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A Study on Determination of Boron Makeup Flow Rate During the Load Follow Operation

Yong-Mann Song, Un Chul Lee and Chang Hyun Chung
Seoul National University
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부하추종 운전시 보론 보충 수량 결정에 관한 연구

송용만 · 이은철 · 정창현
서울대학교
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Abstract

During power plant operation, the flow rate from the CVCS makeup system is estimated using the continuity equation and mass balance equation, when the primary loop boron concentration change is required due to the power transient.

For this purpose, primary loop, pressurizer and VCT(volume control tank)(in CVCS) are modeled by three control volumes which contain each mass and boron concentration. Connecting pipes between primary loop, pressurizer and CVCS are also modeled by time delay.

Calculation for 14-2-6-2 (power 100-50-100) load follow case (at EOL, for KNU 7) is made using these models.

요 약

상업용 발전소의 가동시, 출력 변화에 의해 1차 계통 보론 농도의 변화가 요구되었을때 CVCS보충 시스템에서의 보충 유량이 연속 방정식과 질량 평형 방정식을 이용하여 측정된다.

이를 위하여, 1차 계통, 가압기, 그리고 volume control tank가 각각 질량과 보론 농도를 가진 control volume으로 그리고 1차측과 가압기, CVCS를 연결하는 파이프들이 시간 지연 요소로 모델화 되었다.

14-2-6-2(출력변화 100-50-100) 부하 추종운전의 경우(7호기 EOL에서)를 이 모델을 이용하여, 계산하였다.

Nomenclature

M_{10}, M_{1F}: primary loop mass at zero & full power

M_{30}, M_{3F}: pressurizer water mass at zero & full power(1bm).

$T_1(t)$: average primary loop temperature(F).

T_c: cold leg temperature.

$\triangle T$: temperature difference between zero & full power.

h_t, M_t, V_t: total enthalpy, mass, & volume of pressurizer.

h_l, M_3, ρ_l: liquid phase enthalpy, mass, & density of pressurizer.

h_v, M_{3v}, ρ_v: vapor phase enthalpy, mass, & density of pressurizer.

h_a: enthalpy of water in cold leg (Btu/lbm).

Q_c: heating power of immersion heaters (Btu/sec).

Q_F: heat loss rate from pressurizer wall.

F_5: letdown flow rate (gpm).

F_{10}: seal leakage return flow rate.

F_{11}: seal leakage flow rate to RCP (reacter coolant pump).

F_8: flow rate to charging pump.

F_9: charging flow rate to primary loop.

C: concentration (ppm)

τ: time constant (min.)

M: mass of coolant (lbm)

W: mass flow rate (lbm/min.)

(*Each substription for above nomenclature follows by region explanation (Table 1).)

1. Introduction

During reactor operation, changes in the reactor coolant boron concentration are required for the following conditions: reactor startup, load follow operation, fuel burnup and cold shutdwn. The chemical and volume control system(CVCS) controls the change in concentration of the chemical neutron absorber(boron). Especially during the load follow operation using the SPINR method (a kind of load follow operation) which maximizes spinning reserve capacity (part of the difference between full power rating and percent power rating which is reliable in the event of a sudden large demand for power), the boron concentration of the primary loop may be changed by large quantity.

In CVCS, boration and dilution modes are switched to permit the addition of preselected quantity of makeup water (of boric acid). So, the total amount of makeup water should be determined when the change of the primary loop boron concentration is required during power transient.

As a result, if the boron concentration in the primary loop varies, boron concentration in control volumes and pipes and makeup water should be known to compensate for the reactivity change in the core.

Table 1. Region explanation.

Number	explanation
1	primary loop (including all primary system except pressurizer & CVCS)
2	pressuizer spray line
3	pressurizer
4	pressurizer surge line
5	CVCS letdown line
6	CVCS volume control tank (VCT)
7	CVCS maekup line
8	CVCS charging line (to charging pump)
9	CVCS charging line (to primary loop)
10	CVCS seal leakage return line
11	CVCS seal leakage charging line to primary loop (pseudo)
D	CVCS departure point (between charging & seal leakage line)
S	CVCS suction collector (to charging pump)

1. Modeling of Each Region

2. 1. Primary loop

The entire primary system except pressurizer and CVCS is modeled as a single control volume which diffuses instantaneously and contains water of mass, M_1 and boron concentration, C_1.

2.2. Pressurizer

The pressurizer is modeled as a control volume and two time delay lines, i.e. spray and surge line. It is supposed that the vapor phase is in equilbrium with the liquid phase and is saturated at costant pressure and temperature.

$[p=2250\text{psia}, T=652.7\ F]$

Spray line, pressurizer and surge line contain water of mass M_2, M_3 and M_4, respectively, and bornon concentration in the pressurizer is assumed as C. The heaters in the pressurizer inner volume supply the electric heat energy and loss rate from the wall is assumed as zero.

2.3. Chemical and volume control system (CVCS)

CVCS is modeled as one control volume, i.e. volume control tank (VCT), three time delay lines which are letdown, charging and seal leakage line, and makeup system.

If boration is needed, boric acid of 4 weight percent(w/o) is surged into the coolant, while pure water is inserted in the case of dilution.

3. Governing Equations

3.1. Mass Calculation

The water of the primary loop and pressurizer can be calculated from the temperature difference (ΔT) fraction if initial mass at zero power (or load) and mass at full power (or nominal load) are known. The average primary temperature increase linearly with the core percent power (Fig. 2) and is used as input data.

A. At primary loop volume(1)

The governing equation is

$$M_1(t)=M_{10}+(M_{1F}-M_{10})\frac{(T_1(t)-T_c)}{\Delta T}. \qquad (1)$$

B. At pressurizer volume(3)

The calculation Scheme is the same as for the primary loop case, and the mass changes according to average primary temperature.

$$M_3(t)=M_{30}+(M_{3F}-M_{30})\frac{(T_1(t)-T_c)}{\Delta T} \qquad (2)$$

C. At VCT colume(6)

The reactor makeup control system(RMCS) maintains the proper reactor coolant inventory, and the VCT water inventory is maintained (normaly around $\pm5\%$) by makeup control functins, following that the mass at VCT(M_6) is constant in normal operation.

3.2. Flow Rate Calculation

The flow rate is calculated at each line in pressurizer(2,4) and CVCS (5,8,9,10,11). The flow rate at makeup line(7) is calculated as a purpose of boration/dilution.

A. pressurizer.

In normal condition, the pressure in the pressurizer is maintained automatically and isobaric process can be assumed. So, the spray and surge flow rates are calculated from the heat and mass blance equations for the isobaric process.

First, the total enthalpy, mass and volume equations are written as follows;

$$h_t=M_3h_l+M_{3v}h_v, \qquad (3)$$

$$M_t=M_3+M_{3v}, \text{ and} \qquad (4)$$

$$V_t=M_3/\rho_l+M_{3v}/\rho_v. \qquad (5)$$

Secondly, using constant total volume, the differential equations for the total mass and enthalpy are obtained by liquid phase mass differential term;

$$\frac{dV_t}{dt}=0, \qquad (6)$$

$$\frac{dM_3}{dt}=-\frac{\rho_l}{\rho_v}\frac{dM_{3v}}{dt}. \qquad (7)$$

From this,

$$\frac{dM_t}{dt}=(1-\frac{\rho_v}{\rho_l})\frac{dM_3}{dt}, \qquad (8)$$

$$\frac{dh_t}{dt}=\{h_l-(\rho_v/\rho_l)h_v\}\frac{dM_3}{dt} = h^*\frac{dM_3}{dt}, \qquad (9)$$

and

$$h^*=h_l-(\rho_v/\rho_l)h_v.$$

Thirdly, the thermal and mass balance equations become respectively, as follows;

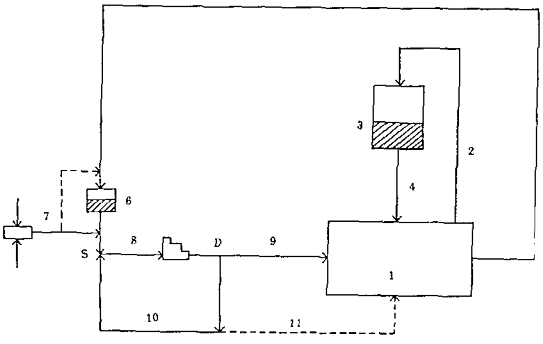

Fig. 1. Proposed Modeling

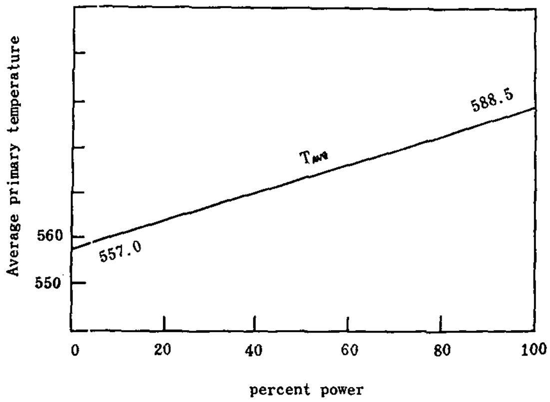

Fig. 2. Araveage Primary Temperature vs. Core Percent Power.

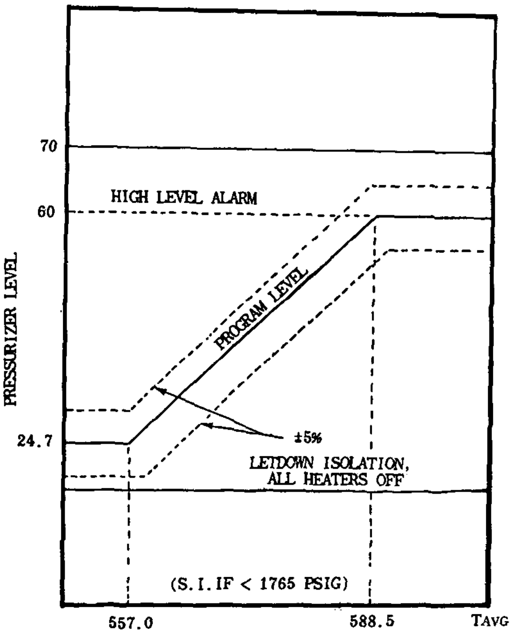

Fig. 3. Programmed Water Level in Pressuirzer.

$$h^* \frac{dM_3}{dt} = Q_c - Q_F + W_2(t)h_a - W_4(t)h_l. \quad (10)$$

$$(1-(\rho_v/\rho_l))\frac{dM_3}{dt} = W_2(t) - W_4(t). \quad (11)$$

Finally, from the above equationst, he surge flow rate is

$$W_4(t) = \frac{Q_c - Q_F - (h^* - (1-\rho_v/\rho_l)h_a)(dM_3/dt)}{(h_l - h_a)}, \quad (12)$$

and the spray flow rate is

$$W_2(t) = W_4(t) + (1-(\rho_v/\rho_l))(dM_3/dt) \quad (13)$$

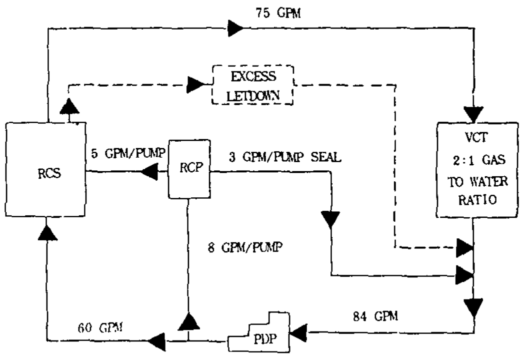

Fig. 4. CVCS Flow Balance.

B. CVCS

The charge and letdown functions of the CVCS are employed to maintain a programmed water level in the pressurizer (Fig. 3) by means of the continuous feed and bleed process. In this paper, all bleed processes are made by one letdown line and all feed processes by a charging line and a pseudo seal leakage charging line.

From the flow rate balances at nodes 8 and 9 (Fig. 1) the following relations can be attained.

$$F_8 = F_{10} + F_5, \quad (14)$$

and

$$F_9 = F_5 - F_{11}, \quad (15)$$

where F_5, F_{10} and F_{11} are determined from the CVCS flow balance (Fig. 4) in normal operation.

3.3. Calculation of boron cocentration

A. Transfer function

In any pipe (line), we can claculate the outlet concentration from the inlet concentration if the transit time constants of the pipe are known as follows:

$$C_{IN}=C_{OUT}(t+\tau(t)), \tag{16}$$

or

$$C_{OUT}=C_{IN}(t-\tau(t)). \tag{17}$$

where, $\tau(t)=M/W(t)$

B. Calculating equations.

a. pressurizer circuit

a.1. spray line

At inlet,

$$C_1(t)=a+bt, \tag{18}$$

where a and b are constant for $t \epsilon [t, t+\Delta t]$,

and at outlet,

$$C_2(t)=C_1[t-\tau_2(t)]=u+vt,$$
$$\text{with } \tau_2(t)=M_2/W_2(t), \tag{19}$$

where u and v are constant for $t \epsilon [t, t+\Delta t]$.

a.2. pressurizer

The boron mass balance in the liquid phase is

$$\frac{d}{dt}\{M_3(t)C_3(t)\}=W_2(t)C_2(t)-W_4(t)C_3(t), \tag{20}$$

with initial condition, $C_3(t_0)=C_{30}$.

If M_3 is constant, $W_2=W_4$, and Eq. (20) is written as

$$\tau_3\{dC_3(t)/dt\}+C_3(t)=u+vt. \tag{21}$$

Then the solution becomes

$$C_3(t)=\{C_{30}-u-v(t_0-\tau_3)\}$$
$$\exp\{-(t-t_0)/\tau_3\}+u+v(t-\tau_3). \tag{22}$$

If $M_3=Z_3+Q_3t$, Eq. (20) is written as

$$(\tau_3+\beta t)(dC_3/dt)+(\beta+1)C_3=(u+vt). \tag{23}$$

Then the solution becomes

$$C_3(t)=[C_{30}-\alpha\{\frac{u}{\beta+1}+\frac{v}{2\beta+1}$$
$$(t_0-\frac{\tau_3}{\beta+1})\}]\{M_3(t_0)/M_3(t)\}^{\epsilon} \tag{24}$$
$$+\alpha\{\frac{u}{\beta+1}+\frac{v}{2\beta+1}(t-\frac{\gamma_3}{\beta+1})\},$$

where

$\tau_3=Z_3/W_4(t)$, $\alpha=W_2/W_4(t)$, $\beta=Q_3/W_4(t)$, $\epsilon=(\beta+1)/\beta$.

a.3. surge line

$$C_4=C_3(t-\tau_4(t)) \text{ with } \tau_4(t)=M_4/W_4(t). \tag{25}$$

b. letdown line and volume control tank (VCT)

b.1. letdown line

$$C_5=C_1(t-\tau_5(t))=c+dt \text{ with } \tau_5(t)=M_5/W_5(t). \tag{26}$$

b.2. VCT

As each of pressurizer and VCT is one control volume and the mass of liquid phase in VCT is constant, the equation for boron concentration in VCT is the same form as Eq.(22). So,

$$C_6=\{C_{60}-c-d(t_0-\tau_6)\}\cdot$$
$$\exp\{-(t-t_0)\tau_6\}$$
$$+c+d(t-\tau_6), \tag{27}$$

with initial conditions, $C_{60}=C_6(t_0)$, and $\tau_6(t)=M_6/W_5(t)$.

c. Charging and seal leakage line

c.1. charging line to primary loop

The concentration at the outlet of the charging line is calculated from the boron and mass balance in the primary loop. The boron balance equation is

$$\frac{d}{dt}\{M_1(t)C_1\}=W_4(t)C_4(t)+(W_9(t)+W_{11}(t))C_9(t)-(W_2(t)+W_5(t))C_1(t). \tag{28}$$

In the above equation, the boron concentration at the inlet of seal leakage line (node 11) is sup-

posed the same with that at the outlet of charging line(9). It is possible because the two lines have the same initial boron concentration at (Fig. 1) and there is little difference in the time constant.
The mass balance equation is

$$\frac{d}{dt}M_1(t) = W_4(t) + W_9(t) + W_{11}(t) - W_2(t) - W_5(t). \quad (29)$$

It follows that

$$M_1(t)\frac{d}{dt}\{C_1\} = W_4(t)(C_4(t) - C_1(t)) + (W_9(t) + W_{11}(t)) \times (C_9(t) - C_1(t)). \quad (30)$$

If we solve for C_9 (t), the solution is

$$C_9(t) = C_1(t) + \frac{M_1(t)\{dC_1(t)/dt\}}{W_9(t) + W_{11}(t)}$$

$$+ \frac{W_4(t)}{W_9(t) + W_{11}(t)}(C_1(t) - C_4(t)). \quad (31)$$

c.2. departure point

$$C_d(t) = C_9(t + \tau_9(t)) \text{ with } \tau_9(t) = M_8/W_8(t). \quad (32)$$

c.3. charging line to charging pump

$$C_8(t) = C_d(t + \tau_8(t)) \text{ with } \tau_8(t) = M_8/W_8(t). \quad (33)$$

c.4. seal leakage return line

$$C_9(t) = C_d(t + \tau_{10}(t)) \text{ with } \tau_{10}(t) = M_{10}/W_{10}(t). \quad (34)$$

d. suction collector
The balance equation at the suction collector is

$$C_8(t) = C_s\frac{W_s(t)}{W_8(t)} + C_{10}(t)\frac{W_{10}(t)}{W_8(t)}$$

$$= C_s\frac{(W_8(t) - W_{10}(t))}{W_8(t)} + C_{10}(t)\frac{W_{10}(t)}{W_8(t)}. \quad (35)$$

If we arrange above equation about $C_s(t)$, it becomes

$$C_s(t) = C_8(t) + \frac{W_{10}(t)}{(W_8(t) + W_3(t))} \cdot (C_8(t) - C_{10}(t)). \quad (36)$$

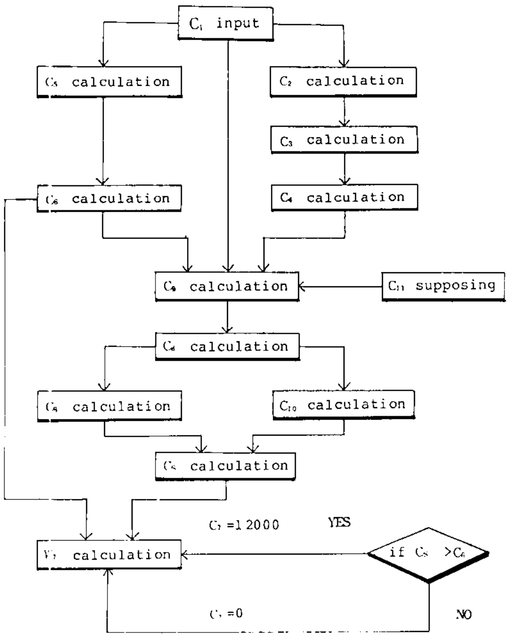

Fig. 5. Flow Chart.

3. makeup line
The balance equation including makeup line is

$$W_5(T)C_s(t) = W_7(t)C_7(t) + (W_5(t) - W_7(t))C_6(t). \quad (37)$$

If we arrange about $W_7(t)$, it becomes

$$W_7(t) = \frac{W_5(t)(C_s(t) - C_6(t))}{C_7 - C_6(t)}$$

or

$$F_7(t) = \frac{W_5(t)(C_s(t) - C_6(t))}{\rho_B(C_7 - C_6(t))}. \quad (38)$$

with C = 12000 ppm(=4%) if $C_5 > C_6$ (boration)
0 ppm if $C_5 < C_6$ (dilution).
Where ρ_B: boron density [=37.456 lbm/ft^3],
F_7: flow rate at makeup line [ft^3/min.].

4. Results and Discussion

The following case is cláculated;
*14-2-6-2- load follow case
—control method: SPINR method
—plant : Korea Nuclear Unit 7 (KNU 7)

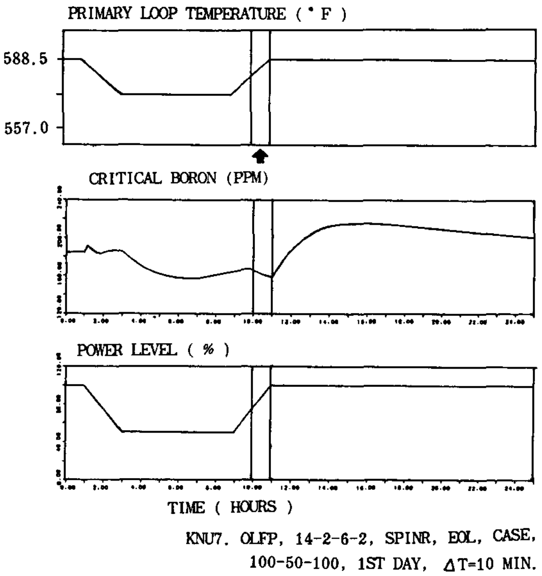

Fig. 6. input Case.

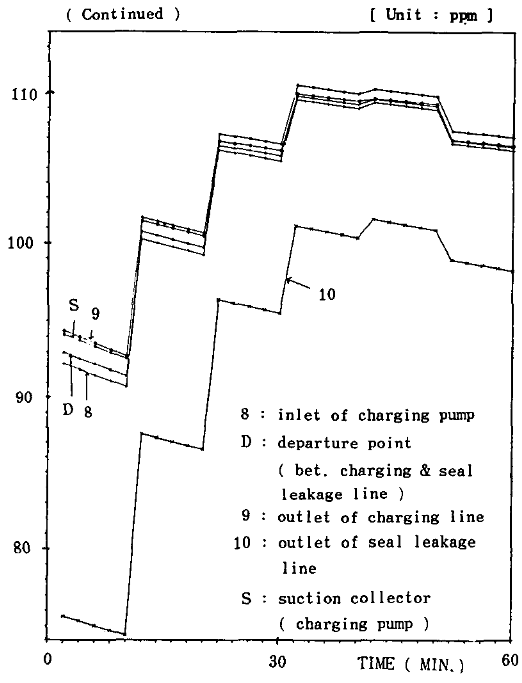

Fig. 8. Boron Concentration Change vs. Time (ii).

—power : 100-50-100(%)
—burnup : 12000(MWD/T)
—time interval : 1 hr (from 10:00-11:00 at 1st day)
—boron mode : dilution.

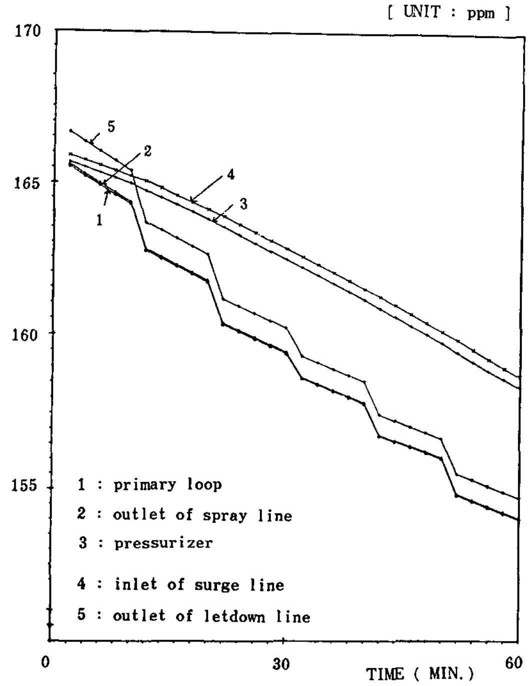

Fig. 7. Boron Concentration Change vs. Time (i).

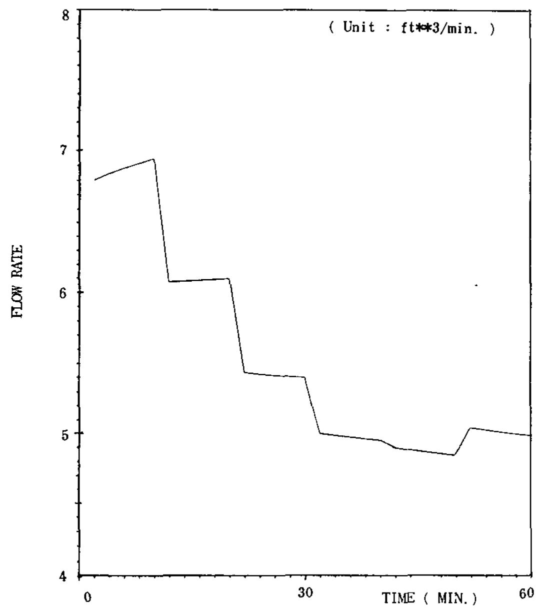

Fig. 9. Boron Make up Flow Rate.

The one hour between 10 and 11 o'clock at 1st day is selected because of noticeable change in the critical boron concentration for the dilution mode.

During the one hour of load follow operation, the calculation is made in detail with time step of 2 minutes. Through this time interval, the boron concentration and makeup flow rate are calculated by the sequence shown in flow chart(Fig. 5). As the primary loop boron concentration changes by 11.85 ppm(Fig. 6), the total fow rate is calculated as 332.3 ft^3[=2486 gallon] according to the following relation,

$$\text{TOTAl FLOW RATE} = \Sigma W^i * \text{TIME INTERVAL}$$

where, W^i: makeup flow rate at i step

The boron concentration at control volumes and pipes during one hour is shown in Figs. 7 and 8, and the makeup flow rate in Fig. 9. The model used in this paper is distinctive by supposing seal leakage charging line to primary loop and it makes flow calculation in CVCS more accurate and easy. We used the postulation that the heat loss rate in the pressurizer wall is zero, but it is possible that a little heat loss occurs. However, we should be cautious, because the heat loss rate has great effect on the evaluation of surge and spray flow rate in the pressurizer.

There exists difficulty in calculating the volumes in CVCS pipes due to structural complication. Therefore, some improvement should be made by making it more realistically.

5. Conclusions

By using developed models, we deduce the following conclusions for the load follow operation analysis.

(1) While primary loop boron concentration is changed by 11.85 ppm, total makeup flow rate inserted is 332.3 ft^3.

(2) The time needed for circulating the CVCS, i.e. CVCS time constant, which sums time constants of letdown line, VCT and charging line excluding seal leakage return line, is about 30 minutes.

(3) There is linear trend in change of boron concentration in the pressurizer compared with others whose shapes are stepwise the pressurizer behaves as a capacitance as shown in Fig. 3.

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