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TRACE simulation of Semiscale S-NC-2 and S-NC-3 tests

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ABSTRACT

Both RELAP5 and TRACE code developers have selected Semiscale natural circulation tests S-NC-2 and S-NC-3 for validation of prediction capability of RELAP5/MOD3.3 and TRACE V5.0 thermal-hydraulics computer codes. The primary objective was to assess the latest TRACE V5.0 Patch 6 thermal-hydraulic computer code. However, we have found out that in the case of S-NC-2 test, the values for the primary mass inventory in the RELAP5 assessment manual are different than in the TRACE assessment manual. Therefore, also the RELAP5 assessment with the same primary mass inventory values as in the case of TRACE has been performed. The natural circulation experiments were performed in the Semiscale Mod-2A test facility, which is a small-scale model of the primary system of a four-loop pressurized water reactor (PWR). The selected experimental tests are Semiscale natural circulation tests S-NC-02, varying primary side mass inventory and S-NC-03, varying steam generator secondary side mass inventory. TRACE input deck has been developed by conversion from RELAP input deck using the Symbolic Nuclear Analysis Package (SNAP). The simulated results of S-NC-2 test showed that the TRACE V5.0 Patch 6 calculation agrees very well with the experimental data. It has been demonstrated that the corrected experimental data of primary mass inventory also perfectly agree with the RELAP5/MOD3.3 results. Further, it has been also shown that the value of primary mass inventory used in the simulation of S-NC-2 test is the most influential for simulation of S-NC-3 test cases.

1 INTRODUCTION

The code assessment of TRACE with Semiscale natural tests S-NC-02 and S-NC-03 is a follow-up of study performed in 2017 with the RELAP5 computer code [1]. Initially, the same experimental data for S-NC-02 have been used as for the RELAP5 code assessment [2]. Other studies, e.g. [3], also use the same data as in the latest RELAP5 code assessment manual [1]. However, when referring to TRACE assessment manual [10], different experimental values are reported for the primary mass inventory. Therefore, the original documents describing Semiscale experiments are investigated first [5], [7] and based on these findings, RELAP5 code calculations are performed, using the new data for the primary mass inventory values (same as in TRACE code assessment manual).

The paper is organized as follows. In Section 2, the methods used are described starting by Semiscale Mod-2A test facility, then S-NC-02 and S-NC-03 natural circulation tests, RELAP5 and TRACE input model and finally, selected scenarios used for simulation. In Section 4 results are presented and in Section 5 conclusions are given.

2 TEST FACILITY AND TEST DETAILS

2.1 Semiscale Mod-2A Test Facility Description

The natural circulation experiments were performed in the Semiscale Mod-2A test facility, which is a small-scale model of the primary system of a four-loop pressurized water reactor (PWR). The facility incorporates the major components of a PWR including steam generators, vessel, downcomer, pumps, pressurizer, and loop piping. One loop (intact loop) is scaled to simulate three intact loops of PWR. For Semiscale natural circulation tests only part of the Mod-2A system was used, so called Semiscale Mod-2A single loop configuration. For more details refer to [4], [7].

2.2 Description of S-NC-02 and S-NC-03 Natural Circulation Tests

The S-NC-02 tests simulated were performed at 60 kW (6% of full Semiscale core power). The objective of the steady-state S-NC-02 natural circulation test was to study thermal hydraulic response during the three modes of natural circulation: single-phase, two-phase, and reflux. The secondary side conditions were constant, while in primary coolant system (PCS) the mass inventory was varied in increments of 1% to 5% of the total PCS mass from 100% to 60%, influencing the natural circulation. At this power level, 16 different steady-state conditions were obtained as shown in Table 1.

Table 1: Calculate mass

Case	PCS Inventory (%) [5], [6]	PCS Inventory (%) [7]	Mass flow rate (kg/s)	Case	PCS Inventory (%) [5], [6]	PCS Inventory (%) [7]	Mass flow rate (kg/s)
C1	100	100	0.36	C9	84.8	79.8	0.6
C2	97.6	97.6	0.38	C10	83.6	78.6	0.58
C3	96.3	91.4	0.58	C11	80.6	75.6	0.5
C4	95.2	90.3	0.68	C12	77.6	72.6	0.2
C5	94.2	89.2	0.74	C13	74.4	69.4	0.08
C6	93.1	88.1	0.77	C14	71.4	66.4	0.06
C7	90.9	85.9	0.74	C15	66.3	61.3	0
C8	87.8	82.8	0.63	C16	61.2	56.2	0

When looking [5] and [6] the mass inventory varies from 100% to 61.2%, while in [7] the mass inventory variation range is between 100% and 56.2%. Nevertheless, later in [8], again, the mass inventory variation ranges from 100% to 61.2% is reported. TRACE assessment manual [10] use PCS inventory data from [7]. RELAP5 manual [2] suggests that the mass inventory variation range is from 100% to 61.2%, like reported in [5], [6] and [8].

The S-NC-3 tests are performed with core power of 62 kW and at constant primary system mass inventory of 91.8% by varying the steam generator secondary side mass inventory. By this process the effective heat transfer area from the primary to secondary side is changed. The objective of the test is to study the effect of different steam generator secondary conditions on the two-phase natural circulation. There are a series of 10 steady state conditions obtained.

3 INPUT MODELS AND SCENARIOS DESCRIPTION

3.1 RELAP5 and TRACE Input Model Description

Transient simulations with RELAP5 [2] are performed using an ASCII input deck prepared by the Idaho National Engineering Laboratory to analyze the S-NC-2 natural circulation experiments [1], which is imported into Symbolic Nuclear Analysis Package (SNAP) [11]. The RELAP5 nodalization scheme of the MOD-2A Semiscale facility consisted of 62 Hydraulic Components and 9 Heat Structures [1]. For simulations with TRACE [4] the RELAP5 input deck is converted to TRACE using SNAP and consists of 86 hydraulic components, 9 heat structures and 367 control systems as shown in Figure 1.

The reactor vessel is modelled with external downcomer, lower plenum, lower head, active core, upper plenum, upper head bypass line, simulated guide tubes and support column. The intact loop is modelled with a hot leg, an intermediate leg, a pump spool piece, and a cold leg. This intact loop hot leg is connected to the reactor vessel upper plenum volume and cold leg is connected to the volume at a reactor downcomer. The pressuriser surge line is connected to the hot leg. The secondary side is modelled with feedwater downcomer, boiling space, a separator, steam dome, a normal steam discharge and an auxiliary feedwater source.

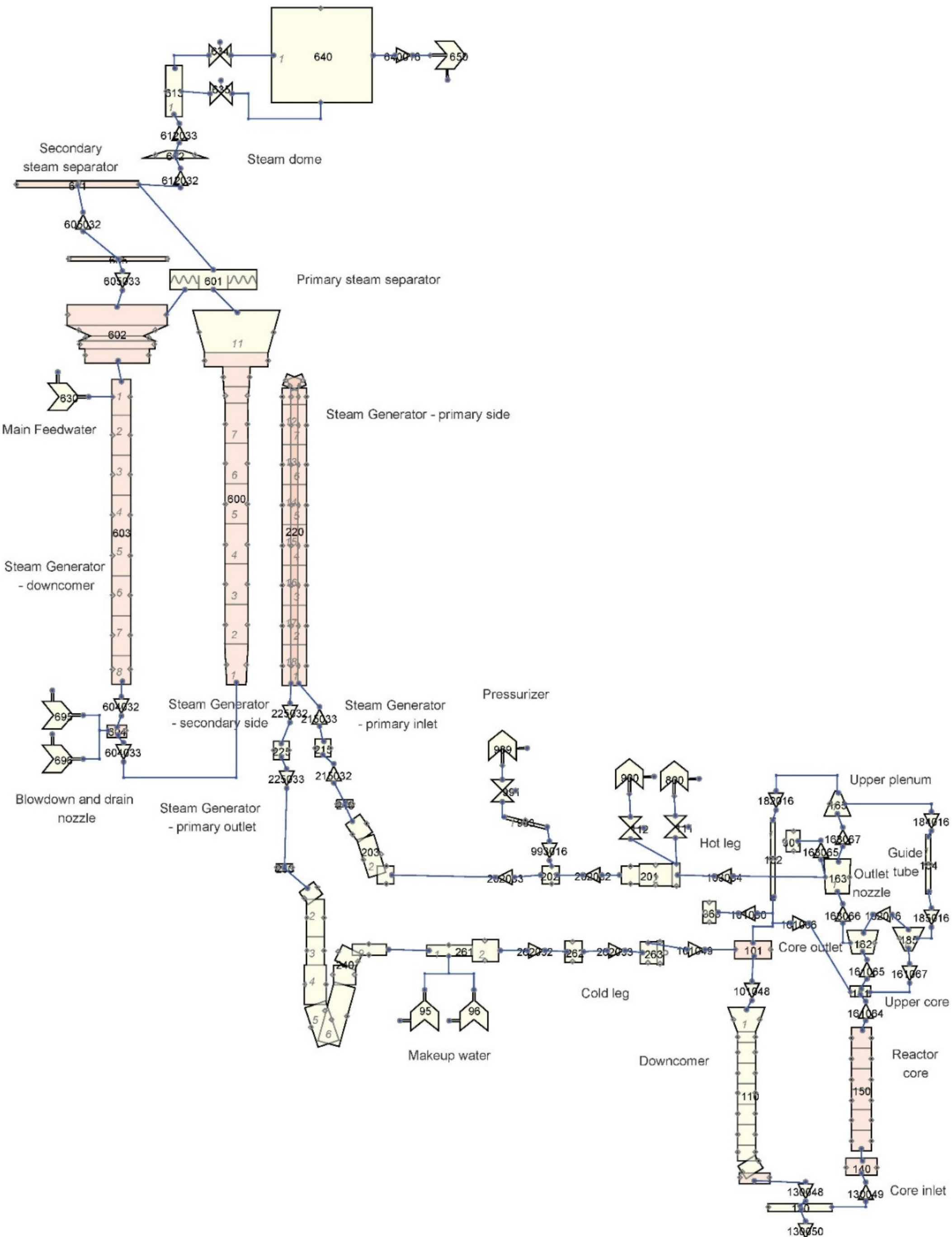

Figure 1: TRACE Semiscale Hydraulic Components View

3.2 Selected scenarios

According to the original report [5], 16 cases of the S-NC-02 test with PCS inventory variation from 100% to 61.2% were used for the RELAP5 assessment as shown in Table 1. The same cases were also used in a recent SPACE study [3]. However, in TRACE code assessment manual [10], 16 cases of the S-NC-02 test with PCS inventory variation from 100% to 56.2% which follows [7] was used (see Table 1). All measured data for RELAP5 and TRACE are the same, except the initial values for the PCS inventory [7]. The values used in TRACE assessment report have been used also in this study.

For S-NC-3 test, the specific value of 91.8% for primary mass inventory was chosen from the result of test S-NC-02 which corresponds to the primary side inventory in which the mass flow rate in the primary side is at its peak (it should be noted that in the simulation the peak mass flow rate may appear at different primary mass inventory). For example, NUREG-CR/3690 [9] stated that agreement was better with the primary mass inventory of 85%. Also, the simulations of S-NC-3 with the TRACE were performed with 89.2% primary system mass inventory, even though the test data indicate a level of 91.8%. The reason for this was that the inventory level (91.8%) quoted for case number 10 in Table B-5 [7] is inconsistent with the stated mass flow rate of 0.75 kg/s. Therefore, also in our sensitivity study the primary mass inventories, selected for S-NC-3 test, range from 91.8% to 82.8%. By varying the steam generator secondary mass, the effective heat transfer area from primary to secondary side has been changed. The objective of the test was to study the effect of different steam generator secondary condition on the two-phase natural circulation. The 10 simulated cases with the varying secondary side mass were: C10 - 100.0%, C11 - 99.1%, C12 - 86.9%, C13 - 75.5%, C14 - 67.4%, C15 - 55.5%, C16 - 43.6%, C17 - 33.2%, C18 - 22.7% and C19 - 15.2%.

4 RESULTS OF RELAP5 AND TRACE

Figure 2 shows the mass flow rate as a function of PCS inventory variation. Two sets of 16 cases are presented, with PCS variation between 61.2-100% and 56.2-100%, respectively. For all calculated cases the same RELAP5/MOD3.3 Patch 5 computer is used. The C3 to C16 calculations in each set are performed at different values of PCS inventory (difference of about 5%), giving different results. Figure 2 shows the comparison of results for mass flow rate with experimental values, where RELAP5 calculation is presented as "R5M33 P5", experimental values from TRACE manual as "EXP-TRACEman", RELAP5 calculation from 2017 [1] as "R5M33 P5-2017" and experimental values from RELAP5 manual as "EXP-RELAP5man". The 5% difference between RELAP5 and TRACE manual assumed values of PCS inventory experimental points in x-direction is clearly seen for C3 to C16 cases.

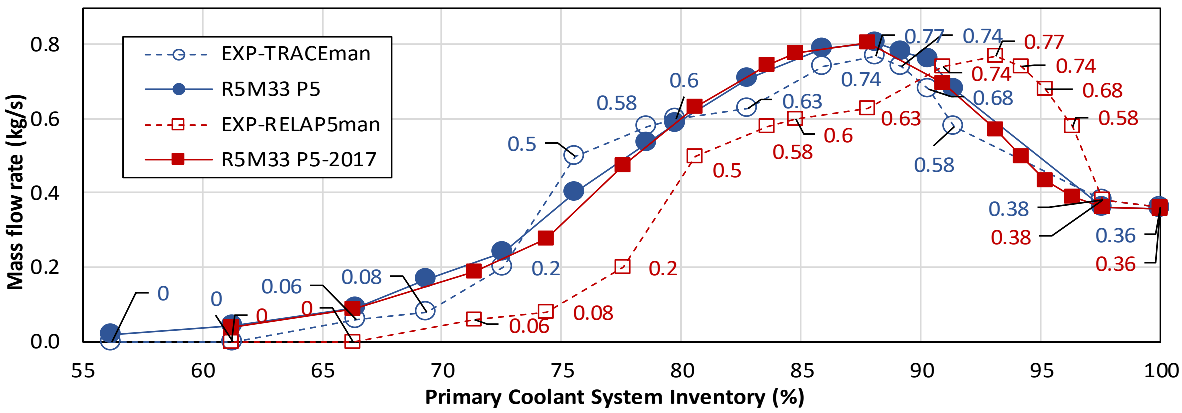

Figure 2: PCS mass flow rate comparison between RELAP5 calculation and experimental data in TRACE and RELAP5 assessment manual for S-NC-2 test

Next, the RELAP5 and TRACE calculated results are compared to experimental data for the mass flow rate, hot leg fluid temperature, primary side steam generator outlet fluid temperature, and primary system pressure. The difference in density is the only driving force for natural circulation. The fluid density variation occurs as a result of fluid heating in the core region and fluid cooling in the steam generators. Natural circulation will occur in PWRs primary loop (in the absence of pumped flow) whenever the buoyant forces caused by difference in the fluid densities in the loop balance the flow resistance of the loop components (steam generators, primary coolant pumps, etc.). Transition from the single-phase mode through the two-phase and reflux condensation modes occurs as primary system liquid mass inventory decreases.

Figure 3 shows the RELAP5 and TRACE calculated results. The additional line shows mass flow rate as continuous function of PCS inventory in the range 100% to 67% (the calculation considered slow emptying of PCS lasting 24 h, with no need to stabilize the steady state – in experiment the step draining lasted 48 minutes). Calculations agree well with the experiment in the PCS inventory range from 97% to 100%. TRACE calculation presented as 'TRACE P6-cont' shows that between 73% and 92% of PCS inventory, there is a two-phase region, while reflux mode appears between 60% and 73% of the PCS inventory (the moving average is therefore used). Also, it can be seen that above 80% of PCS inventory the 'TRACE P6-cont' line crosses the 'TRACE P6' data points. Finally, Figure 3 shows that both, RELAP5 and TRACE, reached peak mass flow rate at around 88% which is in agreement with experimental value assumed in TRACE manual [4]. In the original report [12] it is stated that selecting 91.8% PCS inventory at which peak mass flow is reached, was based on report [7].

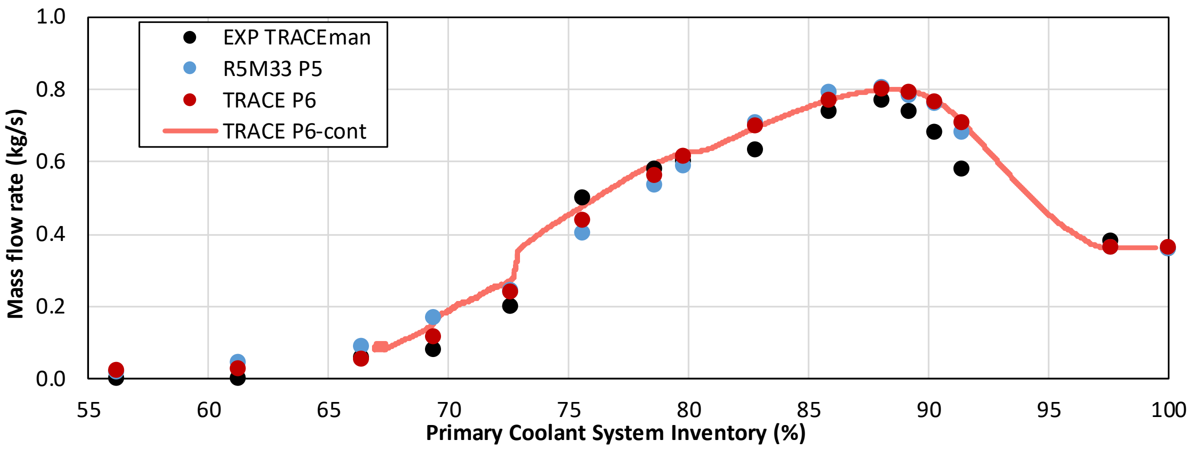

Figure 3: Primary system mass flowrate comparison between RELAP5 calculation, TRACE calculation and experiment for S-NC-2 test

The disagreements of measured pressures and temperatures (see figures 4 to 6) with the RELAP5 and TRACE calculations appear mostly due to the differences between the computed and the measured loop flows. The exceptions to this are the computed steam generator outlet temperatures exhibiting larger deviations, as shown in Figure 5. Figure 4 shows hot leg fluid temperature comparison between RELAP5 calculation, TRACE calculation and experiment. It shows good agreement except in the range between 90 and 92% of the primary mass inventory (the reason is explained above).

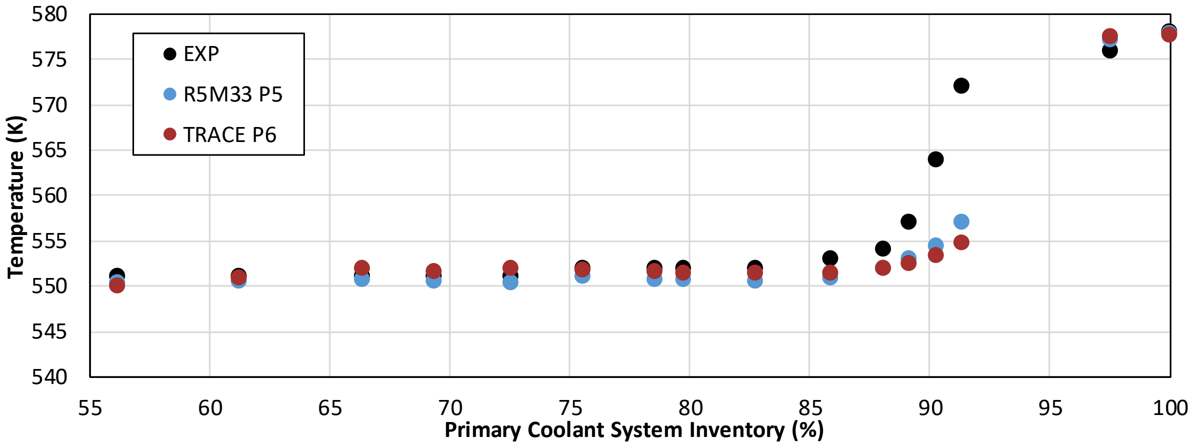

Figure 4: Hot leg fluid temperature comparison between RELAP5 calculation, TRACE calculation and experiment for S-NC-2 test

Figure 5 shows steam generator outlet temperature comparison between RELAP5, TRACE and experiment. Experimental data used in RELAP5 and TRACE assessment manual are given as integer values in the range 547-550 K, where below 85% the value is constant. In case of RELAP5 and TRACE the maximum deviation is 1.9 K and 1.8 K, respectively.

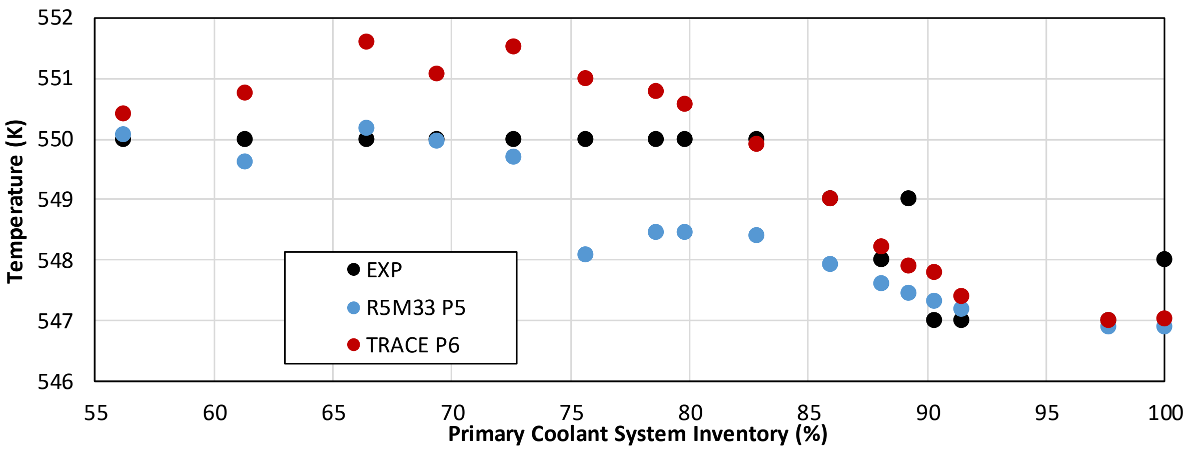

Figure 5: SG outlet temperature comparison between RELAP5 calculation, TRACE calculation and experiment for S-NC-2 test

Figure 6 shows primary pressure comparison between RELAP5 calculation, TRACE calculation. The trends are similar to hot leg fluid temperature shown in Figure 4.

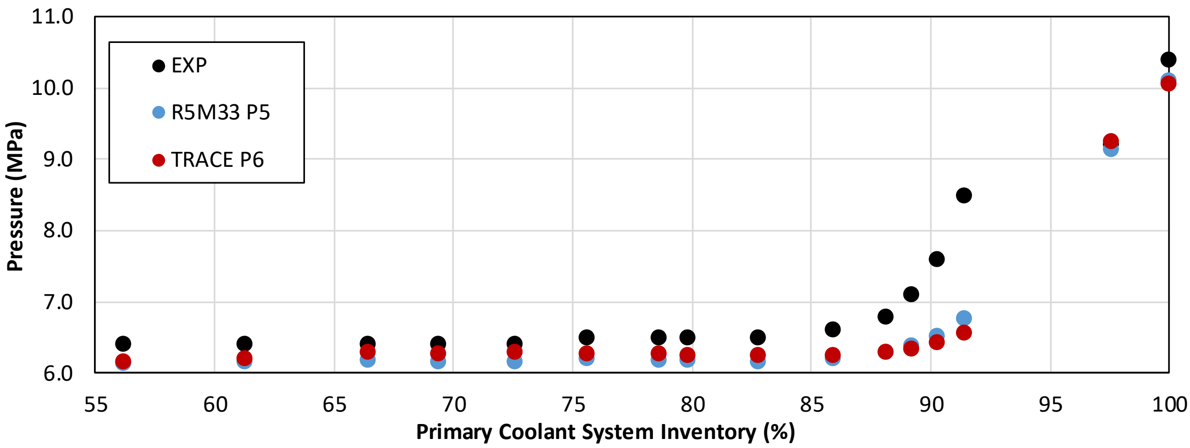

Figure 6: Primary pressure comparison between RELAP5 calculation, TRACE calculation and experiment for S-NC-2 test

Figures 7 and 8 show the comparison between the calculated results and the experimental data for the primary system mass flowrate in the case of S-NC-3 test, when steam generator secondary side mass inventory is varied. The calculated results are significantly affected by the value of primary mass inventory, at which the peak primary mass flowrate has been measured. Study [9] shows better results which are calculated when the value 85% has been used. Also, in the TRACE assessment manual [10], the value 89.2% has been used and in SPACE study [3], the value 87% has been used. According to Figure 3, the peak primary system mass flow rate appears at 88%, for both for RELAP5 and TRACE calculation, and agrees perfectly with the experimental data in NUREG/CR-2335 [7]. Nevertheless, the sensitivity study shows that further reduction of the primary system mass inventory to the value of 82.8% results in a very good agreement. On the other hand, the TRACE is not very sensitive to the value of the primary system mass inventory in the range between 82.8% and 91.%. Nevertheless, the trend improves with the reduction of the primary mass inventory to the value of 82.8%

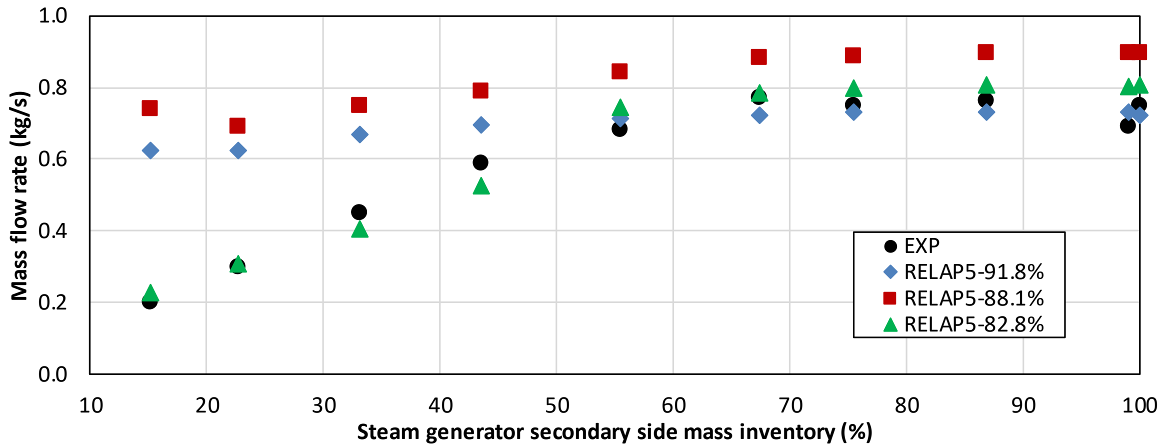

Figure 7: Primary system mass flowrate comparison between RELAP5 calculation and experiment for S-NC-3 test

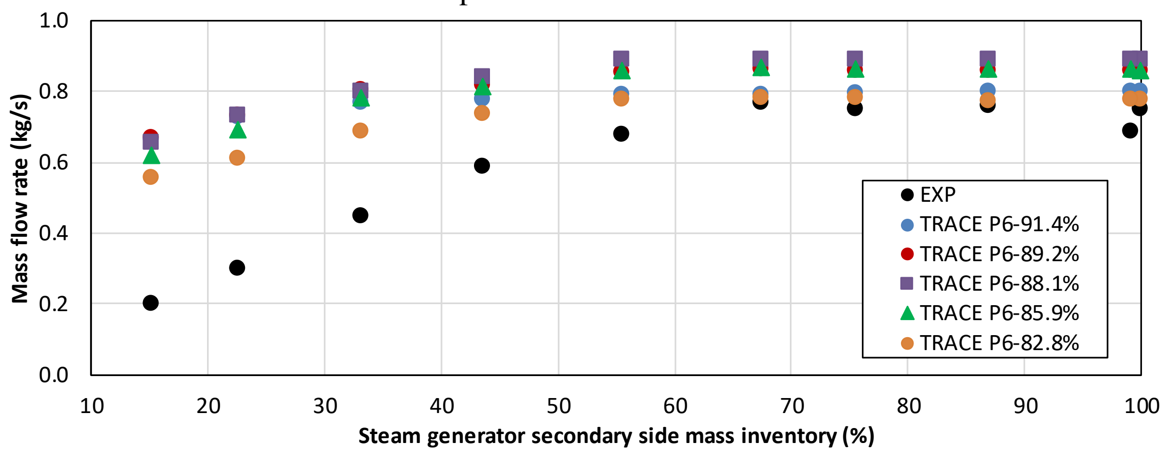

Figure 8: Primary system mass flowrate comparison between TRACE calculation and experiment for S-NC-3 test

5 CONCLUSIONS

The latest RELAP5/MOD3.3 Patch05 and TRACE V5.0 Patch 6 computer codes have been used for calculations of Semiscale S-NC-2 test at a different primary mass inventory and for the S-NC-3 test under the degraded heat transfer conditions. The simulations were compared to the experimental data. The results for S-NC-2 test showed that primary system mass flow rate is very well predicted, comparing to the experimental values of primary mass inventory used in NUREG/CR-2335 [7]. The disagreements between the RELAP5 and TRACE calculations and the measured pressures and temperatures are mostly affected by the differences between the computed and the measured loop flows. The results of sensitivity study on the Semiscale natural circulation test S-NC-3 under the degraded heat transfer conditions showed that a reduced primary mass inventory contributes to a better agreement with the experimental data.

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