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Prediction of Loop Seal Formation and Clearing During Small Break Loss of Coolant Accident

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소형냉각재 상실사고시 루프밀봉 형성 및 제거에 대한 예측

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Abstract

Behavior of loop seal formation and clearing during small break loss of coolant accident is investigated using the RELAP5/MOD2 and /MOD3 codes with the test of SB–CL–18 of the LSTF (Large Scale Test Facility). The present study examines the thermal–hydraulic mechanisms responsible for early core uncovery including the manometric effect due to an asymmetric coolant holdup in the steam generator upflow and downflow side. The analysis with the RELAP5/MOD2 demonstrates the main phenomena occuring in the depressurization transient including the loop seal formation and clearing with sufficient accuracy. Nevertheless, several differences regarding the evolution of phenomena and their timing have been pointed out in the base calculations. The RELAP5/MOD3 predicts overall phenomena, particularly the steam generator liquid holdup better than the RELAP5/MOD2. The nodalization study in the components of the steam generator U–tubes and the cross–over legs with the RELAP5/MOD3 results in good prediction of the loop seal clearing phenomena and their timing.

요 약

소형 냉각재 상실사고시 루프밀봉 형성 및 제거에 대하여 LSTF에서 수행된 실험 SB-CL-18의 결과를 RELAP5/MOD2와 /MOD3를 이용하여 예측하였다. 본 연구는 증기발생기 상향 및 하향 유동에서의 비대칭 냉각재수용에 따른 마노메트릭 유동에 의해 노심노출의 조기발생을 야기시키는 열수력학적 현상을 예측하기 위하여 수행되었다. RELAP5/MOD2를 이용한 해석결과는 루프밀봉 형성 및 제거를 포함하여 감압사고시의 주요 현상을 전반적으로 잘 예측하고 있으나 기초 계산의 결과를 볼 때 현상 및 시간적 순서에 관련하여 몇가지의 차이가 있었다. RELAP5/MOD3는 RELAP5/MOD2보다 전반적인 현상, 특히 증기발생기 액체수용을 보다 잘 예측하고 있으며, 또한 RELAP5/MOD3를 이용하여 증기발생기 U자관과 펌프 흡입관의 nodalization수를 늘린 경우는 루프 밀봉제거현상과 시간적 순서를 잘 예측할 수 있었다.

1. Introduction

During a small break loss of coolant accident, the primary coolant inventory loss will continue until the break flow rate decreases sufficiently, due to break uncovery or primary depressurization, to allow the emergency core cooling system to make up for the coolant loss. Such coolant inventory depletion will involve concurrent liquid level depression in the downflow side of the cross–over leg, for each loop, and in the vessel riser section (upper plenum and core). Meanwhile, the upflow side of the cross–over leg, cold leg and downcomer will remain filled up liquid to the break elevation. The core level depression will continue until the level of the downflow side in the cross–over leg reaches the bottom of the leg and thus allows the vapor to clear the liquid seal in the cross–over legs toward the break. When this liquid clearing (loop seal clearing) initiates, the core liquid level starts to recover. This occurs because the vapor can now reach to the downcomer and allows a manometric flow of the downcomer liquid inventory into the core region[1,2].

The test SB–CL–18 of the Large Scale Test Facility (LSTF) was simulated for 5% cold leg break (loop without pressurizer) and conducted with the main objective of investigating the thermal–hydraulic mechanisms responsible for the early core uncovery, including the manometric effect due to an asymmetric coolant holdup in the steam generator (SG) upflow and downflow side.

The RELAP5/MOD2 and /MOD3 are used in the present analysis and the results are compared with ths test data.

2. Facility and Test Description

The LSTF [3] is a 1/48 volumetrically scaled model of a Westinghouse type 3423 MWt four loop Pressurized Water Reactor (PWR). The LSTF has the same elevations for major components as the reference PWR to simulate the natural circulation phenomena and large loop pipes to simulate the two–phase flow regimes and significant phenomena in an actual plant. The facility is designed to be operated at the same high pressures and temperatures as those for the reference PWR.

The test SB–CL–18 [4] is simulated for 5% cold leg horizontal break and the break point is located in the cold leg (loop without pressurizer), between the reactor coolant pump and the reactor pressure vessel with horizontal nozzle orientation. The test procedures are provided to minimize the effects of LSTF scaling compromise on the transients during the test.

After the break occurs at time zero, the primary system depressurizes quickly. In the first few seconds from the time of break onwards, the pump speed is intentionally increased to simulate the post–scram hot leg temperature decay. At the pressurizer pressure of 12.97 MPa the reactor scrams. Since the loss of offsite power concurrent with the reactor scram is assumed, the primary coolant pumps are tripped to begin coastdown and the core power begins to decrease along the programmed decay curve. The power decay used in the test gives a slower decrease than the ANS standard. The major operational setpoints and ECCS conditions are summarized in Table 1.

3. Code and Modelling Descrption

The RELAP5/MOD2 code has been developed for best–estimate transient simulation of PWRs and associated systems. Recently, the RELAP5 /MOD3 code development program [5] has been initiated to develop a code suitable for the analysis of all transients and postulated accidents in PWR systems including both large and small break LOCAs as well as the full range of operational transients. Although the emphasis of the RELAP5/MOD3 development is on large break LOCA, improvements based on the results

Table 1. Specified Operational Setpoints and Conditions

Reactor scram signal	12.97 MPa
Initiation of RC pump coastdown	with reactor scram
Safety injection (SI) signal	12.27 MPa
High pressure charging	not actuated
Safety injection	not actuated
Accumulator injection	4.51 MPa
Low pressure injection	1.29 MPa
Main feedwater termination	with reactor scram
Turbine throttle valve closure	with reactor scram
Auxiliary feedwater	not actuated
Steam Generator relief valve on/off	8.03/7.82 MPa

of assessments against small break LOCA and operational transient test data are also being made. Table 3 is a list of the phenomena and code models, improved from the RELAP5/MOD2, that are being addressed by the RELAP5/MOD3 code. Although several optional models are avalilable in the RELAP5/MOD3 as listed in Table 3, all of them are not employed the present calculation.

The modifications to the RELAP5/MOD2 input deck to accommodate the RELAP5/MOD3 for the present calculation are as follows :

–Countercurrent and Flow Limiting (CCFL) options added at the inlet to the SG U–tubes and the 40 degree bend in the hot leg
–Junctions in the core region modified for new interphase drag package (flow area and hydraulic diameters)
–Heat structure cards added for new Critical Heat Flux (CHF) calculation

Without a CCFL model, coolant distribution cannot be adequately predicated for certain situations (e.g., LOCA flooding at the core tie plate, small break at the SG inlet plenum). This can result in an improper distribution of liquid and vapor in the reactor coolant system, and therefore an unacceptable uncertainty regarding the maintenance of core coolability during LOCA. A general CCFL model is implemented in the RELAP5/MOD3 that allows the user to select the Wallis form, the Kutateladze form, or a form in between these two forms.

It has been reported in Ref. 6 that the RELAP5/MOD2 overpredicted the void fraction profile in the simulation of the ROSA–IV Two Phase Test Facility (TPTF) and overpredicted the hot leg void fraction in the simulation of LSTF. The TPTF void fraction calculations using RELAP5/MOD3 are significantly improved with this modification, although it is just done for specific junctions. However, it may be expected that this improvement is only for the case where the flow experiences a significant change (e.g., a change in direction, from horizontal to vertical) across the junction. The junction–based interphase drag, which are incorporated into the RELAP5/MOD3, uses the donor void fraction to evaluate the interphase drag rather than using the RELAP5/MOD2 method of averaging the interphase drag from the two volumes on either side of the junction. The TPTF void fraction calculations are significantly improved with this modification, although it is just done for specific junctions. The cell–centered phasic velocity to compute the cell–centered phasic mass fluxes is used. The velocity calculational algorithm uses donored void fractions so that the value computed depends upon the void gradient between adjacent volumes, as well as on the void fraction in the volume in which the velocity is being computed.

The RELAP5/MOD2 has been criticized for using the Biasi correlation for predicting the CHF in rod bundles when the correlation is based on tube data. And it is generally over–predicted the value

Table 2. Chronology of Main Events (unit : second)

	Measured	Calc. 1	Calc. 2	Calc. 3
Break valve opened	0	0	0	0
Scram setpoint reached	9	12	12	12
Safety injection signal generated	9	12	12	12
Ssteam line valve closed	14	17	17	17
SG feedwater tripped	16	17	17	17
Steam line relief valve started Open/close cycling (A/B)		23/22	23/22	23/22
First core uncovery started	120	100	100	120
Loop seal clearing occurred (A/B)	140/140	195/195	135/135	150/150
Primary/secondary pressure reversal occurred	180	210	180	170
Reactor coolant pump stopped	265	285	285	285
Second core uncovery started	420	360	300	340
Accumulator injection started	455	420	365	370
Final core reflooding started	460	430	370	380
Final core reflooding complete	540	665	430	430
(Analysis terminated)		900	900	(650)

+ Calc. 1 : RELAP5/MOD2
Calc. 2 : RELAP5/MOD3
Calc. 3 : RELAP5/MOD3 (Nodalization Change)

Table 3. RELAP5/MOD3 Model Improvements

–Counter Current And Flow Limiting (CCFL)
–Interfacial Friction in Bubbly/Slug Flow Regime
–Vapor Pullthrough, Liquid Entrainment in Horizontal Pipes
–Critical Heat Flux (CHF)
–Interfacial Condensation on Subcooled ECCS Liquid in Horizontal Pipes
–Horizontal Stratification Inception Criterion
–Reflood Heat Transfer
–Vertical Stratification
–Metal–Water Reaction
–Fuel Rod Ballooning and Rupture Model
–Radiation Heat Transfer Model
–Non–Condensible Gas Modelling
–Downcomer Penetration and ECCS Bypass
–Upper Plenum De–entrainment

of CHF particularly in the mid–mass flux range (1500–3000 kg/s– m^2). Therefore the RELAP5/MOD3 has been extended by adding the table lookup method of predicting the CHF. Futhermore the table can be improved as data becomes available in areas where values are obtained by extrapolation from known parameter ranges.

The nodalization used to simulate the LSTF facility of the ROSA–IV program with the RELAP5 code is shown in Fig. 1. The model is based on 162 volumes connected by 169 junctions and 166 heat structures.

4. Base Calculations

The calculated results for the principal events are compared with the experimental values in Table 2. The base calculations with RELAP5 /MOD2, /MOD3 and /MOD3 with nodalization change are represented as "Cal. 1", "Cal. 2", and "Calc. 3", respectively. All the main prim-

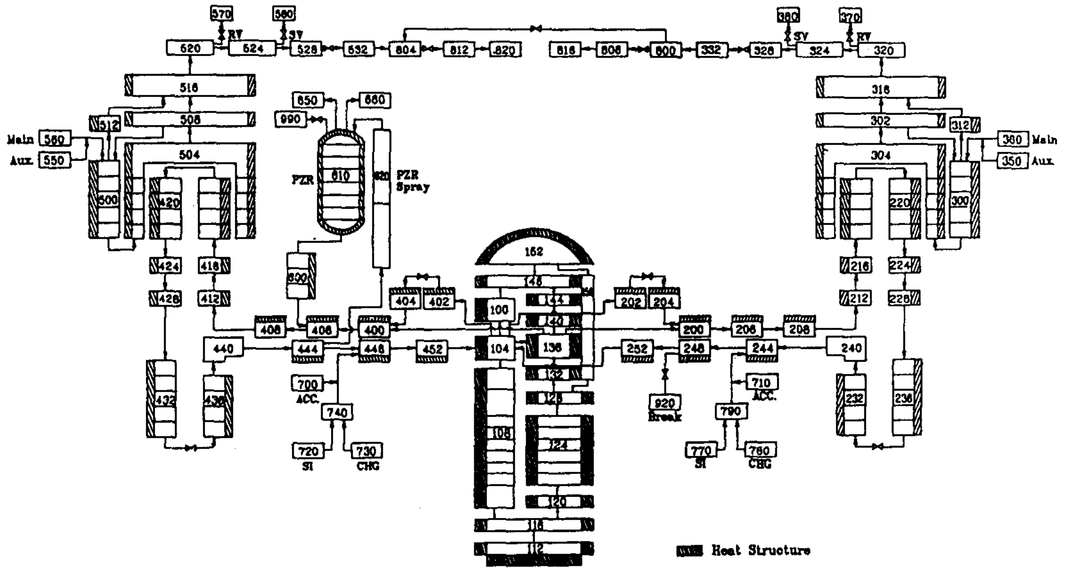

Fig. 1. Nodalization of ROSA-IV LSTF for RELAP5/MOD2 Code

ary phenomena observed during the experiment are reproduced by the code.

4.1. Base Calculation with RELAP5/MOD2

Fig. 2 shows the primary and secondary pressures. The code predicts well the secondary pressure trend. However, some differences are observed in the behavior of the primary depressurization mainly due to different break flow rate in the region between 200 and 600 seconds.

Fig. 3 shows that the break flow rate is first overpredicted by about 30% for subcooled liquid discharge and is underpredicted as approaching saturation condition. In the region between 50 and 150 seconds, the two-phase break flow rate is definitely underestimated by the code. Therefore, the time integrated mass inventory escaping from the break in that period is about one half of the experimental value. The underprediction of liquid and low-quality two-phase break flow rates result in a delay of loop seal clearing relative to the experimental result as shown in Fig. 4. It is considered that the loop seal clearing occurs when the pressure difference between the SG outlet and the bottom of the cross-over leg approaches to zero at 195 seconds (vs. 140 seconds in the experiment). Both loop seals are cleared at the same time as in the case of the experiment. This occurrence results in a delayed beginning of the linear primary pressure decrease with a higher depressurization rate. The above mentioned faster pressure decrease allows an earlier intervention of the accumulator system.

The SG liquid holdup is overpredicted tending to enhance the core level depression during loop

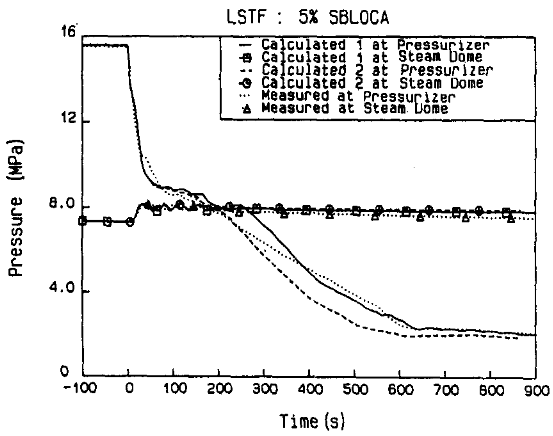

Fig. 2. Primary and Secondary Pressures

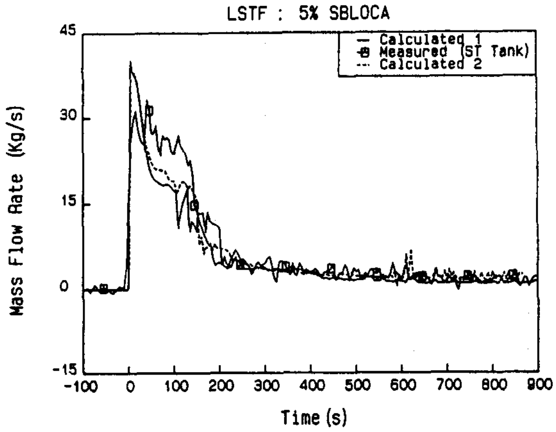

Fig. 3. Break Flow Calculated from Catch Tank Level Rise

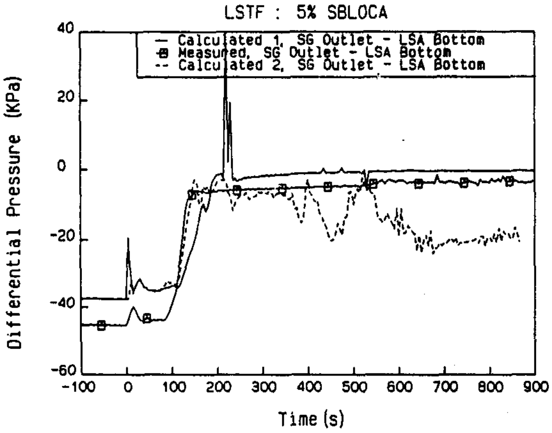

Fig. 4. Crossover Leg Downflow Differential Pressure

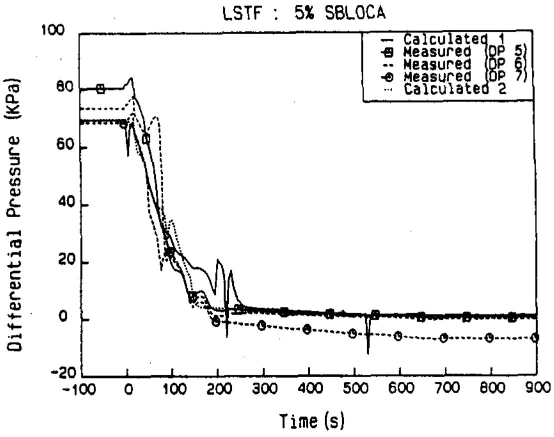

Fig. 5. SG–Inlet–Tube Top Differential Pressure

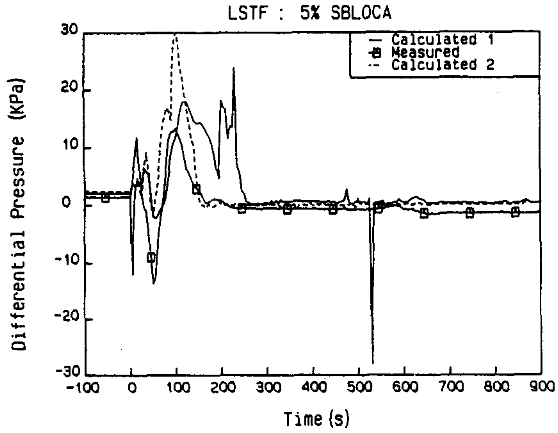

Fig. 6. SG Pressure Difference

seal clearing as shown in Fig. 5. Thus, considerable amout of liquid remained in the upflow side of the SG U–Tube and SG inlet plenum at the time of loop seal clearing.

The SG U–tube inlet to outlet plenum differential pressure as shown in Fig. 6 increases until it reaches a maximum of 18 kPa at about 140 seconds. This increase results from a redistribution of liquid due to the hydrostatic pressure balance throughout the primary system during flow coastdown. During the flow coastdown, the pressure distribution in the primary loops changed since frictional pressure losses (mainly at the pumps) decreases and the core void fractions increases. At 120 seconds, the vertical legs in the cold side loop was liquid filled whereas the hot side loop contains much void. Thus, due to the manometric balance between the hot side loop and the cold side loop, including the SGs, more liquid is retained in the SG upflow side than in the downflow side.

The SG liquid holdup persists after loop seal clearing in this calculation. The differential pressure in the SG inlet plenum becomes zero at 300 seconds (vs. 300 seconds in the experiment) as shown in Fig. 7. Also the differential pressure in the upflow side of the SG U–tube increases after loop seal clearing while such an increase is not

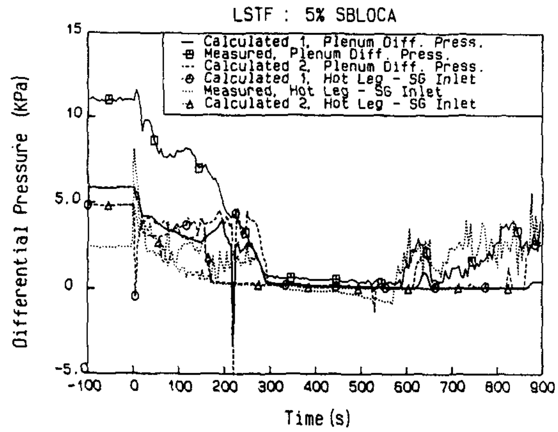

Fig. 7. SG–I Inlet Plenum Differential Pressure

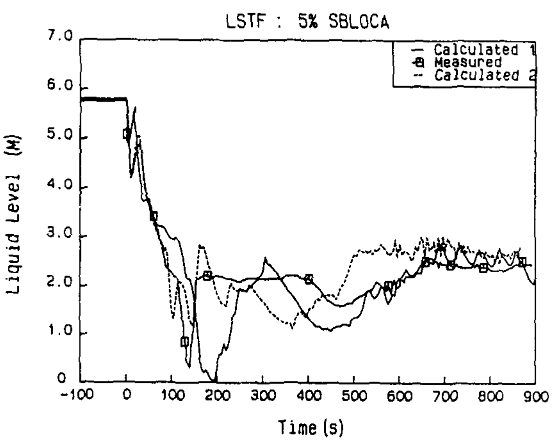

Fig. 8. Core Collapsed Liquid Level

seen or less significant in the experiment. Thus, the liquid level recovery into the upper plenum and hot legs after loop seal clearing is underpredicted or not predicted at all as shown in Fig. 8. The reason for this behavior is not well understood. Consequently, the second core level drop is initiated at 320 seconds (vs. 400 seconds in the experiment), i.e., immediately after the level recovery following loop seal clearing.

The code achieves a good simulation of the core level depression as shown in Fig. 8. One can observe, however, that the first core uncovery and consequent recovery is delayed about 50 seconds, whereas the second core level depression is anticipated earlier about 60 seconds. The reason for this behavior resides in the simultaneous occurrence of several effects. The duration of the first core heatup, associated with loop seal clearing, is overpredicted because of the underprediction of the core liquid level. The reason for the early second core uncovery must be given to the faster linear depressurization predicted by the calculation after loop seal clearing, causing the anticipated vessel mass inventory boil-off.

The core level is depressed manometrically, concurrently with the level drop in cross-over legs, and reaches a minimum immediately before the loop seal clearing starts. This minimum core level is lower than the cross-over leg liquid level which is at the bottom of the leg. After the loop seal clearing, the core liquid level recovered quickly and heater rods are quenched. The core differential pressure is generally underpredicted. This is the case even when the core is covered by two-phase mixture. This occurrs due to an overprediction of core interfacial drag ; a well-known deficiency of the RELAP5/MOD2 interfacial drag models.

4.2. Base Calculation with RELAP5/MOD3

The major areas of the differences between the RELAP5/MOD2 and /MOD3 are the primary system pressure response, the differential pressure in the upper plenum, core heatup prediction, core liquid level depression, and the drainage of SG inlet plena. These differences may be due to modifications to interphase drag model which affects the liquid holdup in the upper plenum and void distributions in the primary loops. Both calculations predict trend well, however each differs in prediction of the magnitude and timing of occurrences. The trend in the break flow rate is almost same as that with the RELAP5/MOD2. Therefore, in the region between 50 and 150 seconds the two-phase break flow rate is still underestimated as shown in Fig. 3. These results are mainly resulted from that the same break flow models are used in both codes. It is shown in Fig. 5 that the strong liquid holdup in the SG upflow side is not occurred unlikely the case with the RELAP5 /MOD2. This improvement may be obtained from the implementation of the new interphase drag model and the CCFL model which is employed in the RELAP5/MOD3.

The RELAP5/MOD3 predicts in general the liquid holdup in the SG upflow side, the timing of the loop seal clearing, and the duration of the core heatup. However, the significant discrepancies are found in the loop seal clearing phenomena as shown in Fig. 4 and the related core level depression. The loop seal clearing is started at 150 seconds, however, is not cleared completely throughout the transient. This occurs since the condensate, which forms in the SG downflow side, drops into the loop seal and accumulates there. The vapor discharge rate of the break is smaller than the core vapor generation rate. Therefore, the loop seal mixture is not cleared by the vapor. It is considered that the RELAP5/MOD3 underpredicts the loop seal void fraction than that in the experiment. However, it is not expected that this discrepancy may come from the model changes in the RELAP5/MOD3.

Fundamentally, the maximum node size is determined by the Courant limit (i.e., the node length divided by the maximum fluid velocity determines the limiting maximum time step size). The basic nodalization of the RELAP5 is described in Ref. 5. In some portions of a system single phase fluid may move in a quiescent fashion while in other of the system the fluid may be highly agitated and exists in both the liquid and gaseous phase. Consequently, finer nodalization may be used to study the fluid behavior in specific location of the model. In this calculation with the RELAP5/MOD3 the volumes, particularly on the loops from SG inlet to reactor coolant pump inlet via the cross-over cold legs, are divided twice

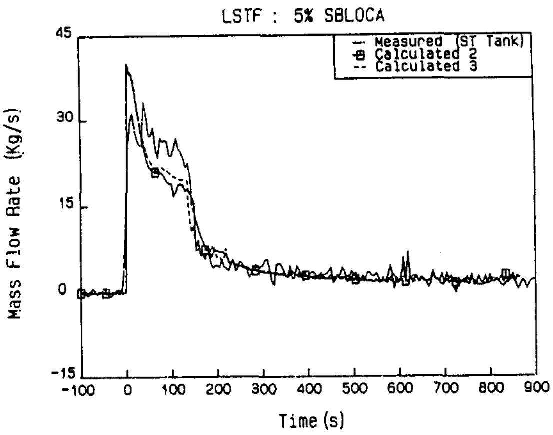

Fig. 9. Break Flow Calculated from Catch Tank Level Rise

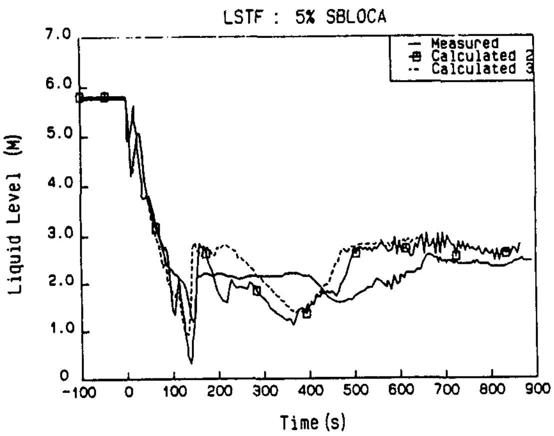

Fig. 10. Pressurizer Pressure

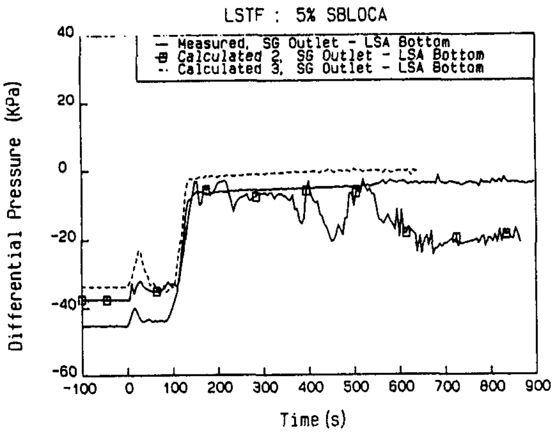

Fig. 11. Crossover Leg Downflow Differential Pressure

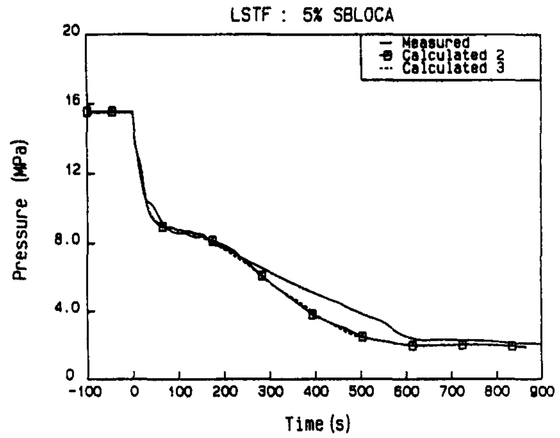

Fig. 12. Core Collapsed Liquid Level

than the base case to quantify the effect of loop seal clearing and related phenomena. This model is based on 204 volumes connected by 211 junctions and 216 heat structures.

The calculated results of the break flow rate, the primary pressure and the differential pressure of the cross-over leg predict better than the base calculation as shown in Figs. 9 to 11. The timing of the first core uncovery and the duration of the core heatup as shown in Fig. 12 are also predicted remarkably well with the experiment.

Hence the implementation of the CCFL model, the new interphase drag model, and the new CHF model to the RELAP5/MOD3 results in better prediction of the distribution of liquid and vapor and void fraction in the reactor coolant system and the core heatup behavior than the RELAP5/MOD2.

5. Conclusions

The LSTF test SB-CL-18, 5% cold leg break LOCA, is analyzed using the RELAP5/MOD2 and /MOD3 codes. The analysis results predict with sufficient accuracy the main phenomena occurring in the depressurization transient including the behavior of loop seal formation and clearing, core level depression and subsequent core heatups. In the base cases, several differences regarding the evolution of such phenomena and their timing have been pointed out.

In the base calculation with the RELAP5 /MOD2, one can observe fundamental disagreements between calculated and experimental transient sequences. That is, the underestimation of the calculated two-phase break flow rate and the overestimation of SG liquid holdup in the upflow side of the SG U-tubes, giving rise to a plug effect hindering the loop seal downflow side level decreasing and delaying the loop seal clearance.

In the base calculation with the RELAP5 /MOD3, the liquid holdup in the upflow side of the SG U-tubes is predicted in agreement with the experiment, however the complete loop seal clearing has not occurred throughout the transient. This discrepancy is improved by the nodalization changes in the SG U-tubes and the cross-over legs. The calculated results are in good agreement with the experiment in the major thermal-hydraulic phenomena and their timing.

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