RELAP5 code study of ROSA/LSTF experiment on a PWR station blackout (TMLB’) transient

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Abstract
RELAP5 code post-test analysis was performed on one of abnormal transient tests conducted with the ROSA/large scale test facility (LSTF) simulating a PWR station blackout (SBO) transient with the TMLB’ scenario in 1995. The TMLB’ scenario involves prolonged complete loss of alternating current power and unavailability of turbine-driven auxiliary feedwater as well as malfunction of primary- and secondary-system relief valves. The LSTF test revealed core uncoverage by core boil-off took place a little after hot leg became empty of liquid while the primary pressure was kept high. The RELAP5 code predicted well the overall trend of the major phenomena observed in the LSTF test, and indicated remaining problems in the predictions of reverse flow U-tubes in steam generator (SG) during long-term single-phase liquid natural circulation. Sensitivity analyses were performed further to clarify effectiveness of depressurization of and coolant injection into SG secondary-side as accident management measures for core cooling, based on the RELAP5 post-test analysis. SG secondary-side depressurization was initiated by fully opening the safety valve in one of two SGs with the incipience of core uncoverage. Coolant injection was done into the secondary-side of the same SG at low pressures considering availability of fire engines. The peak cladding temperature was dependent on the onset timing and flow rate of the SG coolant injection as well as the onset timing of the SG depressurization after core uncoverage. The SG depressurization with the SG coolant injection was found to well contribute to maintain core cooling by the actuation of accumulator system during a PWR SBO (TMLB’) transient.

Key words: PWR, ROSA/LSTF, Station blackout, Accident management, SG depressurization, RELAP5 code

1. Introduction

The earthquake and tsunami-induced station blackout (SBO) accident took place at the Fukushima Dai-ichi boiling water reactors on 11 March 2011 (Hirano, et al., 2012; Watanabe, et al., 2012). Alternative water injection into the reactor as a flexible applied action was then performed by using fire engines due to loss of the core cooling functions. Subsequently, long-term SBO accident analyses of light water reactors have been carried out to evaluate the accident progression. Prošek and Cizelj (2013) have investigated accident management (AM) strategies for SBO scenarios with degradation of primary coolant pump seals to avoid core uncoverage and heatup at a pressurized water reactor (PWR) through the long-term analyses. Experimental data have been obtained for PWR SBO transients with various scenarios by such integral test facilities as Semicscale (Chapman, 1985), IIST (Liu, et al., 1997), PKL (Mull, et al., 1999) and ATLAS (Kim, et al., 2013). The obtained data, however, were not sufficient to clarify specific thermal-hydraulic phenomena because of such atypical features as small volume and low pressure in the primary system.

One of abnormal transient tests (Kukita, et al., 1991) simulating a PWR SBO transient with the TMLB’ scenario (USNRC, 1975) was conducted with the large scale test facility (LSTF) (The ROSA-V Group, 2003) in the rig of safety assessment-V (ROSA-V) program at Japan Atomic Energy Agency (JAEA) in 1995. The LSTF simulates a Westinghouse-type four-loop 3423 MW (thermal) PWR by a full-height and 1/48 volumetrically-scaled two-loop system. The TMLB’ scenario involves prolonged complete loss of alternating current power, including the off-site power and the on-site emergency diesel generator power, and unavailability of turbine-driven auxiliary feedwater (AFW) and malfunction of relief valves in primary system and steam generator (SG) secondary-side system. The main
test objectives are to clarify the specific thermal-hydraulic phenomena.

The LSTF test was analyzed by RELAP5/MOD3.2.1.2 code (RELAP5 Code Development Team, 1995) to well understand observed thermal-hydraulic phenomena and to identify remaining subjects for the code to improve. Change in the number of reverse flow U-tubes during long-term single-phase liquid natural circulation (NC) was discussed based on the LSTF experiment and RELAP5 code analysis results.

In the TMLB’ scenario, high-pressure and low-pressure injection systems of emergency core cooling system (ECCS) are unavailable. After full of liquid in pressurizer (PZR), cycle opening of PZR safety valve (SV) induces loss of primary coolant, which may lead to core uncover at high pressures. If the PZR SV is fully opened as an AM action to make primary depressurization fast, loss of primary coolant becomes greater than in the cycle opening case. Depressurization of and coolant injection into SG secondary-side as AM measures thus are needed to depressurize the primary system to maintain core cooling by the actuation of accumulator (ACC) system of ECCS. Yoshihara (2012) has put forward AM measures that feedwater into and depressurization through the relief valves of SG secondary-side are initiated at early stages of SBO with leakage from primary coolant pump seals, by using the turbine-driven AFW pumps switching over from the AFW pumps to fire engines at low pressures, to ensure long-term core cooling by NC. This study proposes AM measures with symptom-oriented operator actions to perform SG secondary-side depressurization by fully opening the SV in one of two SGs with the incipience of core uncover and to inject coolant into the secondary-side of the same SG at low pressures considering availability of fire engines. Influences of the AM measures onto major phenomena were investigated by sensitivity analyses, based on the RELAP5 post-test analysis. This paper describes major observations in the LSTF experiment and RELAP5 post-test analysis results to clarify thermal-hydraulic responses as well as the sensitivity analysis results to understand the effectiveness of the AM measures for core cooling during a PWR SBO (TMLB’) transient.

2. ROSA/LSTF

The ROSA/LSTF is the world largest integral test facility designed to investigate multi-dimensional thermal-hydraulic responses during PWR transients and accidents. The LSTF simulates a Westinghouse-type four-loop 3423 MWt PWR by a two-loop system model with full-height and 1/48 in volume. The reference PWR is Tsuruga Unit-2 of Japan Atomic Power Company. Figure 1 shows the schematic view of the LSTF that is composed of a pressure vessel, PZR and primary loops. Each loop includes an active SG, primary coolant pump, hot and cold legs. Each SG is furnished with 141 full-size U-tubes (inner-diameter of 19.6 mm, nine different lengths as shown in Table 1), inlet and outlet plena, boiler section, steam separator, steam dome, steam dryer, main steam line, four downcomer pipes and other internals. Six U-tubes are instrumented for each SG. Instrumented-tubes designated as tubes 1 and 6 are short tubes (type 1 in Table 1), tubes 2 and 5 are medium tubes (type 5) and tubes 3 and 4 are long tubes (type 9). The hot and cold legs, 207 mm in inner diameter, are sized to conserve the volumetric scale (2/48) and the ratio of the length to the square root of pipe diameter to better simulate the flow regime transients in the primary loops (Zuber, 1980).

3. Experiment and code analysis

3.1 LSTF test conditions

The experiment was initiated by terminating SG feedwater at time zero. At the same time, a scram signal was generated, causing the closure of SG main steam isolation valves. The coastdown of primary coolant pumps was started
at 18 s, and the pump rotation speed was decreased to zero 250 s after the initiation of the coastdown. Initial steady-state conditions such as PZR pressure, fluid temperatures in hot and cold legs were 15.5 MPa, 599 K and 564 K, respectively, according to the reference PWR conditions. The LSTF core power decay curve after the scram signal was pre-determined based on calculations with the RELAP5 code considering delayed neutron fission power and stored heat in PWR fuel rod (Kumamaru and Tasaka, 1990) in addition to heat losses. Radial core power profile was assumed to be flat. The LSTF core power was maintained at the initial value of 10 MW for 18 s after the scram signal. The LSTF core power started to decay afterwards according to the specified core power. To obtain prototypical initial fluid temperatures with this core power, core flow rate was set to 14% of the scaled nominal flow rate. Initial SG secondary pressure was raised to 7.3 MPa to limit the primary-to-secondary heat transfer rate to 10 MW, while 6.1 MPa is nominal value in the reference PWR.

The experiment assumed total failure of high-pressure and low-pressure injection systems of ECCS and malfunction of relief valves in PZR and SGs. SVs in PZR and SGs respectively were simulated by using sharp-edge orifices of 6.83 and 19.4 mm in inner diameter, which have flow capacities corresponding to about 45 and 140% of the volumetrically-scaled flow rates of the reference PWR. Set point pressures for opening and closure of the PZR SV are 16.20 and 16.07 MPa respectively, and those of the SG SVs are 8.68 and 7.69 MPa referring to the corresponding values in the reference PWR. Initial SG secondary-side collapsed liquid level was set to 6.8 m that corresponds to 2/3 of the medium tube height.

3.2 RELAP5 calculation conditions

The post-test analysis was conducted with the RELAP5/MOD3.2.1.2 code by incorporating a two-phase critical flow model (Asaka, et al., 1991), which may predict the discharge rate through a sharp-edge orifice to simulate the PZR SV. Figure 2 shows a nodding schematic of LSTF for RELAP5 analysis. The LSTF system is modeled in one-dimensional manner including a pressure vessel, primary loops, PZR, SGs and SG secondary-side system. The SG U-tubes were modeled by nine parallel flow channels that correspond to nine different lengths of U-tubes, namely 24 nodes for short to medium tubes (straight length of 9.44-9.89 m, four cases in Table 1) and 26 nodes for medium to long tubes (straight length of 10.04-10.64 m, five cases), for better prediction of non-uniform flow distribution during NC (Susyadi and Yonomoto, 2005; Takeda, et al., 2012a).

The core was represented by nine equal-height volumes that are vertically stacked according to 9-step chopped cosine power profile along the length of the core. The PZR was represented by ten vertical nodes to simulate corresponding facility configuration. RELAP5 liquid entrainment model for a horizontal pipe was applied to the PZR surge-line inlet junction connected to the hot leg. Other initial and boundary conditions were determined according to the LSTF test data.

3.3 LSTF test and RELAP5 post-test analysis results

Table 2 summarizes the chronology of major events obtained in the LSTF test and RELAP5 post-test analysis. The LSTF test results are shown in Figs. 3-16 as a comparison with RELAP5 post-test analysis results. Compared time duration in Figs. 11-16 is up to 3000 s to focus on the primary-side fluid temperatures in upflow and downflow sides of SG U-tube during single-phase liquid NC.

<table>
<thead>
<tr>
<th>Event</th>
<th>Test (s)</th>
<th>Anal. (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG feedwater termination</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SG main steam isolation valve closure</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Start of primary coolant pumps</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>coastdown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start of single-phase liquid NC</td>
<td>267</td>
<td>267</td>
</tr>
<tr>
<td>Full of liquid in PZR</td>
<td>3710</td>
<td>3850</td>
</tr>
<tr>
<td>Empty of liquid in SG secondary-side</td>
<td>4260</td>
<td>3720</td>
</tr>
<tr>
<td>Termination of single-phase liquid NC</td>
<td>5220</td>
<td>5200</td>
</tr>
<tr>
<td>Start of drop in PZR liquid level</td>
<td>6140</td>
<td>5430</td>
</tr>
<tr>
<td>Termination of two-phase NC</td>
<td>6700</td>
<td>5700</td>
</tr>
<tr>
<td>Empty of liquid in hot leg</td>
<td>7760</td>
<td>7260</td>
</tr>
<tr>
<td>Start of core uncovery</td>
<td>8010</td>
<td>7900</td>
</tr>
<tr>
<td>Cladding surface temperature:</td>
<td>8070</td>
<td>7980</td>
</tr>
<tr>
<td>653 K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.3.1 Major phenomena observed in the LSTF experiment

The SG secondary pressure increased rapidly up to about 8.6 MPa after the closure of the SG main steam isolation valves (Fig. 3). The SG secondary pressure fluctuated between 8.68 and 7.69 MPa by cycle opening of the SG SVs until 3650 s. The SG secondary-side collapsed liquid level gradually decreased with some fluctuation (Fig. 4) because of cycle opening of the SG SVs. The SG secondary-side liquid level became lost at 4260 s. The primary pressure decreased because of the core power decay following the scram signal. The primary pressure turned to increase at around 1500 s when the SG secondary-side collapsed liquid level decreased to about 3 m (Figs. 3 and 4), which caused an increase in the PZR liquid level by volumetric expansion of coolant (Fig. 5). The PZR became full of liquid at 3710 s when the PZR SV opened for the second time. The primary pressure reached 16.2 MPa by cycle opening of the PZR SV when the PZR liquid level was kept full, which caused loss of primary coolant. During the time period around 3300-5600 s, the primary pressure fluctuation became larger than the difference in the set point pressures for the PZR SV cycle opening probably due to influences of remained steam at the PZR top. The PZR liquid level began to drop at 6140 s after significant drop started in the hot leg liquid level (Figs. 5 and 6). The hot leg liquid level temporarily recovered to the top probably because of a continuous but small increase in the primary pressure. Another valve (sharp-edge orifice of 11.83 mm in inner diameter) in PZR was temporarily opened when the primary pressure increased up to 16.5 MPa, which caused the primary pressure decrease and the second significant drop in the PZR liquid level. The hot leg became empty of liquid at 7760 s after the SG U-tubes became voided (Figs. 6 and 8).

Long-term single-phase liquid NC continued until liquid level formed in the hot leg after the primary coolant pumps stop. The primary mass flow rate gradually decreased after the voiding started in the SG U-tubes (Figs. 7 and 8). Two-phase NC terminated when the primary mass flow rate decreased to zero. Liquid level in the core started to decrease following significant drop in the SG U-tube liquid level (Figs. 8 and 9). Core uncovery by boil-off took place a little after the hot leg became empty of liquid, while the primary pressure was kept high. At 8070 s (Fig. 10), the maximum cladding surface temperature of simulated fuel rod reached 653 K that corresponds to 30 K of the temperature rise after the core uncovery. During the single-phase liquid NC, the primary-side fluid temperatures in the SG U-tubes indicated non-uniform flow distribution including reverse flow when the liquid level decreased in the SG secondary-side (Figs. 11, 13 and 15). Such non-uniform flow was also observed in the steady-state NC tests under core powers of 2 and 5% of the volumetrically-scaled PWR nominal core power where the pressure and collapsed liquid level in the SG secondary-side were kept at 6.5 MPa and at the level equivalent to the short tube height respectively (Kukita, et al., 1988). The reverse flow was observed during the time period around 2230-2290 s in the short tube (tube 1 mentioned in Chapter 2) in the loop with PZR, while around 1070-1220 s, 1510-1590 s and 1980-2040 s in the medium tube (tube 2). Reverse flow appeared in the long tube (tube 3) during the time period around 420-1000 s, 1080-1220 s, 1510-1670 s, 1980-2040 s, 2120-2150 s and 2250-2300 s. The reverse flow duration was longer as the tube is longer. During the reverse flow, the primary-side fluid temperature is close to the secondary-side saturation temperature along the entire length of the tube. The reverse flow timings were different among the SG U-tubes due to influences of different locations and lengths.

![Fig. 3](image-url) LSTF and RELAP5 results for primary and SG secondary pressures in loop with PZR.

![Fig. 4](image-url) LSTF and RELAP5 results for SG secondary-side collapsed liquid level in loop with PZR.
Fig. 5  LSTF and RELAP5 results for PZR liquid level.

Fig. 6  LSTF and RELAP5 results for hot leg liquid level in loop with PZR.

Fig. 7  LSTF and RELAP5 results for primary mass flow rate in loop with PZR.

Fig. 8  LSTF and RELAP5 results for collapsed liquid levels in SG U-tube upflow side in loop with PZR.

Fig. 9  LSTF and RELAP5 results for core collapsed liquid level.

Fig. 10  LSTF and RELAP5 results for cladding surface temperature.
Fig. 11 LSTF results for primary-side fluid temperatures in upflow and downflow sides of SG short tube in loop with PZR.

Fig. 12 RELAP5 results for primary-side fluid temperatures in upflow and downflow sides of SG short tube in loop with PZR.

Fig. 13 LSTF results for primary-side fluid temperatures in upflow and downflow sides of SG medium tube in loop with PZR.

Fig. 14 RELAP5 results for primary-side fluid temperatures in upflow and downflow sides of SG medium tube in loop with PZR.

Fig. 15 LSTF results for primary-side fluid temperatures in upflow and downflow sides of SG long tube in loop with PZR.

Fig. 16 RELAP5 results for primary-side fluid temperatures in upflow and downflow sides of SG long tube in loop with PZR.
3.3.2 Comparison of calculated results with LSTF data

Initial steady-state values obtained by the RELAP5 code analysis were in reasonable agreement with those in the LSTF test, as shown in Table 3. Initial steady-state value of the primary mass flow rate was a little underpredicted, while that of the fluid temperature difference between the hot and cold legs was a little overpredicted.

The RELAP5 code predicted well the overall trend of thermal-hydraulic response observed in the LSTF test as compared in Figs. 3-16. Cycle opening of the SG SVs was predicted reasonably well, which caused reasonably-well predictions of the pressure and collapsed liquid level in the SG secondary-side (Figs. 3 and 4).

Some discrepancies from the measured data, however, appeared in the timings of major events as shown in Table 2. Until the PZR became full of liquid, the pressure and liquid level in the PZR were underpredicted (Figs. 3 and 5) because of larger number of the SG SVs opening thus larger integrated discharge steam flow through the SG SVs due to the SVs closure at a bit lower secondary pressure in the test than the set point pressure as the analysis condition.

Table 3 Difference between initial steady-state values obtained by RELAP5 code analysis and LSTF test.

<table>
<thead>
<tr>
<th>Item</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core power</td>
<td>0</td>
</tr>
<tr>
<td>Primary pressure</td>
<td>0.8</td>
</tr>
<tr>
<td>Hot leg fluid temperature</td>
<td>0.2</td>
</tr>
<tr>
<td>Cold leg fluid temperature</td>
<td>0.8</td>
</tr>
<tr>
<td>Primary mass flow rate</td>
<td>4.8</td>
</tr>
<tr>
<td>SG secondary pressure</td>
<td>0.3</td>
</tr>
<tr>
<td>SG feedwater flow rate</td>
<td>0</td>
</tr>
<tr>
<td>SG secondary collapsed liquid level</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Significant drop in the liquid levels at the PZR, hot leg and SG U-tubes as well as core uncover started earlier than in the LSTF test (Figs. 5, 6, 8 and 9) because of larger number of the PZR SV opening thus larger integrated discharge coolant flow through the PZR SV. The primary mass flow rate was calculated reasonably well, though with a tendency that the flow rate decreased to zero earlier than in the LSTF test causing earlier termination of two-phase NC (Fig. 7). The code failed to reproduce the primary pressure increase after the liquid level formation in the PZR, which caused failure of temporal recovery to the top in the hot leg liquid level and the second significant drop in the PZR liquid level. Earlier core uncover caused earlier initiation of the cladding surface temperature rise (Figs. 9 and 10).

The code also failed to reproduce the reverse flow U-tubes because of prediction of stable NC flow in all the tubes due to inadequate prediction of the pressure difference between the SG outlet and inlet plena (Figs. 12, 14 and 16). In the post-test analysis, the primary-to-secondary heat transfer continued at the upflow side of all the tubes during the single-phase liquid NC. Almost the same trend of the primary-side fluid temperature among the U-tubes has happened in response to the cycle opening of the SG SVs.

4. Effectiveness of AM measures for core cooling

4.1 Sensitivity analysis conditions

Effectiveness of depressurization of and coolant injection into SG secondary-side as the AM measures for core cooling was studied through RELAP5 code sensitivity analyses. Employed analysis models were the same as those for the post-test analysis. SG secondary-side depressurization through the SG valve(s) with the SG coolant injection is one of major AM measures to cool and depressurize the primary system to introduce ACC system especially when high-pressure injection system is totally failed such as the TMLB’ scenario.

Table 4 shows the sensitivity analysis conditions. SG depressurization was performed by fully opening the SV in the loop without PZR (loop-B); one of two SGs. The SG-B depressurization was started with the incipience of core uncover, that is, the maximum cladding surface temperature reached 653 K as observed in the LSTF test. The coolant injection into the SG-B secondary-side was started when the SG-B secondary pressure was lowered to 1.0 or 0.5 MPa considering availability and characteristics of fire engines. The SG-B coolant injection flow rate was at a constant value, ranging from 0.4 to 1.0 kg/s, assuming the performance of fire engines. Among the injection conditions, the flow rate of 0.7 kg/s corresponds to the volumetrically-scaled AFW flow rate of the reference PWR. The SG-B coolant injection temperature of 310 K is assumed to be the same as the AFW temperature in the reference PWR.
4.2 Influences of AM measures onto major phenomena

Figures 17-25 show the influences of the AM measures onto the major phenomena, under the certain condition that the SG-B secondary-side depressurization is initiated when the maximum cladding surface temperature reaches 653 K. The SG-B secondary pressure started to decrease when the SG-B SV was fully opened at 7980 s. The SG-B secondary pressure decreased down to 1.0 and 0.5 MPa at 8160 and 8220 s, thus in rather short time within 180 and 240 s, respectively. However, the primary pressure was kept high because the SG secondary-side was empty of liquid during the SG-B depressurization, resulting in continuous core boil-off and heatup due to continuous loss of primary coolant.

The primary-to-secondary heat removal by SG-B resumed when the SG-B secondary-side collapsed liquid level began to recover soon after the coolant injection into the SG-B secondary-side at low pressures, namely the SG-B secondary pressure less than 1.0 MPa (Figs. 18 and 19), which caused decreases in the pressure and liquid level at the PZR (Figs. 20 and 21). The liquid levels at the core and hot leg recovered by coolant from the PZR (Figs. 22 and 23), and the whole core was quenched as the primary pressure decreased (Figs. 20 and 24). The SG-B secondary pressure once increased, and decreased being followed by the increased collapsed liquid level in the SG-B secondary-side because of an increase in the SG-B integrated injection coolant flow thereafter (Figs. 17 and 19).

The peak cladding temperature (PCT), which appeared at Position 7 (= about 2.6 m above the core bottom), was dependent on the onset timing and flow rate of the SG-B coolant injection (Fig. 24). The PCT was 780, 789, 801, 820 and 853 K depending on the SG-B coolant injection flow rates of 1.0, 0.7, 0.6, 0.5 and 0.4 kg/s respectively when the SG-B coolant injection was started at the SG-B secondary pressure of 1.0 MPa. On the other hand, the PCT was 803, 825, 842, 866 and 899 K respectively when the SG-B coolant injection was initiated at 0.5 MPa. Influences of the onset timing of the SG-B depressurization after core uncoverage onto the PCT are studied in Section 4.3.

The ACC system is initiated coolant injection into both cold legs at the primary pressure of 4.51 MPa, according to the reference PWR condition. The ACC actuation became possible when the SG-B coolant injection flow rate was from 0.4 to 1.0 kg/s (Fig. 25). The ACC actuation became to start earlier as the coolant injection flow rate was increased because of more effective heat removal by the SG-B. When the SG-B coolant injection with flow rate of 0.4 kg/s was initiated at 1.0 and 0.5 MPa, the ACC actuation started at 19710 and 19800 s respectively because of slow decrease in the primary pressure due to slow liquid level recovery in the SG-B secondary-side (Figs. 19 and 20). The influences of the SG-B coolant injection flow rate were significant as above onto the actuation time of ACC system. The core liquid level decreased temporarily after the ACC initiation because of steam condensation on the ACC coolant in the cold legs, and recovered thereafter which caused the whole core was covered by two-phase mixture. Core cooling was ensured finally by the coolant injection from ACC system after the SG secondary-side fast depressurization because of empty secondary-side and full opening of the SV in one of two SGs with the incurrence of core uncoverage and the coolant injection with certain large flow rate is done into the secondary-side of the same SG as the AM measures. Non-condensable gas (nitrogen gas) for pressurization of ACC tanks may start to enter the primary system when the ACC coolant injection is completed due to failure of the system isolation. Such gas inflow from ACC tanks was not considered in the sensitivity analyses. The primary depressurization worsened after the gas ingress due to degradation in the condensation heat transfer in the SG U-tubes in LSTF tests on PWR small-break loss-of-coolant accidents with SG depressurization and AFW injection as AM measures (Takeda, et al., 2012b, 2013). Influences of non-condensable gas onto the long-term SBO (TMLB”) transient with AM measures will be clarified by LSTF tests in the future.

4.3 Influences of onset timing of SG-B depressurization after core uncoverage onto PCT

The PCT was also dependent on the onset timing of the SG-B depressurization after core uncoverage, as shown in Fig. 26. The SG-B depressurization was started at 7980, 8015, 8050, 8085 and 8120 s respectively when the maximum cladding surface temperature reached 653, 668, 683, 698 and 713 K that correspond to 30, 45, 60, 75 and 90 K of the temperature rise after the core uncoverage. The case that the SG-B coolant injection with flow rate of 0.4 kg/s is started at the SG-B secondary pressure of 0.5 MPa was the worst case for the core cooling among the SG-B coolant injection conditions. On the other hand, the case that the SG-B coolant injection with 1.0 kg/s is started at 1.0 MPa was the best case. When the SG-B depressurization was initiated at the maximum cladding surface temperatures of 653 and 713 K, the PCT was 899 and 984 K respectively if the SG-B coolant injection with 0.4 kg/s is started at 0.5 MPa. On the other hand, the PCT was 780 and 852 K respectively if the SG-B coolant injection with 1.0 kg/s is started at 1.0 MPa.

The PCT would thus exceed 900 K in case that it takes several minutes until the start of the SG-B depressurization after the core uncoverage especially when the SG-B coolant injection with certain small flow rate is initiated at 0.5 MPa.
Fig. 17  Influences of AM measures onto SG secondary pressure in loop without PZR by RELAP5 analyses.

Fig. 18  Coolant flow rate injected into secondary-side of SG in loop without PZR in RELAP5 analyses.

Fig. 19  Influences of AM measures onto SG secondary-side collapsed liquid level in loop without PZR by RELAP5 analyses.

Fig. 20  Influences of AM measures onto primary pressure by RELAP5 analyses.
Fig. 21  Influences of AM measures onto PZR liquid level by RELAP5 analyses.

Fig. 22  Influences of AM measures onto hot leg liquid level in loop with PZR by RELAP5 analyses.

Fig. 23  Influences of AM measures onto core collapsed liquid level by RELAP5 analyses.

Fig. 24  Influences of AM measures onto cladding surface temperature by RELAP5 analyses.
5. Conclusions

RELAP5 code post-test analysis was performed on one of ROSA/LSTF abnormal transient tests that simulated a PWR SBO transient with the TMLB’ scenario in 1995. The RELAP5/MOD3.2.1.2 code was used for this study to well understand observed thermal-hydraulic phenomena and to identify remaining subjects for the code to improve. Sensitivity analyses were conducted further to clarify effectiveness of depressurization of and coolant injection into SG secondary-side as AM measures for core cooling, based on the RELAP5 post-test analysis. The SG secondary-side depressurization was initiated by fully opening the SV in one of two SGs with the incipience of core uncovery. The coolant injection was done into the secondary-side of the same SG at low pressures considering availability of fire engines. Major results are summarized as follows;

1. In the LSTF test, the primary and SG secondary pressures were kept almost constant for a long time because of cycle opening of SVs in PZR and SGs as a typical response of SBO. Non-uniform flow distribution including reverse flow appeared in the SG U-tubes during long-term single-phase liquid NC. Core temperature excursion took place by core boil-off, while the primary pressure was kept high.

2. The RELAP5 code predicted well the overall trend of the major phenomena observed in the LSTF test. The code, however, failed to reproduce the reverse flow U-tubes because of prediction of stable NC flow in all the tubes. Significant drop in the liquid levels at the PZR, hot leg and SG U-tubes as well as core uncovery started earlier than in the LSTF test because of larger number of the PZR SV opening thus larger integrated discharge coolant flow through the PZR SV. Earlier core uncovery caused earlier initiation of the core temperature excursion.

3. The RELAP5 sensitivity analyses indicated that the SG-B secondary pressure decreases down to low pressure rapidly because of empty SG secondary-side and full steam discharge through the SG-B SV. The primary pressure started to decrease when the primary-to-secondary heat removal by SG-B resumed due to the recovery in the SG-B secondary-side collapsed liquid level soon after the coolant injection into the SG-B secondary-side at low pressures. The liquid levels at the core and hot leg recovered by coolant from the PZR, and the whole core was quenched as the primary pressure decreased. The peak cladding temperature was dependent on the onset timing and flow rate of the SG coolant injection as well as the onset timing of the SG depressurization after core uncovery. The SG coolant injection flow rate influenced the ACC actuation time significantly.

4. An insight was obtained from the sensitivity analyses that core cooling could be maintained by the ACC actuation if the SG coolant injection is successful by using fire engines into the depressurized SG during a PWR SBO (TMLB’) transient.

JAIAE is planning to perform LSTF tests with SBO scenarios including TMLB’ and AM measures to clarify the thermal-hydraulic responses as well as the effectiveness of the AM measures for core cooling.
Nomenclature

ACC accumulator
AFW auxiliary feedwater
AM accident management
ECCS emergency core cooling system
JAEA Japan Atomic Energy Agency
LSTF large scale test facility
NC natural circulation
PCT peak cladding temperature
PWR pressurized water reactor
PZR pressurizer
ROSA rig of safety assessment
SBO station blackout
SG steam generator
SV safety valve

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