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WCOBRA/TRAC-TF2 Simulation of ROSA-IV/LSTF Natural Circulation Test ST-NC-02

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Abstract

The paper presents WCOBRA/TRAC-TF2 simulation results of the high-pressure (~7 MPa) steady-state natural circulation test ST-NC-02 conducted at the ROSA-IV Large Scale Test Facility (LSTF). The simulations used a fairly detailed noding of the LSTF particularly in the vessel and the primary and secondary side of the steam generators. A single flow channel is used to model the primary side of the steam generator U-tubes. In general, the results are in good agreement with those observed in the ST-NC-02 test.

Introduction

Natural circulation is an important thermo-hydraulic mechanism of residual heat removal following a loss of coolant accident (LOCA) in pressurized water reactors (PWRs). In the past, this phenomenon has been tested with various degree of detail at a number of test facilities. The knowledge gained and the test data obtained from these tests provide a basis for validation of various thermo-hydraulic computer codes used for safety analysis of PWR following LOCA. The current paper presents WCOBRA/TRAC-TF2 simulation results of the high-pressure (~7 MPa) steady-state natural circulation test ST-NC-02 conducted at the ROSA-IV Large Scale Test Facility (LSTF) [1].

1. Description of the ROSA-IV LSTF and the ST-NC-02 experiment

1.1 Test Facility

The LSTF is a 1/48 volume scale representation of a Westinghouse four-loop 3423 MWt Pressurized Water Reactor (PWR). Figure 1 provides a general view of the LSTF. It consists of two equal volume loops, with a pressurizer attached to one of the hot legs. The core simulator contains 16 square 7x7 and 8 semi-crescent heater rod assemblies. The heater rods are 9.5 mm in diameter and 3.66 m in length. To simulate possible effects of non-uniform radial power distribution there are low, average and high power assemblies. The core utilizes chopped cosine axial power distribution.

The maximum power in the facility at steady state is 10 MW, which is equivalent to 14 percent of the scaled steady state core power of the reference PWR.

The secondary coolant system consists of two steam generators, main and auxiliary feed water pumps, and condensing system. The height of the LSTF steam generator is the same as in the reference PWR. The downcomer of each steam generator consists of four pipes located outside the steam generator vessel. The pipes are sized to provide a representative volume and width of a typical steam generator downcomer. Each steam generator contains 141 U-tubes with 19.6 mm inside diameter and 25.4 mm outside diameter. Primary and secondary steam separators are installed in each steam generator secondary side.

The LSTF Emergency Core Cooling System (ECCS) consists of a high pressure charging system, a high pressure injection system, a low pressure injection system, an accumulator system, and a residual heat removal system.

More detailed description of the facility is available in the Japan Atomic Energy Research Institute (JAERI) documents (JAERI-M 84-237, 1985 and JAERI-M 98-113, 1989).

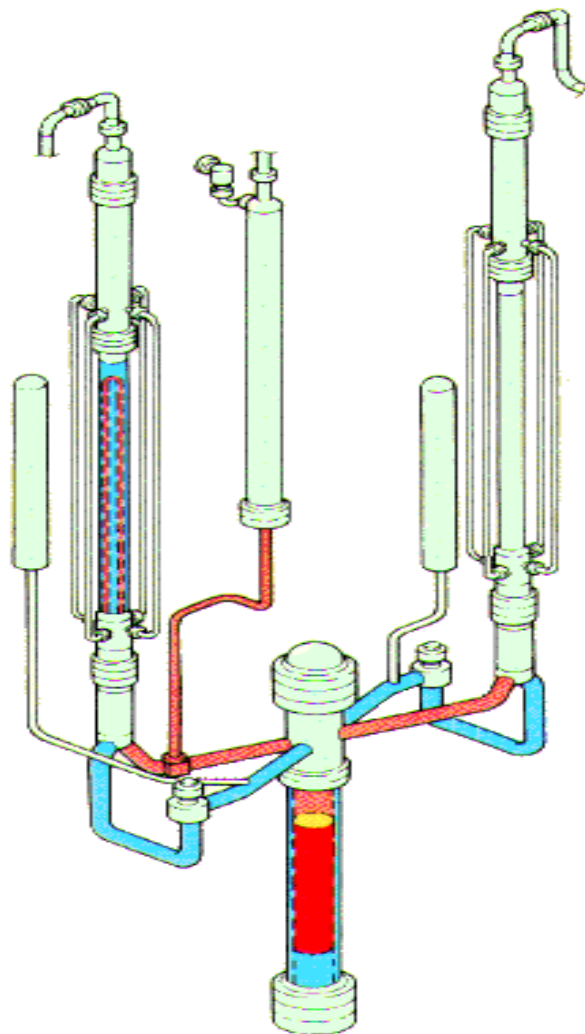


Figure 1 JAERI ROSA-IV Large Scale Test Facility General View

1.2 WCOBRA/TRAC-TF2 model of LSTF

The WCOBRA/TRAC-TF2 model of the LSTF is fairly detailed representation of the test facility. The volume of the pressure vessel is modelled by the 3-D vessel component of the code, which uses a two-fluid, three-field representation of the flow. It is divided into ten vertical sections, representing different characteristic regions like lower plenum, core region, upper plenum, etc., and is modelled using more than 30 axial levels. The downcomer region is represented by multiple stacks of parallel channels. Consistent with radial power distribution, implemented in the LSTF core simulator, the core is simulated by interconnected low, average and high power channels.

The piping outside the LSTF pressure vessel is modeled by interconnected 1-D components, which use two-phase, two-fluid model representation of the flow. Figure 2 shows the general loop noding diagram of the LSTF. The steam generator secondary side includes sufficient detail to model recirculation in the downcomer and separation in the vapor dome region. The detail implemented in the hot legs, steam generators and the cross-over legs is sufficient to calculate effects of flow stratification that might occur during the transient.

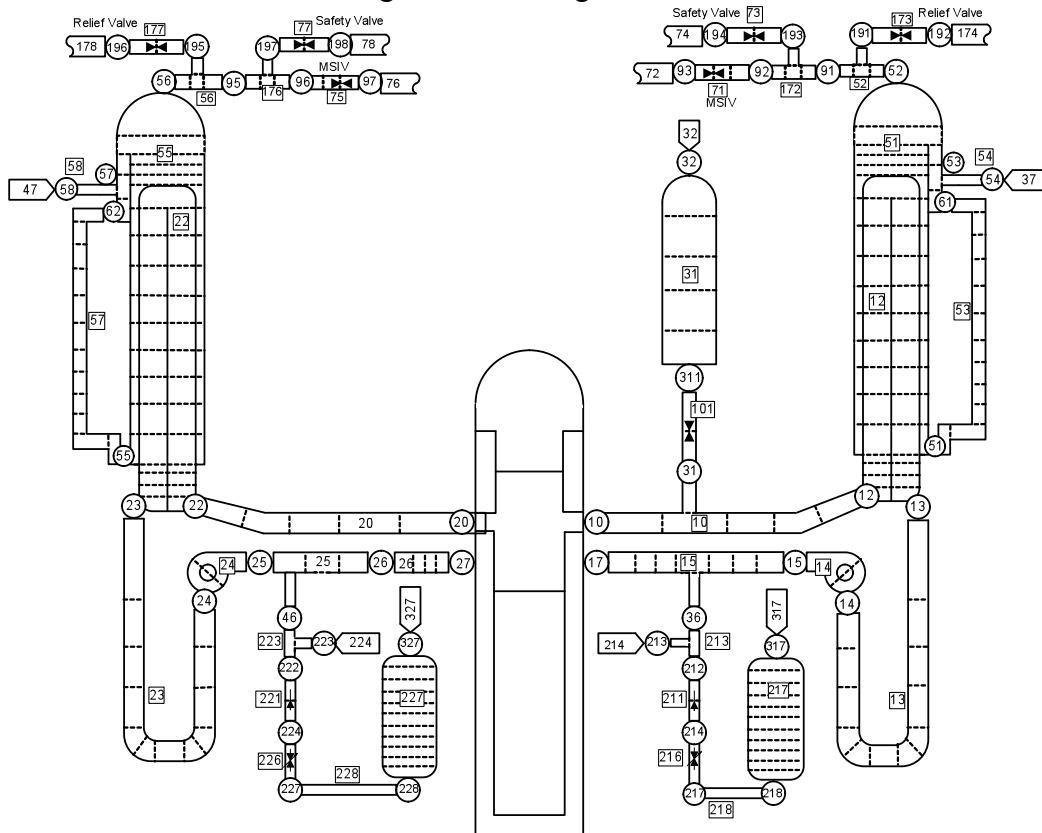


Figure 2 WCOBRA/TRAC-TF2 Loop Noding Diagram of LSTF

2. ST-NC-02 description and WCOBRA/TRAC-TF2 simulation results

2.1 Test procedure and conditions of the ST-NC-02 test

JAERI-M-88-215 [2] documents results of simulations of the ST-NC-02 test with RELAP5/MOD2, and contains a fair amount of detail related to the initialization and execution of the ST-NC-02 natural circulation test and RELAP5/MOD2 simulation results.

References 3, 4, 5 and 6 present additional analyses of the ST-NC-02 test and provide additional information that cannot be easily found in (or inferred from) JAERI-M-88-215.

The first stage of the experiment was performed at the LSTF nominal conditions: full power (10 MW), pumps on, temperature increase across the core as in the actual plant. The second stage was designed to study the natural circulation at 100% primary side inventory. The core power was reduced down to 1.42 MW (this is 2% power of the reference PWR) and was kept at that level for the rest of the entire experiment. The pumps were turned off and the secondary side pressure was reduced to 6.6 MPa and kept constant until the end of the experiment. Figure 4 of [4] illustrates the measured evolution of the primary side pressure and loop flow and sheds some light on the timing of the different stages of the experiment. At the end of the second stage of the experiment, when the pressurizer pressure was established at 12.2 MPa, the pressurizer surge line valve was closed and the pressurizer isolated prior to the drain of the primary side inventory.

During the rest of the experiment, the primary side water inventory was reduced step-wise by bleeding through the drain line at the bottom of the vessel. The drain valve at the bottom was closed when certain inventory reduction was reached and kept closed for some time until intermediate steady state primary pressure and loop flow was achieved at that inventory level. Constant secondary side water level was maintained throughout the experiment.

2.2 ST-NC-02 simulation and results

The test simulation followed a procedure similar to the one implemented during the real test, except that shorter time periods were simulated to achieve a quasi-steady state during each drain period. The length of the individual drain periods and the drain flows used in the simulation were estimated from the information available in Figure 4 of [4]. Prior to the beginning of the draining, the pressurizer was isolated from the primary system.

The results of the simulation of the ST-NC-02 natural circulation test (2% core power) are presented in Figure 3 through Figure 11.

Figure 3 compares the measured primary system loop circulation flow against the calculated by the code. During the single-phase natural circulation (primary side inventory from 100% to 90%) the circulation flow is predicted fairly well. With the onset of the two-phase natural circulation, with the current model, the code calculates higher peak of the circulation flow

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(~11.5 kg/sec), which occurs at about 80% inventory. For system inventories less than 80% the calculated circulation flow matches very well that measured during the test. The natural circulation is terminated at about 62%, as observed in the test as well.

As seen on Figure 3, the code calculates fairly significant oscillation of the circulation flow for system inventories between 75% and 65%. According to [2] and [6], noticeable flow oscillations during the ST-NC-02 test were observed at these inventories as well, with a standard deviation values of about 1.0 to 1.5 kg/sec. The standard deviations of the calculated circulation flows for system inventories between 75% and 65% are in the range between 1.5 kg/sec and 2.5 kg/sec. Although visually Figure 3 shows much greater magnitude of the flow oscillation calculated by the code, the actual standard deviation values tend to be closer to the ones observed during the test.

The system pressure comparisons, Figure 4, shows a fairly good prediction of the depressurization for system inventory from 100% down to 80%. For inventories less than 80% the code calculates a holdup and some increase of the primary system pressure (measured in the upper plenum), while during the test the primary system pressure was gradually decreasing. The over-prediction of the primary pressure is in the range of 0.2-0.3 MPa. Most likely this is due to reduced steam removal by condensation as a result of excessive liquid holdup in one of the steam generators. The excessive liquid holdup in the steam generators would decrease the potential for the steam generated in the core to enter the SG tube bundle and condense. To a certain extent, the results shown in Figure 5 might support this judgment. Figure 5 provides comparison of the measured and calculated differential pressures across the U-tube uphill side, which is an indicator of the amount of liquid available in this region. The calculation results match fairly well the measured differential pressure for inventories down to about 80%. However, it is seen that for inventories between 80% and 60% the code calculates higher differential pressure (hence more liquid hold-up) in the uphill side of both steam generators, with steam generator A (SGA) remaining plugged until about 40% inventory is reached. This might explain the overall decreased steam venting capability leading to the calculated primary pressure holdup. It is also quite possible that excessive liquid hold-up is calculated in the steam generator inlet plenums as well, but there is no test measurement to support this claim.

The amount of liquid in the core, Figure 6, is predicted well for inventories down to 60%. Slight over-prediction (~1 kPa) is observed below 60% inventory. The upper plenum differential pressure, Figure 7, is also predicted well including the onset of the upper plenum draining that occurs at about 40% to 35% inventory.

The comparison of the downcomer differential pressures, Figure 8, shows a good prediction of the amount of liquid in the downcomer.

Figure 9 shows a comparison of the downcomer-to-upper plenum differential pressures. Fairly good prediction is achieved during the period of single-phase natural circulation for inventory down to about 85%. The visible mismatch calculated between 80% and 60% inventory is explained by inconsistency between the modeled and actual bypass between the downcomer and the upper head. Furthermore, as evident on Figure 9, upon the termination of the natural

circulation for inventories below 62%, the code calculates slightly higher downcomer-to-upper plenum differential pressure.

The following major conclusions are made with respect to the ability of the code to calculate primary-to-secondary side heat transfer.

- For purely reflux condensation conditions in the steam generators, the code calculates overall effective heat transfer coefficient (normalized for the outside steam generator surface area) of around 1.25 kW/m²K. This value is determined from Figure 10 for system inventories when the steam generators are drained and the entire surface of the U-tubes is exposed for the steam to condense – these are inventories less than 40% for steam generator A (SGA) and less than 60% for steam generator B (SGB). The calculated value is lower than the average minimum reflux heat transfer coefficient of 1.7 kW/m²K measured on the LSTF post-natural circulation test ST-SG-02, as reported in [3]. It is therefore concluded that the code tends to under-predict the heat transfer during reflux conditions.
- The simulation results indicated significant exposure of the steam generator inside surface to local reflux condensation conditions during the period of still well developed two-phase natural circulation. These conditions were calculated to occur on the downhill side of the steam generator U-tubes for inventories 75% to 40% for SGA and 80% to 60% for SGB. By extending the previous conclusion (regarding the overall reflux condensation heat transfer coefficient, HTC) to the periods characterized with existing local reflux condensation, it is judged that the code tends to under predict the overall primary-to-secondary side HTC for system inventories below 80% as well.
- The calculated steam generator primary-to-secondary side temperature difference (Figure 11) shows the tendency of the code to compensate for the reduced heat transfer coefficient by equilibrating primary-to-secondary power transfer at a higher temperature difference; hence the predicted increase of the primary side pressure for inventories less than 80%, as seen in Figure 4.

Natural Circulation Test ST-NC-02 Simulation
Loop Circulation Flows

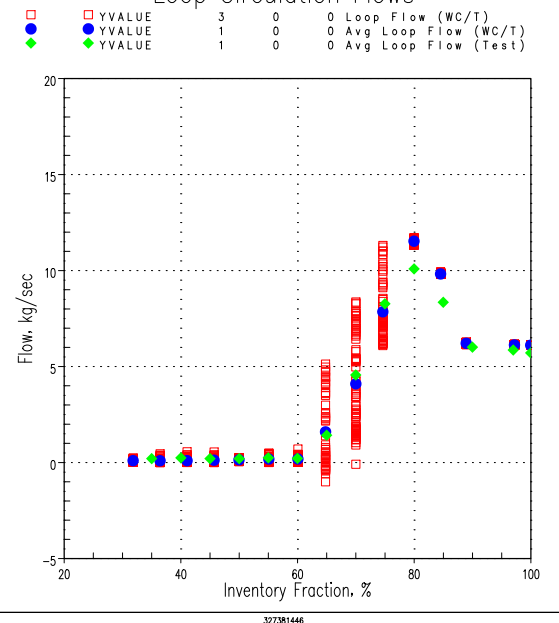


Figure 3 Primary Side Circulation Flow as a Function of Primary Side Inventory

Natural Circulation Test ST-NC-02 Simulation
System Pressures

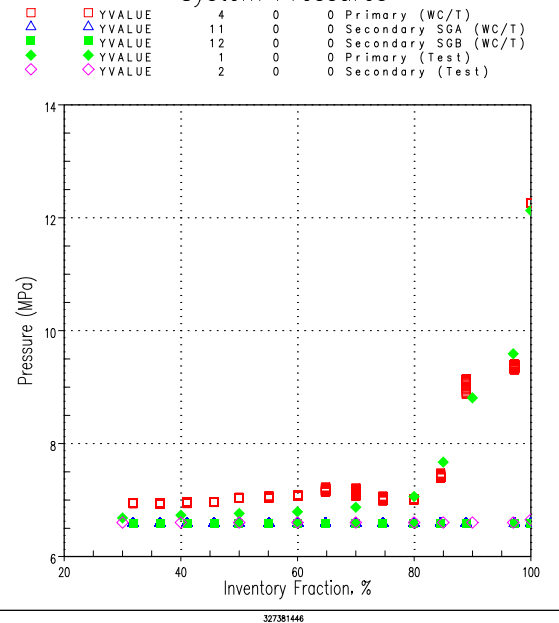


Figure 4 ST-NC-02 Primary and Secondary System Pressures

Natural Circulation Test ST-NC-02 Simulation
Steam Generator U-tube Upflow Differential Pressure

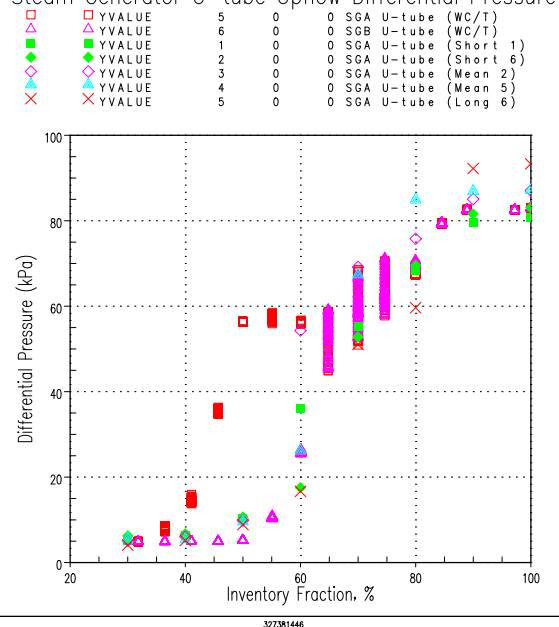


Figure 5 Steam Generator U-tube Upflow Side Differential Pressures

Natural Circulation Test ST-NC-02 Simulation
Core Differential Pressure

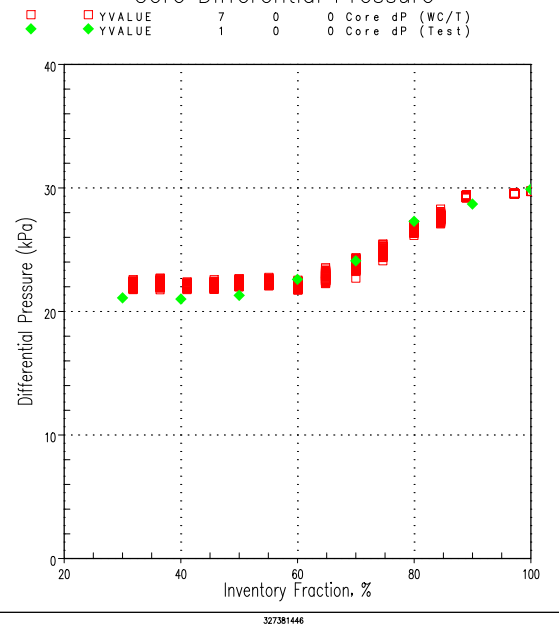


Figure 6 Core Differential Pressure

Natural Circulation Test ST-NC-02 Simulation
Upper Plenum Differential Pressure

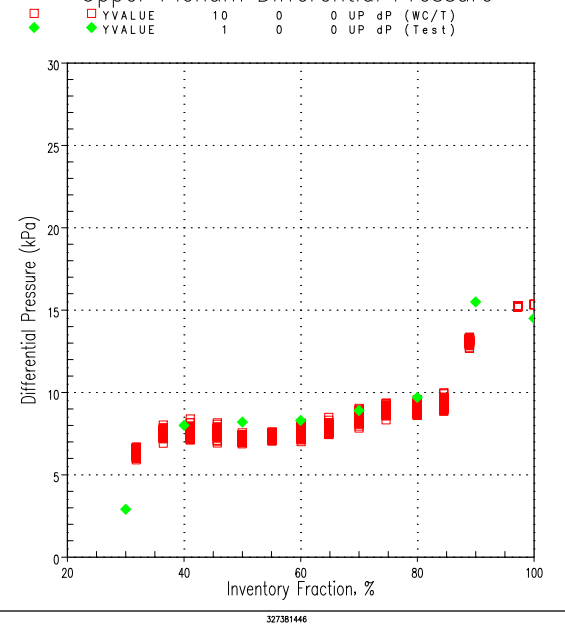


Figure 7 Upper Plenum Differential Pressure

Natural Circulation Test ST-NC-02 Simulation
Downcomer Differential Pressure

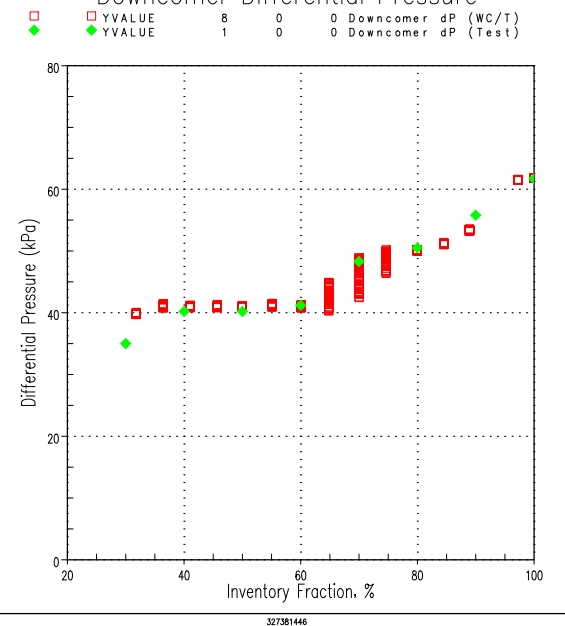


Figure 8 Downcomer Differential Pressure

Natural Circulation Test ST-NC-02 Simulation
Downcomer to Upper Plenum Differential Pressure

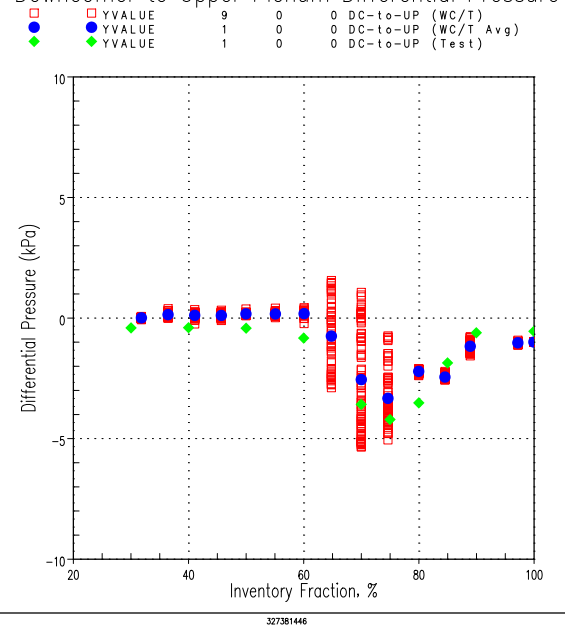


Figure 9 Downcomer-to-Upper Plenum Differential Pressure

Natural Circulation Test ST-NC-02 Simulation
Steam Generator Heat Transfer Coefficients

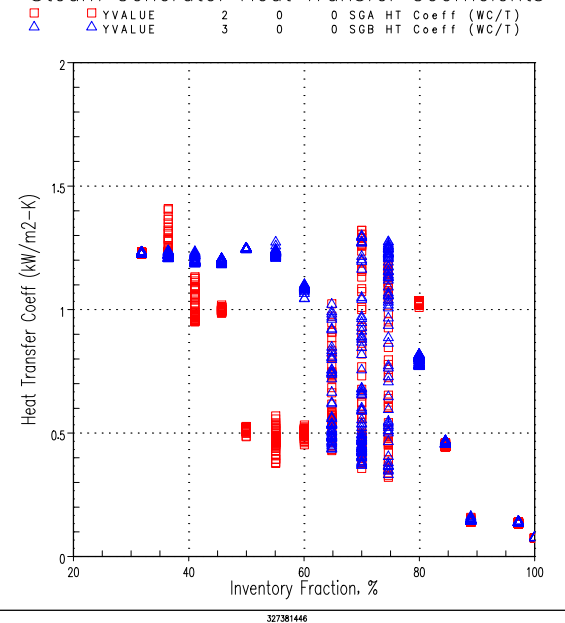


Figure 10 SG Primary-to-Secondary Side Heat Transfer Coefficients

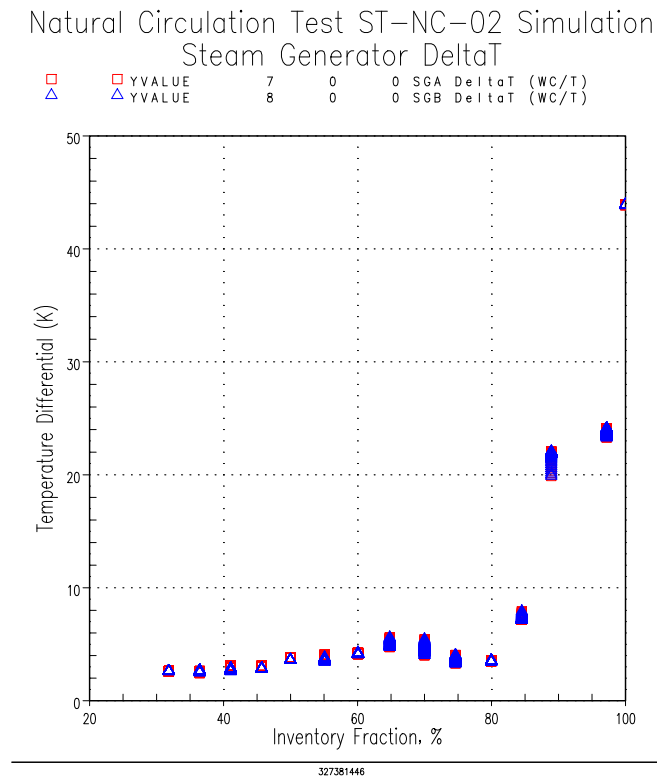


Figure 11 Steam Generator Primary-to-Secondary Side Temperature Difference

3. Conclusion

The calculated transition from single-phase to two-phase natural circulation and then to reflux condensation is consistent with the test observations. The peak of the natural circulation flow is predicted to occur at 80% inventory and the calculated flow rate is about 15% higher than the observed in the test. This is comparable to results obtained by other similar system code simulations in the past. The natural circulation mode was calculated to end when the vessel mass became less than 62%, which agrees with the observation from the test. During the two-phase circulation period, the code calculates asymmetrical behaviour with respect to liquid holdup in the uphill side U-tube uphill side. The code tends to under-predict the overall effective primary-to-secondary side heat transfer coefficient during reflux conditions. As a result, the power transfer is equilibrated at somewhat higher temperature difference and the code predicts increase of the primary side pressure for inventories less than 80 percent.

4. References

- [1] JAERI-M 84-237, 1985, "ROSA-IV Large Scale Test Facility (LSTF) System Description."
- [2] JAERI-M 88-215, "Post-Test Analysis with RELAP5/MOD2 of ROSA-IV/LSTF Natural Circulation Test ST-NC-02," October 1988.
- [3] K. Tasaka, et al., "The Results of 5% Small Break LOCA Tests and Natural Recirculation Tests at the ROSA-IV LSTF," *Nuclear Engineering and Design*, 108, 1988.
- [4] Y. Kukita, et al., "Nonuniform Steam Generator U-Tube Flow Distribution During Natural Circulation Tests in ROSA-IV Large Scale Test Facility," *Nuclear Science and Engineering* 99, 1988.
- [5] H. Stumpf, F. Motley, R. Schultz, J. Chapman, Y. Kukita, "Reverse Primary-Side Flow in Steam Generators During Natural Circulation Cooling," *ASME FED Vol.61, HTD Vol. 92*, 1987.
- [6] T. Yonomoto, "ROSA/LSTF Experiments of PWR Natural Circulation and Validation of RELAP5/MOD3.3, IAEA-TECDOC-1149, Proceedings of 1998 IAEA Technical Meeting on Experimental Test and Qualification of Analytical Methods to Address Thermohydraulic Phenomena in Advanced Water Cooled Reactors."