Proceedings of the Korean Nuclear Society Autumn Meeting
Taejon, Korea, October 2000

ECC Delivery to Lower Plenum under Downcomer Injection
Part 1. TRAC-M/F77 Assessment

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Abstract

Introducing Direct Vessel Injection to KNGR ECCS, it is more necessary to assess the capability and limit of codes utilized in audit calculation. In this study, The capability of TRAC-M/F77 code in predicting multi-dimensional phenomena 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 is simulated. 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

Analytical and experimental justification of the core cooling performance of the direct vessel injection (DVI)-typed Emergency Core Cooling System (ECCS) design during a postulated large break loss-of-coolant-accident (LBLOCA) has been requested by the introduction of the ECCS having DVI nozzle into reactor vessel downcomer to the Korea Next Generation Reactor (KNGR) design [1]. 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.

Generally, it is expected that thermal-hydraulic phenomena during refill and reflood phases of LBLOCA under DVI condition may bring about 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. And its effect on the degradation of core reflooding rate may be significant [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 counter-current 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 for TRAC code [4] in predicting the steam-water interaction and the related ECC delivery to lower plenum under DVI condition during refill phase. For this purpose, the code was assessed using the experiment data of the UPTF Test 21A [2]. The test 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 identified from the present assessment can be 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 21~25 cm. The major thermal hydraulic phenomena with multidimensional nature during end-of-blowdown to reflood phase of LBLOCA have been investigated in the UPTF. In UPTF both cold leg and hot leg breaks have been investigated including emergency core cooling system (ECCS) injected into the intact and broken cold legs and/or hot legs and into the downcomer. 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 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 water 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 into 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, Input deck was modified from that of UPTF Test 6 run 133 particularly on upper downcomer region volume and flow area, ECC injection pipe and nozzles, lower plenum nodding and broken cold leg pipe to water separator. Three intact loops with hot leg, steam generator simulator, crossover leg, pump simulator, and cold leg and a broken loop were separately modeled. The loop nodalization is identical to the based input deck, The loop 1 and 3 nodalization diagram was shown in Figure 1. For loop 2 is nearly identical but pressurizer is connected in the middle of hot leg. For broken loop hot leg is connected with steam generator simulator to pump simulator and cold log is connected to water separator that separate water and steam out of break flow. Separated steam in water separator is sent to containment simulator and separated water to KTA water collecting tank via drainage vessel. In TRAC modeling broken cold leg pipe to water separator is modeled and connected to BREAK component as a pressure boundary. Test vessel was modeled in 8-azimuthal cells, 3-radial ring and 14 axial cells as shown in Figure 2. Downcomer region is modeled with stacked 10 axial levels with outer radial ring and bounded from axial level 4 to 13. Cold leg (CL)s and Hot leg(HL)s were connected at level 12, ECC injection nozzles at level 13. Azimuthal ECC nozzle connection is somewhat different from real configuration. The Nozzle connection point was modeled 22.5° shifted in azimuthal direction and 80cm higher in z-direction than actual location. The boundary condition such as SG steam injection, core simulator steam injection, and containment pressure was modeled by fill and break component based on the experimental condition.

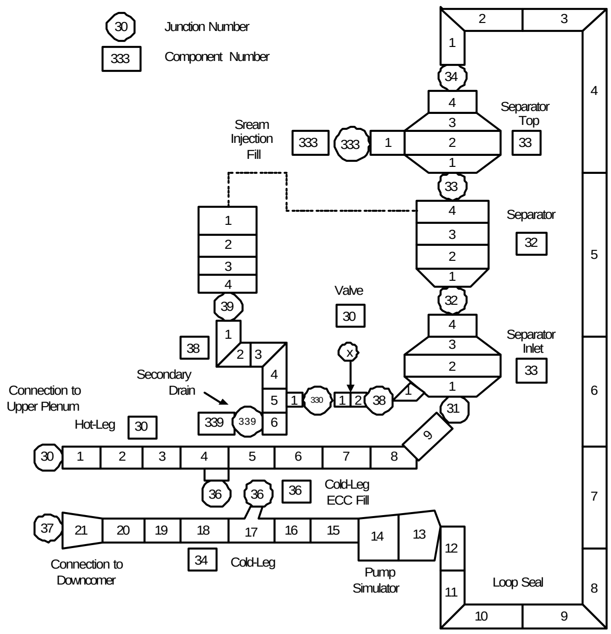


Figure 1 UPTF loop modeling

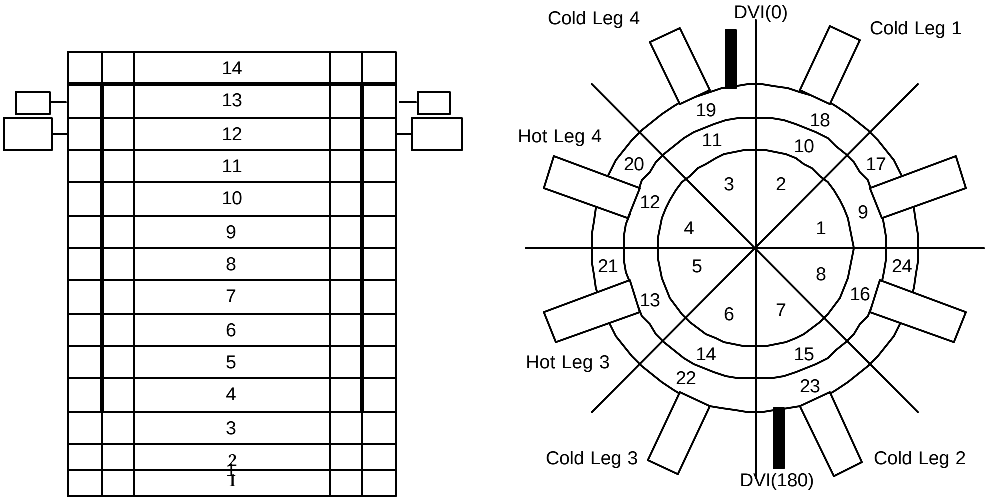


Figure 2　UPTF Test vessel nodding diagram

4. Results 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 TRAC code. In experiment, the pressure increased sharply from 304 to 607 kPa, after the start of steam injection. Shortly after the ECC injection was initiated, condensation of steam by sub-cooled ECC water occurred leading to a rapid pressure decrease. After then, the pressure gradually increased with oscillation due to water distribution in downcomer and lower plenum , and to condensation of steam by high sub-cooled ECC water.

The calculation result was comparatively well agreed to the test data before the ECC injection. However, the calculated pressure drop due to sub-cooled ECC water was under-estimated about 1 bar. This pressure difference between experiment data and code estimation was believed due to the uncertainty in ECC water temperature during early injection period. The calculated pressure started to decrease after 80 seconds of test due to broad sub-cooled water distribution in downcomer region read to pressure decrease. The pressure decrease due to the condensation by the ECC injection and the proceeding oscillation was well simulated.

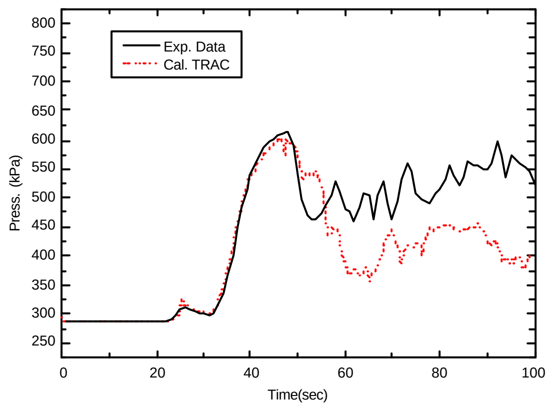


Figure 3　Test pressure response

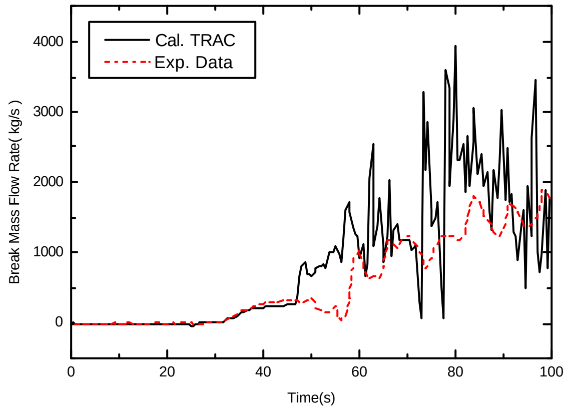


Figure 4　Break flow rate

ECC Bypass

Figure 4 shows a comparison of break flow between the experiment data drain mass flow of drainage vessel and the calculated break pipe mass flow by TRAC code. In experiment, the break flow increased from 32 sec when the steam injection was initiated and then decreased from 46.5 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 or entrapped in pump simulator connected in the middle of broken cold leg pipe. 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 TRAC calculation before the ECC injection was well agreed to the test data. However, shortly after ECC injection a rapid increase of break flow was observed earlier than the experiment. It implies that almost all of the injected ECC water at that time was predicted to bypass out. Figure 5 shows a comparison of the integrated break flow between the experiment data and the calculated one . The experimental data indicated that the water of 70,000 kg among the injected ECC water of 83,585 kg was discharged out until 100 sec.

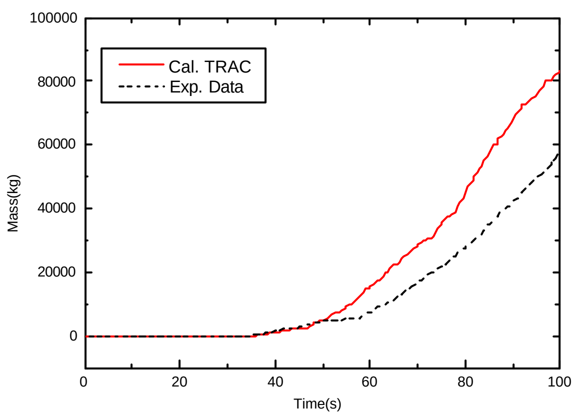


Figure 5　Break mass change

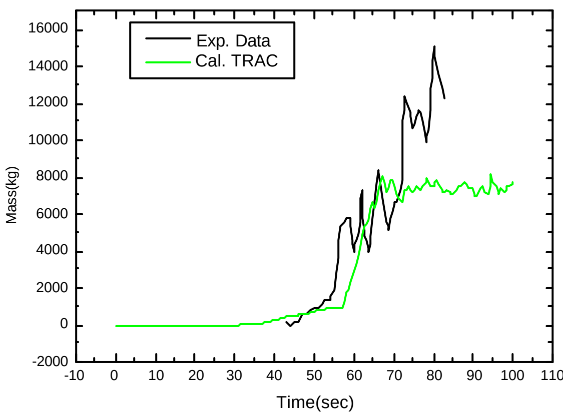


Figure 6　Lower plenum inventory change

Lower Plenum Delivery

Figure 6 show a comparison of water mass at the lower plenum between the experiment data and the calculated one by TRAC code. The sited experimental data was measured at the point 1.07m away from the center of the lower plenum. In experiment, the level was initially maintained at 0.6 m from the vessel bottom and 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 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 TRAC calculation shows an overall agreement with the experimental data before 70 second. After that period, water accumulated in downcomer did not penetrated.

Especially, the low delivery phase was not observed in the TRAC calculation, which is obviously related to the over-predicted 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.

Water Mass Distribution

In the experiment, it was found that only 60,000 kg of coolant among the injected ECC water (97,112 kg) and injected steam (19,890 kg) until 100 sec was discharged out and 57,000 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 3,200 kg.

Figure 7 shows a comparison of the total fluid mass in downcomer and lower plenum calculated by the TRAC code code. The corresponded experimental data was not available. In that figure, the calculation result shows that the water was started to accumulated from 48 sec and 9,000 kg of water contained in downcomer until 100 sec. 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_{ADDED_RV}	M_{LP}	M_{DC}	M_{CL}	M_{BCL}
Experiment	97,112*	19,890	60,000	57,000	15,000	28,000	11,000	3,200
TRAC	97,112	19,890	83,585	33,417	9,000	11,756	11,497	2,998

* Measured Value was smaller than input value.

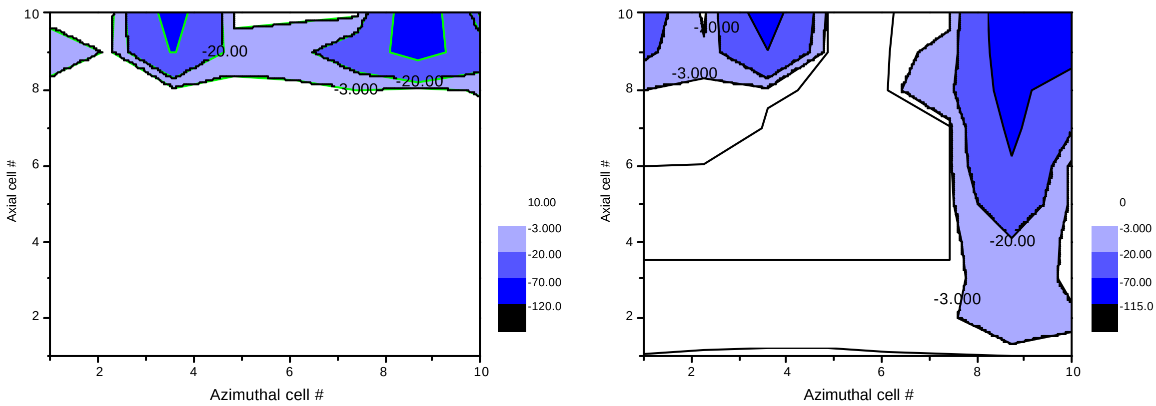
** Estimated value

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 plots, in nature, do not have the same meaning, however, the qualitative comparison of two-dimensional water distribution in downcomer between the test and the calculation can be achieved.

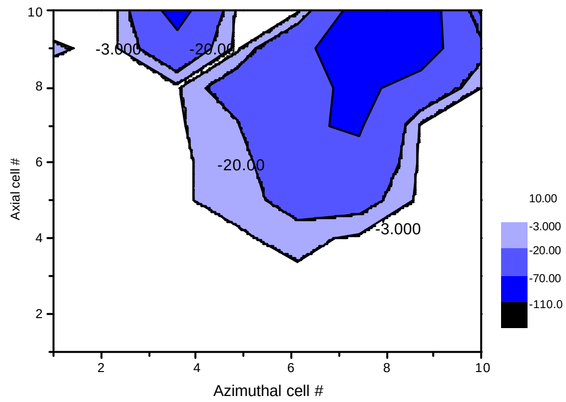
In the experiment, at the beginning of the refill phase (48.8 sec), the subcooled ECC water injected to the upper annulus of the downcomer interacted with steam up-flowing from the core. Some of the steam was condensed and merged into water side, while the large portion of steam still resisted against 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, however, 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 TRAC 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. And all of ECC injected near broken cold leg was bypassed. During the late refill phase, strong sub-cooled water slug was formatted in upper downcomer region. However broad saturated water region was observed in lower downcomer region, which did not effect on lower plenum inventory increase. It may partly due to the absence of the water accumulation at cold legs 2 and 3 in the code calculation



(a) (b)

Figure 8 Calculated sub-cooling contour of ECC water in downcomer in 47.1s(a), 57.1s(b), 71.8(c)



(c)

Figure 8 Calculated sub-cooling contour of ECC water in downcomer in 47.1s(a), 57.1s(b), 71.8(c)

5. Conclusions

In the present study, the capability of TRAC-M/F77 code in predicting the steam-water interaction and the related ECC delivery to lower plenum under downcomer injection 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 both code calculations. From the analysis on the predicted behavior and the comparison with the test result, the obtained conclusions are as follows:

The TRAC-M/F77 code can reasonably predict the global parameter behavior including system break mass flow, vessel mass and intact cold leg filling during the refill phase under downcomer injection condition and have reasonably good predictability in upper downcomer water distribution. And the some local phenomena such as the delay of ECC bypass and pressure response at steam and high sub-cooled water interaction was not accurately predicted.

References

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