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Analysis of Reflux Cooling in the SG U-Tubes Under Loss of RHRS During Midloop Operation with Primary System Partly Open

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Abstract

The present study is to assess the applicability of the best-estimate thermal-hydraulic codes, RELAP5/MOD3.2 and CATHARE2V1.3U, to the analysis of thermal-hydraulic behavior in PWRs during midloop operation following the loss of RHRS. The codes simulate an integral test, BETHSY 6.9d, which was conducted in the large scale test facility of BETHSY in France. The test represents the accident where the loss of RHRS occurs during midloop operation with the pressurizer and upper head vents open and the sight level indicator broken. Besides, the hot legs are half filled with water and the upper parts of the primary cooling system are filled with nitrogen, with a letdown line open and only one SG available. The purposes of this study are to understand the physical phenomena associated with reflux cooling in the SG U-tubes when noncondensable gas is present under low pressure and to assess the applicability of the codes to simulate the loss of RHRS event by comparing the predictions with the test results. The results of the study may contribute to actual applications for plant safety evaluation and description of the emergency operating procedure.

1. Introduction

For a pressurized water reactor (PWR), midloop operations after reactor shutdown are needed for inspection or maintenance of components such as reactor coolant pump (RCP) seal, reactor coolant system (RCS) related valves, and steam generator (SG) U-tubes to reduce refueling outage period. The main characteristics of midloop operations are i) the RCS is in low pressure and low temperature condition, ii) the RCS is partially drained to the hot leg mid-plane, iii) the upper part of the RCS is filled with air or noncondensable gases (mostly nitrogen), iv) some safety systems may be unavailable due to maintenance, and v) various RCS enclosures may not be tightly fastened. During midloop operation, the residual heat removal system (RHRS) is operated to remove the core decay heat with the reactor water level reduced to the height of the hot leg centerline. If the RHRS fails and alternate heat removal methods are unavailable during midloop operation, the coolant would be heated up due to decay heat from core. The heatup of the reactor coolant may sequentially lead to core coolant boiling, core uncovery, fuel rod heatup, and eventually core damage. The loss of RHRS events during midloop operations have occurred at several PWRs. For example, Kori Unit 2 in June 1984, Waterfold Unit 3 in July 1986, Diablo Canyon Unit 2 in April 1987, and Vogtle Unit 1 in March 1990 experienced the loss of RHRS events. Although these accidents did not lead to the core damage, there exists the potential for severe accident under shutdown condition. Following these accidents, the consequences of loss of RHRS during midloop operation in PWRs have been of increasing concern for years even though core damage had not occurred by the recovery of RHRS. Probabilistic safety assessment (PSA) results also showed that the core damage frequency (CDF) due to the loss of RHRS during midloop operation is comparable to that of normal operation [1].

The transients following the loss of RHRS depend on various factors, including reactor configuration, reactor core power level, the availability of vent paths, the existence of noncondensable gases, the available number of SGs, and SG secondary side condition, etc. The various possible operation modes and cooling methods to mitigate the accident in the event of the loss of RHRS are summarized in Chu et al. [2]. To investigate physical phenomena in the event of the loss of RHRS during midloop operation, a series of experiments was conducted at the ROSA-IV/LSTF [3] and the BETHSY test facility [4]. Hassan and Banerjee [5] simulated the cold leg break accident test during midloop operation conducted at ROSA-IV/LSTF experiment using RELAP5/MOD3. The capability of the code to simulate the loss of RHRS event was evaluated by comparing the predictions and test results. There was a good agreement between the measured and the calculated data until loop seal clearing, however it was found that the steam condensation was underpredicted in the calculation. The Arizona Public Service Company analyzed the transient following the loss of RHRS during midloop operation at the Palo Verde plant using RETRAN2/MOD4 [6]. Simulations of events following a loss of RHRS were used to determine the time for RCS coolant to reach boiling and to evaluate the potential for a rapid core uncovery due to the pressurization of the reactor vessel head with corresponding liquid ejection from a cold leg breach. Boiling occurred about 12 min. after the loss of RHRS and the core was uncovered in about 88 min. for the large cold leg breach case. The consequences of a loss of RHRS event for the H. B. Robinson plant which is a three-loop Westinghouse PWR were assessed using RELAP5/MOD3 [7]. As a result, if the steam generators were used as an alternate means of decay heat removal, the RCS pressure and temperature were determined by the efficiency of the reflux condensation process. Thermal-hydraulic analysis was performed in the event of the loss of RHRS during midloop operation for a typical four-loop PWR using RELAP5/MOD3 [8]. The presence of air in the RCS was modeled, and its effect on the transients was calculated. The results of simulation showed that reflux condensation in the SG U-tubes contributed to the decay heat removal and delayed the rapid uncovery of the core. However, these researches concentrated on the application of the existing codes to the simulation of real plants without confidence of the applicability of the codes.

In this study, RELAP5/MOD3.2 and

CATHARE2 which are best-estimate thermal-hydraulic codes simulate an integral test, BETHSY 6.9d, which was conducted in the large scale test facility of BETHSY in CEN-Grenoble, CEA, France. The test represents the loss of RHRS accident during midloop operation with the pressurizer and upper head vents open and the sight level indicator broken. The hot legs are half filled with water and the upper parts of the primary cooling system (PCS) are filled with nitrogen, with a letdown line open and one SG available. Therefore, the applicability of RELAP5/MOD3.2 and CATHARE2 to the analysis of thermal-hydraulic behavior in PWRs during midloop operation following the loss of RHRS is assessed. The objectives of the present study are i) to understand the physical phenomena associated with reflux cooling in the SG U-tubes when noncondensable gas is present under low pressure and ii) to assess the applicability of the codes to simulate the loss of RHRS accident by comparing the predictions with the test results. The results of the study may contribute to actual applications for plant safety evaluation and provide base data for description of the emergency operating procedure.

2. Description of Experiment

The BETHSY test facility is a 1/100 scale, 3-loop integral facility at Grenoble, France, and capable of conducting tests relevant to a wide range of LOCA and non-LOCA transients. A schematic diagram of the BETHSY test facility and a detailed description are available in BETHSY data base [9]. There are four tests (6.9 series) for midloop operation in the BETHSY according to the configuration of the test. Test 6.9a, b, and c represent the accident where the loss of RHRS occurs during midloop operation with the pressurizer, pressurizer and SG inlet plenum, pressurizer and SG outlet plenum manways open, respectively. These tests concentrate on investigation of the physical phenomena related to boiling away and liquid entrainment through manways. The overall purpose of BETHSY test 6.9d is to study the accident transient following the loss of RHRS during midloop operation with small vents open and noncondensable gas present in the primary system.

In the BETHSY test 6.9d [10], the primary cooling system was initially in a depressurized cold shutdown state with the hot legs half filled (nitrogen is filled above the water level) and temperature of 60 ℃ with only one SG available. Residual heat was being removed by the RHRS and the letdown (dia. = 4.29 mm) via the RHRS was operating. The upper head and pressurizer vents (dia. = 1.81 mm) were open. The loss of RHRS was assumed to occur 48 hours after reactor shutdown, and the core power at this time corresponds to 0.5% of nominal power (143 kW). The operator intervened 30 minutes after the start of the transient. The letdown line was isolated, the turbine bypass system arranged to the available steam generator (SG1) was fully opened, and the SG was fed if the level was too low. Even though the sight level indicator (dia. = 1.2 mm) could be broken by pressurization as the chemical and volume control system (CVCS) letdown remained open, it was assumed in this test that the sight level indicator was broken immediately after the loss of RHRS and the feedwater was supplied to the available SG as late as possible (level 0.6 m).

After the initial conditions were established, the test could be divided into two relatively distinct phases. The first phase extended from opening of both the letdown and sight level indicator to closing of the letdown at 1800 s, while the core power was raised to 143 kW in approximately 14 s. The first phase lasted for the first 1800 s and

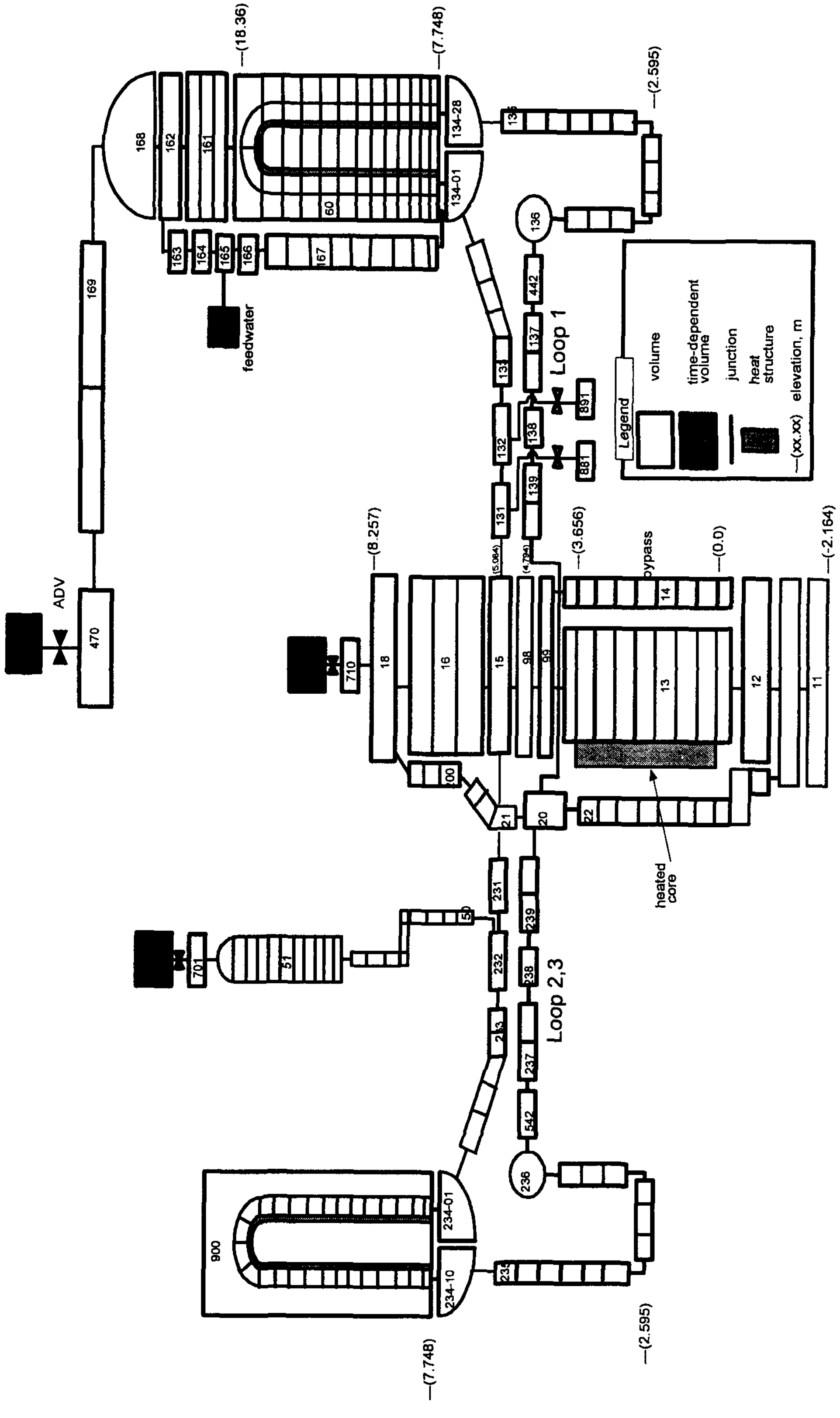

Fig. 1 BETHSY Test 6.9d Nodalization for RELAP5/MOD3.2

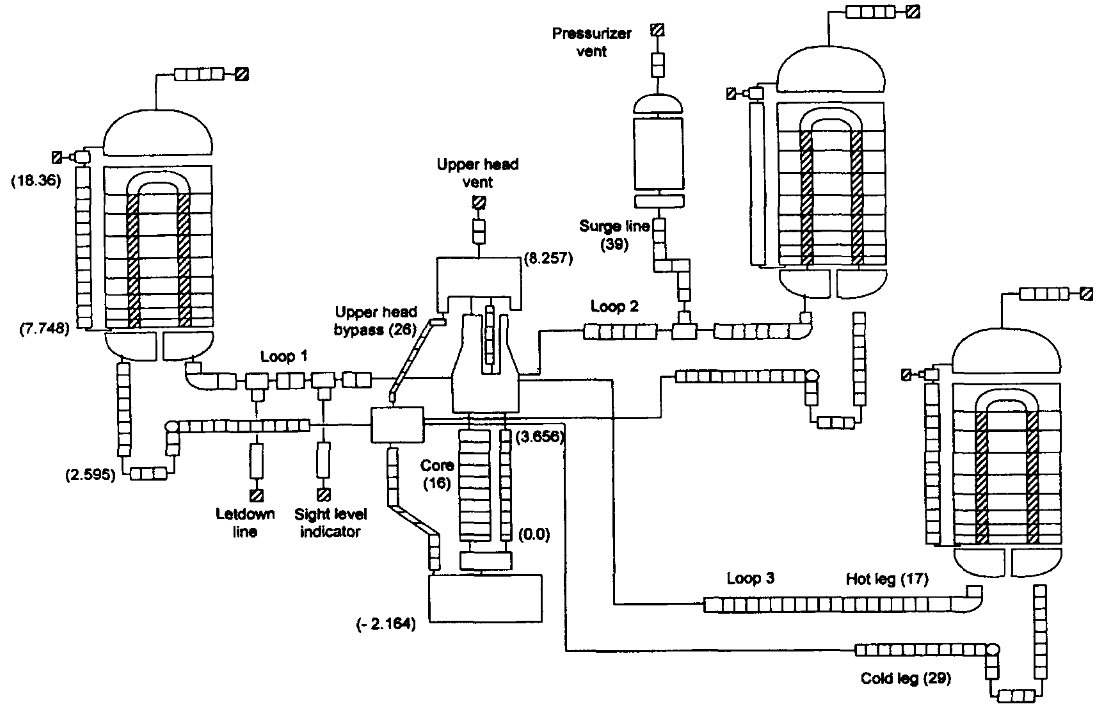

Fig. 2. BETHSY Test 6.9d Nodalization for CATHARE2

response of the system was dominated by balancing of the system between the power increase and openings of both the letdown and sight line break valves. The second phase was characterized by 70% opening of the SG1 atmospheric dump valve (ADV). When the SG1 secondary system level dropped below 0.6 m (t = 31668 s), the auxiliary feedwater of 40 ℃ was supplied. Boiling off of the active SG was dominant phenomenon during the second phase, and the test was terminated at 32452 s.

The aim of the test was to study the physical phenomena occurring at very low system pressure and power with the presence of noncondensable gas. The detailed objectives of the test are to identify i) restarting of reflux condensation between the primary and secondary systems in the available SG with the presence of noncondensable gas, ii) distribution of the noncondensable gas in the primary cooling system, and iii) level of pressurization reached in the primary system before the available SG is completely emptied.

3. Analysis Method

3.1. Geometrical Modeling

BETHSY test 6.9d is simulated by RELAP5/MOD3.2.1.2 [11] and CATHARE2V1.3U. Fig. 1 and 2 show the nodalization used in modeling of the test facility for RELAP5 and CATHARE2, respectively. As shown in the figures, the test facility consists of three primary coolant loops. For the RELAP5, the reactor core in the reactor vessel is modeled using 9 volumes. Each loop consists of a hot leg, a SG which has U-tubes modeled using 26 volumes, a suction leg, a reactor coolant pump (RCP), and a cold leg. A pressurizer and a surge line modeled using 11 and 10 volumes, respectively, are connected to the loop 2. The vents at the top of the pressurizer and the upper head (dia. = 1.81 mm) are modeled to be kept open to atmosphere all the time. A small break (dia. = 1.2 mm) representing the broken sight level indicator is connected to the loop 1 and is opened at the beginning of the transient. The CVCS letdown (dia. = 4.29 mm) is also connected to the loop 1 and is opened at the transient initiation. The letdown line, however, is closed 30 minutes after the transient to simulate operator intervention. In the secondary system, the SG1 which is connected to the loop 1 is available, while steam generators in loop 2 and 3 are full of air and isolated at a pressure of 0.1 MPa. The secondary side of the SG1 consists of cylindrical shell, downcomer, separator, and steam dome. The ADV is connected to the steam line, and is opened 30 minutes after the transient initiation. Both the heated reactor core and SG U-tubes modeled by means of heat structures with or without heat sources, respectively. The RELAP5 model has 264 volumes, 268 junctions, and 180 heat structures.

The input model of CATHARE2 [12] is basically the same as that of RELAP5 but has 375 and 136 nodes for the primary and secondary sides, respectively. Generally, vertical parts which are related with liquid hold-up and liquid entrainment (for example, surge line) are nodalized with fine meshes. The calculation of the initial conditions is carried out by use of SINK and SOURCE operators at lower and upper plenum to adjust the vessel mixture level and the primary pressure.

3.2. Condensation Model in the Codes

The default option for wall condensation in both RELAP5 and CATHARE2 is Shah correlation [13]. Following is the Shah correlation for predicting heat transfer coefficients on film condensation with turbulent flow.

$$h = h_\ell[1+3.8\{x/(1-x)\}^{0.76}(P_{cr}/P)^{0.36}](1-x)^{0.8} \tag{1}$$

where

$$h_\ell = 0.023\, Re_\ell^{0.8}\, \mathrm{Pr}^{0.4}\, K_\ell/D$$

and

h = condensation heat transfer coefficient

h_ℓ = Dittus-Boelter coefficient assuming all fluid is liquid

x = vapor quality

P_{cr} = critical pressure

P = actual pressure

The model for the influence of noncondensables on condensation for the RELAP5/MOD3.2 is based on the Colburn and Hougen diffusion method. In this method, the temperature at the interface between the steam and water film in the presence of noncondensables is solved using an iterative process. When noncondensables accumulate at the liquid-vapor interface, it reduces the interface saturation temperature (T_{vi}) below the bulk saturation temperature (T). The heat flux through the liquid-vapor interface is the sum of heat fluxes due to the latent and sensible heat transfers through the interface, but the model is developed under the assumption that the sensible is negligible because it is much lower than the latent. This heat transfer should equal to the heat transfer through the condensate film.

The heat flux by condensation of vapor mass flux flowing toward the liquid-vapor interface is

$$q_v'' = h_m h_{fgb} \rho_{vb} \ln[\{1-(P_{vi}/P)\}/\{1-(P_{vb}/P)\}] \tag{2}$$

where

h_{fgb} = $h_{fgsat}(P_{vb})$ enthalpy difference between steam

Table 1. BETHSY Test 6.9d Initial Conditions

Parameters	Experiment	RELAP5	CATHARE2
Upper plenum pressure (MPa)	0.10±0.008	0.10	0.10
Total primary mass (kg)	1135±30	1110	1106
Hot leg void fraction	0.5	0.49	0.6
Temperatures (℃)			
Core inlet/outlet	63.6±2 / 63.6±2	62.2 / 65.2	65.0 / 63.0
Hot leg	62.8±2	63.7	62.7
Cold leg	52.4±2	53.8	52.2
Nitrogen mass fraction			
Upper plenum	0.88	0.83	0.85
Pressurizer	0.85	0.85	0.85
Hot leg	0.89	0.83	0.84
SG inlet plenum	0.84	0.84	0.80
SG 1 secondary side			
Pressure (MPa)	0.122±0.004	0.122	0.122
Average temperature (℃)	65.0±2	65.6	65.0
Nitrogen mass fraction	0.90±0.05	0.92	0.93
Total mass (kg)	1134±25	1134	1137

and liquid saturation enthalpy in the bulk

P_{vb} = steam partial pressure in the bulk
P = total pressure
P_{vi} = partial pressure of steam at liquid-gas-vapor interface
h_m = mass transfer coefficient
ρ_{vb} = saturation vapor density at Pvb

and

$$Sh = 0.023\,(Re_v^{0.83})\,(Sc^{0.44})$$

where

Sh = Sherwood number, $(h_m D/D_{vn})$
Re_v = gas Reynolds number $(\rho v D/\mu)$
Sc = Schmidt number $(\mu_{vb}/\rho_{vb} D_{vn})$
D = hydraulic diameter
D_{vn} = vapor mass diffusivity
μ_{vb} = bulk vapor viscosity

and

$$D_{vn} = 0.0101325\ \frac{(1/M_v+1/M_n)^{0.5}T^{1.75}}{P[(\epsilon_v)^{1/3} + (\epsilon_n)^{1/3}]^2}$$

where

M_v = molecular weight of steam
M_n = molecular weight of noncondensable
T = bulk gas temperature
ϵ_v = atomic diffusion volume of steam
ϵ_n = atomic diffusion volume of non-condensable

The heat flux from the liquid film to the wall is calculated by

$$q_l'' = h_c\,(T_{vi} - T_w) \tag{3}$$

where

$T_{vi} = T_{sat}(P_{vi})$ saturation temperature corresponding to the interface vapor pressure

The energy balance equation can be checked by

$$q_l'' = q_v'' \text{ or } h_c(T_{vi} - T_w) = h_m h_{fgb} \rho_{vb} \ln[\{1-(P_{vi}/P)\}/\{1-(P_{vb}/P)\}] \quad (4)$$

The initial guess for the interface pressure is the saturation pressure based on the wall temperature. Next, the interface temperature is calculated and then it is compared with the assumed value. If different, the above equation is solved iteratively.

3.3. Steady and Transient Calculations

To simulate the loss of RHRS event accurately, the conditions just before the accident during midloop operation should be determined and provided as the initial conditions for the transient calculations. The PCS is under midloop operation with the initial pressure of 0.1 MPa. In BETHSY test, the hot legs are half full of water but the cold legs, being at a lower elevation, are completely full. All volumes above the water level are filled with nitrogen. The secondary side of the SG1 is at the water level of normal operation with pressure and temperature of 0.122 MPa and 65 ℃, respectively. On the other hand, the SG2 and SG3 are filled with air and isolated throughout the test. Both main and auxiliary feedwater is not supplied to the SG1 at beginning, but the auxiliary feedwater is supplied (temperature = 40 ℃) when the SG1 secondary system level drops below 0.6 m. The core power is 0 kW during steady state. RELAP5/MOD3.2.1.2 calculation was performed on a DEC Alpha workstation. It was necessary to run for 5000 seconds of simulation time to obtain a steady state, and about 5 hours of CPU time were required with maximum time step of 0.1 second. In CATHARE2, about 3 hours of CPU time were taken for 480 seconds steady state

Table 2. Time Sequence for the Major Events

Events	Experiment (s)	RELAP5 (s)	CATHARE2 (s)
Loss of RHRS occurs	0	0	0
Letdown via RHRS opening	0	0	0
Sight level indicator opening	0	0	0
Core power build-up	0	0	0
Core power stabilized at 143kW	14	14	14
Upper plenum saturated	519	500	500
Upper head vent steaming	1120	1200	3500
Reflux cooling starts	1207	1300	1200
Pressurizer vent steaming	1792	2800	5000
Letdown closed	1800	1800	1800
SG1 ADV opening	1800	1800	1800
SG1 riser fluid saturated	4454	9500	4500
Cold leg empty	25000	9000	31000
Hot leg empty	28000	28000	33500
Auxiliary Feedwater supply starts	31668	32800	34300
End of test/calculation	32452	35000	35000

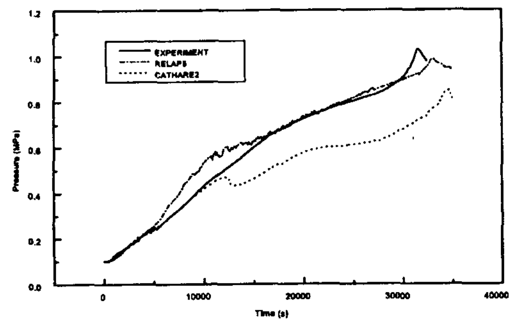

Fig. 3. Upper Plenum Pressure

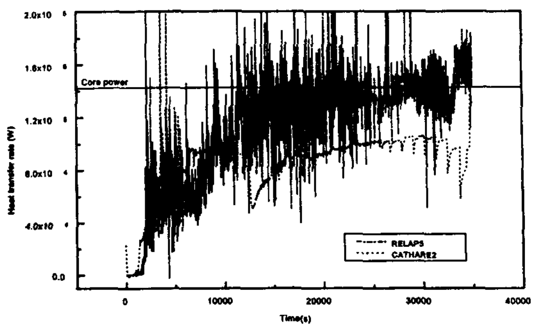

Fig. 4. Total Heat Transfer Rates from Coolant to SG1 U-tubes

calculation on a HP C180 workstation. The steady state conditions obtained are compared with measurements in Table 1. As shown in the table, the calculated steady state conditions are in good agreement with the experimental observations within measurement errors.

The steady state conditions are used as the initial conditions for the transient calculations. The transient is started by opening the break valves for the letdown line and sight level indicator to atmosphere and increasing the core power to 143 kW representing 0.5% of nominal reactor power, simultaneously. The primary and secondary heat losses are balanced by the trace heating. The transient is assumed to occur at 0 s when the RHRS flow is lost. The transient was simulated for 35000 seconds (about 9 hours and 43 minutes) after the loss of RHRS (the test was stopped at 32452 s) using RELAP5. The maximum time step used in the calculations was 0.1 second, and about 52 hours of CPU time was taken on a DEC Alpha workstation. The mass error accumulated at the end of transient was about 8% of the initial mass in the primary cooling system. In CATHARE2 calculation, about 70 hours of CPU time was required for 35000 seconds of the transient simulation on a HP C180 workstation.

4. Results and Discussion

The chronology of the major events predicted by both RELAP5 and CATHARE2 are compared with experimental data in Table 2. The calculated transient results and experimental data are compared in figures. Fig. 3 shows the pressure transients in the reactor upper plenum. In experiment, the measured pressures show nearly steady values for the first 500 s since the core liquid is heating up to saturation during this period. After this period the pressure begins to rise because the vents and breaks are too small to allow all the generated vapor to escape. The upper plenum pressure increases rapidly and then slows down at about 1200 s in experiment because heat transfer through the SG U-tubes occurs by reflux condensation. The pressurization is noticed at about 30000 s because reflux condensation is degraded. The pressure goes down again at about 31700 s due to initiation of the auxiliary feedwater supply when the water level of the SG1 secondary system drops below 0.6 m. Fig. 4 shows total heat transfer rates from coolant to the SG1 U-tubes. As shown in the figure, heat transfer by SG1 (SG2 and SG3 are unavailable) is insufficient to remove the core decay heat. Consequently, the upper plenum

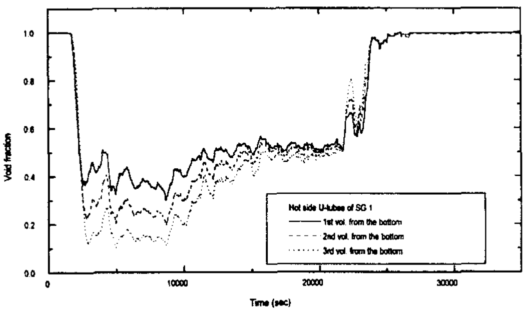

Fig. 5. Void Fraction Distribution in SG1 U-tubes Predicted by RELAP5

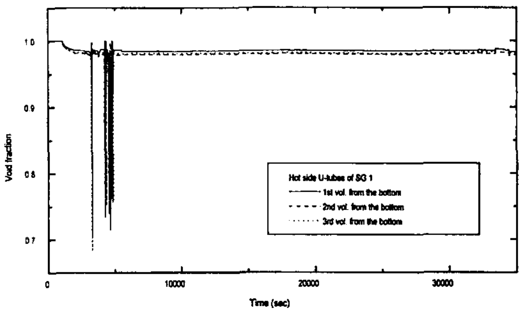

Fig. 6. Void Fraction Distribution in SG1 U-tubes Predicted by CATHARE2

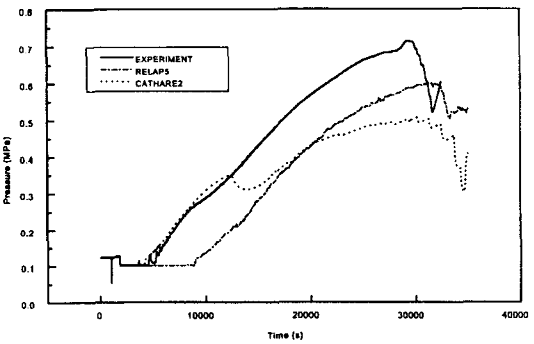

Fig. 7. SG1 Secondary Side Pressure

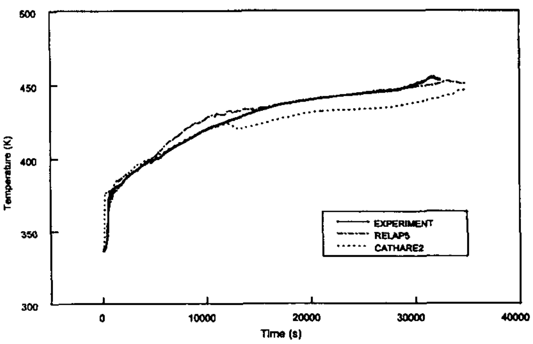

Fig. 8. Upper Plenum Liquid Coolant Temperature

pressure builds up continuously during the transient. As can be verified in Fig. 4, heat transfer through the SG U-tubes occurs by reflux condensation at about 1300 s in RELAP5 and 1200 s in CATHARE2. At this time, the primary pressure has build up sufficiently to push the nitrogen toward the SG U-tubes. Reflux condensation in the SG U-tube region begins when steam is exposed to the surface of the U-tubes. Reflux condensation is observed only in lower volumes of inlet side of the SG U-tubes, which are so called "active region", while it does not occur in other volumes where accumulated nitrogen separates steam from the inner surfaces.

In RELAP5 calculation, the predicted primary pressure is generally in good agreement with the experimental data as shown in Fig. 3. It should be noted that the predicted results are obtained by using 10% of the original interphase drag coefficient in RELAP5. When the original coefficient is used, the primary pressure is too high compared with the measurement due to too low heat transfer through the SG U-tubes. The void fraction distribution in the SG U-tubes is unrealistic because reflux condensate in the upper parts of the U-tubes does not fall downwards due to the overpredicted interphase drag, resulting in much low heat transfer. Reduction of the RELAP5 interphase drag did improve the problem considerably, however, large amount of condensed liquid is still held up in the top of the vapor region until 10000 s (Fig. 5). The comparison study using CATHARE2 is also performed to understand whether this unrealistic void distribution comes from a unique problem in RELAP5 or not. As shown in Fig. 6, the unrealistic void distribution calculated by RELAP5 does not appear in CATHARE2 calculation. The predicted primary pressurization by RELAP5 is higher than that of the measurement over the period from 5000 s to 15000 s because, as can be seen in Fig. 4, the heat transfer through the SG U-tubes during this period is much lower than the core decay heat and the predicted reflux condensation is lower than the experiment. The pressure decrease due to the auxiliary feedwater supply is delayed by about 1500 s, since the level of the SG1 secondary system drops more slowly in the calculation (which will be shown later in Fig. 16). The peak primary pressure in the experiment is about 1.02 MPa, while it is about 1.0 MPa in the calculation .

The upper plenum pressure in CATHARE2 calculation decreases rapidly in 12000 s. During this period, colder water in the downcomer enters to the core, leading to reduction of vapor generation rate in the core. At the same time, the cold leg begins empty so that more condensation area could be provided in the cold leg and downcomer. Consequently, upper head bypass steam flow from the dome to the downcomer increases steam condensation in both the downcomer and cold leg. The condensation induces more mass flow into the core due to elevated hydrostatic head in the downcomer. As water temperature in the cold leg and downcomer approaches to the saturation gradually, the upper head bypass and the core entrainment flow reduces and therefore the upper plenum pressurizes again. In the experiment, the cold leg begins empty early in the transient and the upper head bypass flow establishes slowly. There is no rapid pressurization in the experiment because temperatures in the downcomer, cold leg, and core increase slowly and there is upper head bypass flow throughout the experiment. The main reason for the discrepancy between the calculation and the experiment is that the CATHARE2 predicts the cold leg void fraction and upper head bypass flow poorly. The calculated peak primary pressure is 0.84 MPa which is 0.18 MPa lower than the experimental result.

Fig. 7 shows the pressure in the SG1 secondary side. The SG1 secondary side pressure which is maintained at 0.122 MPa initially, drops to 0.1 MPa when the ADV is opened at 1800 s, and remains at this value until the liquid in the riser reaches saturation at about 4500 s. The pressure starts to increase at about 4500 s when liquid reaches saturation by heat transfer from the

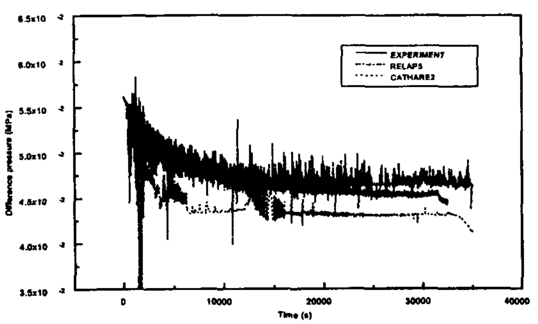

Fig. 9. Differential Pressure in the Reactor Core

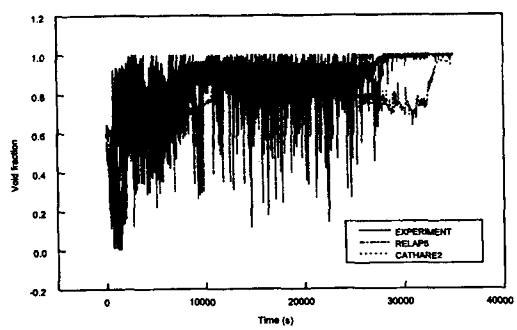

Fig. 10. Hot leg 1 Void Fraction

primary coolant through SG U-tubes. Although the ADV would be open, this is not sufficient to stop the pressurization of the SG1 secondary to about 0.7 MPa. The deterioration of reflux condensation decreases the pressure at about 30000 s. However, the pressure rises again at about 31700 s as the primary heat transfer is reestablished when the auxiliary feedwater is supplied. In RELAP5 calculation, increase of the SG1 secondary pressure is delayed by about 4000 s and the pressure is lower than the measurement by about 0.15 MPa throughout the transient mainly due to lower estimation of reflux condensation. In CATHARE2 calculation, the SG1 secondary pressure starts to increase at 4500 s and then decreases at about 12000 s, since the upper head bypass flow increases rapidly in the primary side. After the decrease of the pressure for a short period, it continues to increase until 30000 s. Thereafter it decreases again due to reduction of reflux cooling. The calculated peak pressure in the SG1 secondary side is 0.5 MPa.

The liquid coolant temperature in the reactor upper plenum is shown in Fig. 8. The temperature increases rapidly during the first 500 s because of the core liquid heat up. Thereafter the coolant saturation temperature increases gradually and behaves in the similar trend as the reactor upper plenum pressure. The RELAP5 prediction of the liquid coolant temperature in the upper plenum is generally in good agreement with the experimental data. In contrast, CATHARE2 gives lower temperature since pressure in the upper plenum is underpredicted. Fig. 9 shows the differential pressure in the reactor core. As shown in the figure, abnormal spikes of the differential pressure are observed many times in the RELAP5 calculation. These spikes apparently come from the numerical problems caused by reduction of the interphase drag because such abrupt differential pressure increases are not expected physically. RELAP5 predicts the differential pressure well, while CATHARE2 underpredicts it since large liquid entrainment from the core to the hot leg is estimated initially.

Fig. 10 shows void fraction in the hot leg in loop 1. Void fraction in the hot leg shows steady value for the first 500 s due to heat up of the core liquid. Since then the void fraction increases as vapor generated in the core moves to the hot leg. In RELAP5 calculation, the predicted time-averaged void fraction in the hot leg is in good agreement with the measurement. There also exist large oscillations in the void fraction throughout the transient due to numerical problems. In CATHARE2 calculation, void fraction of the hot leg 1 is lower than the measurement due to large amount of liquid entrainment from the core to the hot leg at about 500 s. Thereafter, the void fraction is slightly lower than the measurement throughout the transient. The time of complete hot leg empty in CATHARE2 is delayed by about 6000 s compared with the experiment.

The mass flowrates through the pressurizer and upper head vents are shown in Fig. 11 and 12, respectively. In the experiment, no direct measurements are available for the mass flowrates through these vents but they may be deduced from pressure drop across the vents. In the calculation, RELAP5 always overpredicts discharge flows through the vents regardless of various form loss coefficients. For this reason, the calculated values shown in Figs. 11 and 12 are obtained by opening 70% of the vent area in order to match the calculated total discharge flow with the measurement. There is fairly good agreement between predicted and measured discharge flows when the vent area is reduced by 30% in the calculation. The total predicted mass discharged through the pressurizer and upper head vents are 142 kg compared with 140±20 kg in the

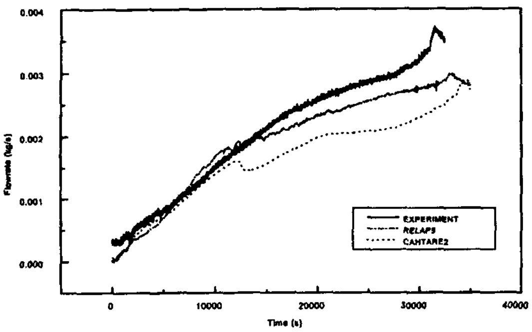

Fig. 11. Mass Flowrate Through Pressurizer Vent

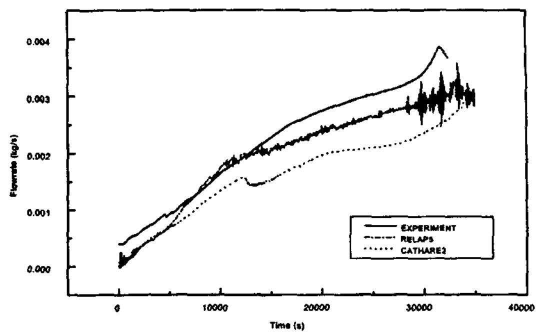

Fig. 12. Mass Flowrate Through Upper Head Vent

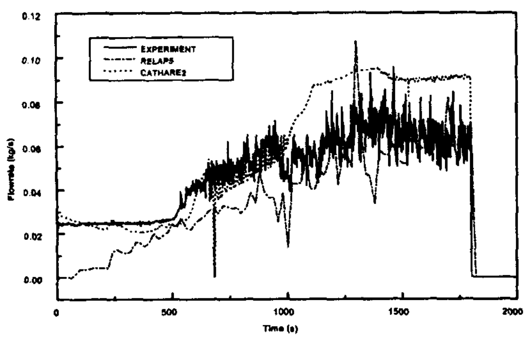

Fig. 13. Mass Flowrate Through Letdown Line

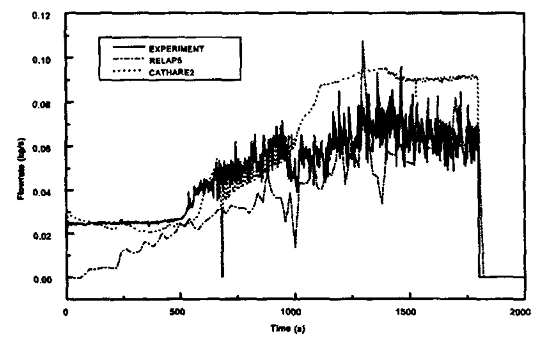

Fig. 14. Mass Flowrate Through Sight Level Indicator

experiment. The flowrate through the pressurizer vent predicted by the CATHARE2 is in agreement with the measurement until 12000 s, but after then it is lower than the measurement depending on the primary pressure behavior. Fig. 13 and 14 show mass flowrates through the letdown line and broken sight level indicator, respectively. For the letdown line the predicted and measured mass flowrates are fairly in good agreement until closing of the letdown at 1800 s (first phase of the experiment). For the broken sight level indicator there exist large oscillations throughout the transient in the predicted mass flowrate by the RELAP5 due to the numerical problems. As mentioned before, the RELAP5 also overpredicted discharge flow through the broken sight level indicator. The calculated value shown in Fig. 14 is obtained by opening 20% of the flow area to match the calculated total discharge flow with measurements. The overprediction of the discharge flow in the RELAP5 is considered to be caused by nonequilibrium between phases which may not be adequately modeled in the discharge flow calculation [14]. The main reason for matching the calculated discharge flow by reducing vent area is to see whether the other models in RELAP5 work well in predicting the phenomena or not.

The calculated and measured fluid mass inventories in the primary coolant system are shown in Fig. 15. There exist large oscillations in the predicted mass inventory by RELAP5 since it is deduced from density and void fraction which

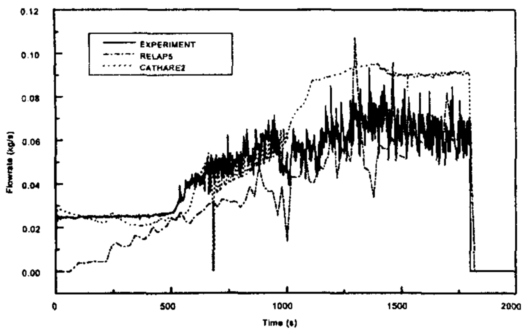

Fig. 15. Primary Coolant System Mass Inventory

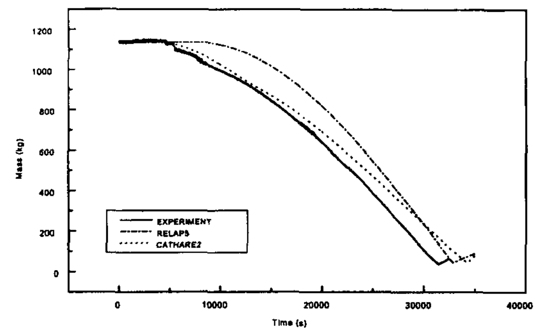

Fig. 16. SG1 Secondary System Mass Inventory

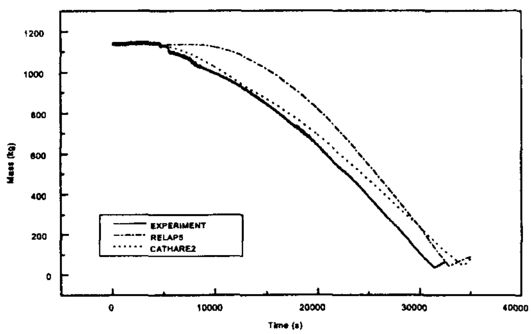

Fig. 17. Noncondensable Mass Fraction in the Upper Head and Pressurizer

oscillate due to the numerical problems. The fluid mass inventory reduces rapidly for the first 1800 s, after then it decreases gradually as the letdown line is closed. The calculated and measured fluid mass inventories are generally in agreement. Fig. 16 shows fluid mass inventory in the SG1 secondary system. The SG1 liquid level falls down slowly as the water boils away and the steam is dumped to the atmosphere through the ADV. As the level approaches the set point of the actuation of the auxiliary feedwater at around 30000 s, there is considerable increase in the primary pressurization (see Fig. 3) resulting from the degradation of the heat transfer through the SG U-tubes. The primary pressure decreases when the auxiliary feed actuates at about 31700 s. The time for auxiliary feedwater supply is delayed by 1100 s and 2600 s in the RELAP5 and CATHARE2 calculations, respectively.

Fig. 17 shows noncondensable gas (nitrogen) mass fraction in the upper head and pressurizer. As shown in the figure, the amount of nitrogen in the upper head and pressurizer falls to zero at about 1200 s and 2800 s (3500 s and 5000 s) in the RELAP5 (CATHARE2) calculations, respectively. Therefore the mixture of steam and nitrogen finally discharges through the upper head and pressurizer vents for the first 1200 s and 2800 s (3500 s and 5000 s) in the RELAP5 (CATHARE2) calculation, respectively. Thereafter only steam flows through those vents. The corresponding times for steam vent through the upper head and pressurizer vents are estimated from the experimental results and they are 1120 s and 1792 s, respectively. After the loss of RHRS, the reactor vessel is pressurized by steam generated in the core after initiation of boiling. The steam generated compresses the nitrogen in the upper plenum, and the compressed nitrogen moves to the hot leg (some of it escapes through the reactor upper head vent). Some fraction of nitrogen in the hot leg moves to the pressurizer and discharges through the pressurizer vent. Rest of it moves to the SG inlet plenum and then accumulates in the SG U-tubes. The nitrogen accumulated in the SG U-tubes hinders reflux condensation. As the accident progresses, the continuing pressurization of the PCS compresses the nitrogen toward upper region of the SG U-tubes, and finally inner surface of the inlet side exposes to steam. Therefore reflux condensation occurs in the inlet side of the SG U-tubes. Mean while, reflux condensation does not occur in the outlet side due to insufficient steam for the wall condensation.

The prediction of condensation heat transfer by the RELAP5 and the CATHARE2 were unrealistic when noncondensable gas was present. In the RELAP5, the Colburn-Hougen diffusion method which involves an iterative process (bisection) is used for the liquid-gas interface temperature when calculation of condensation heat transfer with noncondensable gas is needed. If not converged within 20 iteration, the heat transfer rate is calculated by Dittus-Boelter correlation and the heat transfer mode is treated as wall to single phase liquid heat transfer. This logic led to unrealistic condensation heat transfer prediction when noncondensable gas was present. In the CATHARE2, on the other hand, film condensation and effect of noncondensable gas were not satisfactorily modeled. The heat transfer when film condensation occurs is derived from the Shah correlation. The effect of noncondensable gas is simply described by considering that the interface is at the saturation temperature corresponding to the partial pressure of steam. This model does not predict sufficient degradation of condensation when the noncondensable mass fraction increases [15].

5. Conclusions

In this study, BETHSY test 6.9d was simulated by RELAP5/MOD3.2.1.2 and CATHARE2V 1.3U to assess applicability of the codes to analysis of thermal-hydraulic behavior in PWRs during midloop operation following the loss of RHRS. Reflux condensation, which occurred in the inlet side of the SG U-tubes by exposing inner surface to steam, mitigated the primary coolant system pressurization in the event of the loss of RHRS during midloop operation.

The primary pressure predicted by RELAP5 and CATHARE2 was generally in good agreement with the experimental data. The predicted and measured upper plenum liquid coolant temperatures were also in good agreement. However, RELAP5 overpredicted the interphase drag and discharge flows through the vents. Void fraction distribution in the SG U-tubes was unrealistic since condensed liquid by reflux condensation in the upper parts of the U-tubes could not fall downwards due to overprediction of the interphase drag. Heat transfer through the SG U-tubes was too low due to the unrealistic void fraction distribution, which was improved considerably by reducing the RELAP5 interphase drag by 90%. The comparison study using CATHARE2 showed that the unrealistic void distribution predicted by RELAP5 is a code problem and it is somehow affected by interphase drag because all condensate in the SG U-tubes falls downwards as soon as it is generated in CATHARE2 calculation. CATHARE2 predicted the void fraction in the cold leg and upper head bypass flow poorly, and underpredicted the void fraction in the hot leg due to large initial liquid entrainment from the core to the hot leg. As a result, the core differential pressure was slightly lower than that of the experiment. The prediction of condensation heat transfer by RELAP5 and CATHARE2 were unrealistic when noncondensable gas was present.

The additional results from experimental investigation will provide a better understanding of plant response to events occurring during midloop operation and will be useful in actual plant analyses. In comparison of the RELAP5 and CATHARE2 predictions with experimental data, the codes predicted the test generally reasonably except for overestimation of the interphase drag and discharge flow in RELAP5 and underprediction of the hot leg void fraction due to overestimation of liquid entrainment from the core to the hot leg in CATHARE2. The future study, however, should be continued to improve the numerical oscillations as well as physical modeling of condensation heat transfer with noncondensable gas.

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