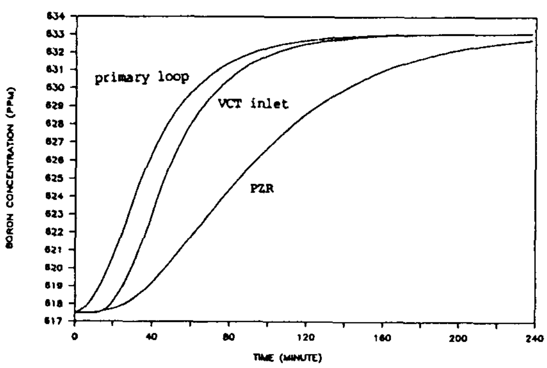

Fig. 7. Boron Concentration Changes at Primary Loop, Pressurizer and VCT Inlet for Indirect Boration

behaviors at each subsystem at 100% power, beginning of cycle (BOC) and ARO condition in the case of boration at a rate of 8 gpm for 30 minutes.

3.2. Direct Mode

Figures 8 and 9 show the boron concentration behaviors at each subsystem in the case of direct dilution through the charging pump at a rate of 10 gpm for 10 minutes at 50% power, MOC and ARO condition. Because the demineralized water is injected directly to the primary loop through the charging pump, the boron concentration at primary loop decreases rapidly during dilution and, then increases very slowly due to the returning flow from the VCT. AT the VCT, boron concentration decreases slowly in accordance with the primary loop. The boron concentration behavior at other subsystems shows the same trend as the indirect mode.

3.3. Effects of Pressurizer Heater Output

It is important to minimize the boron concentration difference between the pressurizer and the primary loop during boration and dilution operation, since the primary loop boron concentration can be affected due to the surged flow from the pressurizer after the completion of boration or

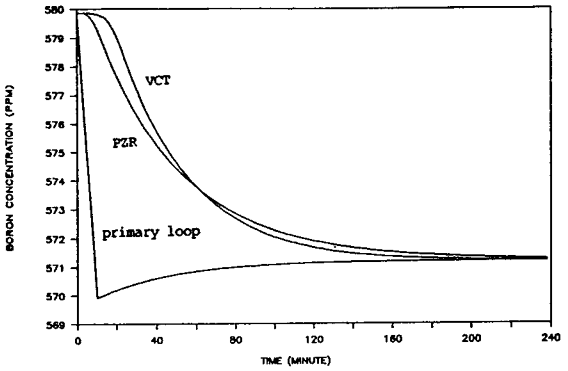

Fig. 8. Boron Concntration Changes at VCT, Primary Loop and Pressurizer for Direct Dilution

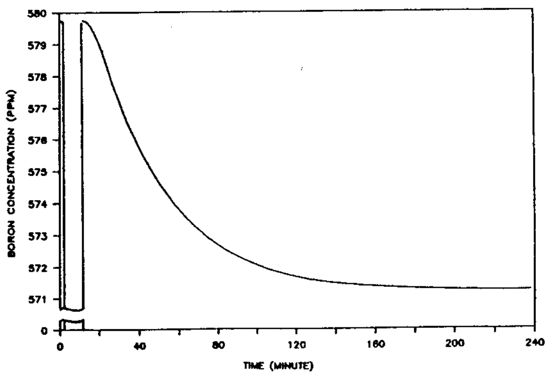

Fig. 9. Boron Concentration Change at Primary Loop Inlet for Direct Dilution

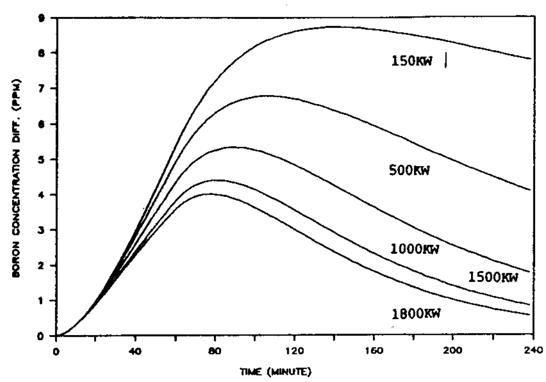

Fig. 10. Boron Concentration Difference Between Primary Loop and Pressurizer as a Function of Pressurizer Heater Output

dilution operation. This boron concentration change in the primary loop leads to a power transient, which will be an additional burden to the reactor operator to maintain the constant power.

Figure 10 shows that the boron concentration difference between the primary loop and the pressurizer strongly depends on the pressurizer heater output. When the heater output is increased manually during RCS boration and dilution, the spray flow is increased in order to maintain constant RCS pressure and the water in the pressurizer is surged into the primary loop in order to maintain the programmed pressurizer water level. Consequently, the boron concentration difference is reduced via recirculation between the primary loop and the pressurizer as the heater output is increased. Based on our analysis, it is concluded that the pressurizer heater output needs to be at its maximum during RCS boration and dilution to minimize the power transient after boration and dilution operation.

4. Conclusions

An integrated boration and dilution model has been developed to predict the boron concentration changes at each subsystem as a function of time. The results showed that the boron concentration calculated by the multi-cell model at equilibrium condition was in a good agreement with the anticipated value from one-cell model. Therefore, it is concluded that this INBAD model can predict the boron concentration behavior accurately at each subsystem for various boration and dilution operation. This model allows the reactor operator to predict the boron concentration behavior easily and accurately at each subsystem within RCS including CVCS, which provides a valuable information for power maneuvering.

However, in order to apply this model to actual operation such as startup, shutdown, and load follow situation, complete benchmark calculation should be performed to verify further this model using actual test data during YGN 3 and 4 startup test.

Nomenclature

C=boron concentration
D=flowrate
M=water mass in control volume
T=temperature
W=water mass in pipe
t=time
h=enthalpy
ρ=mass density
γ=time lag

Subscript

RCS=reactor coolant system
VCT=volume control tank
PZR=pressurizer
a=spray line
d=letdown line
e=surge line
l=liquid
m=makeup
p=charging line
s=seal injection return line
v=vapor

References

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