NURETH14-506

Condensation in the Cold Leg as Results of ECC Water Injection during A LOCA: Modeling and Validation

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Abstract

During postulated LOCA events in pressurized water reactors, cold water is injected into cold legs by emergency core cooling system (ECCS). As the ECC water comes into contact with steam, the amount of condensation in the cold legs which results from mixing of the two phases is expected to have an effect on the thermal hydraulic behavior of the system. During boiloff period and recovery period of a small break LOCA, the condensation in the cold leg is enhanced by the impingement of the ECC jet on the layer of liquid, when the flow in the cold leg is expected to be horizontal stratified. Consequently, the reactor coolant system (RCS) depressurization is accelerated, which in turn increases ECC flow rate and promotes accumulator injection. For a large break LOCA, the condensation process in the cold leg during refill period helps to reduce bypass flow at the top of downcomer, promoting ECC penetration. The condensation in the cold leg during reflood period is an important factor in determining the ECC bypass, the break flow rate, the downcomer and core water inventory, and the liquid subcooling in the downcomer, which in turn impacts the peak cladding temperature during reflood.

A cold leg condensation model was considered for the new release of WCOBRA/TRAC-TF2 safety analysis code and presented in an authors' previous work. The model was further improved to better capture relevant data and a revised model was found to be in better agreement with such experimental data. The intent of this paper is to present the validation for the cold leg condensation model. The improved cold leg condensation model is assessed against various small break and large break LOCA separate effects tests such as COSI experiments, ROSA experiments and UPTF experiments. Those experiments cover a wide range of cold leg dimensions, system pressures, mass flow rates, and fluid properties. All the predicted condensation results match reasonably well with the experimental data.

Keywords

Cold leg condensation, LOCA, WCOBRA/TRAC-TF2

1. Introduction

The condensation of steam by the cold water injected from the ECCS by sources such as the accumulator (ACC), safety injection (SI), and residual heat removal (RHR) injection (also called low head safety injection (LHSI)) into the cold leg is an important phenomenon during both small and large break LOCAs. FULL SPECTRUM™ LOCA (FSLOCA™) Phenomena Identification and Ranking Table (PIRT) ranks cold leg condensation high in the boiloff period and the recovery period of a small break LOCA. During these periods, significant condensation occurs when SI jet impinges onto the layer of liquid in the cold leg as the flow is expected to be horizontal stratified. As the break size increases, the effect of the accumulator injection and the higher pumped SI flow rates leads to an increased importance of condensation in the jet region. For a large break LOCA, the cold leg condensation is the highest ranked phenomenon during the refill period when the condensation process in the cold leg helps to reduce bypass flow at the top of downcomer, promoting ECC penetration. The condensation effects are reduced during the reflood period as the accumulators end their injection and the low head safety injection continues, but condensation still impacts the break flow rate, the downcomer and core water inventory, and the liquid subcooling in the downcomer which in turn impacts the peak cladding temperature during reflood (the downcomer boiling reduces driving head in the downcomer). For intermediate breaks, the cold leg condensation is ranked high for both the accumulator injection period and (low head) safety injection period.

There are several existing cold leg condensation models developed for the nuclear reactor safety analysis codes which are used to simulate this particular cold leg condensation mechanism. Asaka et al. [1] proposed a direct contact condensation model for TRAC-PF1/MOD1 for both hot leg and cold leg ECC injection. The condensation model was based on Theofanous turbulent liquid jet condensation correlation [2]. A constant Stanton number of 0.0035 was recommended for water injection condensation transient. The model was validated against CCTF integral effect test with combined hot leg and cold leg ECC injection.

Bestion and Gros d'Aillon [3] studied direct contact condensation in cold leg with the data from COSI test facility. They divided the entire cold leg to 3 condensation zones and assumed the vicinity of injection plays the most important role in the cold leg condensation. The condensation mechanism was modelled individually in the different condensation zone: the condensation on the jet surface was correlated using Stanton number, Froude number and ratio of jet length and cold leg diameter; the condensation in the vicinity of injection due to turbulence induced by the SI jet was correlated using Nusselt number, Prandtl number and safety injection Reynolds number; and the condensation due to downstream stratified cocurrent flow was correlated using Nusselt number, Prandtl number and cocurrent flow Reynolds number. This model was implemented into CATHARE reactor safety code.

Janicot and Bestion [4] did further theoretical study on the turbulence induced condensation in the vicinity of injection. A more accurate cold leg condensation model was developed from the Bestion and Gros d'Aillon's [3] model. The model was incorporated into the later version of CATHARE reactor safety code and validated against the COSI experiment data.

A Westinghouse cold leg condensation model was incorporated into NOTRUMP small break LOCA safety analysis code. The model assumes the majority of condensation occurs immediately around the zone of the injection point. The heat transfer outside the zone is much less significant. Another assumption in the model is that the shape of SI jet is an ideal cone without breaking. The cone spreading angle was derived using the theory of free turbulent jet. The model was also implemented into TRAC-PF1 code and assessed against COSI test data [5].

A cold leg condensation model was considered for the new release of WCOBRA/TRAC-TF2 safety analysis code and presented in a previous publication [6] by the authors. In this work, the cold leg condensation model is further improved to better capture relevant data and the revised model is found to be in better agreement with the COSI experimental data.

The revised model correlates Nusselt number with Reynolds number and Prandtl number in a form similar to the traditional forced convection heat transfer correlation,

$$\mathrm{Nu} = 0.245\,\mathrm{Re}_l^{1.1}\,\mathrm{Pr}_l^{0.6} \tag{1}$$

The coefficients are determined by best fitting with a subset of data from Westinghouse COSI test [6]. The Reynolds number and Prandtl number are defined with a reference bulk fluid temperature approximated by the median temperature between the SI liquid temperature and the saturation temperature. The revised model is incorporated into WCOBRA/TRAC-TF2 safety analysis code to calculate the direct contact condensation heat transfer rate from cold ECC water injection into the cold leg.

The purpose of this work is to describe the assessment of the cold leg condensation model in WCOBRA/TRAC-TF2 against an independent data set. The model is applied whenever the flow regime in the cold leg is predicted to be horizontal stratified flow regime, wavy-dispersed flow regime, or annular-mist flow regime, regardless of break size or pressure. Therefore, it becomes critical to assess the performance of the model not only for conditions for which the model was derived (COSI experiments) but also at lower pressure and higher flow rate, more typical of a large break LOCA.

The assessment on the cold leg condensation in small break LOCA is performed against experiments designed for small break LOCA, such as Westinghouse COSI experiment, Framatome COSI experiment, and ROSA SB-CL-05 experiment [7]. The assessment on the cold leg condensation of large break LOCA is based on UPTF Test 8A [8] and UPTF Test 25A [9], which are experiments designed for the cold leg condensation in a large break LOCA. It is noted that a subset of Westinghouse COSI data was employed to correlate the cold leg condensation model, and it was excluded from the assessment.

The experiment facilities utilized to validate condensation model are described in Section 2. Since the COSI test facilities were described in more detail on publications [3] [4] [6], Section 2 focuses on the ROSA and UPTF test facilities. The input model for WCOBRA/TRAC-TF2 and the calculation are briefly discussed in Section 3. The results of the validation are presented in Section 4. Section 5 is the conclusions.

2. Cold Leg Condensation Experiments

Five cold leg condensation test facilities are considered for the assessment of the code. Experiments Westinghouse COSI, Framatome COSI and ROSA SB-CL-05 cover the cold leg condensation in small break LOCA, while UPTF 8A and UPTF 25A experiments are designed to address large break LOCA scenario.

In this section, the test facilities designed for the cold leg condensation in small break LOCA are introduced, followed by the facilities for the cold leg condensation in large break LOCA.

2.1 Small break LOCA experiments

Westinghouse COSI

The Westinghouse Condensation On Safety Injection (COSI) facility was an approximately 1:100 scale model of the cold leg and safety injection line of a Westinghouse nuclear power plant (NPP). The facility of Westinghouse COSI was detailed in the previous publication [6].

The data series from the vertical injection (90°) tests in Westinghouse COSI experiment had been utilized to generate the cold leg condensation correlation, while the data series from the horizontal injection (45°) tests in Westinghouse COSI are part of assessment plan for the cold leg condensation model. The Westinghouse COSI horizontal COSI tests had characteristics of large SI line, 45° injection angle. The diameter of the horizontal injection port is larger than those in the vertical injection experiment. This larger diameter and the 45° injection angle cause the water to run only partially full in the SI pipe. The assessment of the Westinghouse horizontal injection COSI tests provides information on the capability of the WCOBRA/TRAC TF2 code with the SI pipe running partially full.

Framatome COSI

The Framatome COSI experiment shared the same test facility as the Westinghouse COSI experiment, but the test section was replaced by the Framatome test section featuring Framatome-type cold leg layout in NPP. The scaling factor of the Framatome COSI facility was the same as the Westinghouse COSI facility. Framatome COSI experiment provided cold leg condensation data at lower pressure, with a large range of SI temperature, and with counter-current flow (Inverse COSI).

ROSA IV SB-CL-05

ROSA IV is an integral effects test (IET) [10] facility for small break LOCA. The facility is a 2-loop test facility with a 1/48 volume scale of a typical Westinghouse 4-loop plant. The ROSA IV had the same major component elevations as the reference PWR plant. The ROSA IV equipment was controlled in the same way as that of the reference PWR to simulate long term reference PWR operational transients. Furthermore, the ROSA IV experiment was designed to be operated at the same high pressures and temperatures as the reference PWR. Figure 1 shows the structure of the ROSA IV. The major dimensions of ROSA facility are given by Reference [9].

The emergency core cooling system (ECCS) of ROSA consists of a charging pump, a high pressure injection (HPI) pump, two accumulator (ACC) tanks, and a low pressure injection (LPI/RHR) pump. In the ROSA IV experiments, ECCS pump flow rates, i.e., high pressure injection system (HPIS) and low pressure injection system (LPIS) simulated one of two pump's capacity for each system in the reference PWR.

A side view of the cold leg is shown in Figure 2. At the left side of cold leg is the reactor coolant pump, and the pressure vessel is at the right. The SI line was attached to the cold leg at 45° inclination angle. The directions of the flow are marked in Figure 2.

We are particularly interested on the analysis of ROSA SB-CL-05 [7] experiment with regards to the assessment of the cold leg condensation process in the cold leg. The ROSA SB-CL-05 was a small break LOCA test with 5% side break in the cold leg and high head safety injection. The purpose of this ROSA SB-CL-05 assessment is limited to the condensation in the cold leg as a separate effects test. Therefore, only the cold leg and SI injection portion in ROSA is modelled and simulated in the separate effects test. The effect of superheated steam on the cold leg condensation model is also assessed against ROSA SB-CL-05 data.

The estimated relative changes on pressure, saturation temperature, and SI flow rate all are slow compared with the condensation process. Thus, it is reasonable to assume the flow and condensation in the cold leg in a quasi-steady state. Only the intact loop is modeled for the cold leg condensation model.

To set up the steady state separate effects test, several instantaneous flow conditions in the cold leg are captured. The test data are available from 200 s to 400 s. Since the major issue to be addressed in the ROSA cold leg condensation SET is the treatment of steam superheating, and the steam superheating before 250 s is relatively small, the selection of instantaneous flow conditions is limited to 250 s to 400 s. There is accumulator injection after 400 s that provides the possibility of validating the cold leg condensation model regarding accumulator injection. However, accumulator injection is a highly transient flow, which violates the quasi-steady state assumption, therefore such data are excluded.

Compared with Westinghouse COSI experiment and Framatome COSI experiment, ROSA SB-CL-05 experiment has a larger cold leg diameter, higher steam and SI flow rate. Therefore, a validation against ROSA is important for the scaling and applicability of the cold leg condensation model. It is noted the steam in cold leg was saturated in the COSI experiments. However, ROSA tests showed the steam was superheated in steam generator before it entered cold leg during the boil-off stage. This provided the opportunity to assess the capability of the cold leg condensation model with superheated steam. Those reasons make ROSA SB-CL-05 an important part of the assessment matrix.

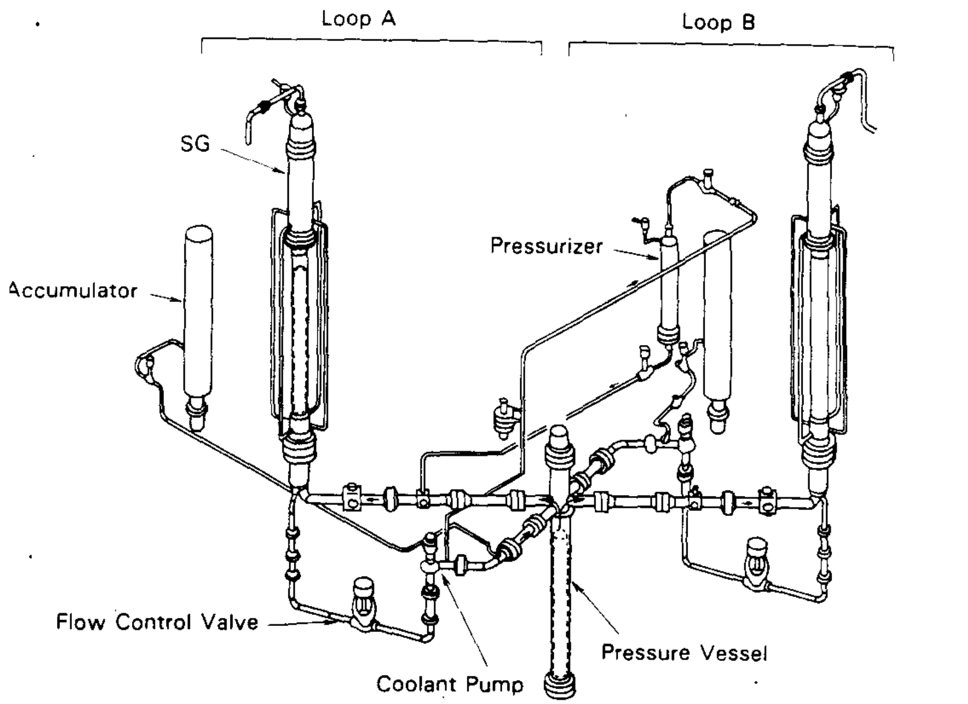

Figure 1 General structure of ROSA IV/LSFT SB-CL-05 [10].

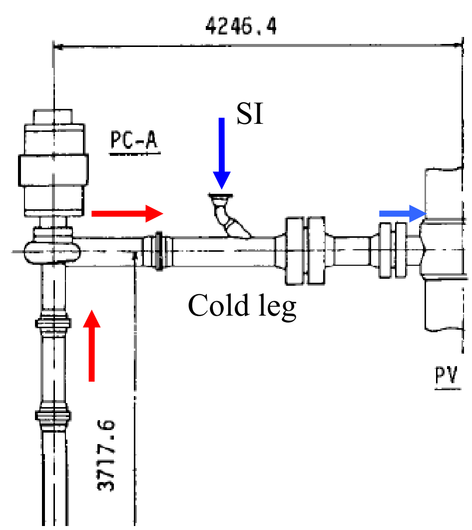

Figure 2 General structure of cold leg from crossover leg to downcomer [10].

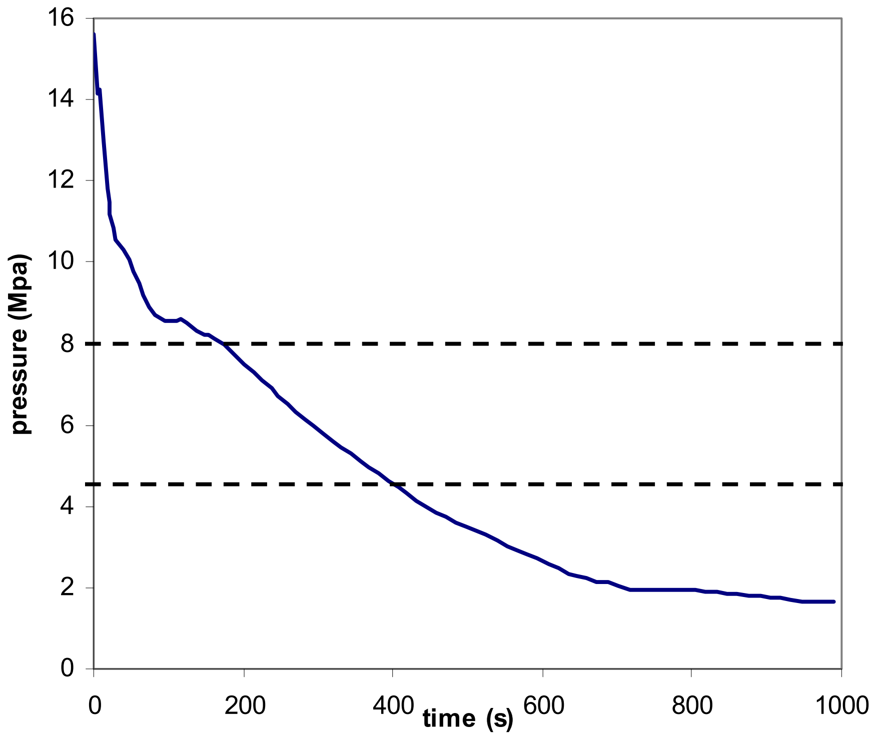

Figure 3 Pressurizer pressure transient in ROSA SB-CL-05 (Reference [7]).

2.2 Large break LOCA experiments

As part of the UPTF test matrix, two cold leg flow regime separate effects tests, Tests 8 and 25, were run to investigate steam/water flow phenomena in the cold legs during the refill/reflood phase of a large break LOCA. These phenomena include steam condensation on subcooled emergency core coolant (ECC) at different flow regimes (e.g., plug flow, stratified flow) in the cold leg. UPTF Test 8A [8] focused the flow regimes that might arise in the intact cold legs of a PWR during a postulated LBLOCA, when subcooled ECC liquid mixes with saturated steam. UPTF Test 25A [9] investigated the effects of steam flow rate and steam superheating.

UPTF Test 8A

UPTF was a full scale, low pressure separated effects test facility. Figure 4 shows the schematics of loop configuration for UPTF Test 8. The cold leg and test vessel upper plenum, lower plenum, and downcomer were geometrically similar to a Westinghouse 4-loop PWR. The components relevant to condensation in the cold leg are discussed in more detail below.

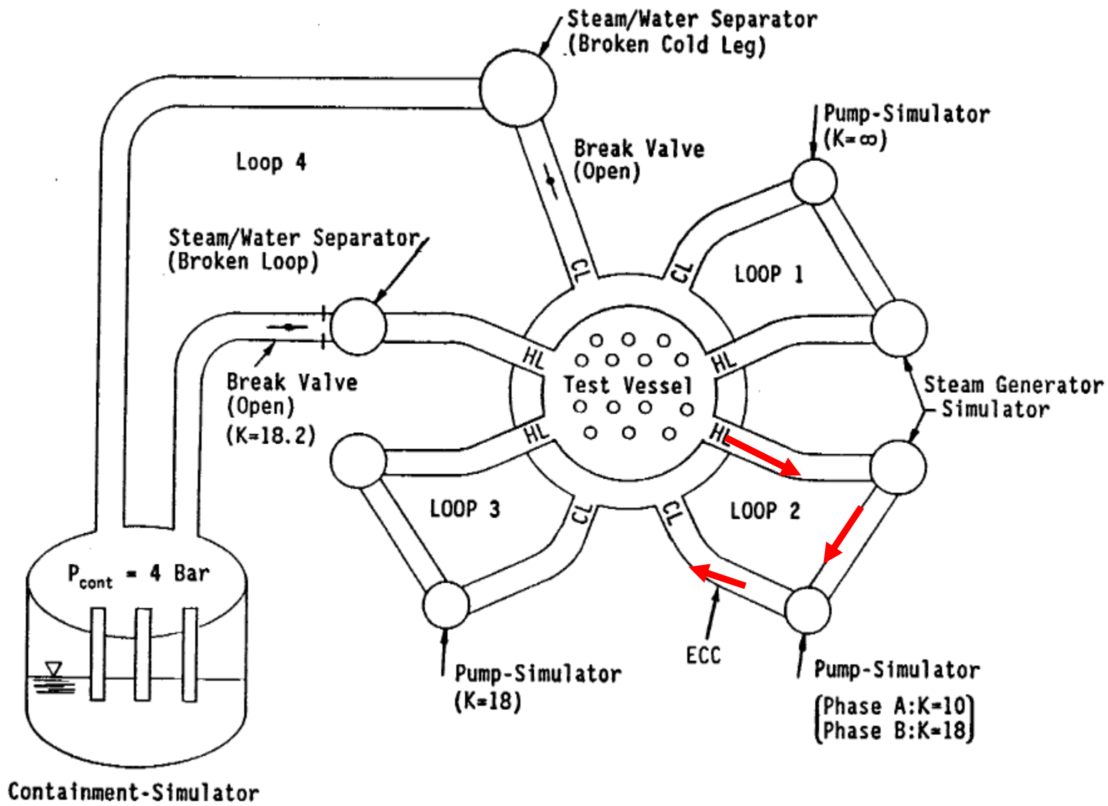

Figure 4 System configuration for UPTF 8. ECC water was injected to loop2 [11].

The cold leg flow regime tests focused on phenomena in the cold legs in the region of ECC injection. This region is bounded by the reactor coolant pump simulator and the test vessel downcomer as shown in Figure 5. The cold leg piping had an internal diameter of 750 mm (29.5 inches) and each loop was 9181 mm (30.1 feet) long from the reactor coolant pump simulator outlet to the inner surface of the test vessel wall at the downcomer. The diameter of safety injection line was 222.5 mm.

The distance from the ECC nozzle to the downcomer is 30% longer at UPTF than at typical PWRs. The ECC nozzle diameters are comparable with the UPTF nozzle diameter slightly smaller (by no more than 16%). The most significant difference is that UPTF used side injection whereas typical PWRs, generally use top injection.

During the blowdown and refill phases, the flow of accumulator water is of sufficient magnitude to theoretically condense all the steam flowing into the cold leg. During reflood the low head safety injection flow (LHSI/RHR), at its minimum levels, is typically insufficient to condense all the steam flowing into the cold leg.

The results of the UPTF cold leg flow regime separate effects tests indicate that plug flow only occurred when the condensation of the ECC exceeded the steam supply. At low steam flows, plug flow was unstable because the momentum of the steam flow was not sufficient to maintain the plug. The cyclic formation and decay of water plugs in unstable plug flow resulted in large pressure and flow oscillations. The test results also indicate that stratified flow always occurred when the steam supply exceeded the ECC condensation potential. In same cases, thermal stratification of the water layer in the bottom of the cold leg limited condensation to be less than its maximum value and prevented total consumption of the steam.

The loop steam flow was completely condensed for plug conditions and only partially condensed for stratified flow conditions. The condensation efficiency (the ratio of condensation heat transfer rate to the condensation rate that would bring liquid to saturation temperature), during stratified flow conditions ranged from 80 to 100%. The efficiency was higher as ECC flow decreased or as steam flow increased.

In UPTF Test 8, the steam was injected only in the core simulator and flowed through the loops. ECC was injected into the cold leg of Loop 2. The steam injection rate was relatively constant while the ECC flow rate was decreased in steps. Each ECC flow rate was maintained for about 30 seconds to allow for the steady-state conditions to be established. The ECC flow rates covered a range of flows expected in a PWR during a large break LOCA. UPTF 8 had two phases with essentially the same conditions; the difference being that the pump simulator K-factor in Loop 2 was higher for Phase B (Run 111) than Phase A (Run112). This condition resulted in a slightly lower Loop 2 steam flow in Phase B compared to Phase A.

The steam flow in Loop 2 was held approximately constant due to Loop 3 being open to maintain a constant differential pressure across the reactor coolant loops. Loop 2 steam flow was maintained between 31 and 38 kg/sec throughout the test.

UPTF Test 8 was conducted in two major phases, each with two parts. In the first part of each phase ECC was injected to the Loop 2 cold leg, and in the second part the ECC injection went to the hot leg. Since U.S. PWRs do not inject into the hot legs, and since the boundary conditions for Phase A (Run 112) and Phase B (Run 111) are similar, only the first part of Phase A (0~200s) is simulated with WCOBRA/TRAC-TF2. A summary of test boundary conditions for UPTF 8A is given in Table 1.

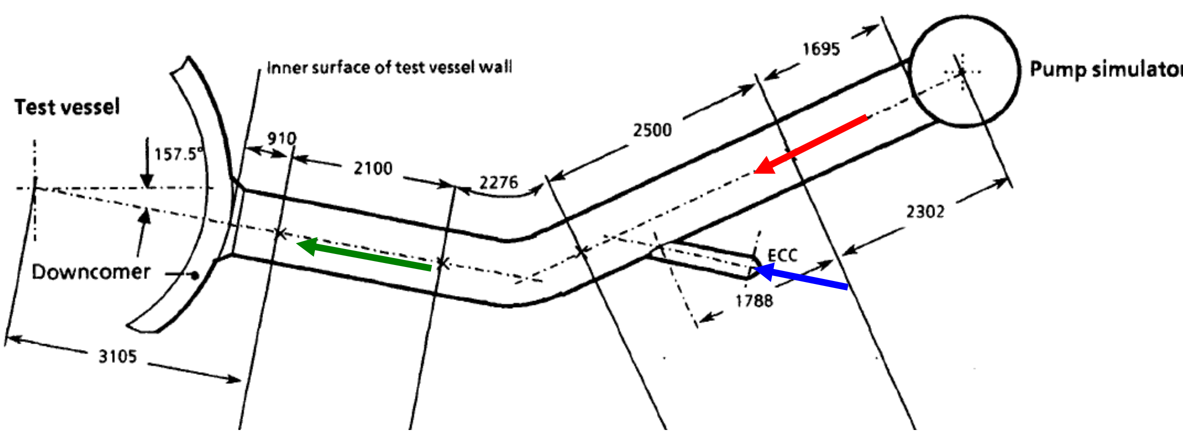

Figure 5 Cold leg piping region (top view) [11].

Table 1 Test boundary conditions of UPTF 8A [[8]]

Conditions	Subphase 1	2	3	4	5	6	7
Pressure (kPa)	405						
Saturation Temperature (°C)	144						
Core Simulator Steam Flow (kg/s)	110						
Loop Steam Flow Rate (kg/s)	31~38(1)						
Steam Temperature (°C)	145(2)						
ECC Flow (Parts 1-7) (kg/s)	600	400	250	200	150	90	15
ECC Subcooling (°C)	110						

Notes:
1. Estiamted steam flow rate in loop 2.
2. This steam temperature is cold leg inlet steam temperature. The nominal temperature of steam injection to core simulator is 201°C.

UPTF Test 25A

UPTF Test 25A [9] is another cold leg condensation test for the reflood stage of LBLOCA characterized with a variable steam flow rate and a substantial steam superheating. Figure 6 shows the system configuration of UPTF Test 25A.

The test was conducted in two phases, Phase A (consisting of sub-phases Ia, Ib, II, III, and IV) and Phase B (not considered for this study). In the test, steam was injected to the steam generator simulators and the vessel water level was maintained to achieve a water seal. Only the cold leg break valve was opened, forcing all the steam to flow through the cold legs, into and around the downcomer, and out the broken cold leg. ECC was injected to the cold legs, while the steam flow was established by injecting steam in the steam generator simulators. A summary of test boundary conditions for UPTF 25A is given in Table 2.

Table 2 Test Boundary Conditions of UPTF 25A [9]

Condition	Part Ia	Ib	II	III	IV
Initial Pressure (bar)	2.8	2.8	2.8	2.6	2.6
Steam Injection Flow/Loop (kg/sec)	31.0	31.0	26.0	21.0	16.0
ECC Injection Flow/Loop (kg/sec)	80.0	80.0	80.0	80.0	80.0
ECC Temperature (°C)	30	30	30	30	30
Vessel Drainage Rate (kg/sec)	0	102	124	109	133
Time Periods (s)	80-160	160-240	240-360	520-650	650-750

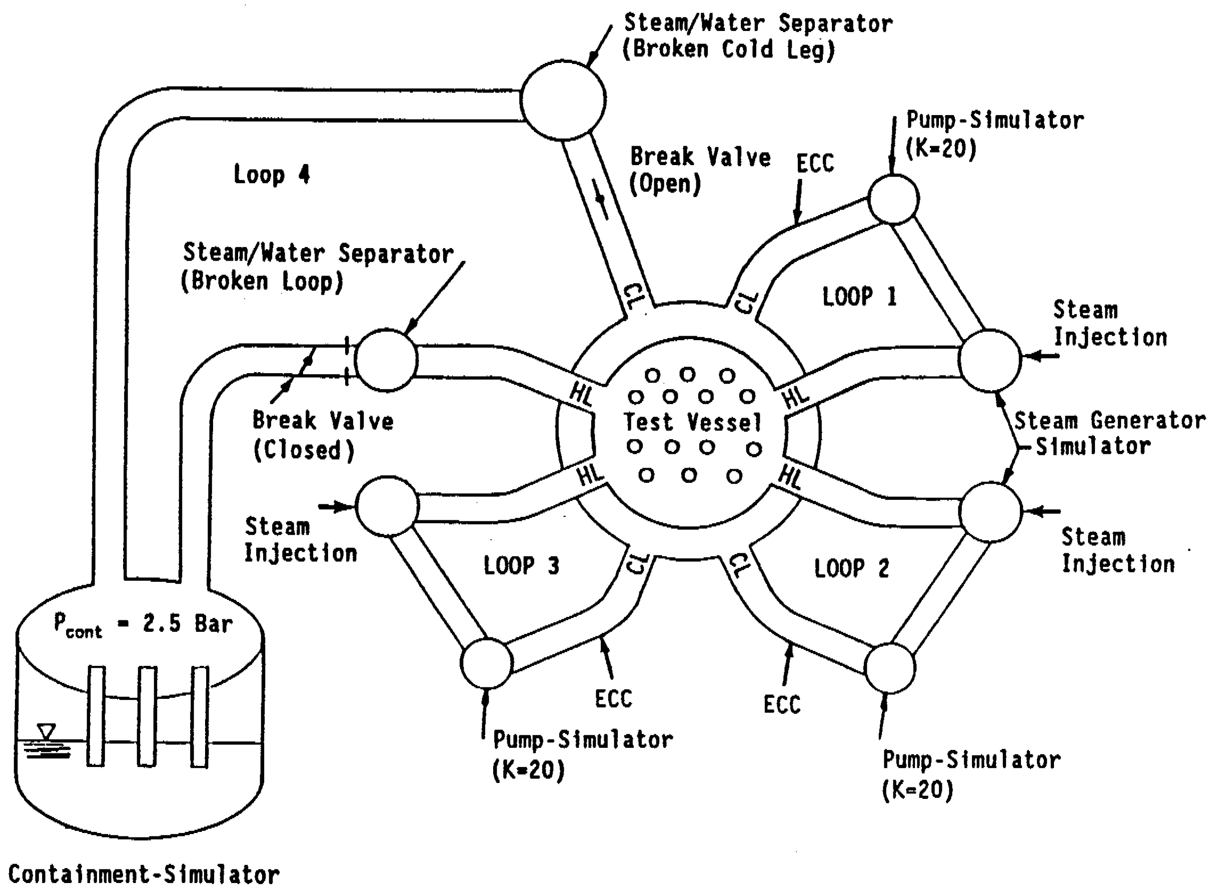

Figure 6 System configuration for UPTF-25A.

3. WCOBRA/TRAC-TF2 Input Model

For the Westinghouse COSI facility and the Framatome COSI facility, only the cold leg portion of test facilities is relevant to cold leg condensation simulation, which is modelled using a single TEE component. The main branch of TEE component represents the cold leg with total 7 nodes, and the side branch of TEE component represents the SI line. A FILL component provides steam flow into the cold leg. SI water is injection to the side branch of TEE via another FILL component. The BREAK component controls pressure in the system. It is noted that the input model for the Framatome Inverse COSI tests utilizes two TEE components to properly model counter-current flow in cold leg. The diameters of cold leg and SI line are consistent with the data in test report. Only the scaled length of cold leg is modelled. The boundary conditions, such as pressure, steam flow rate, SI water flow rate and fluid temperature are obtained from the experimental measurements. Similar single TEE modeling approach is also applied to ROSA SB-CL-05 SET input.

For UPTF 8A and UPTF 25A experiments, since the complication of the flow regime in the cold leg and steam flow distribution to cold legs, the response of entire loop and reactor internal is rather important. Thus, the UPTF 8A input model and UPTF 25A input model include both vessel and loop structure of UPTF test facility.

4. Results

The results of simulating Westinghouse COSI tests, Framatome COSI tests, ROSA IV SB-CL-05 SET, UPTF 8A test and UPTF 25A test are presented in this section.

For Westinghouse COSI, Framatome COSI and ROSA IV SB-CL-05, the results are presented as a comparison between the predicted condensation rate and the measured condensation rate. The condensation rate in Westinghouse COSI and Framatome COSI is calculated using the boiler power and estimated heat loss. The condensation rate in SB-CL-05 is reduced from SI flow rate, SI temperature and measured water temperate at the exit of cold leg. The predicted water temperatures of UPTF 8A and UPTF 25A simulations are compared against thermocouple measurement along the several locations in the cold leg throughout the transient.

Small Break LOCA

The comparison between the calculated condensation heat transfer rate and the measure heat transfer rate for Westinghouse COSI tests is shown in Figure 7. The simulation includes both vertical injection tests and horizontal injection tests. All the predicted Westinghouse COSI condensation heat transfer rates are inside ±25% error bar. These prove the accuracy of Westinghouse cold leg condensation model in WCOBRA/TRAC-TF2 code. The cold leg condensation model in the WCOBRA/TRAC-TF2 code tends to over-predict the condensation heat transfer rate for the vertical injection tests and under-predict the condensation heat transfer rate for the horizontal injection tests. The difference is likely attributed to SI pipe line running partially full in the horizontal injection tests.

The comparison between the calculated condensation heat transfer rate and the measure heat transfer rate for the Framatome COSI tests is shown in Figure 8. Most of the predicted Framatome COSI condensation heat transfer rates are inside ±25% error bar. The low pressure data confirms the good performance of the cold leg condensation model. Although the cold leg condensation model does not explicitly incorporate the counter-current flow condition, the predicted condensation heat transfer rates of the inverse COSI tests are also in good agreement with the experimental data. Two high SI temperature tests are predicted slightly above 25% error bar, which is considered acceptable. Another over-predicted point is a low SI temperature co-current flow test. In general, the WCOBRA/TRAC-TF2 predictions for the cases with high SI temperature and low system pressure are in good agreement with the data.

The comparison between the calculated condensation heat transfer rate and the measure heat transfer rate for ROSA SB-CL-05 cold leg condensation test is shown in Figure 9. All the predicted ROSA SB-CL-05 SI condensation heat transfer rates are within ±25% accuracy relative to the data. It is noted that the ROSA facility has a larger length scale as compared to the COSI facility. There is also the effect of steam superheating in the ROSA tests. The comparison shows that WCOBRA/TRAC-TF2 adequately predicts cold leg condensation in a larger scale facility and the effect of the steam superheating is properly accounted for. The heat transfer rates tend to be under-predicted.

In the simulation, the steam superheating is a constant upstream of the safety injection and the steam superheating gradually decreases downstream of the safety injection. This generally matches the steam behavior in the boiloff stage in the ROSA SB-CL-05 data report, which shows that the steam temperature steam gradually decreases without sudden de-superheating, from the inlet of the intact cold leg, to the downstream of the SI injection point, then to the vessel side of the intact cold leg, and finally to the top of the downcomer.

In general, the comparison with SBLOCA experimental results shows that the code is able to predict condensation rates within a reasonable range of uncertainty. The accuracy of the WCOBRA/TRAC-TF2 results is judged to be adequate over a range of scales, system pressures, SI flow rates, SI temperatures, and steam superheating. In the presence of steam superheating, the cold leg condensation model reduces the steam temperature gradually. In the cases of high SI temperature, WCOBRA/TRAC-TF2 marginally over-predicts the condensation heat transfer rate, but the results are acceptable.

The uncertainty range of the cold leg condensation model is identified by comparison between the predicted the measured condensation heat transfer rate of SBLOCA simulations. The uncertainty of cold leg condensation is applied to the SBLOCA region in the FSLOCA methodology.

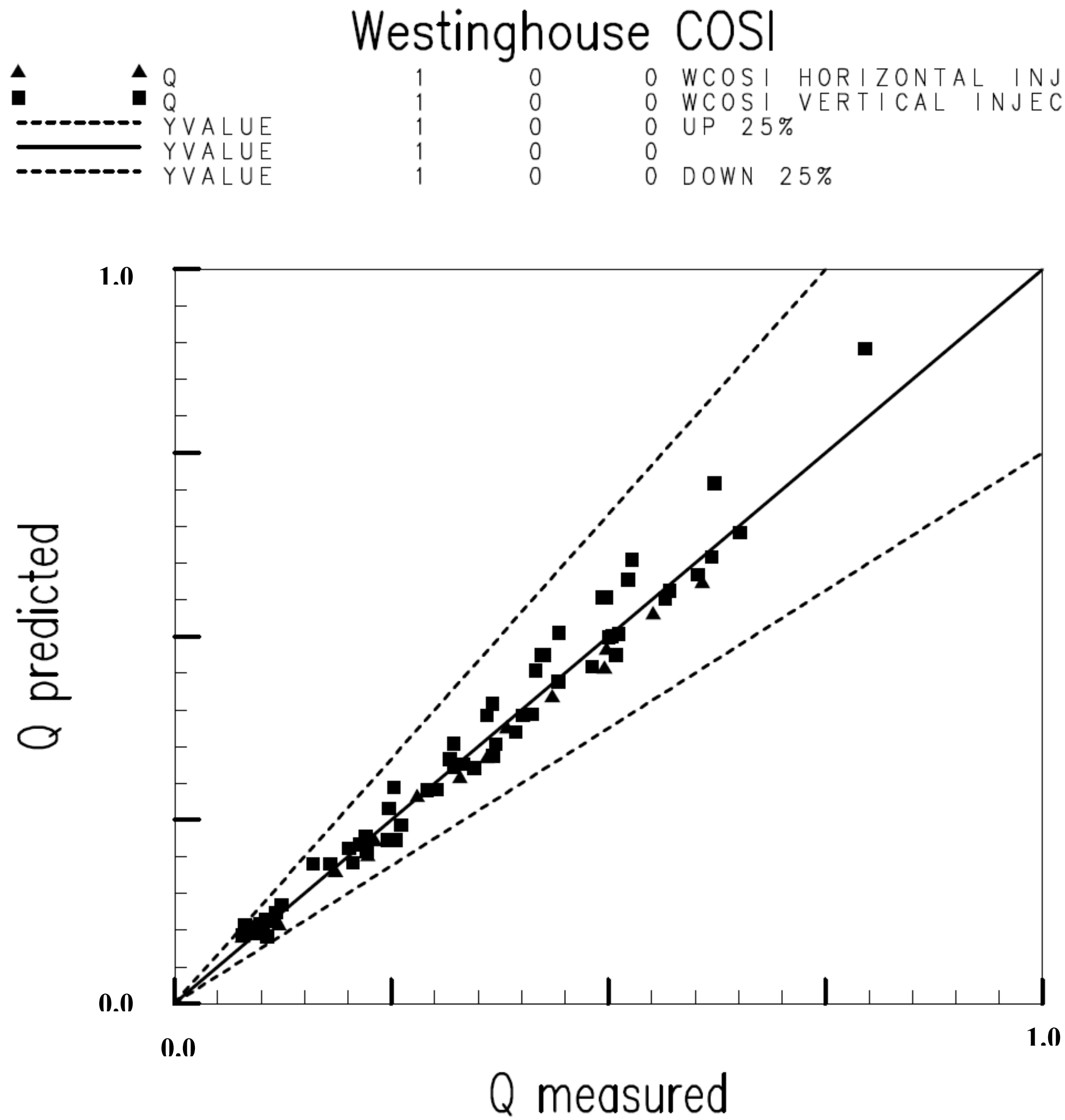

Figure 7 Comparison between the predicted condensation heat transfer rate and the measured condensation heat transfer rate in Westinghouse COSI experiments. Note, condensation heat transfer rate is normalized.

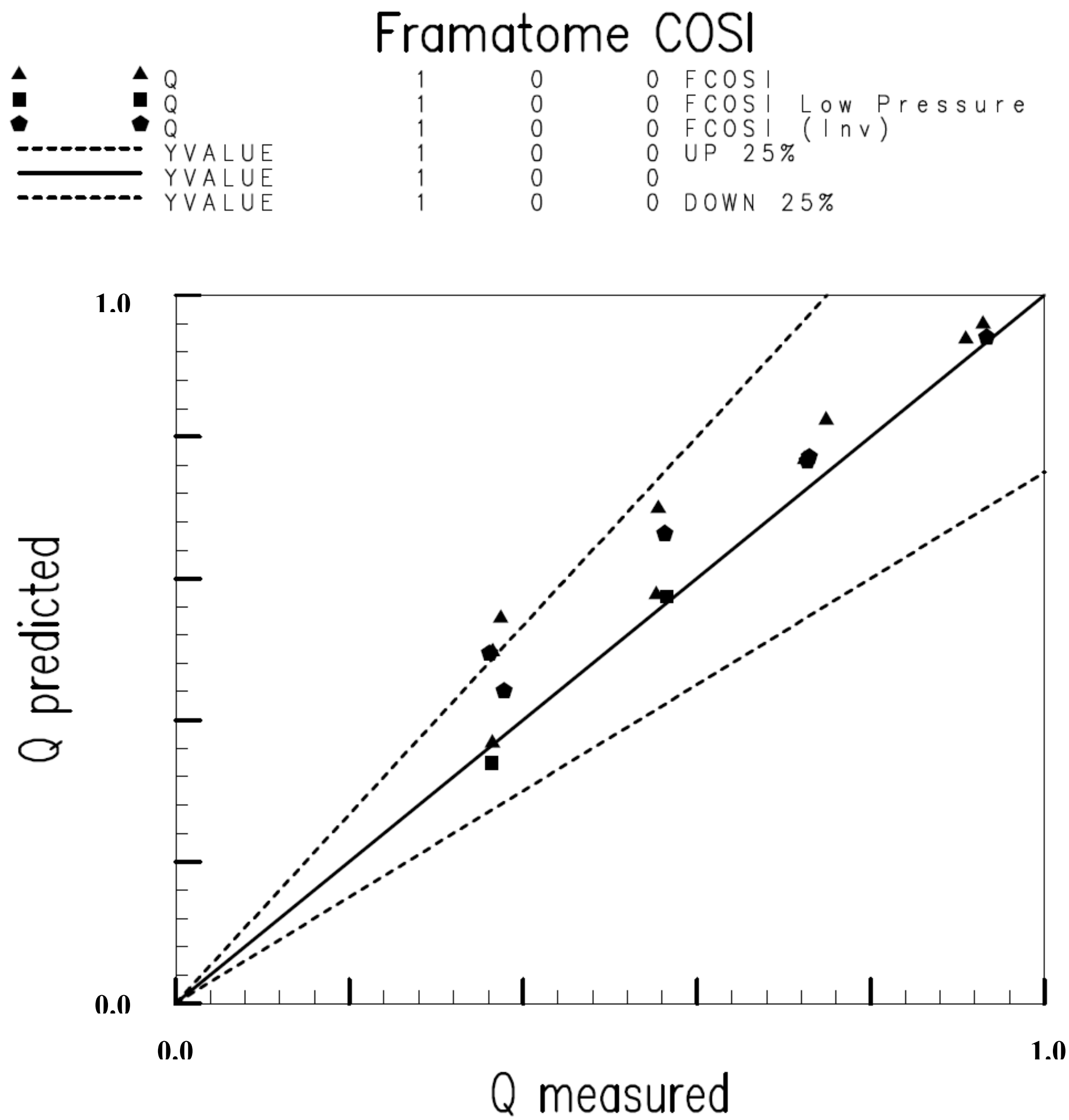

Figure 8 Comparison between the predicted condensation heat transfer rate and the measured condensation heat transfer rate in Framatome COSI experiments. Note, condensation heat transfer rate is normalized.

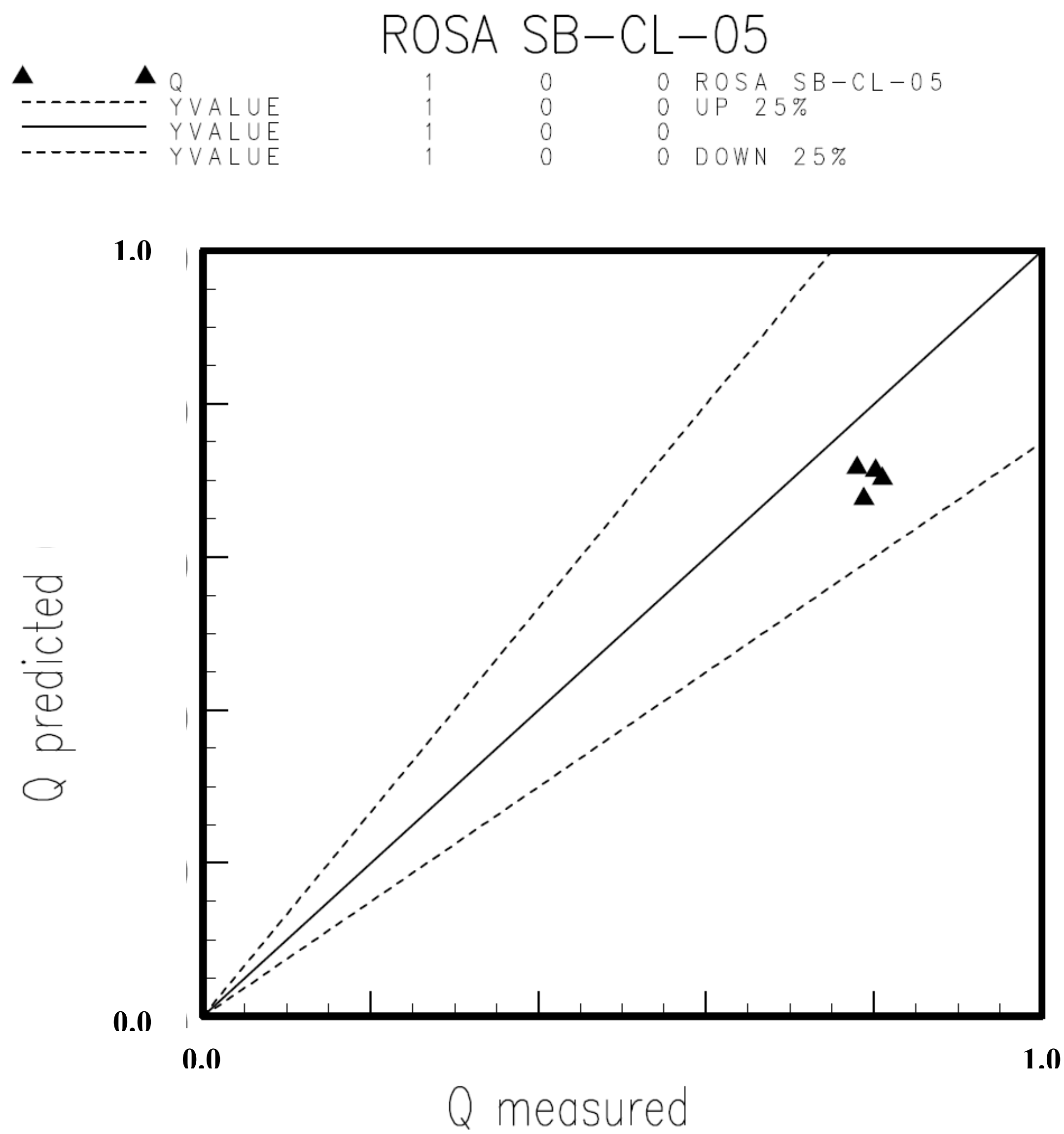

Figure 9 Comparison between the predicted condensation heat transfer rate and the measured condensation heat transfer rate in ROSA SB-CL-05 experiments. Note, condensation heat transfer rate is normalized.

Large Break LOCA

The WCOBRA/TRAC-TF2 simulation of UPTF Test 8A was run for the first 200 seconds of the test, which covered the period where flow was injected into loop 2 intact cold leg. The as measured injection flow rates were used as boundary conditions in the WCOBRA/TRAC-TF2 model.

The measured and predicted temperatures in the loop 2 cold leg are compared in Figures 10 through 12. In the experiment, at the pump exit, the steam entered the cold leg at saturation temperature with some oscillations as shown in Figure 10. The oscillation of the measured temperature likely was caused by the intermittent dry out and rewetting of thermocouples [11].

Figure 11 shows the measured temperature and the predicted water temperature immediately downstream the injection point, which is node 4. During stages 1 through 3, the ECC flow condensed most of the steam from the upstream and flow is expected to be in bubbly/bubbly-slug regime. The lower bound of the measured temperature is representative of the actual water temperature, while the saturation temperature in the cold leg can be inferred from Figure 10. WCOBRA/TRAC-TF2 predicts all steam to be condensed and flow regime to be bubbly/bubbly-slug flow. There is a good match between the measured temperature and the predicted water temperature immediately downstream the injection point for the stages 1 through 3 as shown in Figure 11. During stages 4 to 6, thermal stratification was recorded and the lower bound of the measured temperature represents the actual water temperature. The measured saturation temperature in the plot is the result of the vapor in a slug flow or a stratified flow, in which the dryout time period for the thermocouples is long enough to reach thermal equilibrium state. The water temperatures at the stages 4 through 6 are slightly over-predicted near the injection point.

Figure 12 shows the comparison between the measured temperature and the WCOBRA/TRAC-TF2 predicted water temperature downstream of the injection point (node 5). The vapor is completely condensed for stages 1, 2, and 3, and the measured temperature indicates water temperature with only a little oscillation. Again the lower bound of the measured temperature shows the actual water temperature, which is higher than the water temperature in the injection point. The predicted water temperatures match well with the test data in stages 1 through 3, but slightly over-prediction exists for stages 4 through 6.

Figure 13 shows the comparison between the measured temperature and the WCOBRA/TRAC-TF2 predicted water temperature at the cold leg near the vessel inlet. It is shown that the water temperature rose further from node 5, especially in stages 4 to 6, because the two phase flow downstream the injection point allows for additional interfacial heat/mass transfer. Relative to the measured temperature, the water temperature is predicted well for all the stages except stage 4. The predicted bubbly flow downstream of the injection point in stage 4 likely leads to a strong condensation in additional to the heat transfer predicted by the cold leg condensation model (see the following discussion on the flow regime in the cold leg).

In addition, the predicted steam condensation rate in loop 2 cold leg is compared with the estimated steam condensation rate by MPR [11]. The steam condensation rate is defined as the steam flow rate difference between the inlet and the exit of cold leg. Figure 14 shows the predicted values match well with the measured values from ECC flow rate of up to 500 kg/s. Note, the measured steam condensation rate is larger than the actual inlet steam flow rate at ECC flow rate of 600kg/s.

To facilitate the understanding on the hydraulics and interfacial mass/heat transfer in the cold leg during the condensation in UPTF 8A, the flow regimes are studied. Figure 15 showed the estimated water distribution in cold leg 2 in the UPTF 8A test by MPR [11] together with predicted liquid fraction in cold leg 2. A reasonable match on the liquid fraction in the cold leg in UPTF 8A test is achieved.

The WCOBRA/TRAC-TF2 calculated transient corresponding to the UPTF Test 25A simulation is run for nearly the entire 900 seconds of the test. The measured and predicted fluid temperatures in the loop 2 cold leg are compared in Figures 16 through 18. Figure 16 shows the comparison between the measured temperature and the WCOBRA/TRAC-TF2 predicted water temperature at the ECC injection point. The measured temperature profiles from the top of cold leg to the bottom of cold leg indicate a stratified flow pattern in all sub-phases, with superheated steam at the top and subcooled water at the bottom. The fluid temperature drops from sub-phase I to sub-phase IV as the steam flow rate reduces in a stepwise manner. The predicted liquid temperature shows the same trend from sub-phase I to IV. However, the predicted value is higher than the measured temperature at the bottom of cold leg.

Figure 17 shows the comparison between the measured temperature and the TF2 predicted water temperature downstream of the injection point. Thermocouples were wetted by the liquid during the experiment and showed saturated or subcooled temperature. The measured liquid temperature at the bottom of cold leg increased substantially from measured temperature at the ECC injection point, which implies further condensation downstream of the ECC injection point. The predicted fluid temperature agrees well with the measured temperature in sub-phases I and II. The liquid temperature in sub-phase III and IV are over-predicted compared with the measured temperature at the bottom of the cold leg.

Figure 18 shows the comparison between the measured temperature and the WCOBRA/TRAC-TF2 predicted water temperature at the cold leg near the vessel inlet. It is shown that the water temperature rose further for all four sub-phases. WCOBRA/TRAC-TF2 gives a good prediction of fluid temperature at the exit of cold leg for sub-phases I to III. The over-prediction of condensation in sub-phase IV results in a lower steam flow rate to the downcomer. The over-prediction of condensation in sub-phase IV leads to low void height in the intact side and high void height in the broken side.

Generally, the WCOBRA/TRAC-TF2 simulation of UPTF 8A shows flow pattern in the cold leg is reasonably predicted. A good agreement between the predicted water temperature and the experimental data is achieved except stage 4. For UPTF 25A, WCOBRA/TRAC-TF2 predicted cold leg temperature and break flow rate agree well with measured value except sub-phase IV.

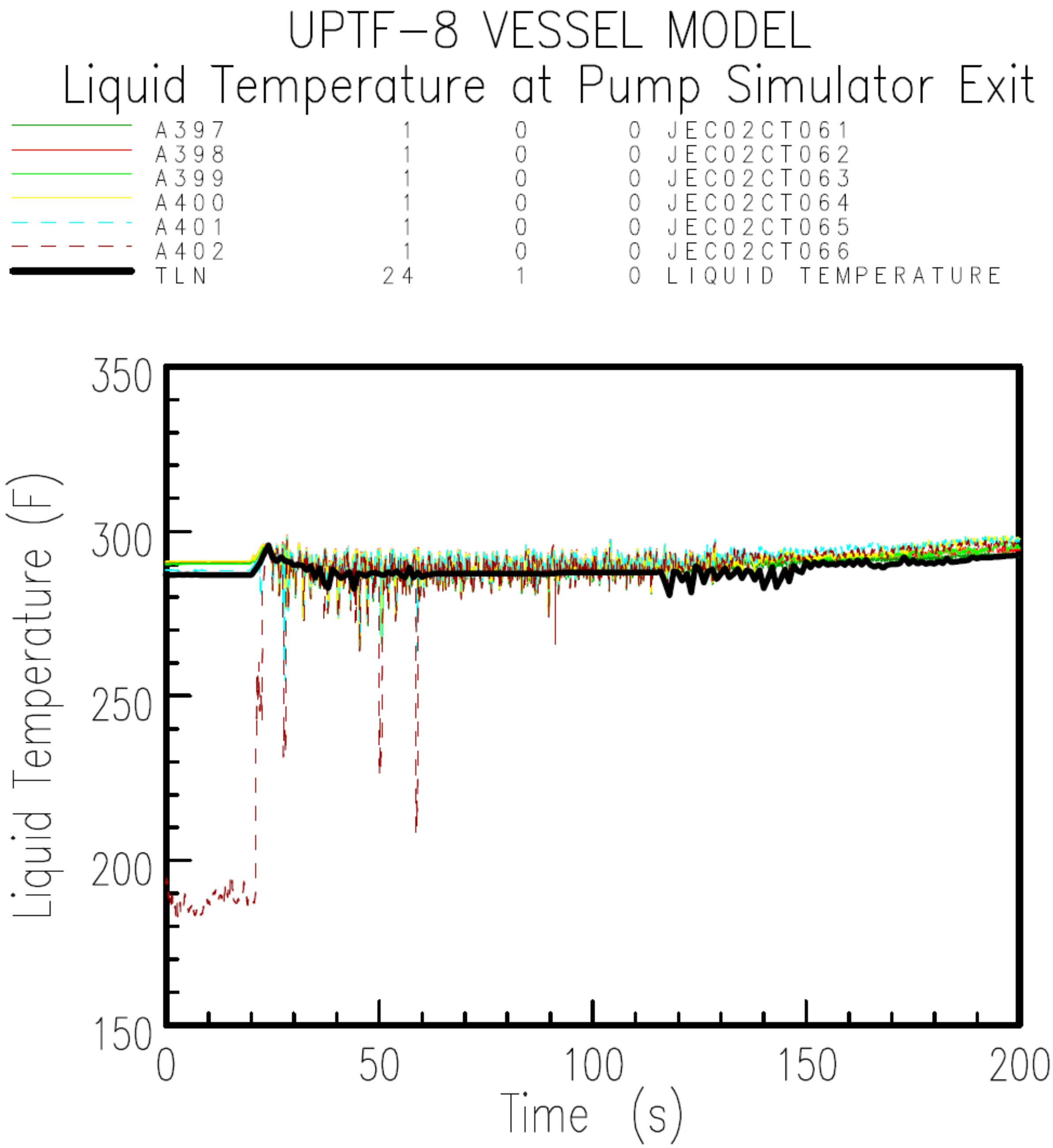

Figure 10 Comparison between the predicted water temperature and the measured water temperature in cold leg at the pump exit. TLN is the predicted water temperature.

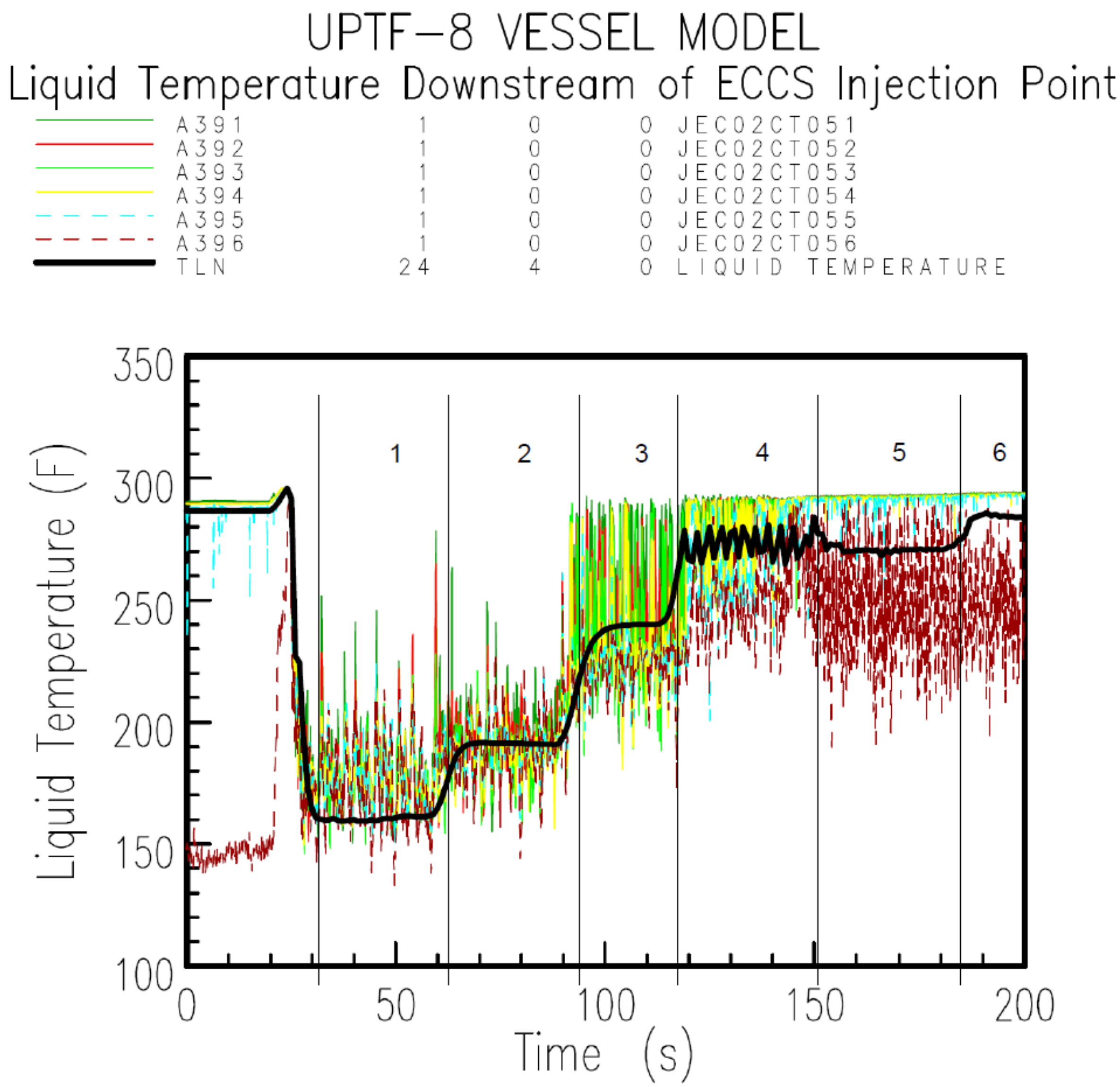

Figure 11 Comparison between the predicted water temperature and the measured water temperature in cold leg near SI injection in UPTF 8 Run 112 experiment. TLN is the predicted water temperature.

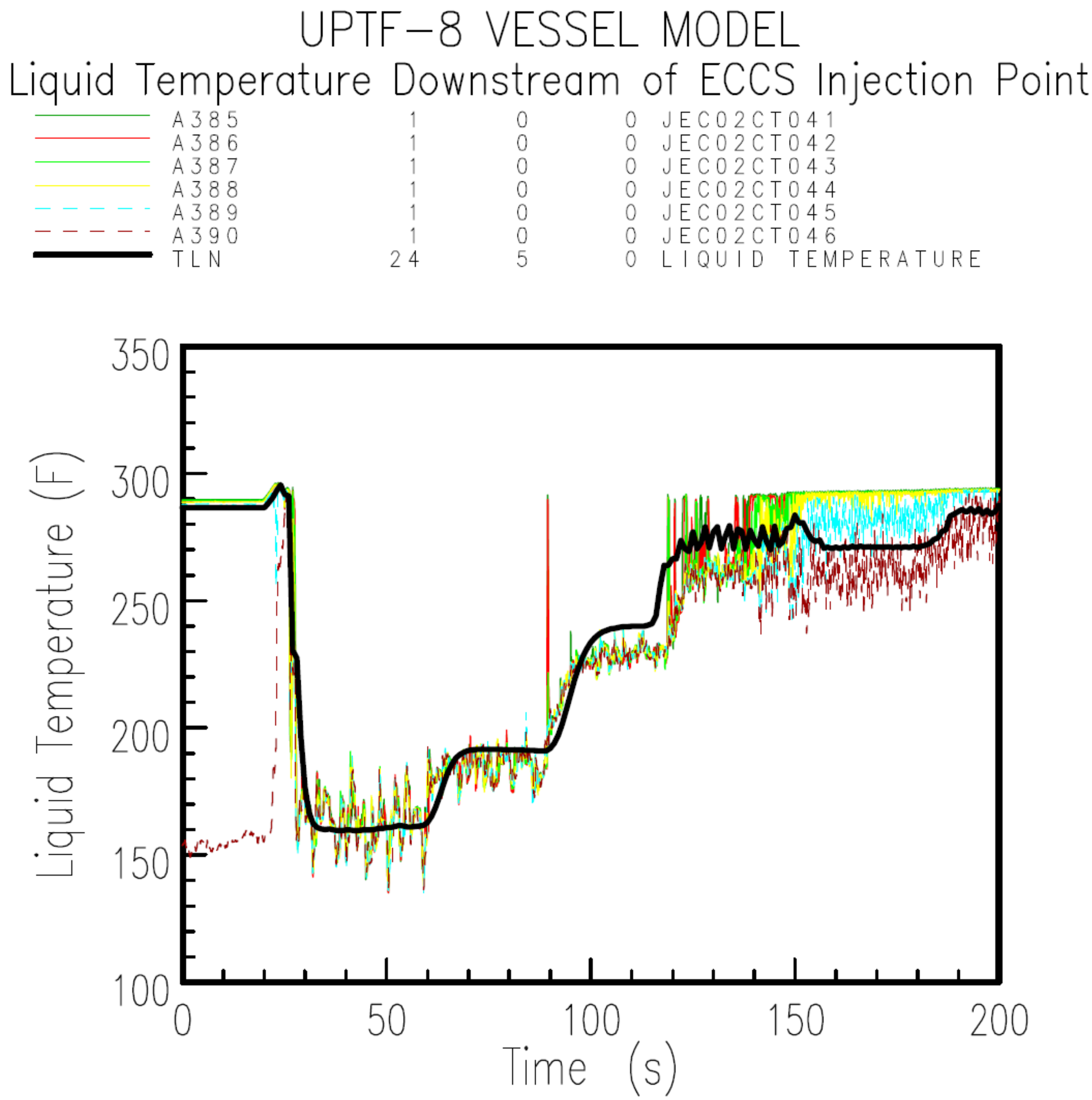

Figure 12 Comparison between the predicted water temperature and the measured water temperature in cold leg downstream of SI injection in UPTF 8 Run 112 experiment. TLN is the predicted water temperature.

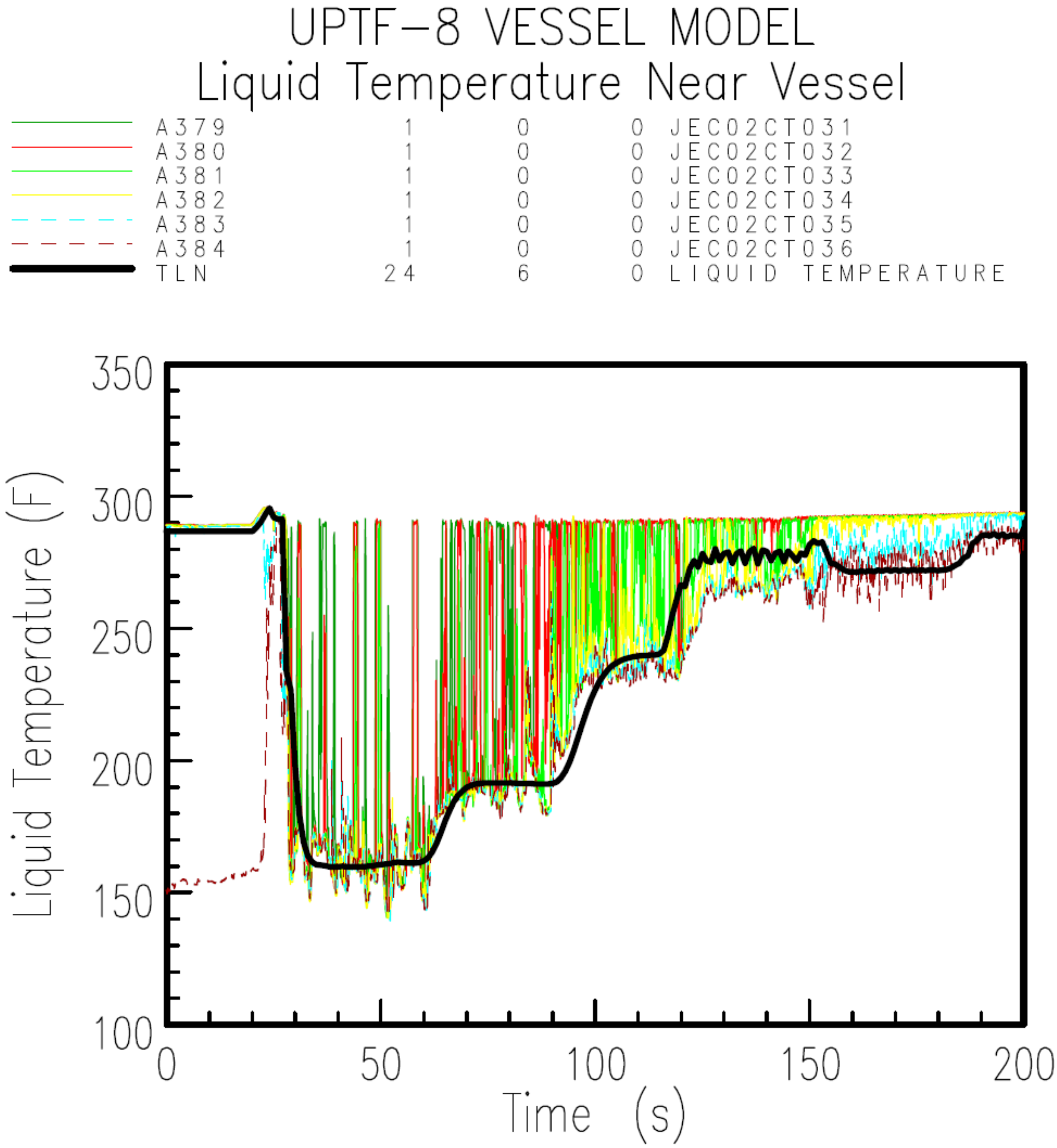

Figure 13 Comparison between the predicted water temperature and the measured water temperature at the exit of cold leg in UPTF 8 Run 112 experiment. TLN is the predicted water temperature.

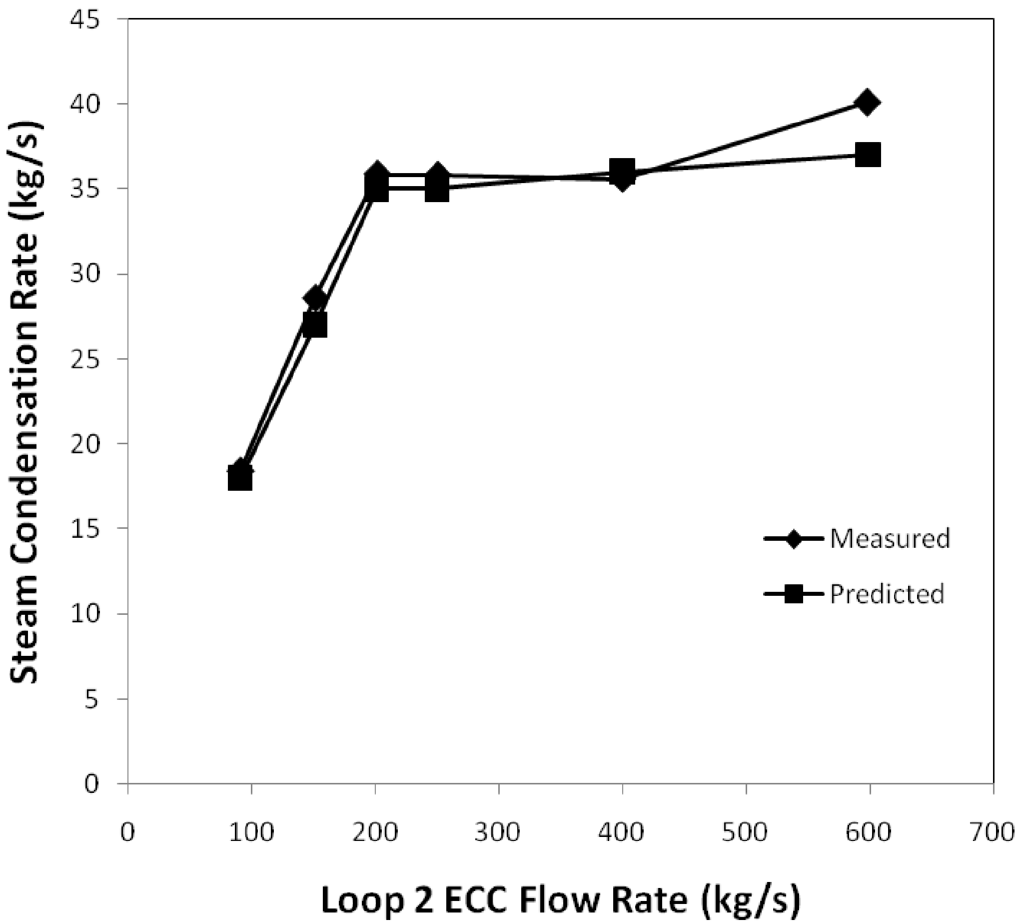

Figure 14 Comparison between the predicted steam condensation rate and the measured steam condensation rate in UPTF 8 Run 112 experiment. The ECC flow rate points (100kg/s to 600kg/s) correspond to UPTF8A stages 6 through 1.

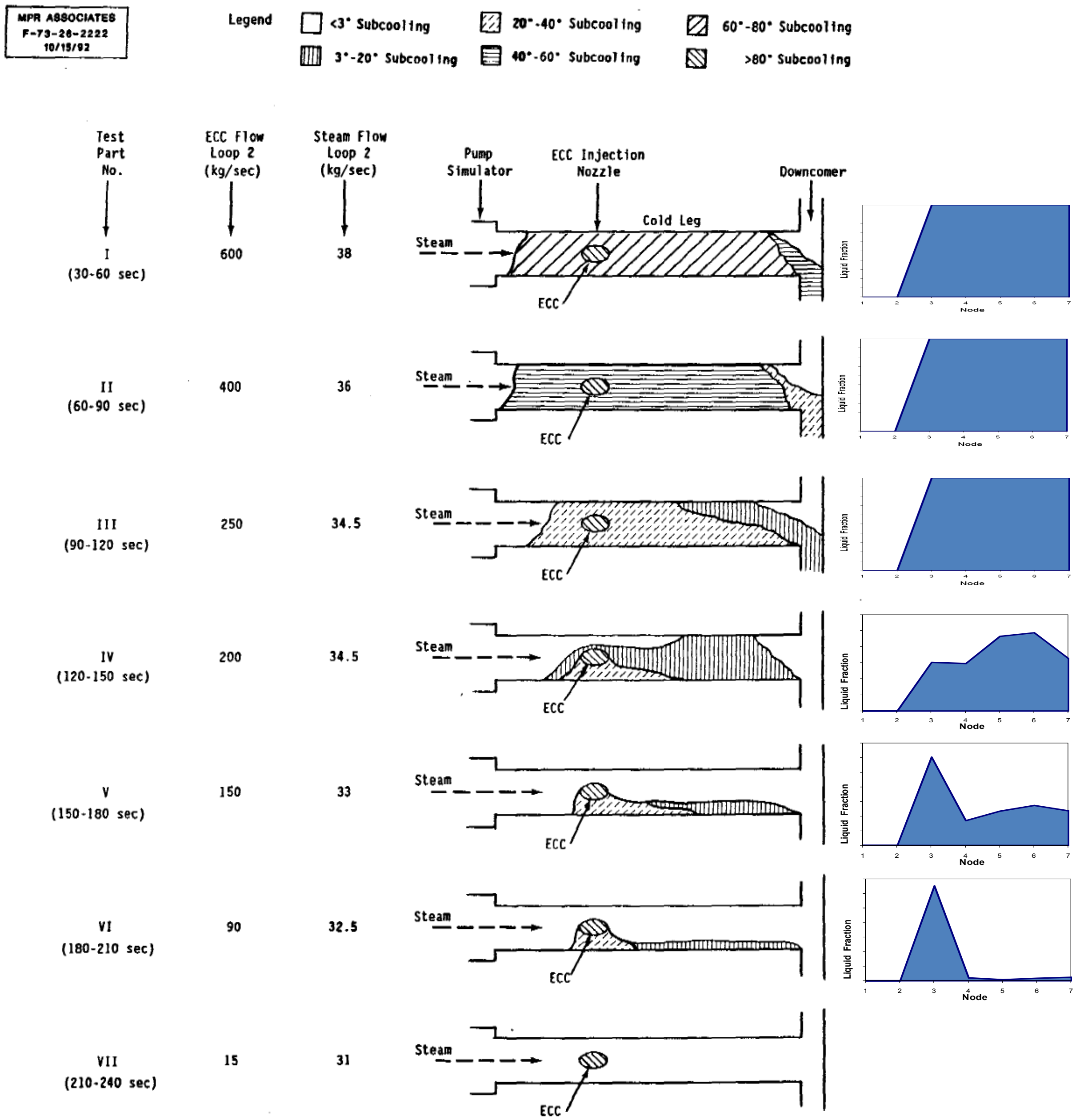

Figure 15 Observation on temperature distribution in UPTF 8A experiment [11] and comparison with predictions from WCOBRA/TRAC-TF2.

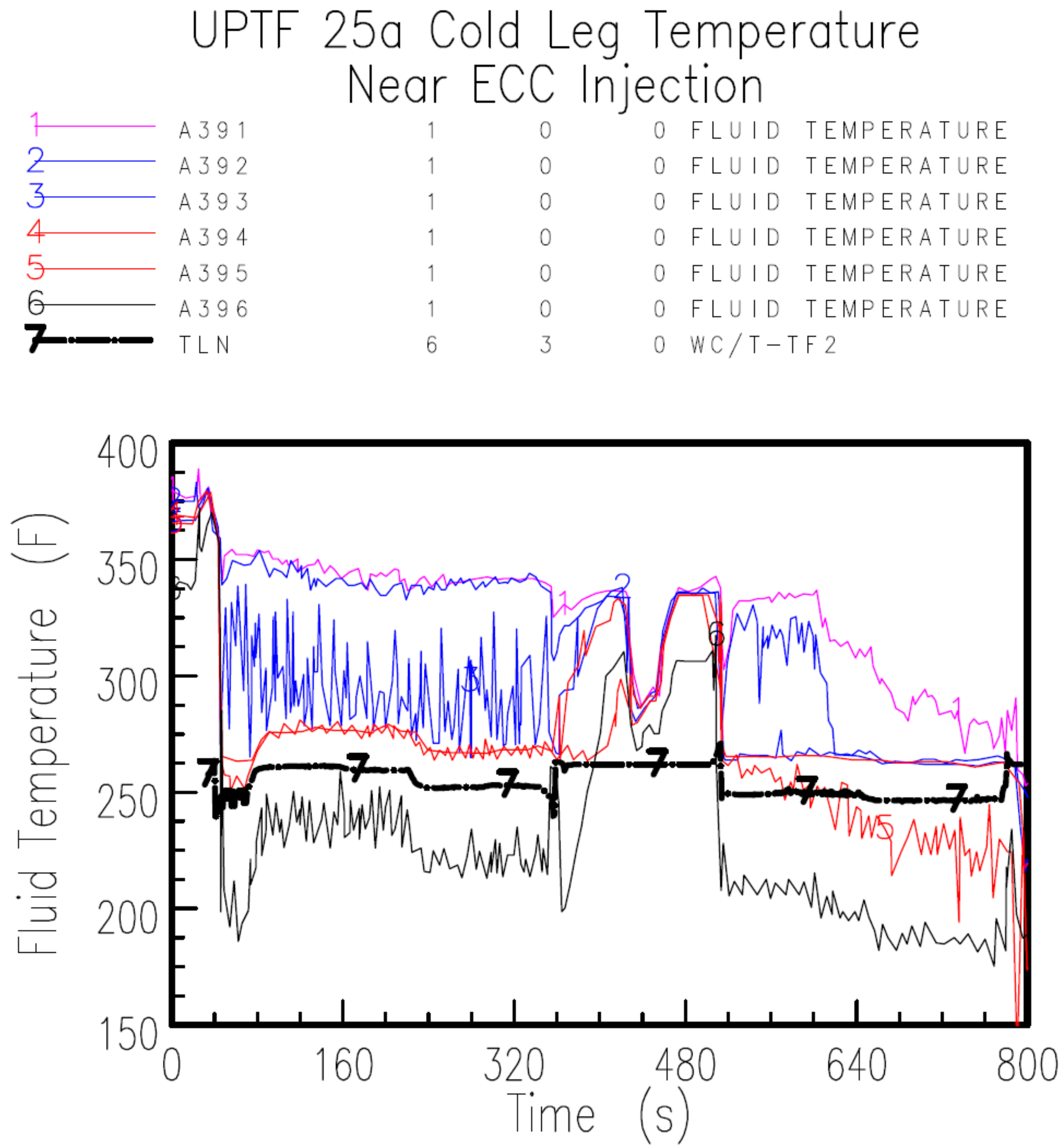

Figure 16 Comparison between the predicted water temperature and the measured water temperature near ECC injection in UPTF 25A experiment. TLN is the predicted water temperature.

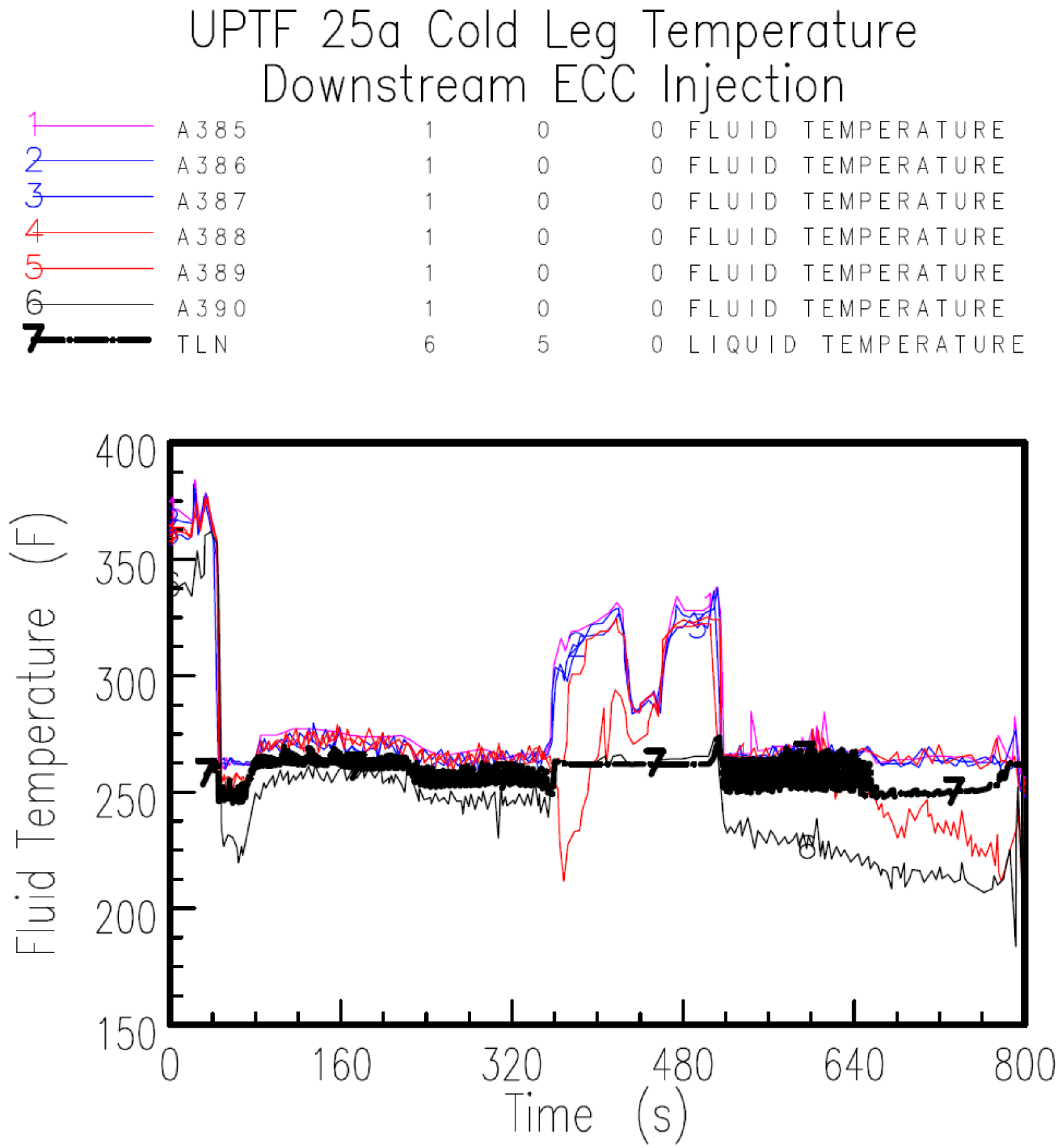

Figure 17 Comparison between the predicted water temperature and the measured water temperature downstream ECC injection in UPTF 25A experiment. TLN is the predicted water temperature.

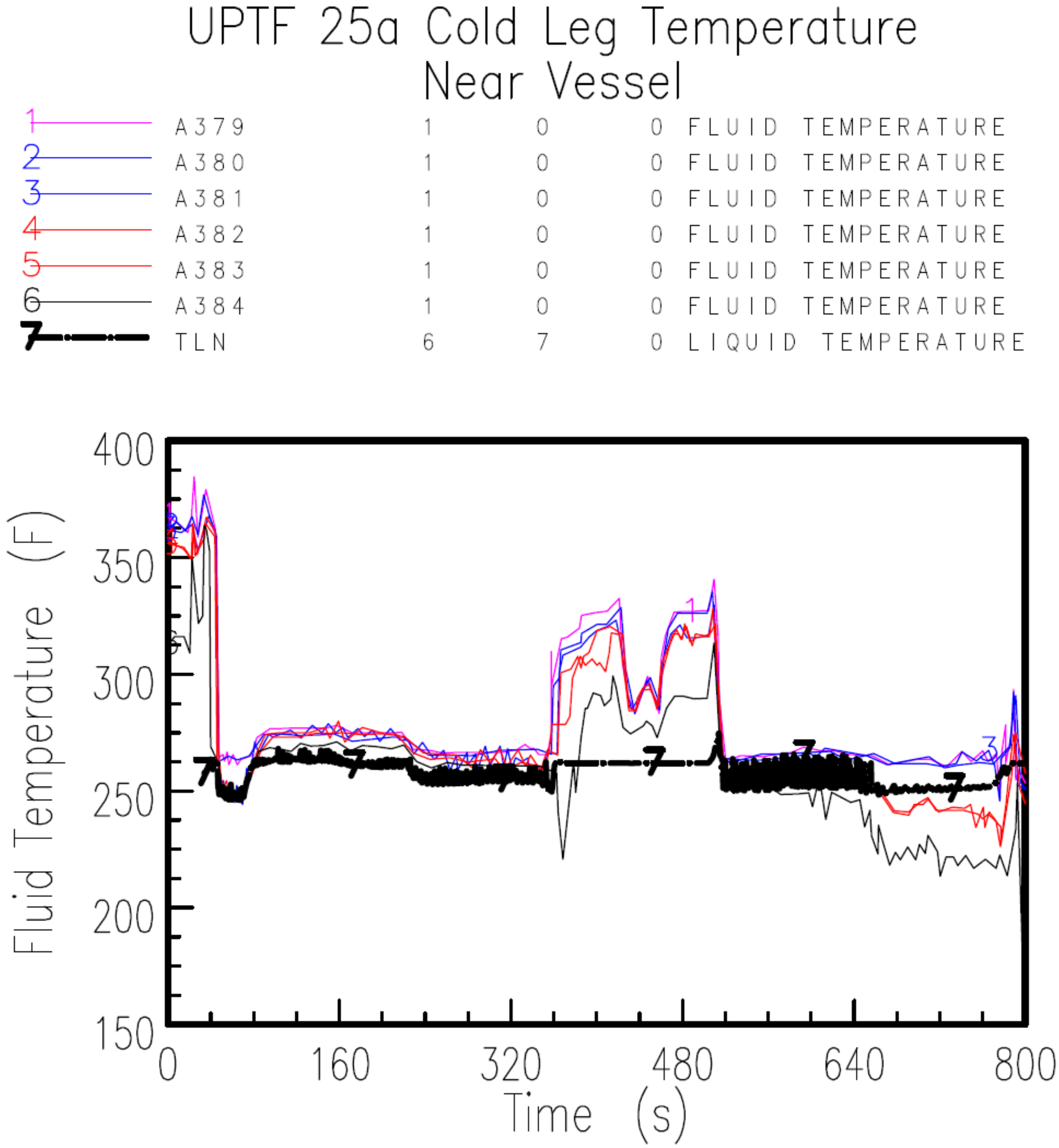

Figure 18 Comparison between the predicted water temperature and the measured water temperature at the exit of cold leg in UPTF 25A experiment. TLN is the predicted water temperature.

5. Conclusions

The direct contact condensation in cold leg due to ECC injection is an important phenomenon for both small break and large break LOCA. This work reviewed current cold leg condensation models in various reactor safety analysis codes. A revised cold leg condensation model is developed to better capture relevant test data. The new correlation is implemented in the latest version of WCOBRA/TRAC-TF2 reactor safety analysis code and assessed against experimental data representative of both small break and large break LOCA conditions, namely Westinghouse COSI, Framatome COSI, ROSA SB-CL-05, UPTF 8A and UPTF 25A. The comparison with experimental results shows that the WCOBRA/TRAC-TF2 code is able to predict condensation within a reasonable range of uncertainty. The WCOBRA/TRAC-TF2 predictions are judged to be acceptable for the purpose of analysing a full spectrum of break sizes in a PWR LOCA.

6. References

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