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RELAP5/MOD3 Analysis for Hydraulic Load Calculation of the SEBIM POSRV Discharge Piping System

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SEBIM POSRV 방출배관계통의 수력학적 하중계산을 위한 RELAP5 / MOD3 분석

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Abstract

The sudden discharge of the loop seal water, which is present upstream of the SEBIM POSRV, creates large momentum and inertia forces on the downstream of the discharge piping system. This study provides the procedures and results of analysis of the thermal-hydraulic transient in the SEBIM POSRV discharge piping during the valve opening. The analysis is performed by RELAP5/MOD3. The appropriate modeling of the discharge piping system, SEBIM POSRV opening characteristics, and loop seal water discharge for the RELAP5/MOD3 analysis is suggested. Also performed is the sensitivity study for the selection of proper options for the junction and volume control flags. The analysis results demonstrate the adequacy of the RELAP5/MOD3 for the thermal-hydraulic transient analysis of the loop seal water discharge of the SEBIM POSRV discharge piping system. From the sensitivity analysis results, it is shown that the smooth area change option with reasonable geometric pressure drop distribution, non-equilibrium option, and proper time step should be selected for loop seal water discharge analysis.

요 약

SEBIM 밸브 상부에 위치한 밀봉수의 급격한 방출은 밸브 후단의 방출배관계통에 큰 운동량과 관성력의 작용을 초래한다. 본 연구는 밸브개방시 방출배관계통의 후단에 발생하는 열수력학적 과도현상을 분석하기 위한 해석절차 및 해석결과를 다루고 있으며, 이 분석을 위해 RELAP5 /MOD3 를 사용하였다. RELAP5 /MOD3 분석을 위하여, 방출관 계통과 SEBIM 밸브의 개방특성 및 밀봉수 방출등의 적절한 모델방법이 제시되었다. 또한 접합부(junction)와 체적(volume)의 제어 플래그 (flag)에서 옵션(option)의 적절한 선택을 위하여 민감도분석도 수행되었다. 분석결과, SEBIM 밸브 방출배관계통의 밀봉수 방출에 따른 열수력학적 과도현상을 분석하는데 RELAP5 /MOD3가 적절히 사용될 수 있음을 알 수 있었다. 민감도 분석결과로부터, 밀봉수 방출해석을 위해서는 적절한 기하학적 압력분포를 가지는 완만한(smooth) 면적변화 및 비평형 옵션(option), 적절한 시간간격(time step)의 사용이 필수적인 것을 알 수 있었다.

1. Introduction

The SEBIM Pilot Operated Safety and Relief Valve (POSRV) discharge piping system[1] has a water loop seal(water plug or swan neck containing subcooled water) on the upstream side of the valves to minimize steam or noncondensible gas leakage through the valves. During the overpressure transients of the Pressurized Water Reactor (PWR) with SEBIM POSRV system, the protection valves of the SEBIM POSRV are opened to maintain the RCS pressure below acceptable range. Since SEBIM POSRV employs swan neck design, a subcooled water plug followed by a steam is discharged during a protection valve opening. This phase change creates very significant momentum and inertia forces (i.e., thermal-hydraulic loads) on the discharge piping.

Van Duyne et al.[2] suggested that RELAP code is not particularly well suited for the simulation of water slug or plug discharge. Reference 3 investigated the potential capability of RELAP5/MOD1 for the hydraulic load calculation of safety and relief valve discharge piping. The analysis results[3] where several code modifications were employed to avoid deficiencies of RELAP5/MOD1, were compared to EPRI tests. The analytical versus experimental comparisons demonstrated the adequacy of RELAP5/MOD1. Since several new models and improvements to models of the previous RELAP version have been added to a recently developed RELAP5/MOD3 computer code[4], application of RELAP5/MOD3 for hydraulic load analysis is challangeable.

The objectives of this study are to investigate the thermal-hydraulic behavior of the transient flow in the SEBIM POSRV discharge piping system, to develop the analysis procedures, and to demonstrate the potential capability of the RELAP5/MOD3 for the transient hydraulic load calculation of the discharge piping system.

2. SEBIM POSRV Discharge Piping System

The SEBIM POSRV discharge piping system consists of three discharge lines extending from the top of pressurizer, three Monobloc tandems with double outlet pipings, torus, and discharge pipings from the torus to the reactor drain tank(see Figure 1). The Monobloc tandem consists of protection valve, intervalve volume, and isolation valve. Each of discharge line includes swan neck containing subcooled water which provides leak tightness for noncondensible gas. During normal operation the protection valves are closed and the isolation valves are open.

3. Analysis Methods

The computer code used for this analysis is RELAP5/MOD3 version 7j and was run on Apollo DN-10000 workstation. Since rigorous assessment of thermal-hydraulic results of the concerning structural loading by using RELAP5/MOD3 has rarely been executed[4], the modeling of the problem is undertaken with great care and the sensitivity study for the RELAP5/MOD3 input options is performed.

3.1. Nodalization

The discharge pipings from the pressurizer to the reactor drain tank are modeled by volume and junction network as shown in Figure 1. The double outlet pipings with the opening of the protection valve are denoted by line E and line F. The whole discharge circuit including dead ends is modeled with PIPE component. Tee is modeled with BRANCH component. For this analysis the maximum time steps(Δt) are selected to be less than 10^{-4} second 6 and 7 in section 4.1). For the passive portions The successive maximum time steps which do not differ by more than 25% are used to maintain numerical stability. The mesh size(Δx) for the active portion of the pipe is selected to be less than or

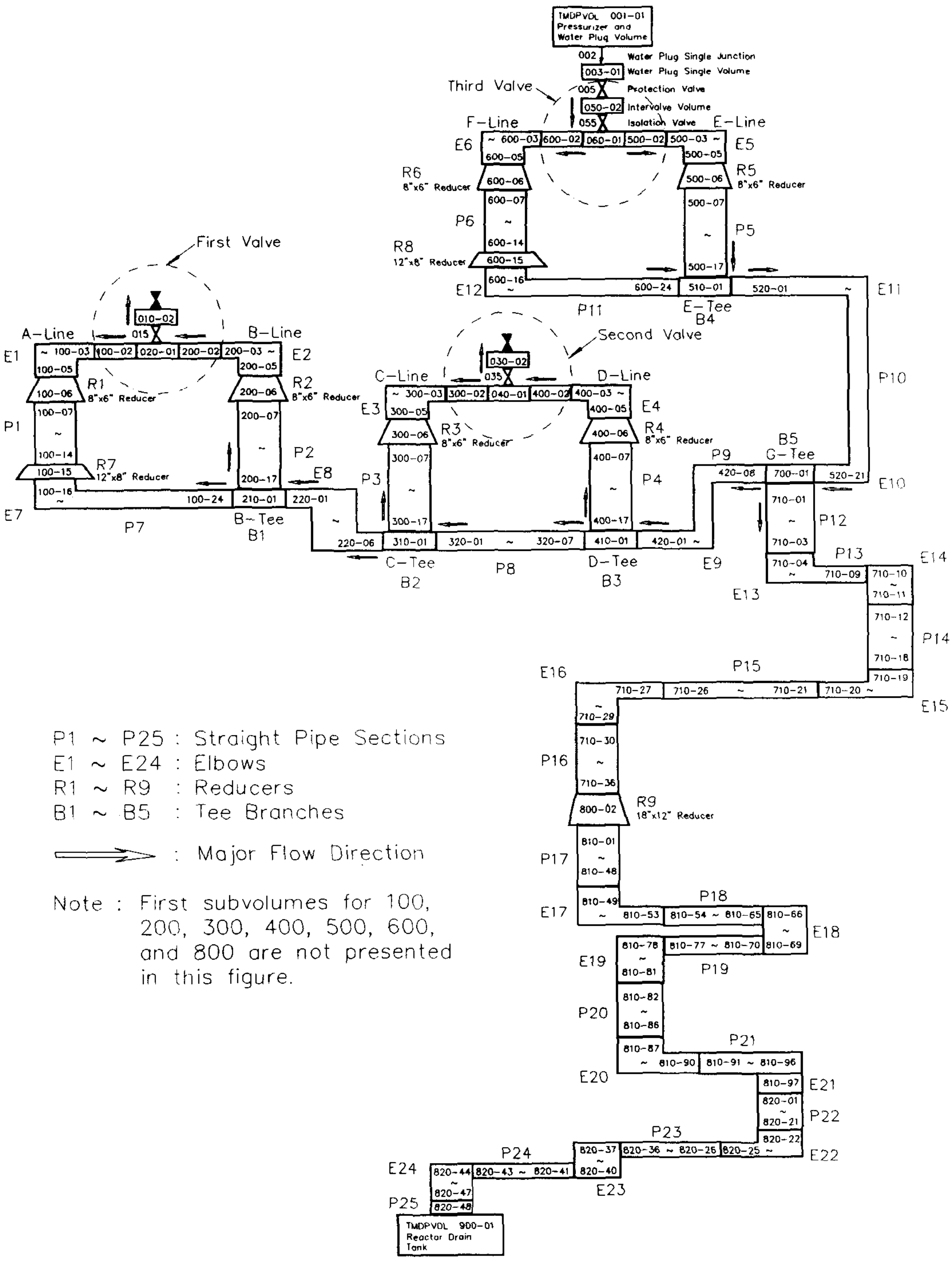


Fig. 1. RELAP5 Nodalization Scheme for the SEBIM POSRV Discharge Piping System

equal to 0.15 m which is short enough to calculate acoustic wave propagation[3]. The $\Delta x/\Delta t$ of 1500 m/s used in this analysis as described above is judged to be fast enough not to attenuate or distort the pressure wave(See the sensitivity analysis results of Cases 6 and 7 in section 4.1). For the passive portions the mesh size is taken to be equal to pipe diameter to reduce number of meshes.

The area of branches is taken to be either sum of upstream flow areas or sum of downstream flow areas depending on the direction of flow[5]. Forward and reverse flow energy loss coefficients for the elbows, tees, and reducers are obtained from Crane Technical Paper[6]

Choking option is declared only at the protection valve to avoid numerical instability. Heat transfer along the pipe is neglected in the analysis of RELAP5/MOD3.

3.2. POSRV Setpoints and Opening Characteristics

Protection valves open linearly to full open area during 1.7 seconds with 0.3 second valve opening time delay. However, the only third valve is assumed to open linearly to full open area during 1 second for conservatism[5].

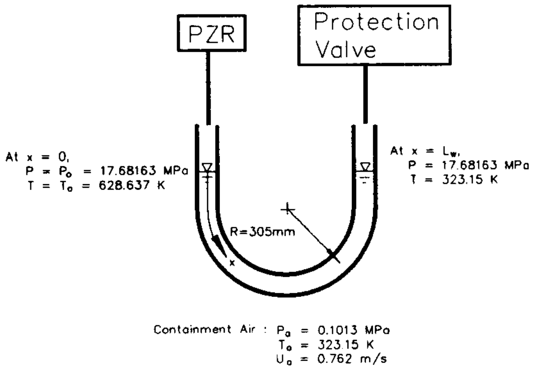
The third protection valve (See Figure 1) is modeled with RELAP5 servo VALVE component which has a normalized linear opening characteristics during 1 second. The opening setpoint is set as 17.681 MPa (176.81 bars) including uncertainties. Since the valve has steam flow capacity of 253 t/hr under 172.3 absolute bars which is maximum flow including uncertainties, the area of protection valve is adjusted to be consistent with that steam flow rate. Discharge coefficients of 0.6 for subcooled water and 0.8 for two-phase and steam are used[5].

Isolation valves are modeled with SNGLJUN component and have the same characteristics as the protection valve except for the initial opening state and choking option.

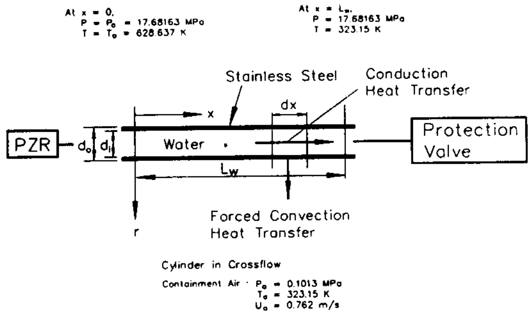
3.3. Loop Seal Water Discharge

A schematic diagram of swan neck containing water and the analytically calculated temperature distribution along the swan neck are shown in Figures 2 and 3, respectively. While protection valves are being opened during overpressure transients, the loop seal water contained in the swan neck is discharged and followed by steam discharge. This phenomena induce hydraulic load in the discharge piping.

If water loop seal is directly modeled in RELAP5/MOD3, the hydraulic load induced by the protection valve opening will be reduced, because the subcooled water in the swan neck would mix with the slightly superheated steam of the pressurizer during the valve opening. Therefore, the loop seal water discharge through the protection valve is



(a) Schematic of Swan Neck Containing Water



(b) Simplified Schematic of Swan Neck Containing Water

Fig. 2. Schematics of Swan Neck Containing Water

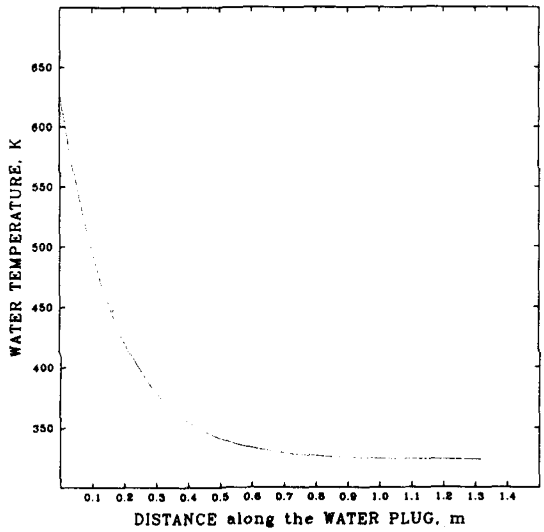


Fig. 3. Water Temperature Distribution along the Water Plug

modeled by imposing time dependent pressure and temperature history boundary condition upstream of the protection valve. The upstream boundary condition is modeled by large time dependent volume of pressurizer and water plug.

The construction of time dependent boundary condition is performed by two step procedures. The first step is the analytical determination of water temperature distribution along the swan neck and the second step is determination of water plug transit time through the protection valve and corresponding pressure and temperature time history for the time dependent volume.

To determine the water temperature distribution along the swan neck, the swan neck is assumed to be a circular stainless pipe filled with water (See Figure 2). The steady state temperature distribution along the pipe is analytically determined by the energy balance of conduction and forced convection heat transfers as can be seen in Figure 3. The temperature distribution is biased to have more subcooled liquid inventory.

As a second step RELAP TMDPVOL input to represent the pressure and temperature time history is obtained by successive approximation. By using the above analytically determined water temperature distribution and pressurizer pressure of 17.681 MPa and by dividing the water plug into six subvolumes, water mass at each subvolume can be calculated as follows:

$m_1 = 7.46\text{kg},\ p_1 = 17.681\ \text{MPa},\ T_1 = 323\text{K}$
$m_2 = 3.84\text{kg},\ p_2 = 17.681\ \text{MPa},\ T_2 = 328\text{K}$
$m_3 = 2.57\text{kg},\ p_3 = 17.681\ \text{MPa},\ T_3 = 348\text{K}$
$m_4 = 1.85\text{kg},\ p_4 = 17.681\ \text{MPa},\ T_4 = 398\text{K}$
$m_5 = 1.00\text{kg},\ p_5 = 17.681\ \text{MPa},\ T_5 = 498\text{K}$
$m_6 = 0.01\text{kg},\ p_6 = 17.681\ \text{MPa},\ T_6 = 627\text{K}$

The first guess of pressure and temperature time history for the valve upstream boundary condition can be obtained based on the water plug transit time through the protection valve which can be estimated by the Darcy equation with proper valve flow area and pressure drop across the valve. By imposing this approximated time history as a boundary condition the water plug discharge through the valve can be calculated by RELAP5/MOD3. After performing a RELAP calculation, the calculated mass flow rate through the protection valve junction is integrated and then compared with the above actual water plug masses determined analytically. If there exist differences in the RELAP calculated masses and the actual masses, the water plug transit time of the time dependent pressure and temperature history is adjusted until two masses become equal.

4. Results

4.1. Sensitivity Study for the RELAP5/MOD3 Options

Since the RELAP5/MOD3 computer code has not been rigorously assessed for this kind of application [4], the effects of various options of the RELAP5/MOD3 on the analysis results were investigated. Table 1 summarizes the cases analyzed

Table 1. Options for Sensitivity Studies

	Non-Eq.	Abrupt	K-Adj.	Small Δt	RDT Size/K-factor
CASE 1	×	×	×	×	$10^9 \times 10^9$/[0, 0]
CASE 2	×	×	○	×	$10^9 \times 10^9$/[0, 0]
CASE 3	×	○	○	×	$10^9 \times 10^9$/[0, 0]
CASE 4	×	○	○	×	$10^2 \times 10^2$/[1, 0.5]
CASE 5	○	○	○	×	$10^9 \times 10^9$/[0, 0]
CASE 6	○	×	○	×	$10^2 \times 10^2$/[1, 0.5]
CASE 7	○	×	○	○	$10^2 \times 10^2$/[1, 0.5]

Note: × = Not Used, ○ = Used, K-factor = [Forward, Reverse]

and options employed in each case. The equilibrium option for the volume enforces thermal equilibrium condition(Non-Eq = x). The selection of non-equilibrium option utilizes the full feature of six equation modeling of the RELAP5/MOD3 (Non-Eq = o). If smooth area change option for the junction is used, the pressure drop along the junction is calculated based on the input K-factor(Abrupt = x). The use of abrupt area change option adds the pressure drop induced by area change to the pressure drop calculated by the input K-factor(Abrupt = o). The distribution of K-factors for the subnodes in the elbow and branch is tested. The even distribution is indicated by K-Adj = o. The distribution with total K-factor assigned on the upstream node is denoted by K-Adj = x. Finally, varied are the dimension of reactor drain tank (RDT) and the K-factor for the junction connecting the discharge piping to the reactor drain tank.

Case 1 is the base case from which the options are varied. Case 1 employed equilibrium option, smooth area change option, and very big reactor drain tank with zero pressure loss in the inlet junction. And the K-factor is not adjusted evenly. To evaluate the acceptability of the analysis results the mass flow rate and pressure distribution are checked at two instants, i. e., at 0.33 second when the protection valve starts to bleed steam and significantly subcooled water exists in the several volumes downstream of the protection valve and at 0.63 second when water plug sweeps the volumes far downstream of the valve but does not reach the reactor drain tank yet. As shown in Table 2-1 just after the steam discharge at 0.33 second the mass flow rate and pressure distribution in the piping E-line and piping F-line are nearly symmetric. This trend is also observed during the steam discharge at 0.63 second. However, Case 1 shows two kinds of anomalous behavior. At first, unrealistically low pressures less than atmospheric pressure are observed in the discharge piping just before the reactor drain tank. Secondly the pressures in the reducer region adjacent to the protection valve are very oscillatory during the significant time period as noted in Table 2-2.

To assess the effect of RELAP5/MOD3 input options on this anomalous behavior, several options were tested subsequently. Case 2 is the same as Case 1 except that K-factor is adjusted. As shown in Tables 2-1 and 2-2 this case resulted in less duration of pressure oscillation, but general trends are same.

Case 3 employs abrupt area change option, which results in additional anomaly indicated by unrealistically low pressure in the elbow region adjac-

Table 2−1. Results of RELAP Sensitivity Analysis

	At 0.33 second		At 0.63 second	
	Symmetry/Size of (p, $\dot{m}$)	$p<p_{atm}$ at elbow	Symmetry of (p, $\dot{m}$)	$p<p_{atm}$ just before RDT
CASE 1	○○, ○○/1.0, 1.0	×	○, ○○	○
CASE 2	○○, ○○/1.3, 1.0	×	○, ○○	○
CASE 3	○, ○○/0.7, 0.9	○	○○, ○○	○
CASE 4	○, ○○/0.7, 0.9	○	○○, ○○	×
CASE 5	○○, ○○/3.8, 3.0	×	○○, ○○	○
CASE 6	○○, ○○/3.0, 3.0	×	○○, ○○	×
CASE 7	○○, ○○/3.0, 2.9	×	○○, ○○	×

Note : ○ = Occurred, ○○ = Occurred Noticeably, × = Not Occurred

Symmetry = Since the outlet pipings just downstream of protection valve denoted by line E and line F are geometrically similar, pressure and mass flow rate are expected to be nearly similar.

Size = Normalized peak values compared to those of Case 1.

Table 2−2. Results of Sensitivity RELAP Analysis

	Occurrence of Pressure Oscillations at Components 050−01 and 500−06	
CASE 1	Hi-Hi	(t = 0.22, 0.33 < t < 0.73)
CASE 2	Hi	(t = 0.22, 0.33 < t < 0.38)
CASE 3	Hi	(t = 0.22, 0.33 < t < 0.60)
CASE 4	Hi	(t = 0.22, 0.33 < t < 0.60)
CASE 5	Lo-Lo	
CASE 6	Lo-Lo	
CASE 7	Lo-Lo	

Note : Hi-Hi = Oscillation with very high frequency
Hi = Oscillation with high frequency
Lo-Lo = Oscillation with high frequency is negligible.
t = time in second

ent to the protection valve as shown in Table 2−1. Other trends are similar to those of Case 1 and Case 2. The comparison of these cases implies that the abrupt area change option may have impact on the anomalous behavior in the elbow region of the piping.

Case 4 is the same as Case 3 except the changes in the reactor drain tank modeling. The reactor drain tank is modeled with finite size of 100 square meter by 100 meter and with realistic K-factor. The trends in the thermal hydraulic behavior are the same as Case 3 except the fact that the anomalous low pressure observed in the downstream piping just before reactor drain tank for Cases 1 through 3 is removed. This implies that realistic modeling of reactor drain tank helps to remove anomaly observed in the discharge piping near reactor drain tank.

Case 5 employs non-equilibrium option and infinitely big reactor drain tank, and abrupt area change option. This case does not show any anomaly in the elbow but shows anomaly in the piping near reactor drain tank. This confirms that reactor drain tank modeling is closely related to the anomalous behavior in the piping near reactor drain tank. The disappearance of anomaly in the elbow implies that the anomaly observed in the elbow is not strongly dependent on the abrupt area change option. The use of non-equilibrium option seems to be more effective. The noticeable results of Case 5 are that the oscillations in the thermal-hydraulic parameters in the reducer(500−06) and intervalve volume (050−01) are significantly reduced. This implies that the assumption of thermal equilibrium between the steam and water results in excessive heating of the subcooled water slug[2] and that the use of nonequilibrium option would simulate the transient more reliably.

Case 6 is a sort of final case run deduced from the analyses of Case 1 through Case 5. For this case employed are the smooth area option, non-equilibrium option, and realistic modeling of reactor drain tank. The results does not show any anomaly and any numerically induced oscillations. Case 7 which is a replica of Case 6 with small time step was run to investigate whether small oscillations observed in the results of Case 6 is numerically induced or physically meaningful. The results of Case 7 are almost the same as those of Case 6. This implies that the time steps employed in Case 6 are appropriate.

Just after the steam discharge at 0.33 second, the peak values of pressure and mass flow rate in the discharge piping are presented in Table 2−1. The peak values of other cases are normalized with those of Case 1. Larger peak values of pressure and mass flow rate are expected to have more hydraulic load on the piping for the hydraulic load analysis.

In summary, it is suggested that the smooth area change option with reasonable K-factor distribution, non-equilibrium option, realistic modeling of reactor drain tank and proper time step be selected for the thermal-hydraulic analysis of the SEBIM POSRV discharge piping system.

4.2. Thermal-hydraulic Behavior of Valve Actuation Transient

By using the RELAP5/MOD3 models and options discussed in the previous sections, the thermal-hydraulic behavior of SEBIM POSRV discharge piping system was analyzed. The transient mixture density, pressure, and mass flow rate are shown in Figures 4 through 7.

The typical transient thermal-hydraulic behavior for Case 6 described in the previous section is dis-

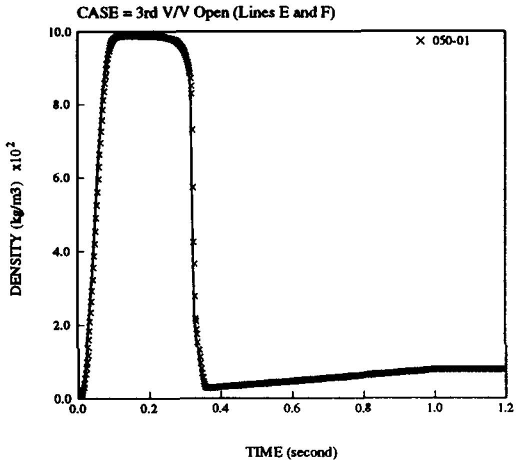


Figure 4 (a) Mixture Density Time History of 050-01

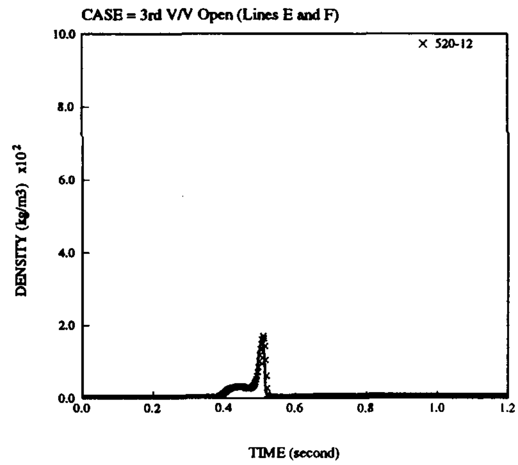


Figure 4 (b) Mixture Density Time History of 520-12

Fig. 4. Mixture Density Time Histories

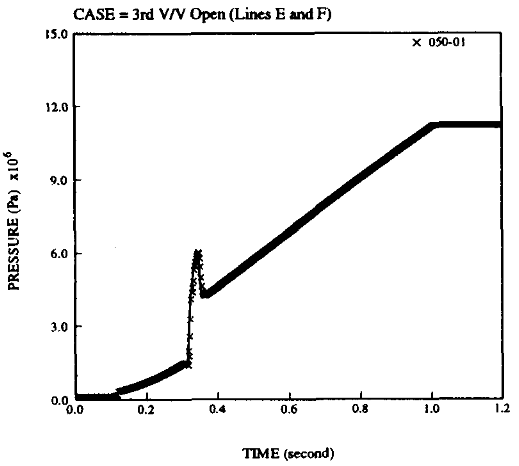


Figure 5(a) Transient Pressure Behavior of 050-01

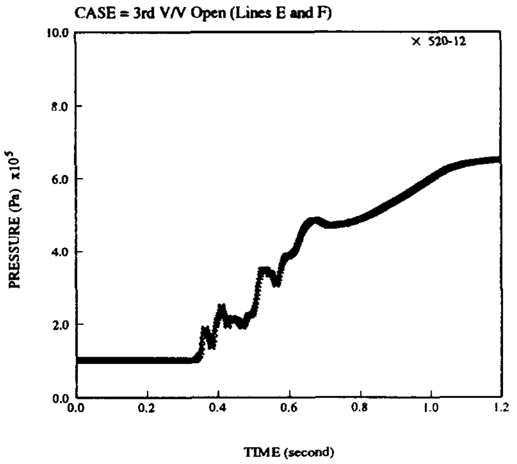


Figure 5(b) Transient Pressure Behavior of 520-12

Fig. 5. Transient Pressure Behavior

cussed here. The transient mixture density and pressure of intervalve volume 050−01 just downstream of protection valve are shown in Figure 4(a) and Figure 5(a), respectively.

As the water discharged through the protection valve fills the volume, the mixture density of the volume increases until mixture density reaches saturated liquid density corresponding to the downstream piping pressure, which occurs at around 0.1 second. Until 0.33 second the subcooled water passes through the volume 050−01. After 0.35 second the volume fills with steam.

The pressure of the volume 050−01 slightly increases until the steam discharge at 0.33 second. The abrupt increase in pressure occurs at 0.33 second when the protection valve starts to bleed steam. This is because steam with high velocity can not sufficiently push the water plug which is slow compared to steam and has larger inertia. Therefore kinetic energy of steam is converted into pressure energy(See undershoot of mass flow rates at junctions 002−00 and 005−00 in Figures 6(a) and 6(b)). When the water column is sufficiently accelerated and the space between the water column and protection valve subsequently increases as time goes on, the pressure in the volume decreases abruptly as can be seen in Figure 5(a) and then the pressure increases linearly until 1 second. When the protection valve becomes fully open after 1 second, the pressure becomes constant.

The mixture density peak of volume 520−12 of Figure 4(b) is less than that of volume 050−01 because the initial loop seal water mixes with the steam and noncondensible gas downstream of the protection valve. Transient pressure of Figure 5(b) starts to increase around 0.35 second with pressure oscillation.

Since the pressure spike abruptly accelerates the water column downstream of protection valve, a rapid change in junction mass flow rate occurs along the discharge piping as can be seen in Figures 6(c) and 6(d).

Figure 7 shows transient mass flow rates at various junctions. As can be seen in the Figures 6 and 7 the peak mass flow rate during the transient increases and becomes maximum and then decreases along the downstream of discharge piping. The transient mass flow rate for junction 825−00 of Figure 7(d) shows that water plug reaches the reactor drain tank at around 0.8 second.

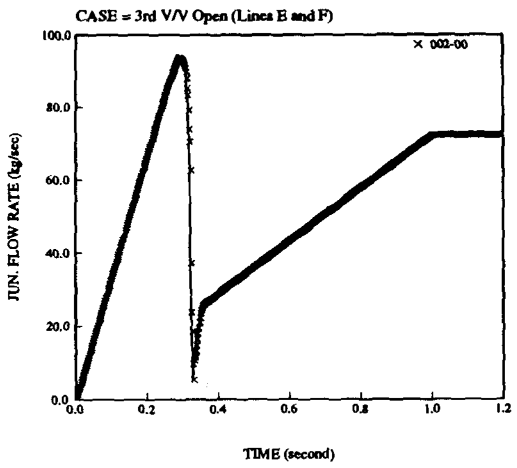


Figure 6(a) Transient Mass Flowrate of Junction 002-00

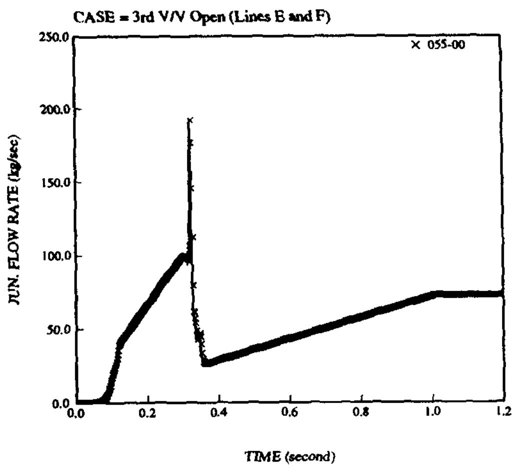


Figure 6(c) Transient Mass Flowrate of Junction 055-00

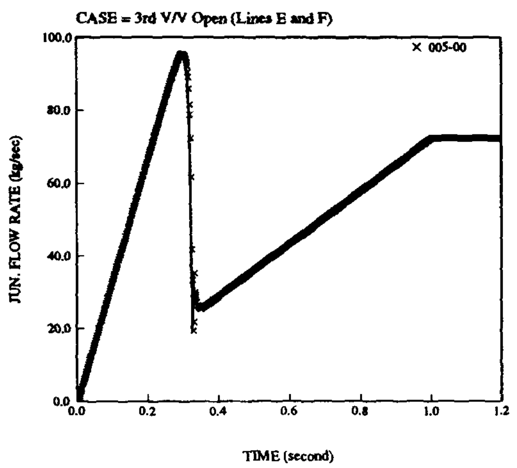


Figure 6(b) Transient Mass Flowrate of Junction 005-00

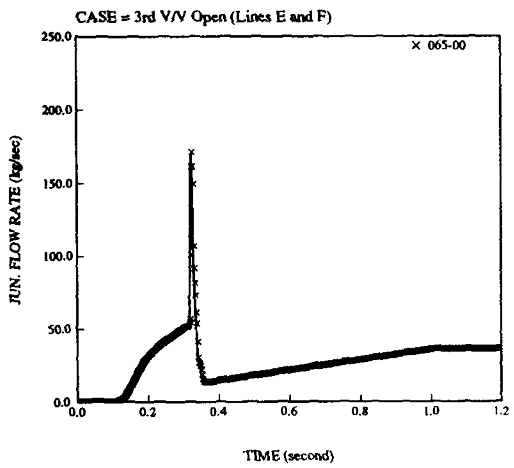


Figure 6(d) Transient Mass Flowrate of Junction 065-00

Fig. 6. Transient Mass Flow Rates

5. Conclusion

The transient mixture density, pressure, and mass flow rate in the SEBIM POSRV discharge piping system during the protection valve opening were simulated using RELAP5/MOD3 computer code. The sensitivity study was performed to select appropriate options of the RELAP5/MOD3 for the hydraulic load analysis.

The analysis results have demonstrated the potential capability of the RELAP5/MOD3 for the hydraulic load calculation of SEBIM POSRV discharge piping system. From the sensitivity study, it is recommended that the smooth area change option with reasonable K-factor distribution, non-equilibrium option, realistic modeling of reactor drain tank and proper time step be selected for the thermal-hydraulic analysis of the SEBIM POSRV discharge

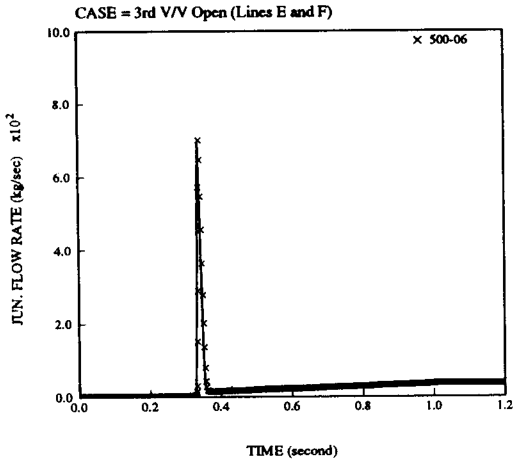


Figure 7(a) Transient Mass Flowrate of Junction 500-06

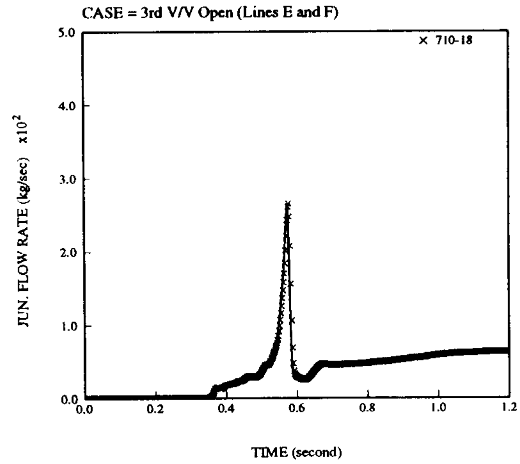


Figure 7(c) Transient Mass Flowrate of Junction 710-18

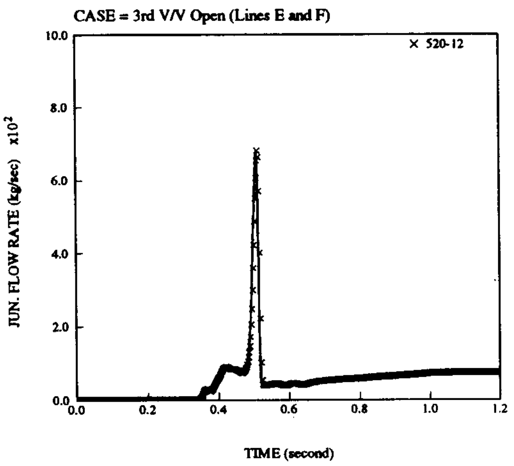


Figure 7(b) Transient Mass Flowrate of Junction 520-12

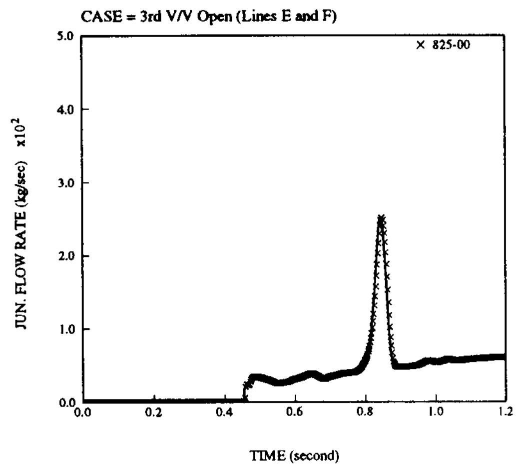


Figure 7(d) Transient Mass Flowrate of Junction 825-00

Fig. 7. Transient Mass Flow Rates

piping system.

Acknowledgment

This work has been carried out as a feasibility study for the adaptation of SEBIM POSRV discharge piping system to YGN 5&6 Nuclear Power Plants. The authors wish to acknowledge the helpful suggestions and comments of Framatome engineers on the present study.

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