Comparison of LSTF Test (SB-CL-18) and PWR Plant Analysis

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Abstract: Confirmation of the reliability of thermal-hydraulic analyses is important in the evaluation of the effectiveness of plant safety measures and the analysis of success criteria for probabilistic risk assessment. The Nuclear Regulation Authority of Japan has been developing analytical models of PWR plants using the TRACE code. Herein, to validate the model for small break loss of coolant accident (SBLOCA), the analytical conditions of the model were set as close as possible to the experimental conditions of the SBLOCA experiment (SB-CL-18) at LSTF taking into account the volume scale ratio, and the analytical results were compared with the measured data, and then the differences were analyzed and discussed.

Keywords: PWR, TRACE, Small break LOCA, LSTF

1. INTRODUCTION

In order to confirm the safety of nuclear power plants, it is necessary to evaluate the response of the plant under various accident sequences using simulation codes. The validity of this evaluation is ensured through the verification and validation (V&V) of the simulation code as well as validation of the analytical model. Measured data on nuclear power plant behavior during accidents is very limited. Therefore, the validity of analytical models is indirectly verified via an integral effect test (IET) conducted in an appropriately scaled-down test facility modeling the assessed nuclear power plant. In previous studies by the other authors, comparisons have been made between the Large Scale Test Facility (LSTF) [1] and Siemens-KWU Type PWR [2], the Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS) and APR1400 [3], and the Advanced Core-cooling Mechanism Experiment (ACME) and CAP1400 [4]. Through such efforts, the validity of analytical models and the effects of scaling have been examined. The Nuclear Regulation Authority of Japan (NRA) has been developing analytical models for PWR plants using system analysis code TRACE V5.0 Patch 5 [5] and is currently validating the developed analytical models. As part of these efforts, the present study focused on the characteristics of phenomena that should be reproduced in PWR plant analysis. Herein, TRACE simulations of PWR plants were conducted to validate the input data for the analytical models. We compared the results of our analytical model of the PWR plant with the experimental data of the small break loss of coolant accident (SBLOCA) test, SB-CL-18, at the LSTF where the analytical conditions were set as close as possible to the experimental ones taking into account the volume scale ratio. The differences between the analytical and experimental results were analyzed and appropriate modeling was discussed through sensitivity analyses.

2. DESCRIPTION OF LSTF

2.1. Test Facility

Herein, LSTF refers to a large scale test facility owned by the Japan Atomic Energy Agency. Figure 1 shows an overview of the LSTF, a scaled-down facility of the reference plant, Westinghouse-type 4-loop PWR with a volume scale ratio of 1/48. As shown in Table 1, the LSTF has the same height of the main facilities as the reference PWR plant and exhibits good performance in simulating the natural circulation of the plant, so the LSTF is expected to accurately simulate the accident behavior of the modeled PWR plant.

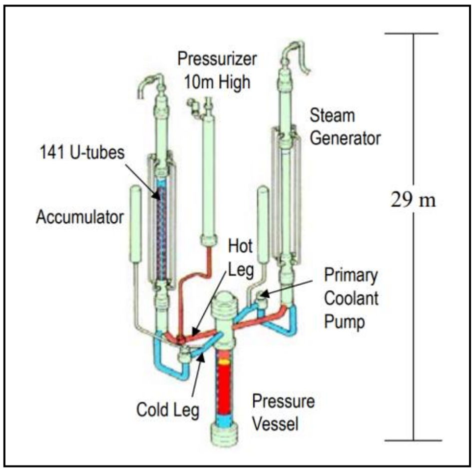


Figure 1. Schematic of LSTF [6]

Table 1. Design Characteristics of LSTF and PWR

	LSTF	4-loop PWR (Reference)	3-loop PWR (NRA model)
Core Power (MW)	10	3423	2652
Pressure of Primary System (MPa)	15.5		
Temperature of Primary System (K)	598		
Core height (m)	3.7		
Number of fuel rods	1064	50952	41448
Volume of Pressure Vessel (m^3)	2.7	132	102

2.2. SB-CL-18

SB-CL-18 [7], conducted at the LSTF, was designed to investigate the mechanism through which thermal hydraulics may cause early core exposure during SBLOCA (5% cold leg break) assuming a failure of the high-pressure injection system. This test was performed in 1988 as part of the ROSA-IV program of the OECD/NEA project [8]. Figure 2 shows the measured data of the peak cladding temperature (PCT) in the test.

In SB-CL-18, a small break occurred in the cold leg, resulting in a gradual decrease in pressure in the primary system. The pressure decreased below the saturation pressure, leading to the generation of steam due to decompression boiling (flashing). Continued release from the break reduced the water level in the primary system. The generated steam that was passing through the hot leg and the SG tubes was sealed by water remaining in the crossover leg (COL) causing a drop in the core water level, which is called loop seal formation. The loop seal was then cleared as water in the COL was pushed to the cold leg side. The temporarily lowered core water level was recovered by the loop seal clearing. Subsequently, the coolant evaporated owing to the effect of decay heat in the core, and the core water level slowly dropped, which is called boil-off. When the primary system pressure reached 4.5 MPa, the accumulator injection system automatically started and the core water level recovered. Thus, in SB-CL-18, the core water level dropped because of loop seal formation and boil-off, which temporarily exposed the core and resulted in the detection of PCT peaks.

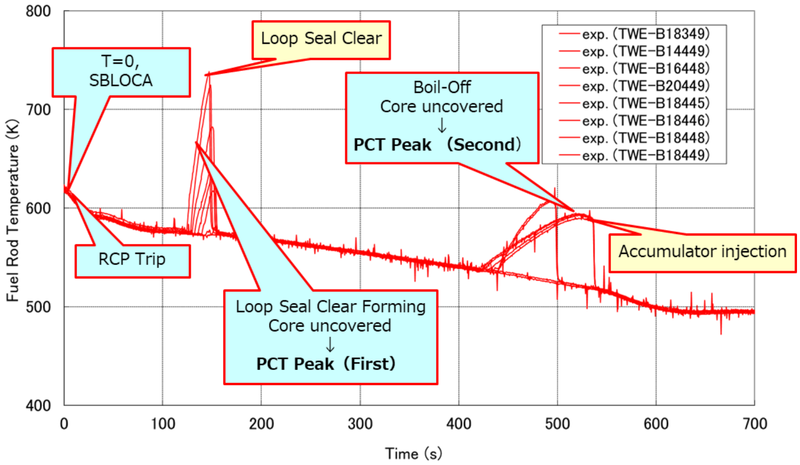


Figure 2. Measured Data of PCT in SB-CL-18

2.3. TRACE Analysis of SB-CL-18

The results of the TRACE analysis [9] of SB-CL-18 (SB-CL-18(TRACE)) and the experimental results (SB-CL-18(exp.)) are shown in Figure 3. The TRACE analysis reproduces the measured data of SB-CL-18 for the pressures in the primary and secondary systems, core water level, and PCT. This indicates that the combination of the TRACE and the analytical model of LSTF can well simulate the SBLOCA test.

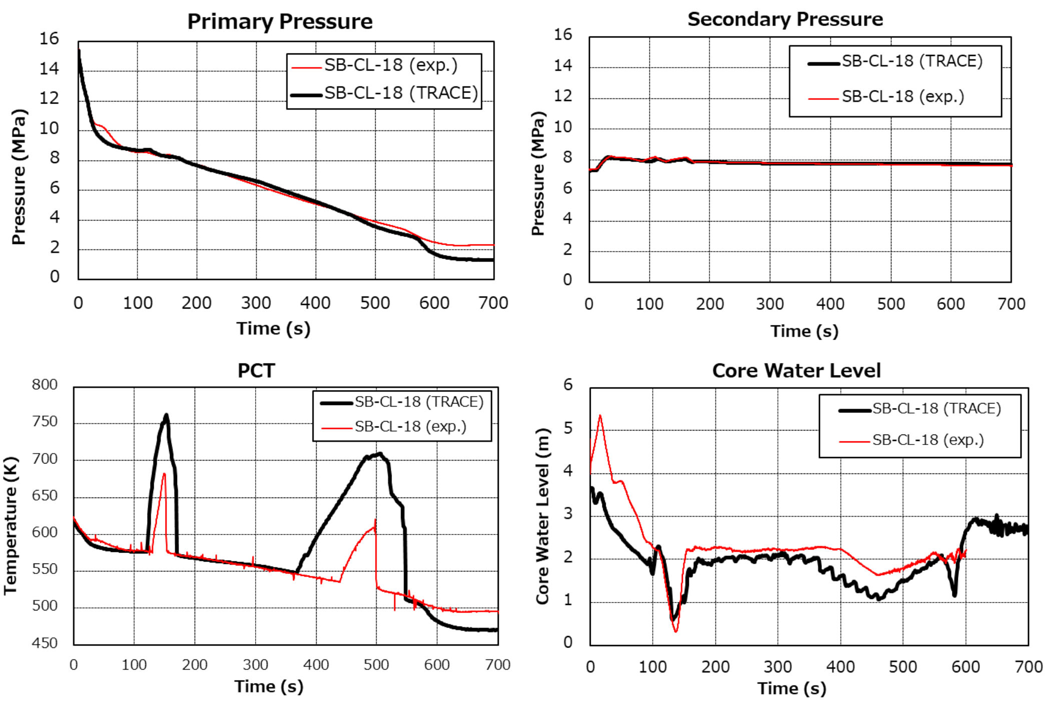


Figure 3. Analysis of the Results of SB-CL-18 [9]

3. TRACE ANALYSIS OF 3-LOOP PWR PLANT

3.1. Analytical Model and Conditions

Figure 4 shows the analytical model of a 3-loop Westinghouse-type PWR plant. The pressure vessel is modeled using VESSEL, a cylindrical 3D component, with 5 × 3 ×18 nodalization (R, Θ, Z). The containment vessel is modeled using a CONTAN component. Other flow paths are modeled using 1D components.

As described in Table 2, the analytical conditions were set as close as possible to SB-CL-18 conditions taking into account the volume scale ratio; for example, the core power of the 3-loop PWR was set at 36 (= 48 × 3/4) times the thermal power of the LSTF. The break location was cold leg as in SB-CL-18. The break setting (discharge coefficients for choked flow and break size) was selected so that the pressure decrease in the primary system was in agreement with that measured in SB-CL-18. The opening and closing pressures of the main steam-relief valves were chosen so that the pressure in the secondary system was in agreement with that in SB-CL-18.

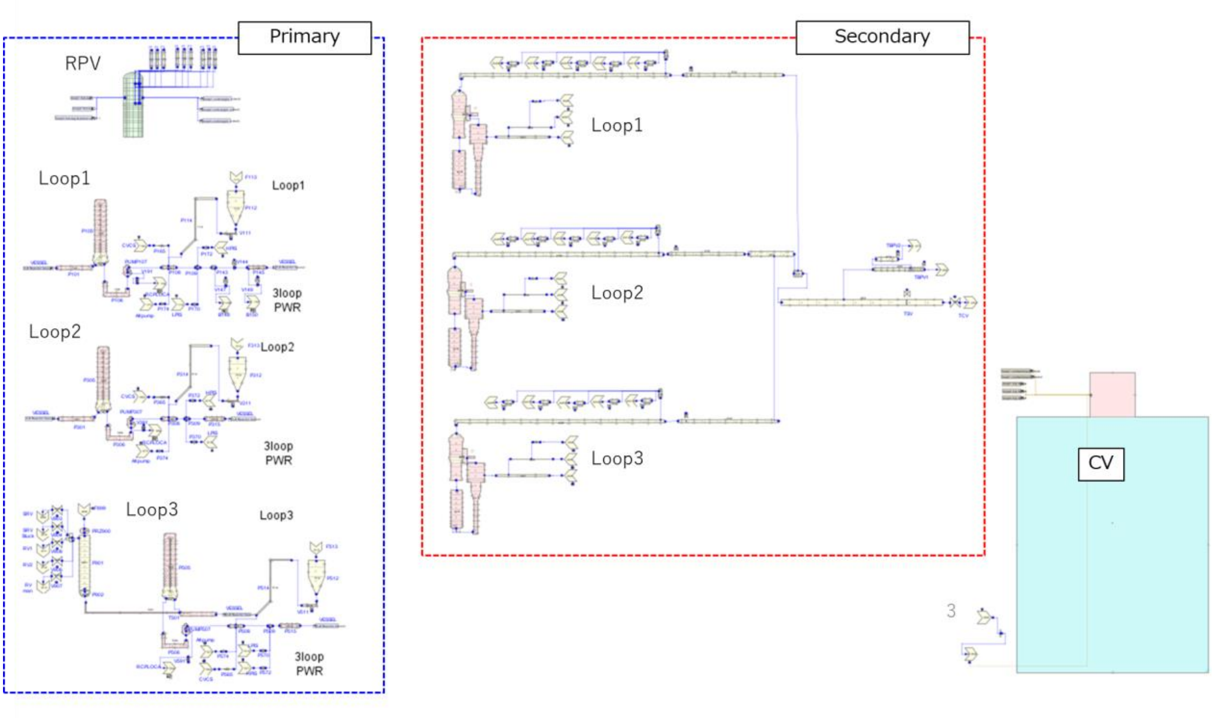


Figure 4. TRACE Analytical Model for the 3-Loop PWR

Table 2. LSTF Test Conditions and TRACE Analytical Conditions

	Test conditions	Analytical conditions
	LSTF	3-loop PWR
Initial core power (MW)	10	360
Primary pressure (MPa)	15.5	15.5
Secondary pressure (MPa)	7.35	5.6
Hot leg fluid temperature (K)	599	595
Cold leg fluid temperature (K)	564	557
Break size (m^2/%)	0.0225/5.0	0.156/4.98
High-pressure injection system	Not actuated	Not actuated
Low-pressure injection system Set pressure (MPa)	1.29	1.36
Accumulator injection system Set pressure (MPa)	4.51	4.14
Auxiliary feedwater	Not actuated	Not actuated

3.2. Comparison between LSTF and 3-Loop PWR

The results of the TRACE analysis of the 3-loop PWR (3loop(TRACE)) are shown in Figure 5. The water level in the core of the 3-loop PWR slowly drops after the break and recovers with water injection that starts at about 500 s. In SB-CL-18, a sudden drop in water level due to loop seal formation at about 130 s is observed, whereas in the 3-loop PWR, a slight change is observed at about 200 s. The water level drop due to boil-off after 400 s is generally consistent between the 3-loop PWR and LSTF. As the pressures in the primary system are almost the same in the PWR and LSTF, the saturation temperatures in the PWR and LSTF are also the same, and thus the overall decreasing trend in PCT is consistent. However, the 3-loop PWR did not experience a peak in PCT due to the loop seal formation because the drop in the core water level was small. As the drops in core water level during boil-off and the recovery of water level due to water injection are generally consistent, the second PCT peaks due to boil-off are also consistent.

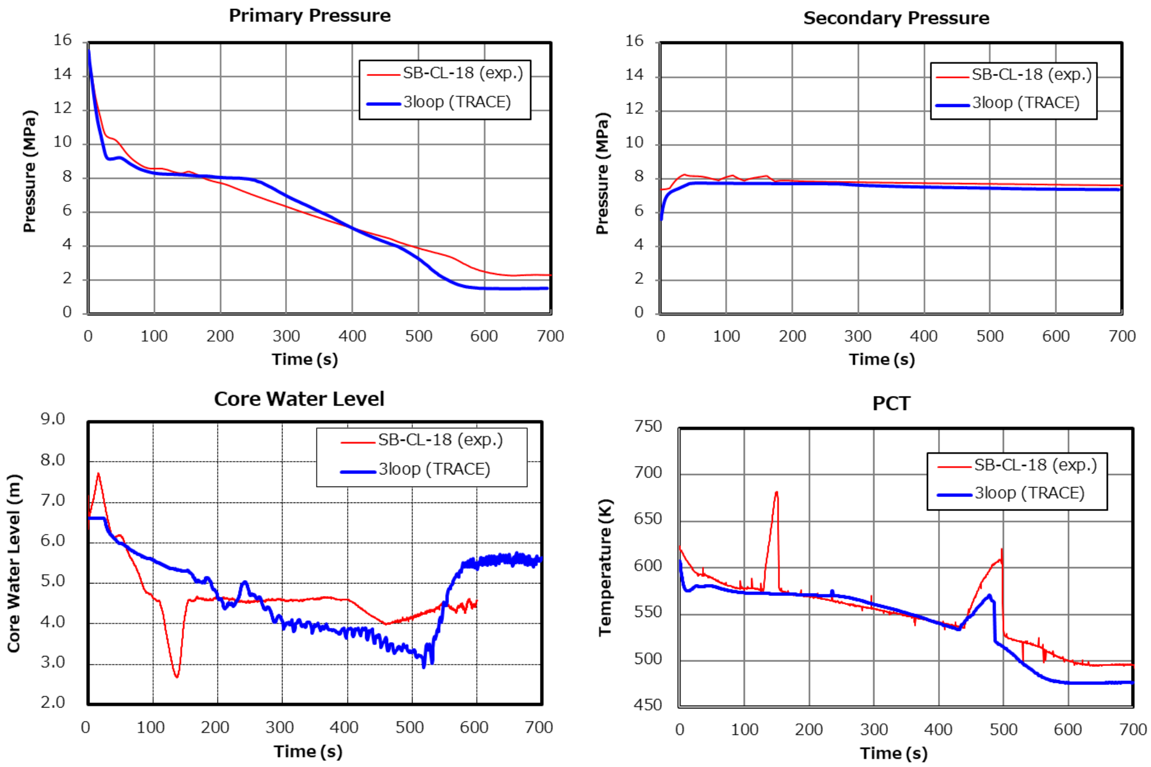


Figure 5. Analysis Results for 3-Loop PWR (Base Case)

4. SENSITIVITY ANALYSIS OF 3-LOOP PWR

As shown in 3.2, the analysis of the 3-loop PWR did not show much of the core water level drop due to the loop seal formation that occurred in SB-CL-18, and therefore, the PCT peak due to the loop seal formation did not occur. As the loop seal formation is the flow behavior at the COL, a sensitivity analysis with different analytical models and conditions of the COL was performed to analyze the difference from the LSTF mentioned above.

4.1. Case 1: Fine Nodalization of the COL

As shown in Figure 6, the nodalization of the COL piping where the loop seal is formed was changed from 6 cells to 13 cells (Case 1). The results for Case 1 are shown in Figure 7. In the model with fine nodalization (3loop(TRACE)_case1), a slight peak in PCT due to the loop seal formation occurred because of a larger drop in the core water level during the loop seal formation.

To elucidate the cause of the larger drop in the core water level, the flow conditions in the COL were examined. Figure 8 shows the results of the base case. The core water level slightly drops in the range indicated by the gray shading, but the void fraction at the bottom of the COL and on the ascending side (cells 3–6) is greater than zero at that time, indicating that steam was passing through. In TRACE, the horizontal stratification is characterized by a weighting factor, which is set to 1.0 for complete stratification, 0.0 for no stratification, and 0.0–1.0 for intermediate conditions. The interfacial friction coefficient is evaluated by interpolating the coefficient for horizontal stratified flow and the coefficient for non-stratified flow by the weighting factor. As shown in the right part of Figure 8, the weighting factor at the cell boundary face at the bottom of the COL is almost 1.0, and the flow is determined to be horizontally stratified at the bottom of the COL. This indicates that the interfacial friction is evaluated to be small and that steam can pass through water in the bottom of the COL. Figure 9 shows the results for Case 1 with fine nodalization. At the time when the core water level decreases (gray shading), the void fraction is almost zero at the bottom of the COL and on the ascending side (cells 8–13), indicating that steam does not pass through and a loop seal is formed. The weighting factor for horizontal stratification at the bottom of the COL is less than 1.0, indicating that only partial stratification occurred and that the interfacial friction was larger than that in the base case, preventing the passage of steam.

The TRACE model tends to evaluate a larger weighting factor for stratification when the void fraction is large. The coarse nodalization of the base case does not maintain the discontinuity of the void fraction at the water surface, and the gas phase spreads by numerical diffusion. Therefore, the void fraction at the bottom of the COL was overestimated when the water surface reached the bottom, the weighting factor for stratification was also overestimated.

In Case 1, the PCT peak at boil-off is smaller because of the slightly slower core water level drop after the clearance of the loop seal. As the PCT peak of boil-off is determined by the timings of the core water level drop, core exposure, and the start of the accumulator injection, it is considered to be sensitive to the analytical model and analytical conditions.

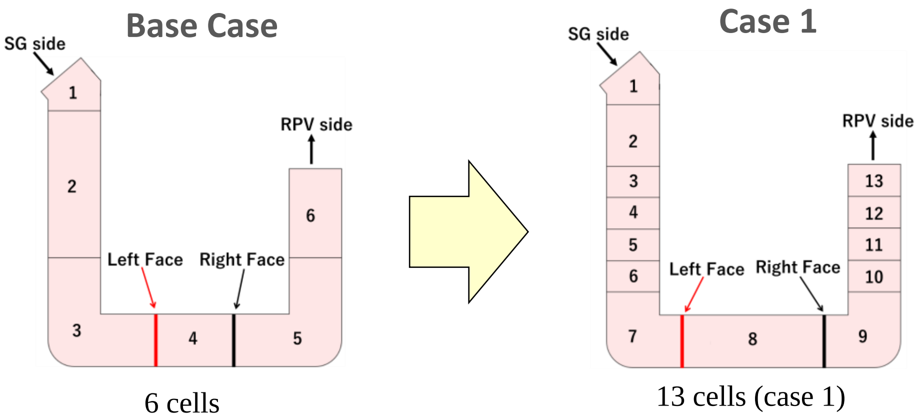


Figure 6. Case 1: Change in the Nodalization of COL

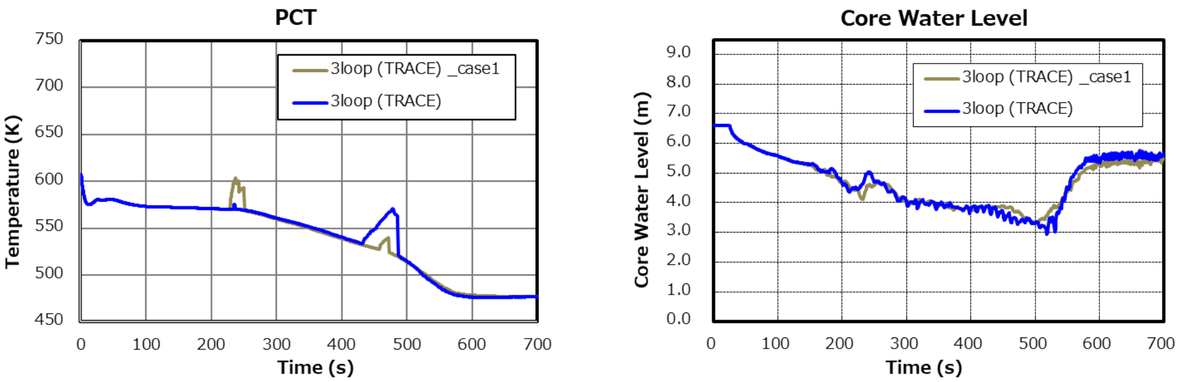


Figure 7. Results for Case 1

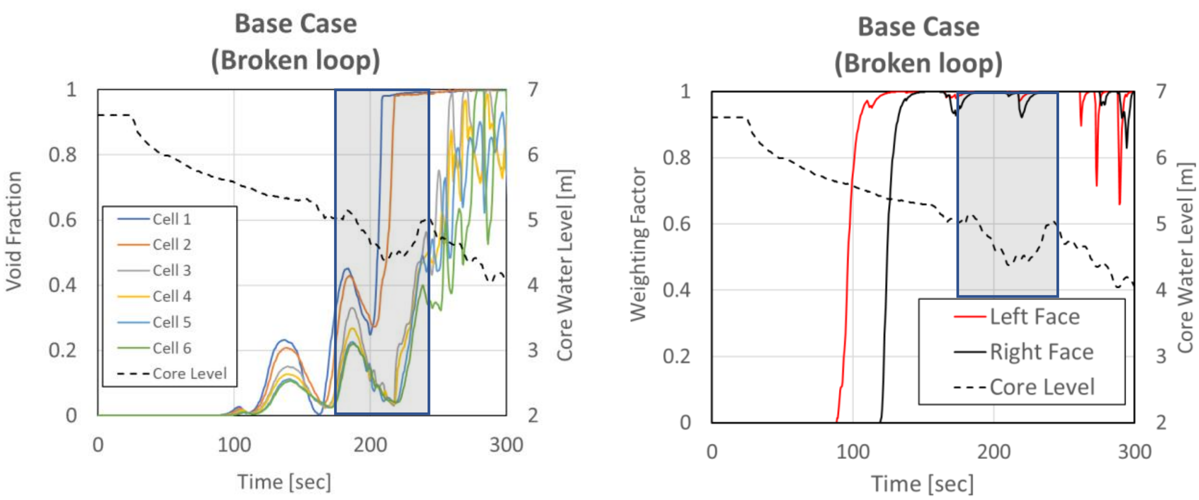


Figure 8. Void Fraction and Weighting Factor for Horizontal Stratification in the COL in Base Case

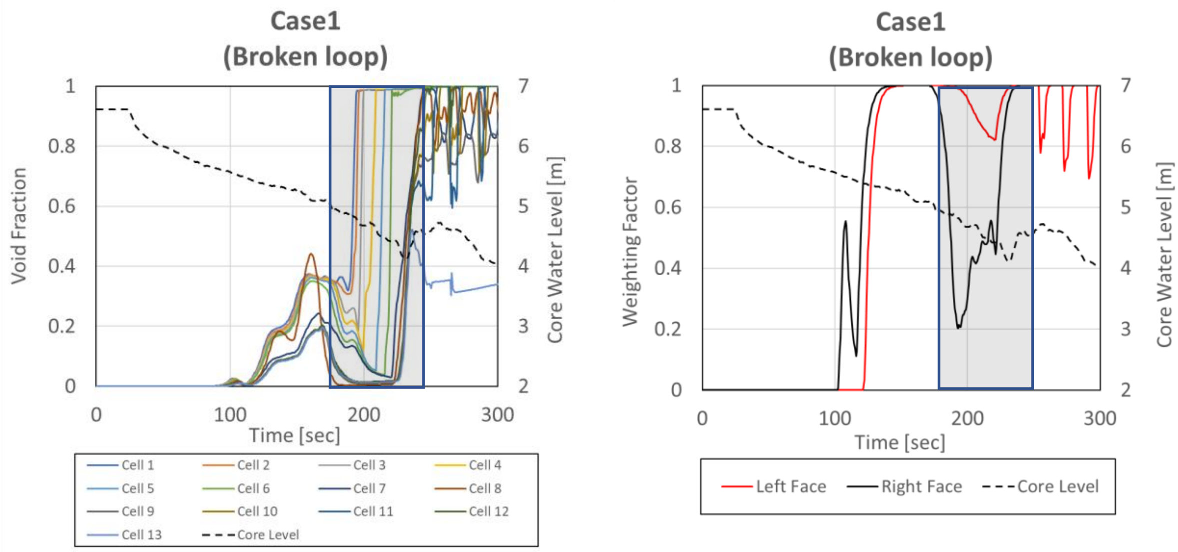


Figure 9. Void Fraction and Weighting Factor for Horizontal Stratification in the COL in Case 1

4.2. Case 2: shape change of COL

As shown in Figure 10, the shape of the COL was changed from a right angle to a U-shape (Case 2), and the results of the analysis (3loop (TRACE)_case2) are shown in Figure 11. This shape change caused a larger drop in core water level due to the loop seal formation, resulting in a PCT peak. As in the previous section, the void fraction and weighting factors for stratification at the COL for Case 2 are shown in Figure 12, where TRACE evaluates the highest weighting factor for stratification when the pipe orientation is horizontal and it decreases as the pipe orientation changes to vertical, resulting in smaller weighting factors than in the base case and Case 1. Therefore, the interfacial friction evaluated larger resulted in a clear loop seal.

As the COL shape change had little effect on the core water level drop after the loop seal formation, the peak due to boil-off is almost the same as that in the base case.

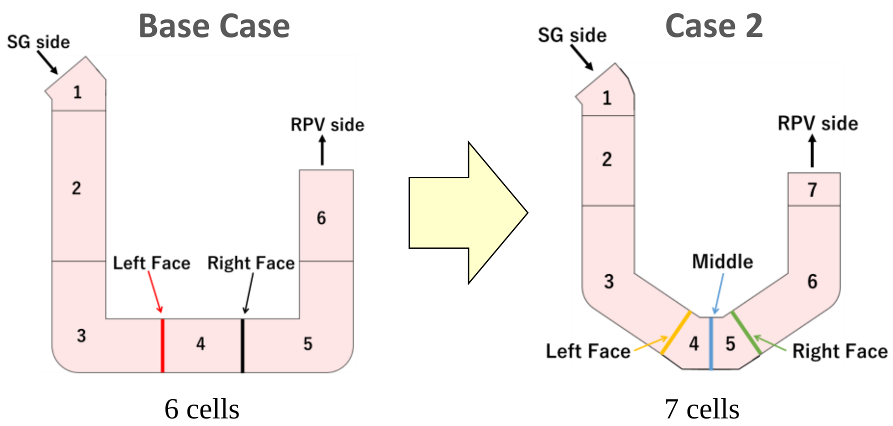


Figure 10. Case 2: Change in the Shape of the COL Bottom (Straight Pipe to U-Shape)

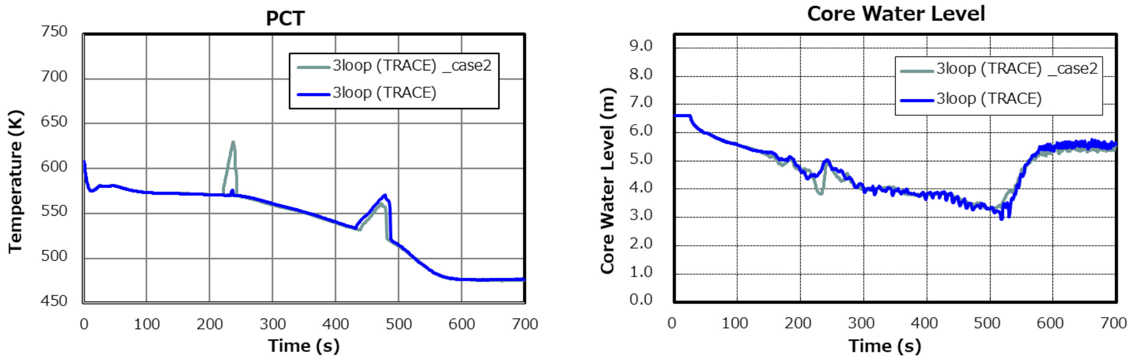


Figure 11. Results for Case 2

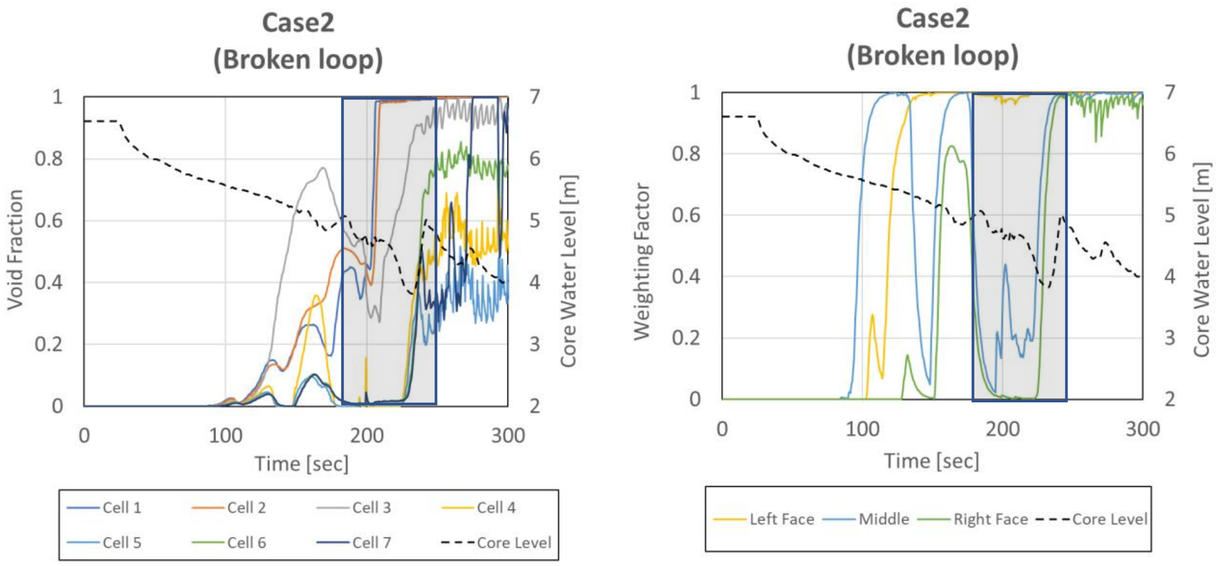
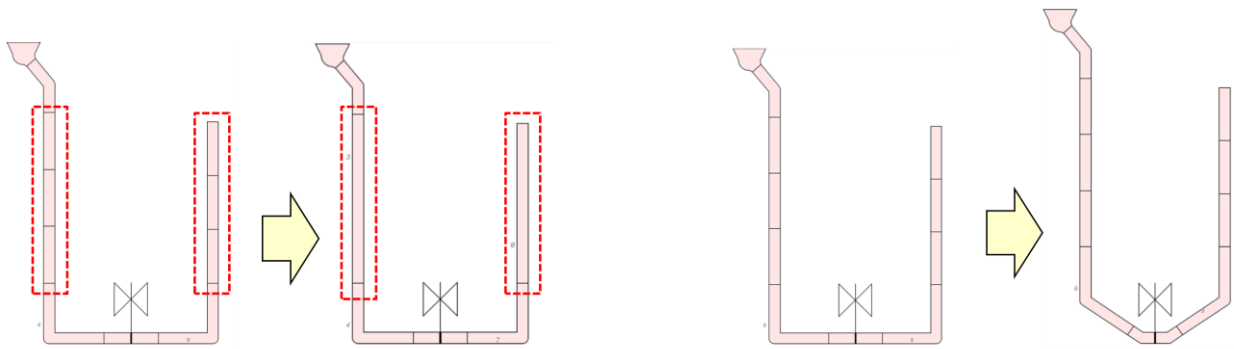


Figure 12. Void Fraction and Weighting Factor for Horizontal Stratification in the COL in Case 2

5. EFFECTS OF COL MODELING IN TRACE ANALYSIS OF SB-CL-18

In the analysis of SB-CL-18 with TRACE, the modeling of the COL has a weak impact on the behavior during loop seal. As shown in Figure 13, sensitivity analyses of SB-CL-18 were performed by changing the COL modeling. Figure 14 shows the results of the analyses of Case 1 (SB-CL-18(TRACE)_case1), with a coarser nodalization of the COL and for Case 2 (SB-CL-18(TRACE)_case2), with a U-shaped COL. Both results are close to those for the base case (SB-CL-18(TRACE)), suggesting that the impact of COL modeling is less significant in LSTF analysis than in the 3-loop PWR analysis. This difference in modeling sensitivity between the PWR plant analysis and LSTF analysis should be considered when developing analytical models for nuclear power plants based on those developed by using the IETs.



SB-CL-18(TRACE)_case1 SB-CL-18(TRACE)_case2

Figure 13. Changes in COL Modeling of LSTF

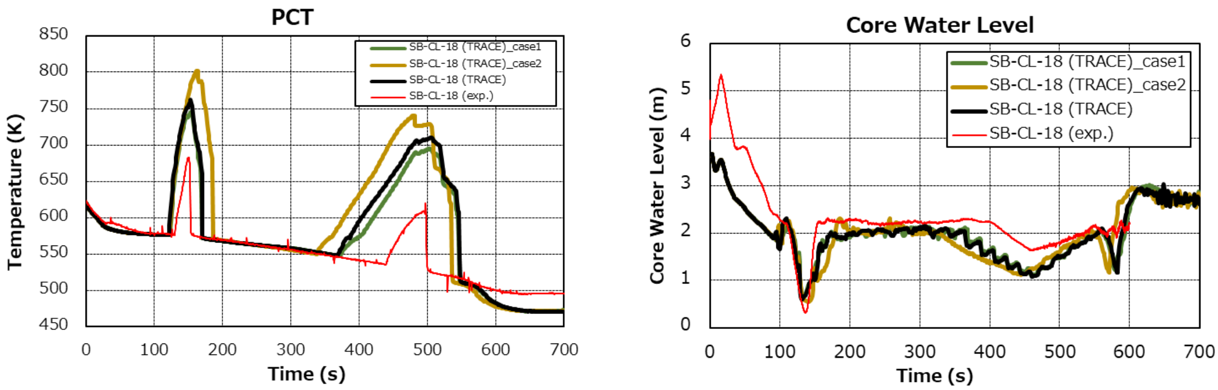


Figure 14. Results of Sensitivity Analysis of COL Modeling of LSTF

6. CONCLUSION

To confirm the applicability of the TRACE analytical model to the SBLOCA analysis of a 3-loop PWR, the results of SB-CL-18 for the LSTF were compared with those of the TRACE analysis. Although the overall transient behaviors of pressure and water level drop were generally consistent, significant differences occurred in the core water level change during the formation and clearance of the loop seal, and in the presence and absence of PCT peaks. To analyze these differences, sensitivity analyses were performed by changing the modeling of the COL (nodalization and shape). The results of the sensitivity analyses revealed that the modeling of the COL had a significant effect on the core water level drop due to the loop seal. Furthermore, it was confirmed that the impact of COL modeling is small in the LSTF analysis, and it should be noted that there are differences in sensitivity between the plant analyses and those of the IETs.

In the future studies, we plan to investigate the effects of scaling with LSTF and other test facilities and to study the optimal modeling for the plant analysis.

Acknowledgements

We are grateful to M. Hirano for his valuable comments based on his many years of experience and knowledge of thermal hydraulics.

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