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ECC Delivery to Lower Plenum under Downcomer Injection
Part 2. RELAP5 Assessment

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Abstract

In the present study, the capability of the thermal-hydraulic codes, RELAP5/MOD3.2.2 gamma, in predicting the steam-water interaction and the related ECC delivery to lower plenum under downcomer injection condition during refill phase is evaluated using the experiment data of the UPTF Test 21A. The facility is modeled in detail, and the test condition simulated for code calculations. The calculation result is compared with the applicable measurement data and discussed for the pressure response, ECC bypass behavior, lower plenum delivery, global water mass distribution, and local behavior in downcomer.

1. Introduction

Since the Direct vessel injection (DVI)-typed Emergency Core Cooling System (ECCS) design having injection nozzle into reactor vessel downcomer has been adopted to the Korea Next Generation Reactor (KNGR) design [1], analytical and experimental justification of the core cooling performance of the ECCS during a postulated large break loss-of-coolant-accident (LBLOCA) has been requested. In analytical approach, it is evident that the reliability as well as validity of the used analysis tool should be verified for the thermal-hydraulic phenomena induced solely by the DVI-typed ECCS. And the major parameter including peak cladding temperature important to the plant safety during LBLOCA should be determined by the proven analytical tool.

Thermal-hydraulic phenomena during refill and reflood phases of LBLOCA under DVI condition was generally expected to be different characteristics from those under the existing cold leg injection (CLI)-type ECCS. Especially, the ECC bypass and lower plenum delivery in refill phase can be drastically changed and the extended refill duration may be needed when compared to those in the existing CLI-type ECCS design. Some of the test result of Upper Plenum Test Facility (UPTF) revealed such a change in lower plenum delivery rate [2]. In reflood phase, direct bypass of ECC water and sweepout of downcomer water level induced by the steam jet impingement from the cold leg may be DVI-specific thermal-hydraulic phenomena. [3].

The basic feature of those complex phenomena can be regarded as three-dimensional two-phase steam-water interaction in downcomer. As a result of the interaction, one can observe the film formation of injected ECC water in upper downcomer wall, the countercurrent flow by upflow of steam, film breakup due to steam impingement, liquid entrainment in transverse steam flow, etc. Therefore, the analytical tool for the DVI performance evaluation should be assessed with a relevant experiment simulating three-dimensional steam-water interaction under DVI. And some thermal-hydraulic models specific to DVI condition might be further developed if necessary.

The present study aims at evaluating the capability of thermal-hydraulic analysis tool such as TRAC code [4] and RELAP5 code [5] in predicting the steam-water interaction and the related ECC delivery to lower plenum under DVI condition during refill phase. For this purpose, the TRAC-M/F77code and the RELAP5/MOD3.2.2gamma code were assessed using the experiment data of the UPTF Test 21A [2]. The part 1 of this paper describes the assessment of TRAC code [6]. The present paper, as a part 2 of the study, was focused on the RELAP5 assessment. The UPTF Test 21A is a unique one simulating the refill phase of LBLOCA of pressurized water reactor (PWR) under the downcomer injection. Although the geometric configuration of the UPTF downcomer injection was not the same as the KNGR one, the basic two-phase interaction could be similar to the KNGR one. The code capability confirmed from the present assessment can be consistently applied to the real plant calculation without any scalability concern, since the UPTF 21A was full-scale separate effect test.

2. UPTF Test Description

The Upper Plenum Test Facility (UPTF) is a full-scale separate effect test (SET) facility of a four-loop 1300 MWe pressurized water reactor (PWR). It is composed of full-size reactor vessel including the downcomer, lower plenum, core simulator, upper plenum and upper head and four loops with pump and steam generator simulator. The test vessel, core barrel and internals are also a full-size representation a PWR. The height and the outer diameter of the test vessel are 13.49 m of 5.03 m, respectively. The gap width of vessel downcomer is 25 cm. The major thermal hydraulic phenomena with multidimensional nature during end-of-blowdown to reflood phase of LBLOCA have been investigated in the UPTF. The steam produced in a real core and the water entrained by the steam flow was simulated by steam and water injection through core simulator. For testing the downcomer injection, two ECC injection nozzles having inner diameter of 0.308 m were located at 0.35 m above from the cold leg center. Two nozzles are connected to the downcomer annulus at the center between the cold leg 1 nozzle and the broken cold leg nozzle (0°) and at the center of cold legs 2 nozzle and and cold legs 3 nozzle (180°).

The Test 21, quasi-steady state experiment, was carried out to obtained full-scale data on downcomer/lower plenum refill and reflood behavior for downcomer ECC injection. The test was subdivided into four phases simulating the refill phase (21A and 21B) and reflood phase (21C and 21 D) of real plant event. In the Test 21A, the test vessel was initially filled with steam at 295 kPa and 464 K while water level of lower plenum was 0.6 m. The pump simulators in the three intact loop cold legs were blocked during the transient. At the beginning of the test, the cold leg break valve was open to the containment simulator through the steam separator and drainage tank. The containment pressure was kept to be 285 kPa. At 31 sec of the transient, steam was injected from the core simulator and steam generator and at 225 kg/sec and 89 kg/sec, respectively. Those injection rates were kept until 120 sec. At 46.2 sec, the ECC water was entered to the downcomer through two ECC injection nozzles (0° and 180°) at 912 and 910 kg/sec, respectively. The ECC injection and the core steam injection were terminated at 120 sec and 130 sec, respectively.

3. Code and Modeling Description

For the simulation of the UPTF Test 21A, the facility was modeled in accordance with RELAP5 modeling syntax by 341 hydrodynamic volumes, 520 junctions, 412 heat structures.

The nodalization diagram was shown in Figure 1. The reactor vessel downcomer model was basically identical to the TRAC modeling scheme [7], i.e., 8-azimuthal volumes and 10-axial volumes. Horizontal crossflow junctions between axial flow volumes were used simulate the circumferential flow during the test. The upper head was modeled with 1 volume and lower plenum with 2-axial, 8-azimuthal, and 3-radial volumes. The core and upper plenum part was modeled by two separated channels with 10-axial volumes. Circumferential variation in the core and upper plenum was ignored. Three intact loops with hot leg, steam generator simulator, crossover leg, pump simulator, and cold leg and a broken loop were separately modeled as in TRAC modeling.

For simulating the ECC injection location at the downcomer, which was at the center of two cold leg nozzles of loop 1 and broken loop and 35 cm higher than cold leg center, the first sub-volume of downcomer annulus was modeled with a twisted pipe component (junction area reduced) with additional junction from the adjacent annulus volume (see Figure 2).

The initial condition of the Test 21A was appropriately established by a steady state run.
As in the TRAC simulation, the boundary condition such as SG steam injection, core simulator steam injection, and containment pressure was modeled by time-dependent junctions and time-dependent volumes based on the experimental condition.

4. Result and Discussion

Pressure Response

Figure 3 shows a comparison of pressure at the reactor vessel downcomer top between the experiment data and the calculated one by RELAP5 code. In experiment, the pressure increased sharply from 304 to 607 kPa, after start of steam injection. Shortly after the ECC injection was initiated, condensation of steam by subcooled ECC water occurred leading to a rapid pressure decrease. After then, the pressure gradually increased with oscillation by the repeated condensation.

The RELAP5 calculation result was comparatively well agreed to the test data. The pressure buildup by steam injection was a little overpredicted. This was believed due to the uncertainty in modeling the geometry and the related loss factor of the facility. This trend was still throughout the transient. The pressure decrease due to the condensation by the ECC injection and the proceeding oscillation was well simulated.

ECC Bypass

Figure 4 shows a comparison of break flow between the experiment data and the calculated one RELAP5 code. In experiment, the break flow increased from 32 sec when the steam injection was initiated and then decreased from 45 sec when the ECC injection was started. It is also found that the injected ECC water was not directly discharged and the substantial increase of the break flow (ECC bypass) was from 56 sec, approximately. Therefore, the injected ECC water during 45 sec to 56 sec was believed to stay at the upper annulus of the downcomer due to the strong upflow of steam and/or dead-end space including the broken cold leg pump simulator. After then, the break flow continued to increase with oscillation. The source of the oscillation, as mentioned in the previous section, was due to the condensation of ECC water. And it can be stated that the injected ECC water was bypassed to the break and the amount of the bypass increased with time. At 100 sec, the flow of 1,800 kg/sec, i.e., total ECC injection flow rate, was discharged.

The break flow from the RELAP5calculation before the ECC injection was well agreed to the test data. However, after 47 sec in the RELAP5 calculation, a rapid increase of break flow was earlier than the experiment. It implies that almost all of the injected ECC water at that time was predicted to bypass out. Such an overprediction may due to the one-dimensional hydrodynamics of the RELAP5 code. Since the circumferential flow in downcomer was modeled only by the crossflow between two axial channels, the flow of the injected ECC water in circumferential direction and its stagnation in the upper annulus was not reasonably predicted. As a result, the ECC water moved down in main flow direction (z) and was discharged by a pressure difference through the break.

Figure 5 shows a comparison of the integrated break flow between the experiment data and the calculated one by RELAP5 code. The experimental data indicated that the water of 60,000 kg among the injected ECC water of 98,380 kg was discharged out until 100 sec. The RELAP5 calculation, as explained previously, indicated that much larger amount of the water (95,000 kg until 100 sec) was bypassed than the experiment.

Lower Plenum Delivery

Figure 6 show a comparison of water level at the lower plenum between the experiment data and the calculated by RELAP5 code. The sited experimental data was the measured one at the center of the lower plenum. In experiment, the level was initially maintained at 0.6 m from the vessel bottom an then increased a little at 32 sec (steam injection initiation). This can be explained by superimposed dynamic pressure on the DP measurement. At 48 sec, the small amount of the injected ECC water reached to the lower plenum, however the water was entrained by the steam flow and discharged to the break. The delivery rate was estimated as 148 kg/sec (low delivery). At 57 sec, the level re-started to increase with oscillation. The averaged delivery rate was 385 kg/sec during 57 sec to 81 sec (high delivery). The difference of two delivery-phases was believed that some of the injected water was accumulated in the cold legs 1, 2, and 3 during low delivery phase and the water was penetrated into the lower plenum during high delivery phase. After 80 sec, the level was not further increased. The injected water was fully bypassed. Until 100 sec, the lower plenum was filled at 1.8 m (72.5 % of height of lower plenum 2.48 m) and the delivered mass was approximately 15,000 kg..

The result from the RELAP5 calculation shows an overall agreement with the experimental data although the liquid level was a little underpredicted over the transient. Especially, the low delivery phase was not observed in the RELAP5 calculation, which is obviously related to the overpredicted break flow. However, the predicted slope of level increase during high delivery phase was almost similar to the measured one. It revealed that one-dimensional flow calculation could be reasonably applied to the prediction of the global water level behavior in lower plenum during high delivery phase.

Global Water Mass Distribution

In the experiment, it was found that only 60,000 kg of coolant among the injected ECC water (98,380 kg) and injected steam (19,890 kg) until 100 sec was discharged out and 58,000 kg of coolant was added to the reactor vessel. And a water of 15,000 kg among the added mass was delivered into the lower plenum. The accumulation in the cold legs 1, 2, and 3 was estimated to be 11,000 kg, approximately. Therefore, the amount of water in downcomer can be regarded as 28,000 kg until 100 sec considering the mass in the broken cold leg less than 3200 kg.

Figure 7 shows a comparison of the total fluid mass in downcomer and lower plenum calculated by the RELAP5 code. The experimental data on the added mass to lower plenum was also compared, the data was guessed from the available measured data. The downcomer mass data was not available. In that figure, the RELAP5 calculation result shows that the water was started to accumulate from 48 sec and that 9,157 kg of water was contained in downcomer until 100 sec, while 9,277 kg in lower plenum. Table 1 summarized the status of the water mass distribution until 100 sec.

Table 1. Summary of Water Mass Distribution until 100 seconds of UPTF Test 21A

(Unit: kg)

Item	M_{ECC}	M_{STEAM}	M_{BREAK}	M_{RV}	M_{LP}	M_{DC}	M_{CL}	M_{BCL}
Testt	97,112*	19,890	60,000	57,000	15,000	28,000	11,000	3,200
RELAP5	97,112	19,890	94,896	18,851	9,277	9,157	0	3,255

* Measured Value was smaller than input value.

** Estimated value

Local Behavior in Downcomer

To further understand the lower plenum delivery and the global water distribution, the local behavior in downcomer was investigated. Figure 8 shows a comparison between the contour plot of the measured fluid temperature and the contour plot of the calculated liquid fraction in downcomer. Those temperature plots, not exact one, could be interpreted ad a two-dimensional water distribution in downcomer between the test and the calculation, since actual liquid distribution was not measured in the experiment.

In the experiment, at the beginning of the refill phase (48 sec), the subcooled ECC water injected to the upper annulus of the downcomer interacted with steam up-flowing from the core. Some of the steam was condensed and merged into water side, while the large portion of steam still resisted against the water dispersion and falling down. As a result, the liquid region was limited to the upper annulus and the adjacent space. Especially, due to high momentum of the ECC water, the liquid region was extended to the azimuthal direction. At 58 sec, the first water slug reached to the lower plenum by the hydrostatic head of the deposited water in upper downcomer. Once the liquid slug moved down, the water delivery was stopped and the water in the lower plenum was re-entrained and swept out by the core steam. Such a delivery and entrainment was repeated as shown in the plots for 70 sec and 74 sec.

The RELAP5 calculation result shows a similar trend to the experiment at the initial period. It is clearly observed that the liquid region was further developed at the part connecting to cold legs 2 and 3. During the late refill phase, although the predicted liquid region was more or less different from the measured one, the water delivery pattern could be clearly observed. However, the steam dominant region and slug formation were not clearly predicted by the RELAP5 code. It may be a limitation of one-dimensional code. The absence of water slug formation in calculation may partly due to the absence of the water accumulation at cold legs 2 and 3 in the code calculation. It also may derived from the limitation of the one-dimensionality. However, in spite of those limitations on the local phenomena, the RELAP5 code indicated a reasonable result on the global parameter including lower plenum delivery in overall sense.

Impact on Plant Calculation

The ECC flow rate and steam flow rate of UPTF Test 21A were 910 kg/sec/nozzle and 315 kg/sec, respectively. The preliminary REALP5 analysis on KNGR LBLOCA [8] showed the flow rate of each Safety Injection Tank (SIT) and the mass flow rate upflowing steam during refill period were 860 kg/sec/nozzle and 600 kg/sec, respectively. Especially the steam velocity at the downcomer bottom was about 30 m/sec. Those conditions were similar to the experimental conditions, thus, the difference of the current result on UPTF Test 21A including the excessive ECC bypass flow and the delayed lower plenum delivery from the experimental data can be consistently applied to the real plant calculation.

5. Conclusions

In the present study, the capability of two thermal-hydraulic codes, RELAP5/MOD3.2.2 gamma, in predicting the steam-water interaction and the related ECC delivery to lower plenum under DVI condition during refill phase was evaluated using the experiment data of the UPTF Test 21A. The facility was modeled in detail, and the test condition was simulated for code calculation. From the analysis on the predicted behavior and the comparison with the test result, the obtained conclusions are as follows:

1) The RELAP5 code can reasonably predict the global parameter behavior including system pressure and lower plenum level during the refill phase under downcomer injection condition.
2) The calculated ECC bypass flow rate was higher than the experiment data, which was believed due to the one-dimensionality of the code. Such a conservative result can be expected in the real plant calculation.
3) Due to lack of multi-dimensional capability of the code, the deposition of ECC water in the intact loop cold legs was not predicted. This difference resulted in a compensation of the delay in lower plenum delivery.
4) The predicted local thermal-hydraulic behavior in the downcomer was more or less different from the experiment during the late delivery phase due to the limitation of one-dimensional nature, however, the basic trend of lower plenum delivery can be observed.

References

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[7] B.E. Boyack, et al., *TRAC-M/F77, Version 5.5, Developmental Assessment Manual, Draft*, March 1998.

[8] H.R.Choi, et. al., *Large Break LOCA Analysis for KNGR Using R5V322beta*, The 12th CAMP Working Group Meeting, Cheju, June 1999.

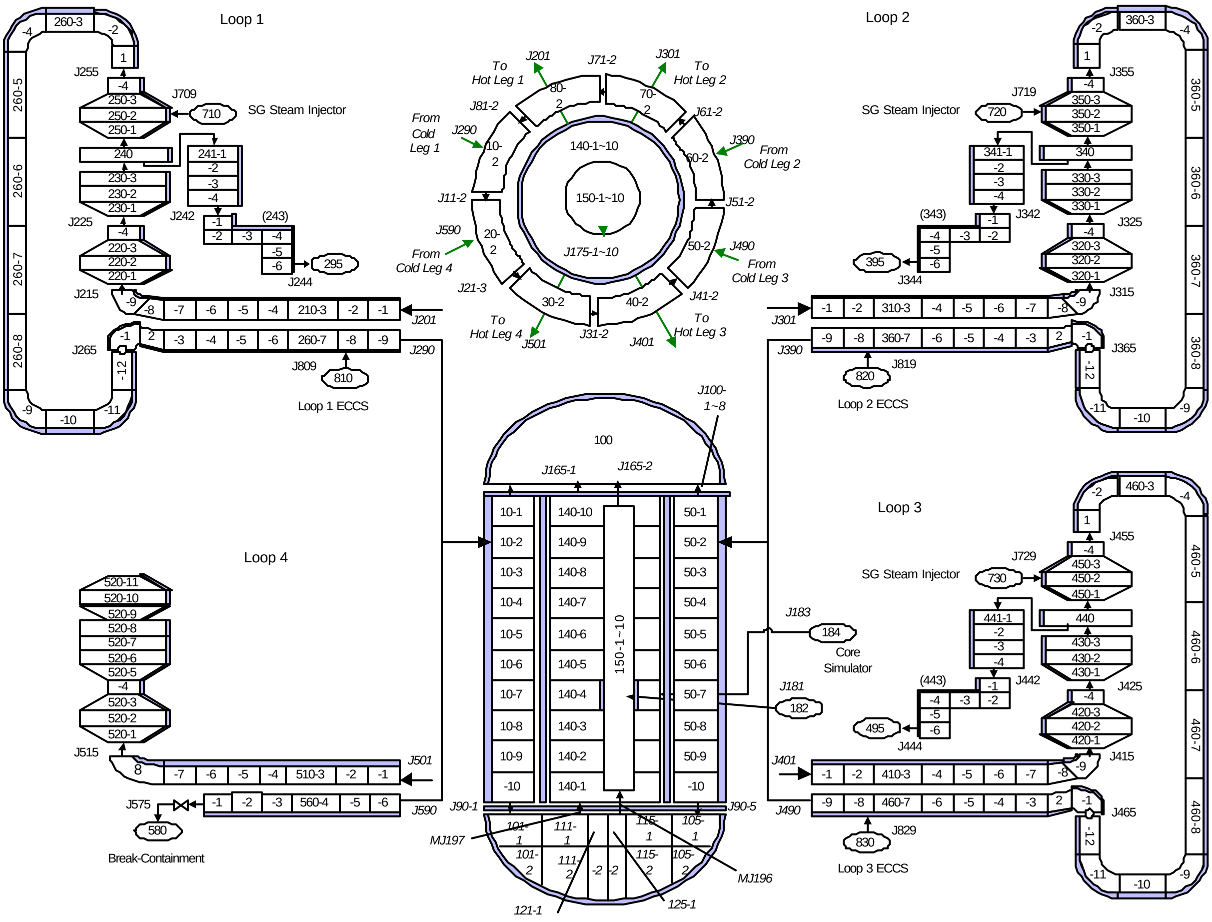


Fig. 1. RELAP5 Nodalization of UPTF Facility

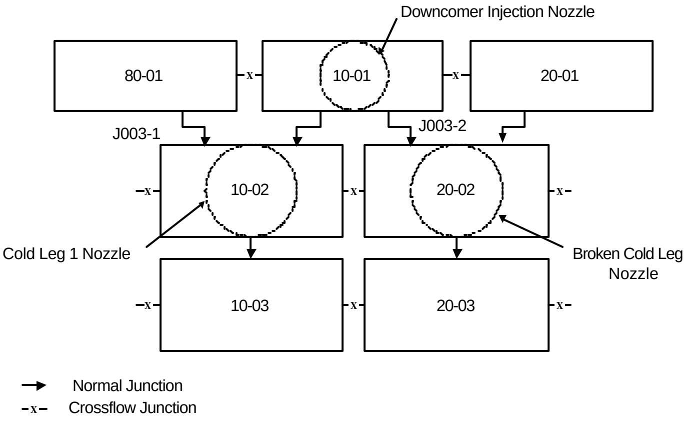


Fig. 2. Modeling of Downcomer Injection Nozzle

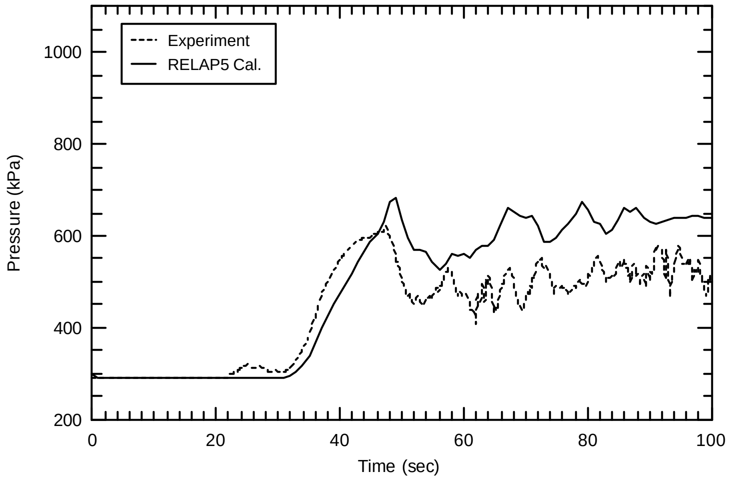


Fig.3. Comparison of System Pressure

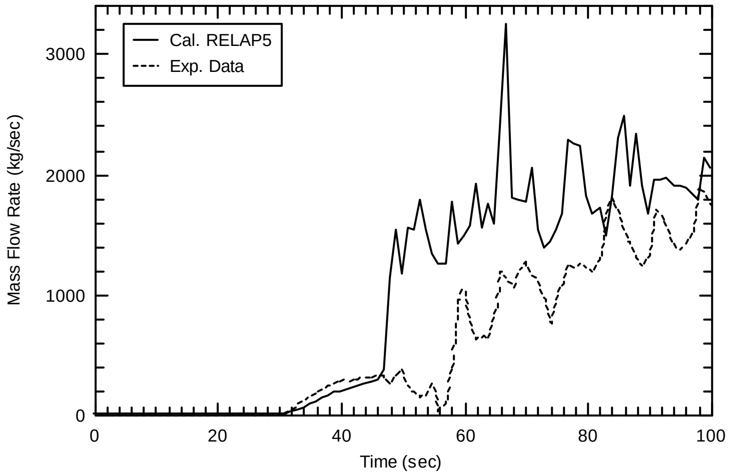


Fig. 4. Comparison of Break Flow

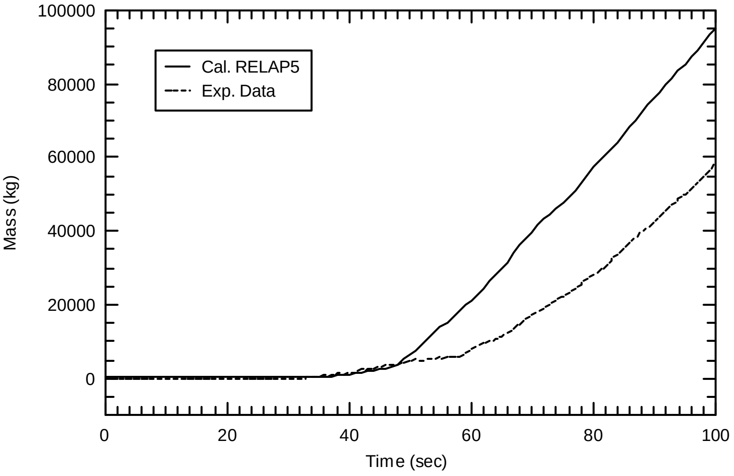


Fig. 5. Comparison of Integrated Break Mass

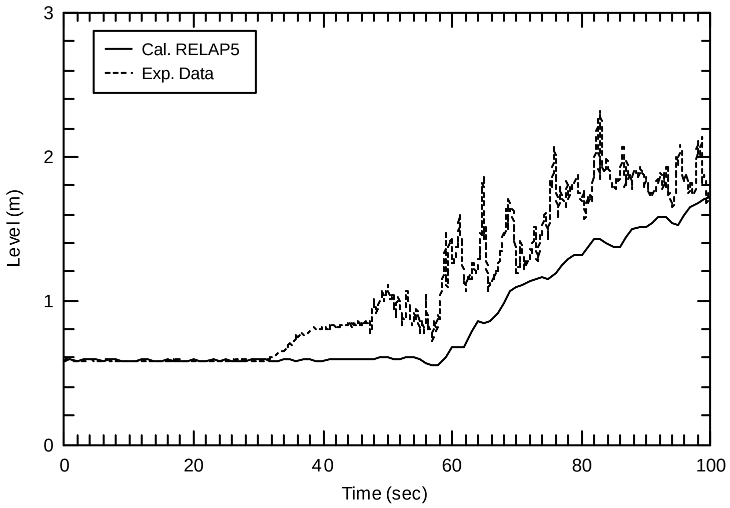


Fig. 6. Comparison of Lower Plenum Level

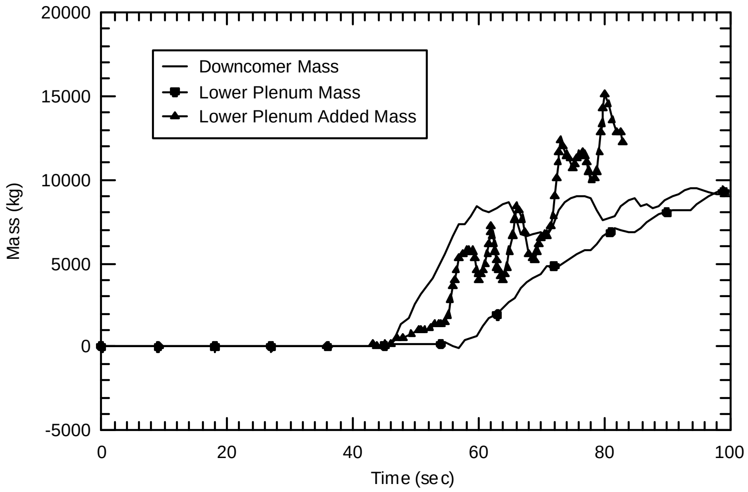
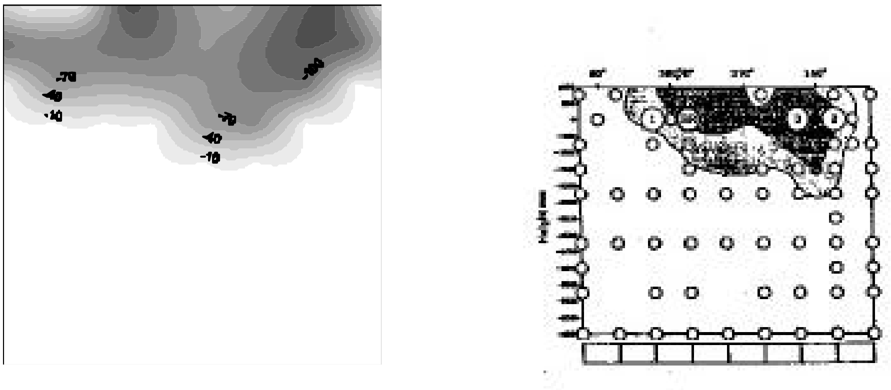
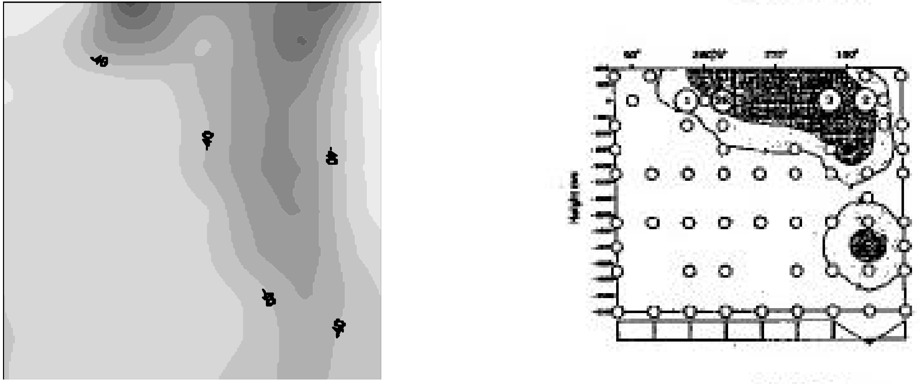


Fig. 7. Comparison of Mass in Downcomer and Lower Plenum



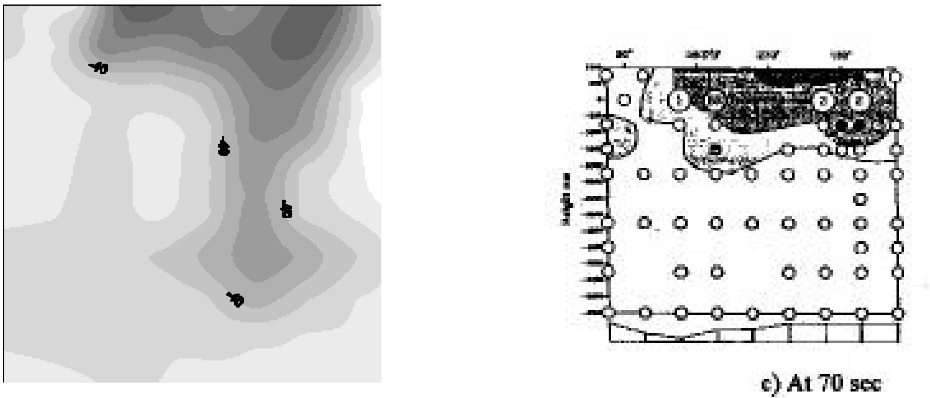
a) Calculation at 48 sec

a) At 48 sec



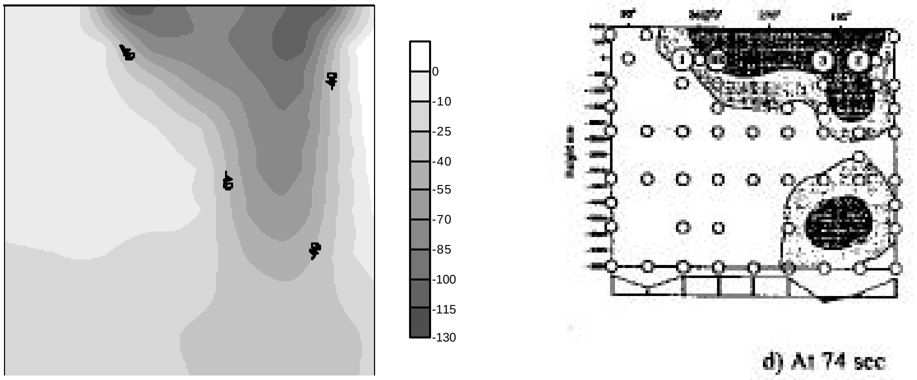
b) Calculation at 58 sec

b) At 58 sec



c) At 70 sec

c) Calculation at 70 sec



d) At 74 sec

d) Calculation at 74 sec

Fig. 8. Comparison of Liquid Temperature Contour in Downcomer