

MODELING OF THE PACTEL FACILITY AND SIMULATION OF A SMALL BREAK LOCA EXPERIMENT WITH THE TRACE V5.0 CODE

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Abstract

The applicability of the TRACE code to analyze VVER type PWRs is being studied in Finland. To this end the PACTEL integral test facility of Lappeenranta University of Technology (LUT), has been modeled using the TRACE V5.0 patch2 code. PACTEL is a full height model of VVER-440 type nuclear reactor located in Loviisa. A small break loss-of-coolant-accident (SBLOCA) experiment SBL-30 with multiple loops included in the test was chosen to be simulated using the model. The calculation results succeeded reasonably well in estimating the experiment propagation.

Introduction

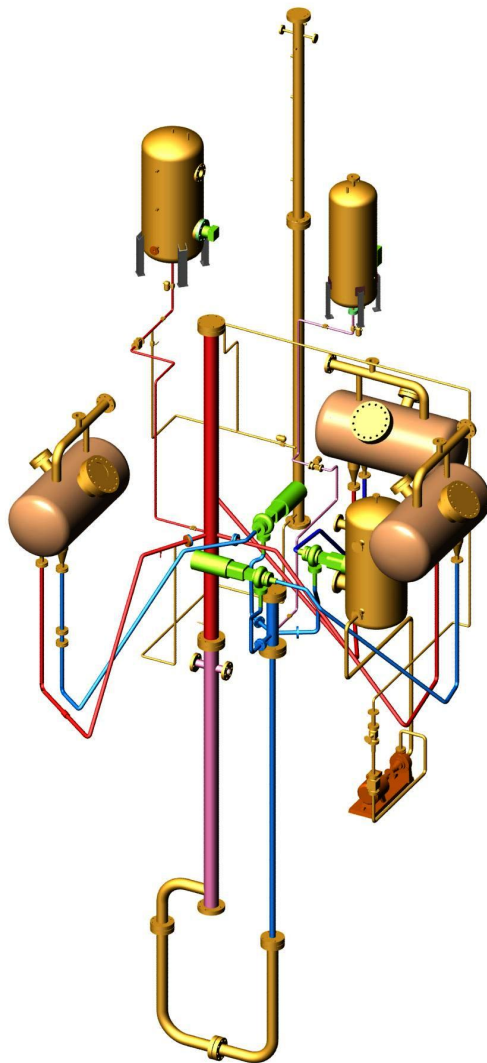
Parallel Channel Test Loop (PACTEL) is an integral test facility for modeling a VVER-440 type nuclear reactor [1]. The PACTEL facility is one of the largest facilities of its kind. So far, more than 200 PACTEL experiments have been carried out. PACTEL experiments have provided unique data for model developers to validate APROS, RELAP5, and CATHARE thermal hydraulic computer codes. A new TRACE V5.0 thermal hydraulic code has been recently implemented at LUT in Finland. The main objectives of the presented work were to prepare a full simulation model of the PACTEL facility with the TRACE thermal hydraulic code and to assess different modelling options of the code. This paper introduces the TRACE code model of the PACTEL facility and presents the calculation results compared to the SBLOCA experiment SBL-30.

1. PACTEL facility

PACTEL facility is a volumetrically scaled (1:305) out-of-pile model of the VVER-440 type nuclear power plants located at Loviisa and managed by Fortum Power and Heat Oy. All the main parts of the reference reactor primary circuit are included in PACTEL: a pressure vessel, main circulation loops, steam generators, and a pressurizer. Also, the emergency core cooling systems are modeled in PACTEL. The original elevations have been kept to preserve the natural circulation pressure heads. The PACTEL facility consists of a U-tube pressure vessel including a downcomer, core section and lower and upper plenum. The primary side has also a pressurizer and three circuit loops each including a horizontal steam generator.

The maximum primary and secondary side pressures are 8.0 MPa and 5.0 MPa, respectively. The core consists of 144 electrically heated fuel rod simulators. The maximum heating power in the core is 1000 kW, which is roughly 20 % of the scaled down nominal power (nominal thermal power of the reference reactor after modernization is now 1500 MW). The PACTEL test facility consists of three primary loops while the reference reactor has six primary loops. The PACTEL test loop is shown in Figure 1.

As the new EPR type NPP is under construction in Olkiluoto, Finland, the domestic research activities on Pressurized Water Reactor (PWR) behavior are being intensified. Hence, the new PWR PACTEL facility, a modified version of the original PACTEL facility with two new loops and vertical steam generators, has been introduced, in order to stimulate research activities on PWR and EPR specifics [2].



	PACTEL	Loviisa VVER-440
Reference Power Plant	VVER-440	-
Volumetric scaling ratio	1:305	-
Scaling factor of component heights and elevations	1:1	-
Number of primary loops	3	6
Maximum heating power/thermal power	1 MW	1500 MW (1375 MW)
Number of rods	144	39438
Outer diameter of fuel rod simulators	9.1 mm	9.1 mm
Fuel rod pitch	12.2 mm	12.2 mm
Heated length of fuel rod simulators	2.42 m	2.42 m
Axial power distribution	Chopped cosine	-
Max cladding temperature	800 °C	-
Max operating pressure	8.0 MPa	12.3 MPa
Max operating temperature	300 °C	300 °C
Max secondary pressure	5.0 MPa	5.0 MPa
Max secondary temperature	260 °C	260 °C
Feedwater tank pressure	2.5 MPa	2.5 MPa
Feedwater tank temperature	225 °C	225 °C
Accumulator pressure	5.5 MPa	5.5 MPa
Low-pressure ECC-water pressure	0.7 MPa	0.7 MPa
High-pressure ECC-water pressure	8.0 MPa	8.0 MPa
ECC-water temperature	30-50 °C	30-50 °C

Figure 1. View of the PACTEL facility and main parameters compared to the Loviisa reactor.

2. SBL-30 EXPERIMENT

Several series of small break loss-of-coolant accident (SBLOCA) experiments have been carried out in the PACTEL facility [3]. They were run both with original, 0.4 m diameter steam generator and with newer larger diameter (1.0 m) design as well as with and without the primary circulation pumps. A series of SBLOCA experiments focusing on natural circulation and steam generator behavior was carried out after replacing the old steam generators with the new ones. All three loops of the facility were in use. The first experiment focused on the behavior of the new large diameter steam generator design. In the other experiments, feed and bleed procedure, which is an operator action during a LOCA in a power plant, and natural circulation were studied. Different break sizes were used in the experiments.

The initial conditions of the experiments were characterized by a steady-state one-phase forced circulation in the primary loops, except in one experiment, where the flow was one-phase natural circulation. All three different natural circulation flow modes, the one-phase liquid flow, the two-phase mixture flow, and the boiler-condenser mode were clearly visible in each experiment of the series. The different break sizes and ECC measures had an effect on the duration and timing of the transient events, but the general thermal hydraulic behavior of the facility was similar throughout the test series.

Validation plan of TRACE code against PACTEL facility experiments contains totally six experiments of different break sizes. The SBL-30 experiment was chosen for the first case in this plan having the smallest break size (1 mm diameter). In the SBL-30 experiment, all three loops of the PACTEL facility were in use [4]. SBL-30 focused on the behavior of the new Large Diameter Steam Generator and it was a comparison experiment for SBL-7, which was carried out earlier with the Full Length Steam Generators. The test parameters were chosen accordingly. The main circulation pumps were not running during the whole recording period of the SBL-30 experiment, hence all the flows were induced by natural circulation. In the beginning of the experiment the primary side flows were single-phase natural circulation. The initial primary and secondary side pressures were about 7.4 MPa and 4.2 MPa, respectively. The core power set-point was 160 kW. The secondary side inventory was held as constant as possible during each experiment. The level set point was at 75 cm, which is 7.5 cm above the uppermost heat exchanger tube row. A steady-state period of 1000 s was recorded before the transient phase began. The initial conditions of the SBL-30 experiment before opening of the break are presented in Table 1.

The break was located vertically at the bottom of the loop 2 cold leg near the downcomer. A sharp-edged orifice (1 mm diameter) simulated the break. The flow area of the orifice in this experiment corresponded to 0.04, % of the PACTEL cold leg cross-sectional area. Due to the scaling method used this break size corresponds to 0.1 % in the reference reactor.

The transient was initiated by opening the blowdown valve downstream of the break orifice. At the same time the pressurizer heaters were switched off. The pressurizer was disconnected from the rest of the primary system as the break was opened by closing an isolation valve in the pressurizer line. The PACTEL operators terminated the experiment, when the primary circuit liquid inventory had depleted to the point where the core outlet temperatures started to rise. The operators controlled manually the feedwater flow to the steam generators. The purpose was to keep the collapsed level constant at the set point of 75 cm. Therefore the control method was an on/off procedure.

Table 1. Initial conditions in SBL-30 experiment.

Parameter	
Primary pressure [MPa]	7.31
Secondary pressure [MPa]	4.19
Loop 1 / Loop 2 / Loop 3 flow [kg/s]	0.44/0.43/0.46
SG1 / SG2 / SG3 feed water flow [l/min]	1.97/0/1.97
Core inlet temperature [°C]	257
Core outlet temperature [°C]	269
Pressurizer level [m]	5,2
SG1 / SG2 / SG3 level [cm]	69.2 / 79.1 / 78.3

3. TRACE model of PACTEL facility

The hydraulic model is constructed mainly with PIPE components of the TRACE code [5]. A detailed description of the modeling and used components is given in reference [6]. The steam generator modeling and test calculations are described in reference [7]. The primary side model of PACTEL consists of a pressure vessel part modeled with a U-shape piping and three primary loops modeled individually since they have geometry differences. The hot and cold legs are connected to the vertical upper plenum and downcomer piping with crossflow connections. The main circulation pumps and closing valves are also modeled. The pressurizer is modeled using a standard pipe component. The core section is divided into three parallel channels and the heat production in the core as well as in the pressurizer heaters is implemented with POWER components, which can be controlled with time dependent functions and trips. The heat structures are prepared with built-in material stainless steel 304. A special user defined material is introduced for modeling the insulating mineral wool of the PACTEL facility.

3.1 Model set-up for SBL-30 experiment

Figure 2 presents the main view of the graphical set-up of PACTEL created with the SNAP model editor. It shows the loop-1 connections to the upper plenum, pressurizer, steam generator 1 and downcomer. The break was located at cold leg 2. The break was implemented with a single junction component, which simulated the break orifice. The break valve was also modeled to initiate the break correctly. The break setup is presented in Figure 3. All three steam outlets were connected together and thus the secondary side pressure was controlled with one BREAK component.

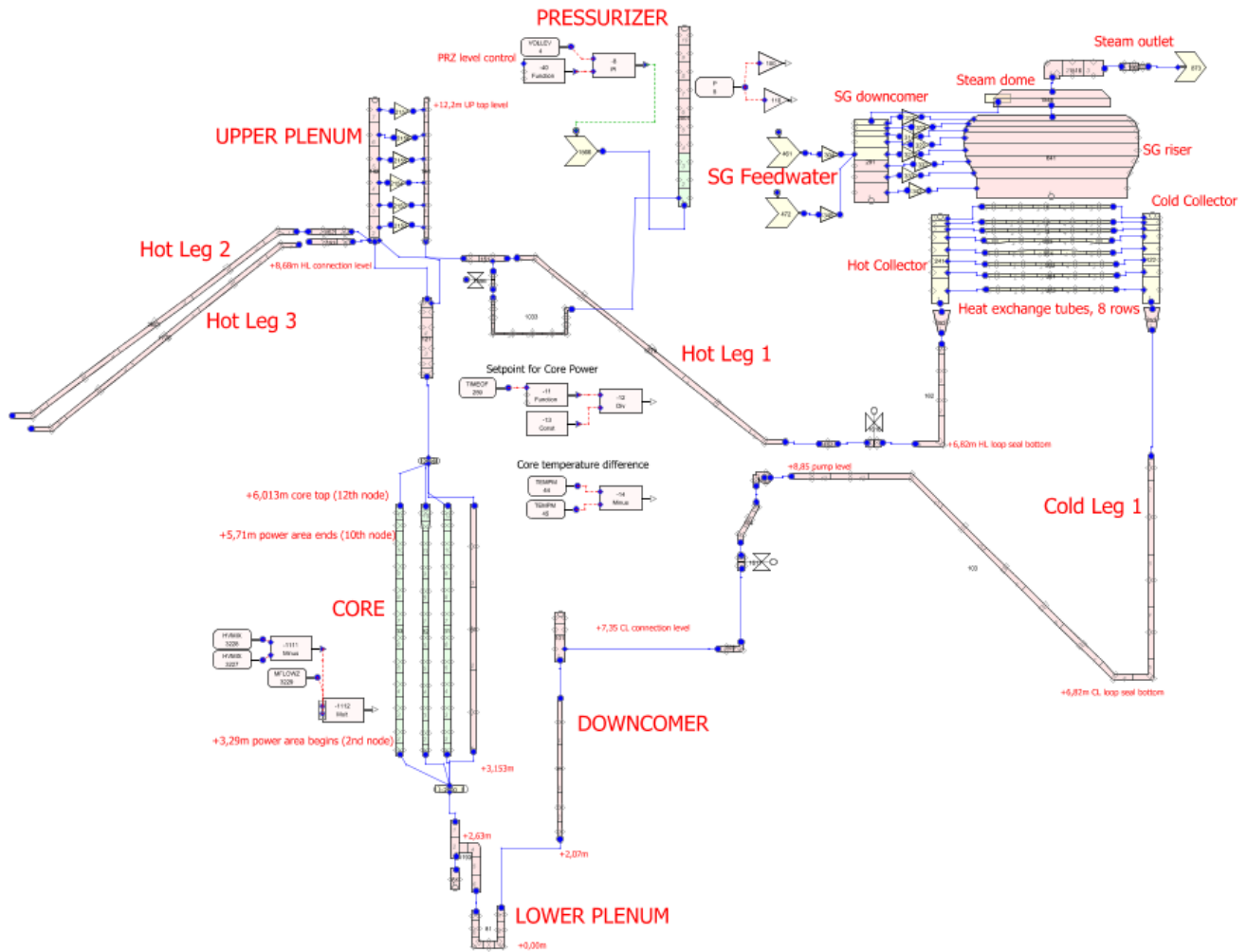


Figure 2. TRACE/SNAP model of PACTEL for calculation of SBL-30-experiment (one loop presented).

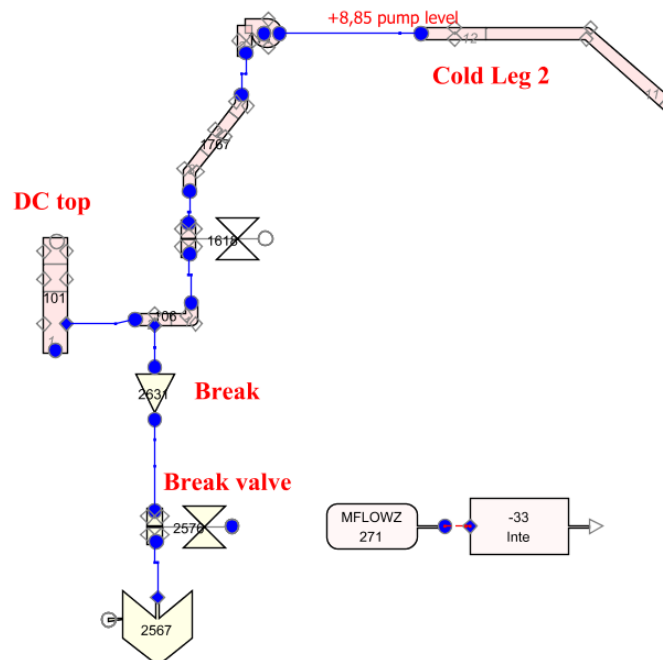


Figure 3. TRACE/SNAP model set-up for break in SBL-30-experiment. Break is located at cold leg 2.

4. TRACE calculation results

The break mass flow rate in the calculation was similar to the experiment data. The flow adjustment was carried out by testing different additive loss factors in the single junction component simulating the break orifice. The main features of the experiment were found also from the calculation. Table 2 presents the timing of the main events in the experiment compared to the calculation. Figures 4-11 present the comparison of selected experiment and calculation results. The time period of the presented results is from 0 to 12000 seconds. The calculation was continued until 12500 s, but no significant findings were met after 12000 s.

Table 2. Timing of main events in experiment SBL-30 and in TRACE calculation.

TIME [s]	EVENT in experiment	Remarks from calculation
1000	Blowdown initiated, PRZ isolated, PRZ heaters switched off	Simultaneous
3360	Loop flows stagnated, primary pressure rise up started	Simultaneous
3665	Loop seals cleared, flows resumed in loops 1 and 2, not in loop 3 (Exp.)	Flow resumed in all 3 loops
3350	Core power off	Simultaneous
3430	Core power on	Simultaneous
3470	Core power off	Simultaneous
3640	Core power on	Simultaneous
10170	Void at the top of the DC	~270s earlier in calculation
11010	Break flow changed from single-phase to two-phase flow	~270s earlier in calculation
12150	Core heat up was observed first time	No core heat up was observed
12301	Cladding temp. exceeded 300 °C, experiment was terminated	No core heat up was observed

Two different options for feedwater injection into the steam generators were tested. The first setup for the feedwater was to use only PI-controllers in order to keep the collapsed level at the initial set-point value. The second option was to follow the on/off type procedure of the experiment. The feedwater flow rates were taken straight from the experiment data and used as a boundary condition. However, the second option brought only small differences to the calculation behavior in the primary side. Hence, the results with the second option level settings are presented in the following figures.

The calculated primary side pressure followed accurately the experiment value during the rapid depressurization and single-phase natural circulation period. Also the periods, when the primary pressure started to rise and then fall down again due to natural circulation flow deterioration and hot leg loop seal clearance, were accurately calculated. From ~3700 s onwards, when the two-phase natural circulation began, some discrepancies appeared and as a result the calculation slightly overestimated the primary side pressure and temperature until the end of the simulation. The integrated break flow in the calculation (Fig. 5) followed the experiment data curve quite accurately and also the change from single- to two-phase flow was quite well-timed. The calculated primary inventory reduction was similar with the experiment. The collapsed level of the upper plenum as well as voiding of the downcomer top found in experiment was calculated satisfactorily (Fig. 6). The core inlet and outlet temperatures followed the primary pressure behavior (Fig. 7).

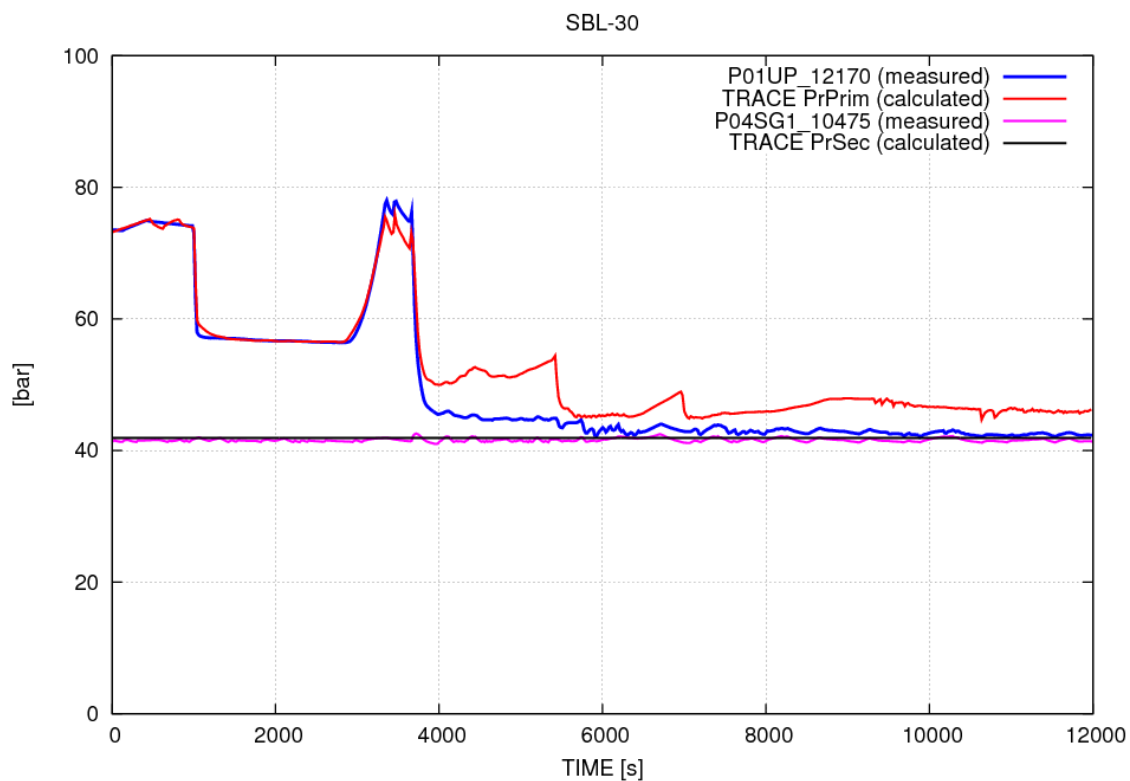


Figure 4. Primary and secondary pressures in PACTEL experiment SBL-30 vs. TRACE calculation.

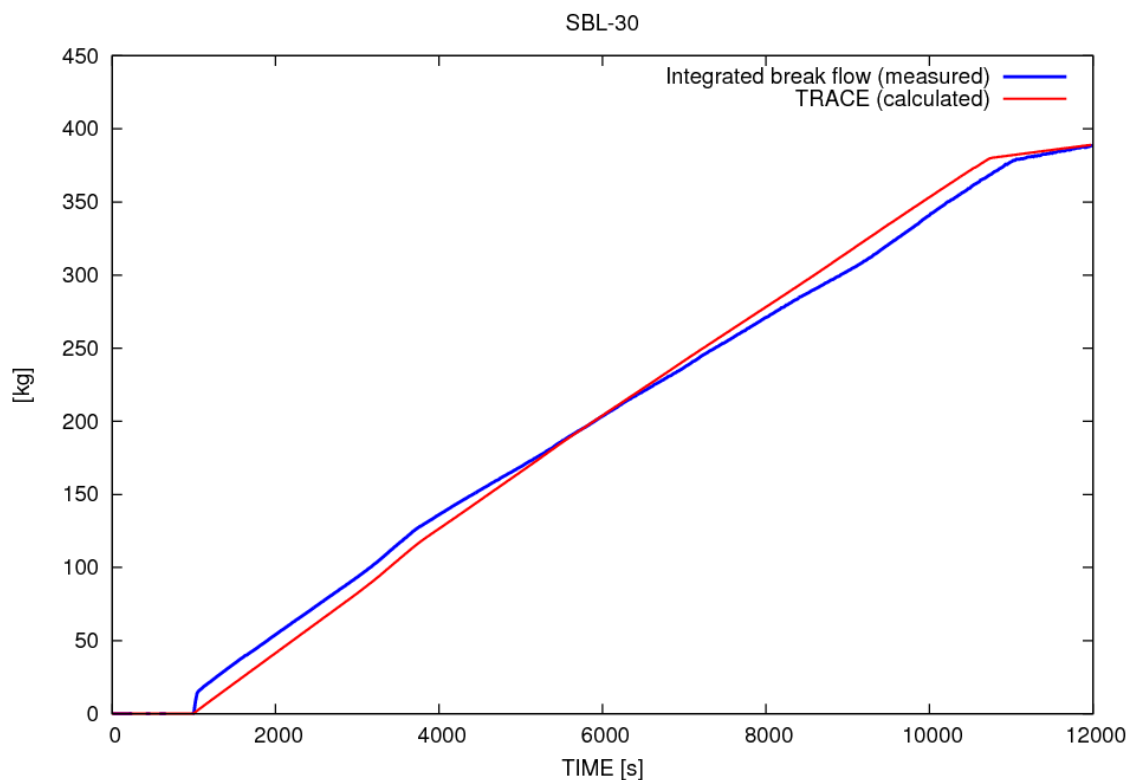


Figure 5. Integrated break flow in PACTEL experiment SBL-30 vs. TRACE calculation.

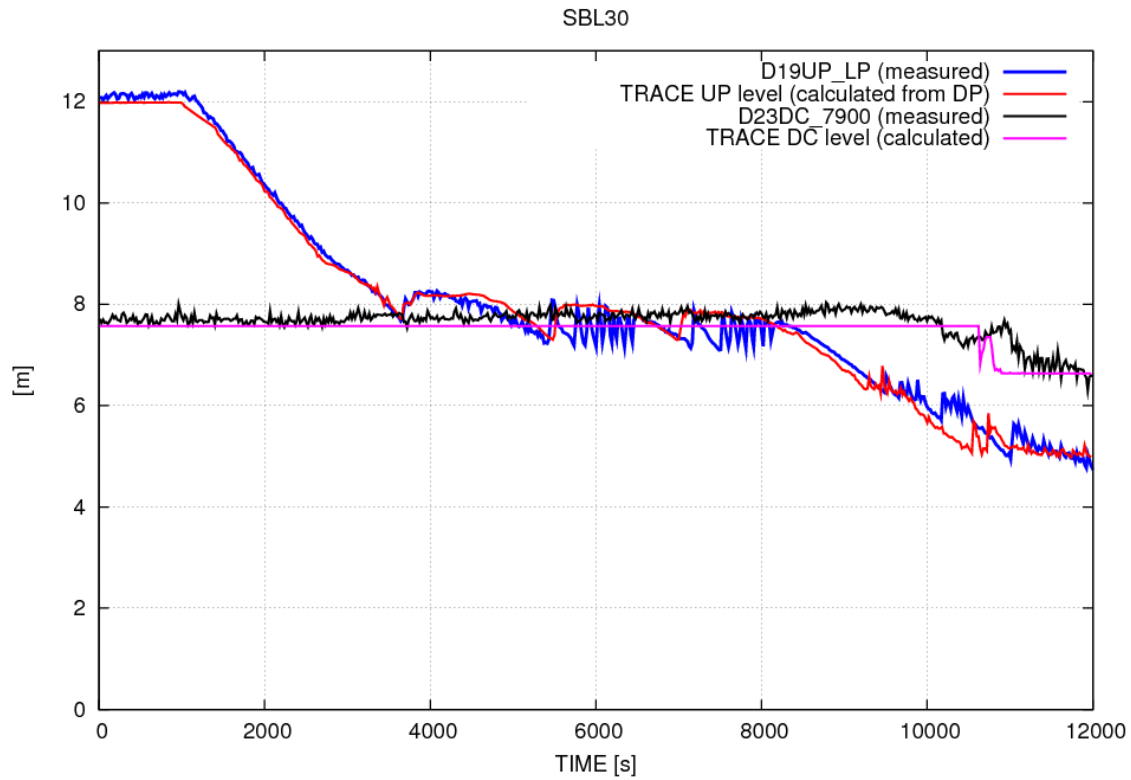


Figure 6. Upper plenum and downcomer collapsed levels in PACTEL experiment SBL-30 vs. TRACE calculation.

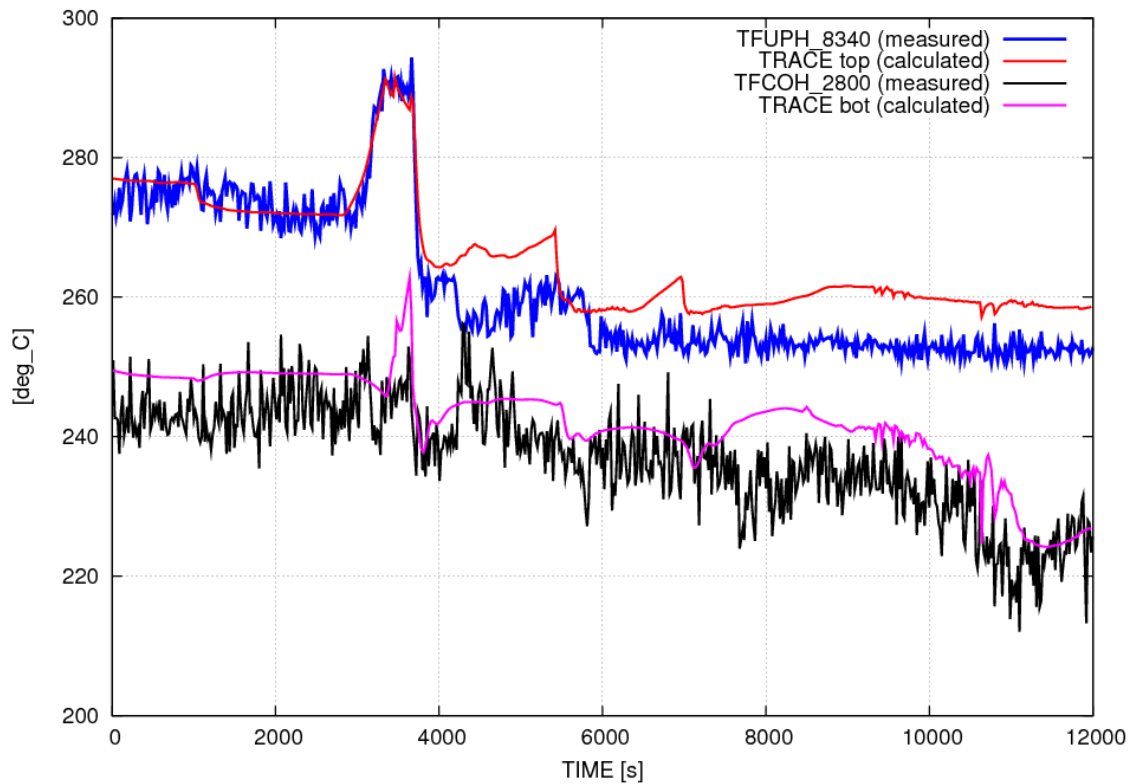


Figure 7. Temperatures above and below core region in PACTEL experiment SBL-30 vs. TRACE calculation.

Due to VVER-440 geometry in the PACTEL facility the natural circulation flow is affected by the loop seal effect, which induces asymmetrical flow stagnations between different loops. These phenomena were also found in the SBL-30 experiment and in the calculation. The first flow stagnation appeared when the water inventory decreased to the level where the hot legs are connected to the upper plenum. Then steam could pass to the hot legs. The flow stagnated in all three loops and caused a rapid rise in primary pressure. The pressure started to decrease when the loop seals cleared and the flow resumed. The calculated mass flow rates in the loops did not match with the experiment values during the two-phase flow period from 3700 s to 8000 s (see Figures 8-11). However, the chaotic behavior of mass flow distribution between the loops during this time phase was repeated also in the calculation, even that e.g. the flow behavior in loops 2 and 3 seemed to have changed places with each other, i.e. the calculated flow in loop 3 resembled more the situation in loop 2 in the experiment. After this phase the calculation showed quite a good agreement with the experiment, when the cold legs started to run out of water after 8000 s and natural circulation changed to boiler-condenser mode.

An accurate modeling of the asymmetric loop flow behavior is a very difficult task, since there are many uncertainties in the experiment situation, which cannot be taken into account in the calculations. The initiation of a loop flow can be very sensitive to the appearance of small pressure or temperature differences and to the mass balance between water and steam. Also, the reliability of measurements when there is a possibility for the presence of two-phase flow, is lower than in a pure single-phase case. The combined mass flow rate at the downcomer resembled better the experiment result (Fig. 11) but still remained lower than the measured value.

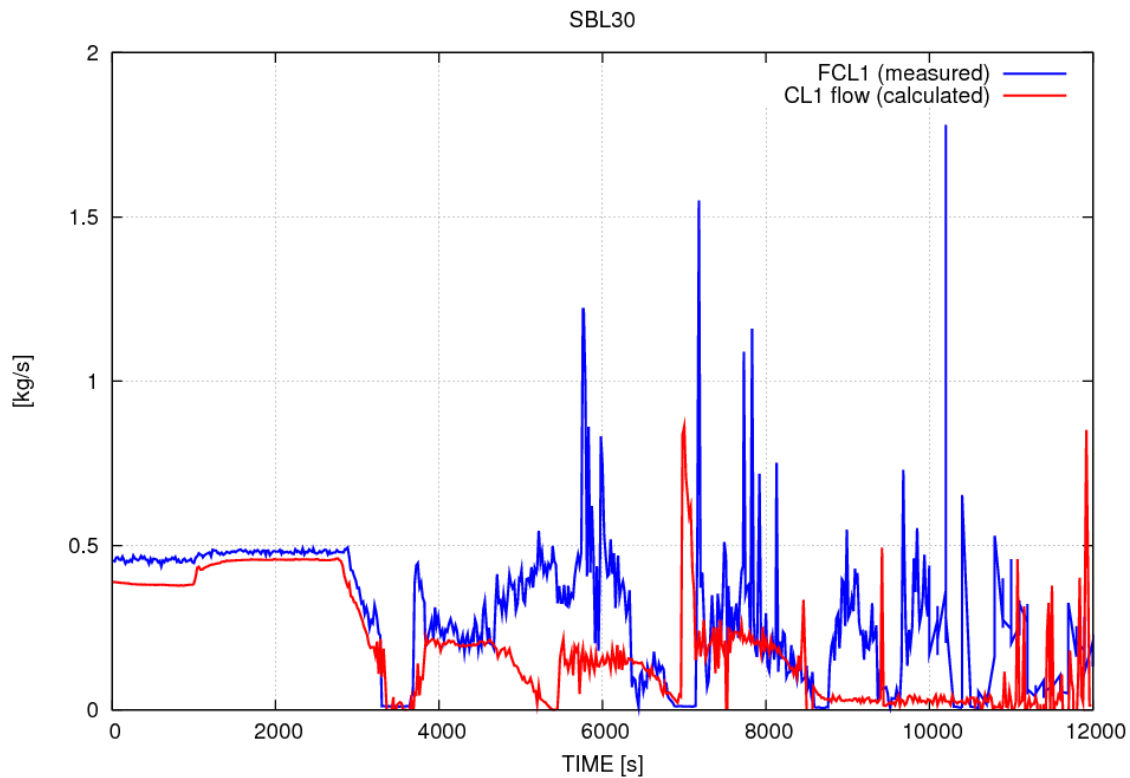


Figure 8. Loop 1 mass flow rate in PACTEL experiment SBL-30 vs. TRACE calculation.

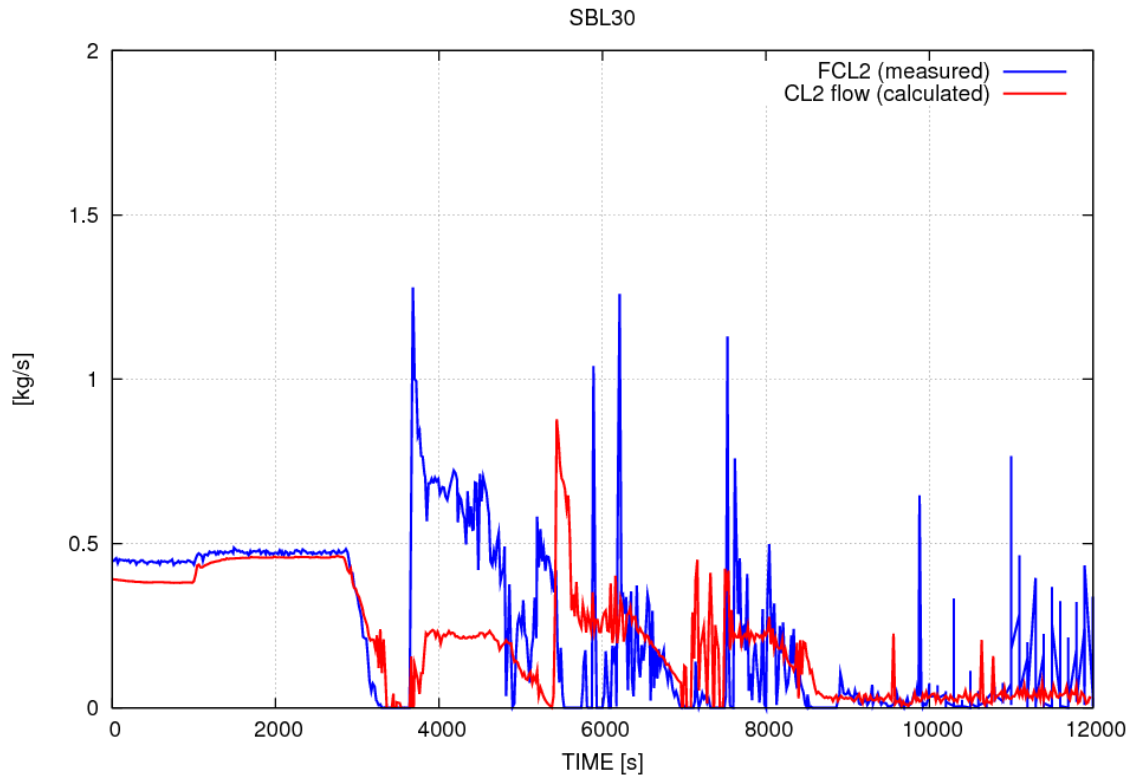


Figure 9. Loop 2 mass flow rate in PACTEL experiment SBL-30 vs. TRACE calculation.

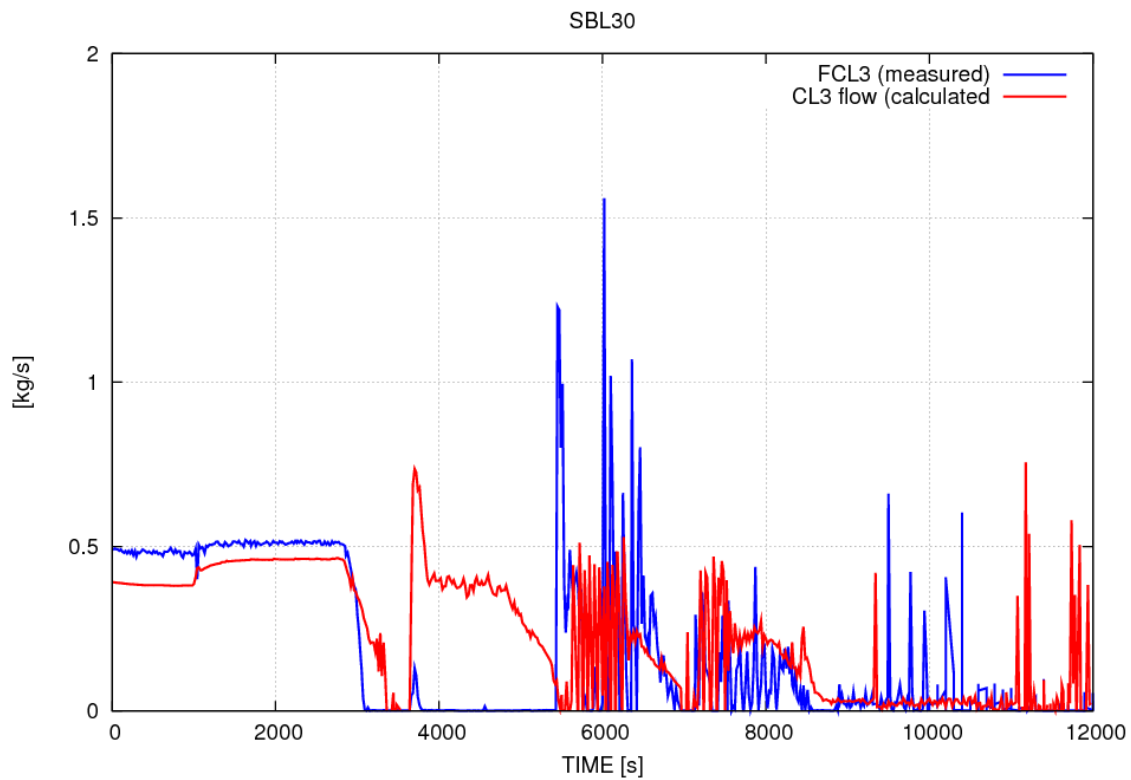


Figure 10. Loop 3 mass flow rate in PACTEL experiment SBL-30 vs. TRACE calculation.

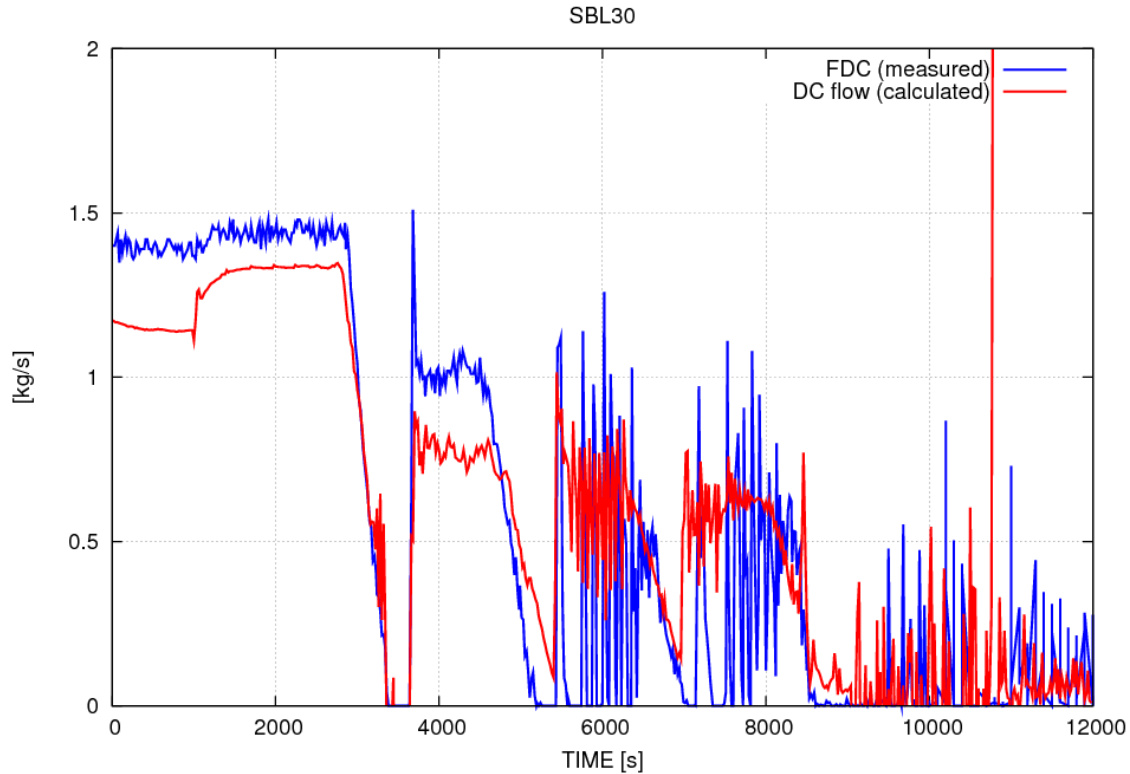


Figure 11. Downcomer mass flow rate in PACTEL experiment SBL-30 vs. TRACE calculation.

5. Conclusion

A full simulation model of the PACTEL test facility, modeling a VVER-440 type nuclear plant, was prepared with the TRACE thermal hydraulic code. The PACTEL experiment SBL-30 was then calculated using the TRACE model. In the SBL-30 experiment, a $\varnothing$ 1 mm continuous break was introduced and the primary inventory was let to decrease until the cladding temperatures started to rise. Modeling of the break flow succeeded quite well also during the difficult two-phase flow period. In primary pressure and loop flow behavior there were some discrepancies between the calculation and experiment results but the overall tendency with several stagnations and resumes of natural circulation flow showed quite a good agreement with the experiment. The main differences between the simulated and experiment results were probably due to inaccuracies in the definition of the heat loss distribution in the calculation model.

6. References

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