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BETHSY 9.1b test calculation with TRACE using 3D vessel component

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ABSTRACT

Recently, several advanced multidimensional computational tools for simulating reactor system behavior during real and hypothetical transient scenarios were developed. One of such advanced, best-estimate reactor systems codes is TRAC/RELAP Advanced Computational Engine (TRACE), developed by the U.S. Nuclear Regulatory Commission. The advanced TRACE comes with a graphical user interface called SNAP (Symbolic Nuclear Analysis Package). It is intended for pre- and post-processing, running codes, RELAP5 to TRACE input deck conversion, input deck database generation etc. The TRACE code is still not fully development and it will have all the capabilities of RELAP5.

The purpose of the present study was therefore to assess the 3D capability of the TRACE on BETHSY 9.1b test. The TRACE input deck was semi-converted (using SNAP and manual corrections) from the RELAP5 input deck. The 3D fluid dynamics within reactor vessel was modeled and compared to 1D fluid dynamics. The TRACE 3D calculation was compared both to TRACE 1D calculation and RELAP5 calculation. Namely, the geometry used in TRACE is basically the same, what gives very good basis for the comparison of the codes. The only exception is 3D reactor vessel model in case of TRACE 3D calculation. The TRACE V5.0 Patch 1 and RELAP5/MOD3.3 Patch 4 were used for calculations. The BETHSY 9.1b test (International Standard Problem no. 27 or ISP-27) was 5.08 cm equivalent diameter cold leg break without high pressure safety injection and with delayed ultimate procedure. BETHSY facility was a 3-loop replica of a 900 MWe FRAMATOME pressurized water reactor.

In general, all presented code calculations were in good agreement with the BETHSY 9.1b test. The TRACE 1D calculation results are comparable to RELAP5 calculated results. For some parameters they are better, this is mostly due to better tuning of the break flow, what influences timing of the transient. When comparing TRACE 1D and TRACE 3D calculation, the latter is slightly better. One reason for comparable results is already good agreement of 1D calculations and there was not much space to further improve the results. The other reason may be that in the facility the phenomena were mostly one dimensional (for example, external downcomer was used for reactor vessel modeling). However, when 3D behavior of the heater rod temperatures was investigated, the advantage of three dimensional treatment was clearly demonstrated.

1 INTRODUCTION

Recently, several advanced multidimensional computational tools for simulating reactor system behavior during real and hypothetical transient scenarios were developed. The TRAC/RELAP Advanced Computational Engine (TRACE) [1] is the latest in a series of advanced, best-estimate reactor systems codes developed by the U.S. Nuclear Regulatory Commission. The advanced TRACE comes with a graphical user interface called SNAP (Symbolic Nuclear Analysis Package) [2]. It is intended for pre- and post-processing, running codes, RELAP5 to TRACE input deck conversion, input deck database generation etc.

The TRACE code is still not fully development and it will have all the capabilities of RELAP5. In addition, it has 3D capability for vessel components, while U.S. NRC RELAP5 is one dimensional code. The developers stated that TRACE has superior capabilities and accuracy for most applications compared to RELAP5. The comparison between RELAP5 and TRACE code with 1D vessel model has already been done [3]. The TRACE 1D calculation results for main safety parameters were as good as or better than the RELAP5 calculated results. The aim of this study is to assess the 3D capability of the TRACE on BETHSY 9.1b test. The TRACE input deck, which was semi-converted (using SNAP and manual corrections) from the legacy RELAP5 input deck, was used as starting point [3]. The reactor vessel was modeled manually. This means that the geometry except the reactor vessel and renodalization done for TRACE is basically the same for RELAP5, TRACE 1D and TRACE 3D model, what gives very good basis for the comparison of the codes.

2 METHODS

The BETHSY 9.1b test (International Standard Problem no. 27 or ISP-27) was 5.08 cm equivalent diameter cold leg break without high pressure safety injection and with delayed ultimate procedure. BETHSY facility was a 3-loop replica of a 900 MWe Framatome pressurized water reactor. For calculations the RELAP5/MOD3.3 Patch 4 [5] and TRACE V5.0 Patch 1 [1] were used. For better presentation of the calculated physical phenomena and processes, animation masks using SNAP were developed for displaying results obtained by RELAP5 and TRACE.

In the following subsections the BETHSY facility and test scenario are described first. Then the RELAP5 and TRACE input models are described. At the end the RELAP5 and TRACE thermal-hydraulic computer codes and SNAP tool are described briefly.

2.1 BETHSY facility

BETHSY was an integral test facility, which was designed to simulate most pressurized water reactor accidents of interest, study accident management procedures and validate the computer codes. The schematic of the BETHSY facility, created by SNAP, is shown in Figure 1. The BETHSY facility was a scaled down model of three loop Framatome (now AREVA NC) nuclear power plant with the thermal power 2775 MW. Volume, mass flow and power were scaled to 1:96.9, while the elevations and the pressures of the primary and secondary system were preserved [6]. The core power has been limited to approximately 10% of nominal value, i.e. 3 MW. This means that the power was limited to the decay heat level and the transients without reactor trip could not be simulated. The design pressure on the primary side was 17.2 MPa and on the secondary side 8 MPa. There were 428 electrically heated rods, which could reach 1273 K. Like in the reference reactor, the BETHSY facility had three identical loops, each equipped with a main coolant pump and an active steam generator. Every primary and secondary side engineered safety system was simulated. This included high and low pressure safety injection systems, accumulators (one per loop), pressurizer spray and relief circuits, auxiliary feedwater system and steam dumps to the atmosphere and to the condenser.

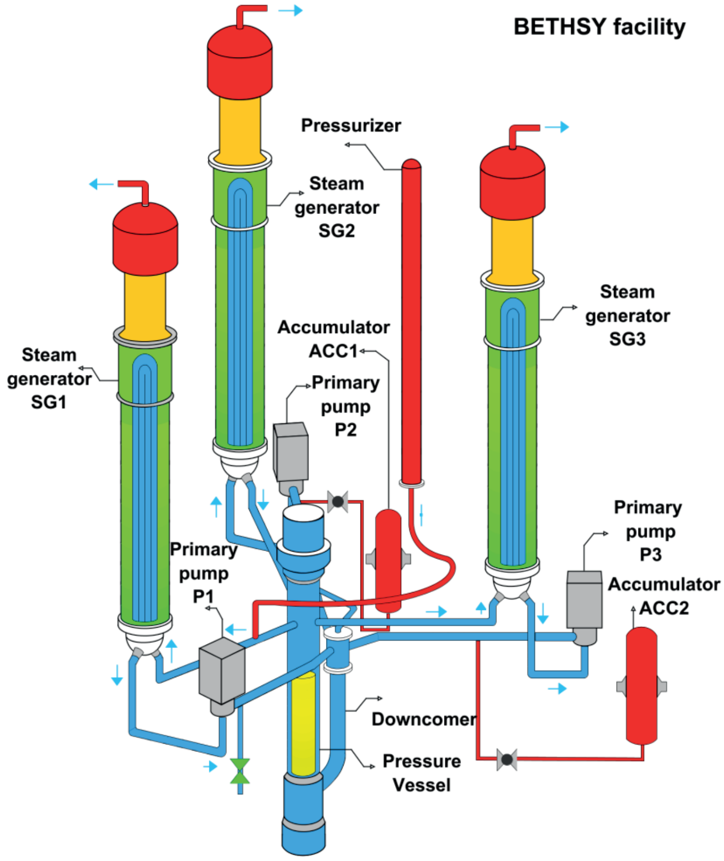

Figure 1: Schematic of the BETHSY facility

2.2 BETHSY 9.1b test description

The BETHSY 9.1.b test was a scaled 5.08 cm cold leg break without high pressure safety injection (HPSI) and with delayed operator action for secondary system depressurization [7]. This transient leads to a large core uncovery and fuel heat-up, requiring the implementation of an ultimate procedure. The scenario of the test started at 10% nominal power. At time 0 s the break was opened. The scram signal was obtained when pressurizer pressure dropped below 13.1 MPa, delayed for 17 s. The safety injection (SI) signal was triggered at 11.9 MPa. However, high pressure safety injection, turbine bypass and main feedwater were assumed to be off. Thirty seconds after SI signal the auxiliary feedwater started. Three hundred seconds after SI signal the reactor coolant pump started to coast down. When the maximum core cladding temperature reaches 723 K, the ultimate procedure was started, i.e. full opening of three steam dumps to atmosphere. Accumulators were available in the intact loops only. They started to inject when pressurizer pressure dropped below 4.2 MPa and were isolated at pressurizer pressure 1.5 MPa. The low pressure safety injection system started at pressurizer pressure 0.91 MPa and injected in the two intact loops. When stable residual heat removal system operating condition prevail (core outlet fluid temperature < 450 K, primary pressure < 2.5 MPa, saturation margin > 20 K), the transient was terminated.

2.3 RELAP5 input model

At the time of participation to ISP-27 the RELAP5/MOD2 input model was developed and initialized according to the specified data. Each of the three coolant loops is represented explicitly without taking into account the small asymmetry between the loops. This model was further adapted to higher versions of RELAP5 computer code [4]. The final RELAP5/MOD3.3 input model consists from 398 volumes, 408 junctions and 402 heat structures. The hydrodynamic view was generated by SNAP from RELAP5 input model in ASCII and then arranged manually using Model Editor of SNAP as shown in Figure 2.

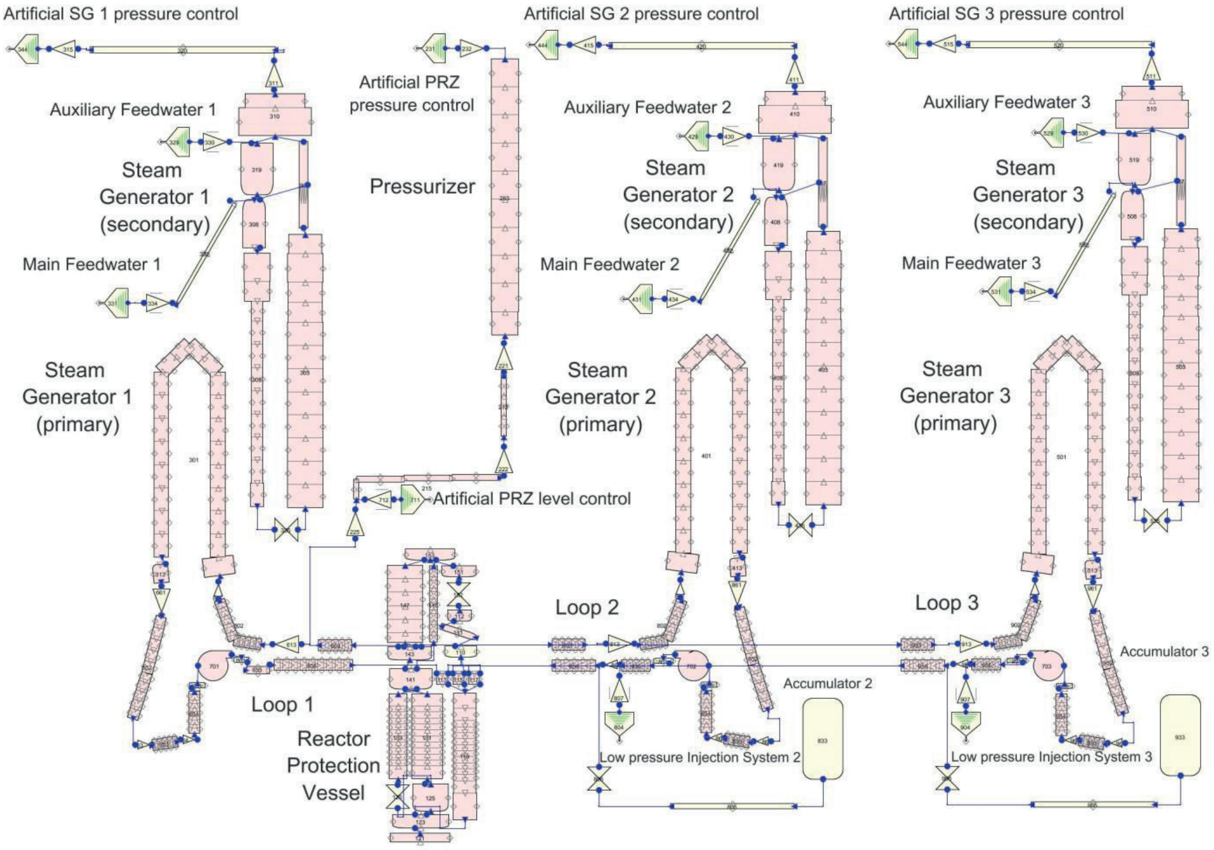

Figure 2: RELAP5/MOD3.3 nodalization of BETHSY facility

2.4 TRACE input models

The TRACE input model was first converted from RELAP5/MOD3.3 input model described in Section 2.3, and is shown in Figure 2. The converted nodalization for 1D TRACE input is similar to the RELAP5 nodalization, except for the few later corrections. The components are mostly preserved. There are 157 hydraulic components and 57 heat structures. The converted input model needed several manual corrections, adaptations of components and introduction of components needed for transient. For further details about TRACE 1D nodalization the reader can refer to reference [3].

The TRACE 1D input model was the basis for the TRACE 3D input model. To get TRACE 3D input model the three dimensional pressure vessel was created using TRACE vessel component. In addition, the external downcomer was slightly modified. The adaptations were done manually using SNAP. The TRACE nodalization of BETHSY facility using 3D vessel is shown in Figure 3. The model consists of 146 hydraulic components and 73 heat structures. The vessel component consists of 31 axial levels, 5 radial rings and 3 azimuthal sectors. The number of hydraulic components in 3D model is decreased compared to 1D model because vessel represents one component. The number of heat structures is increased in 3D model compared to 1D model, because heat structure cannot be shared by radial rings and azimuthal sectors. The core region consists of 12 axial levels, 2 radial rings and 3 azimuthal sectors. Each azimuthal sector within each ring has its own heat structure representing heater rod. This gives in total six heat structures, which can be seen from Figure 3 (on the top of pressure vessel).

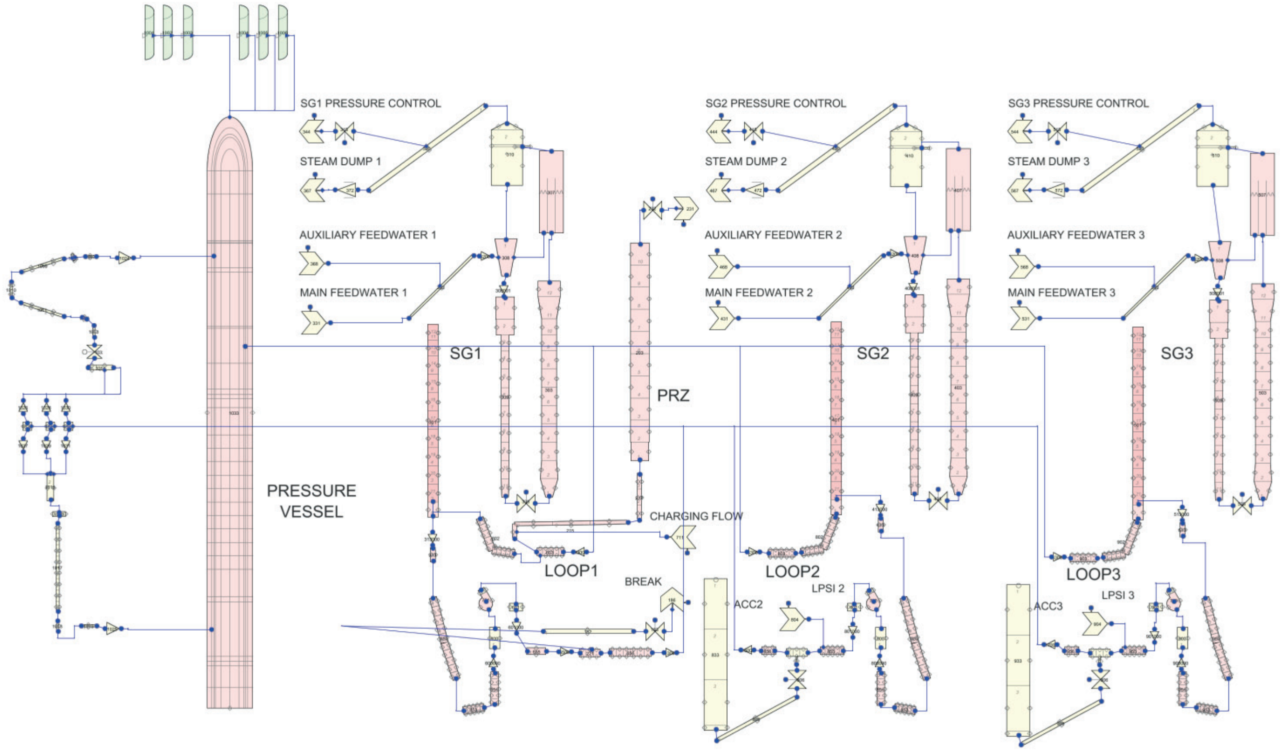

Figure 3: TRACE 3D nodalization of BETHSY facility

2.5 RELAP5, TRACE and SNAP computer codes description

The basic RELAP5 thermal-hydraulic model uses six equations: two mass conservation equations, two momentum conservation equations and two energy conservation equations. Closure of the field equations is provided through the use of constitutive relations and correlations. Since the release of RELAP5/MOD2 in 1985 the code was continuously improved and extended. New models were included like zirconium-water reaction model, level tracking model, thermal stratification model, counter-current flow limiting correlation etc. Several improvements to existing models were also done, for example Henry-Fauske and Moody choking flow models, new correlations for interfacial friction, modified reflood model and new critical heat flux correlation for rod bundles. Finally, user conveniences have been added for code execution on a variety of systems. The latest version is RELAP5/MOD3.3 Patch 04, released in 2010. For more details on RELAP5 the reader can refer to [5].

TRACE was combined from four main systems codes (TRAC-P, TRAC-B, RELAP5 and RAMONA), which were developed under U.S. NRC to perform safety analyses of loss-of-coolant accidents and operational transients, and other accident scenarios in pressurized light-water reactors and boiling light-water reactors. TRACE can also model phenomena occurring in experimental facilities designed to simulate transients in reactor systems. TRACE includes models for multidimensional two-phase flow, nonequilibrium thermo-dynamics, generalized heat transfer, reflood, level tracking, reactor kinetics and passive systems. A component-based approach is used to modeling a reactor system. There is no built-in limit for the number of components or volumes that can be modeled; the size of a problem is theoretically limited only by the available computer memory. There are also heat structures, and components for boundary condition and break. For more details on TRACE the reader can refer to [1].

SNAP [2] consists of a suite of integrated applications designed to simplify the process of performing engineering analysis. SNAP is intended for creating and editing input for engineering analysis codes and it has functionality for submitting, monitoring, and interacting with the codes. SNAP currently support the CONTAIN, COBRA, FRAPCON-3, MELCOR, PARCS, RADTRAD, RELAP5 and TRACE analysis codes. Each code is supported by a separate plug-in. SNAP's interactive and post-processing capabilities are predominately realized within its animation displays. Within such a display, the results of a calculation may be animated in a variety of ways. An animation display retrieves data from the server and represents it visually in some fashion. The data can be from an actively running calculation, a completed calculation, external data, etc.

3 RESULTS

3.1 BETHSY 9.1b transient simulations

Three calculations of BETHSY 9.1b test were performed and compared to experimental data. The first one was RELAP5 calculation performed by latest RELAP5/MOD3.3 Patch 4 computer code. With TRACE V5.0 Patch 1 two calculations were performed, TRACE 1D with one dimensional pressure vessel and TRACE 3D with three dimensional pressure vessel. Both steady-state and transient calculations were performed. With steady-state calculations the desired initial and boundary conditions were set. The results of calculations are shown in Figures 4 through 8.

Table 1 shows initial and boundary conditions for BETHSY 9.1b test. The RELAP5 model was initialized to cold leg temperature; therefore the secondary pressure is not exactly matched. The difference comes from the geometry and the code models. The steam generator levels and masses were matched to average measured values. The pressurizer pressure and level were also matched to average measured values. The core power was input value. In the experiment the electrical trace heating system was installed of the power of 107.5 kW and was operating till ultimate procedure start. In the calculations the heat losses were modeled only after the electrical heat system was off. Before ultimate procedure start there were no heat losses, what is equal to experiment which compensates the heat losses by electrical heat system.

The TRACE input model was converted before the RELAP5 input model was finely initialized to the values in Table 1. Therefore TRACE 1D input model has practically the same values of initial and boundary conditions as the RELAP5 input model. The exceptions are steam generator level and mass. We performed TRACE 1D calculation with already verified restart input model after conversion. The TRACE 3D model, which was built on TRACE 1D model, was initialized with the artificial controllers. This resulted in better match for cold leg temperature, downcomer mass flow rate and steam generator level. In general, the agreement of initial and boundary conditions is good for all calculations.

Table 1 Comparison of initial conditions for BETHSY 9.1b test

Parameter	Measured	RELAP5	TRACE 1D	TRACE 3D
core thermal power	2864 ± 30 kW	2864 kW	2864 kW	2864 kW
cold leg temperature (per loop)	559.9 ± 0.5 K	559.9 K (core inlet)	559.4 K (core inlet)	559.9 K (core inlet)
downcomer mass flow rate	150.0 ± 5.0 kg/s	155.2 kg/s	155.2 kg/s	150.6 kg/s
reactor coolant pump speed (per loop)	2940 ± 30 rpm	2970 rpm	2970 rpm	2940 rpm
pressurizer pressure	15.51 ± 0.09 MPa	15.51 MPa	15.51 MPa	15.51 MPa
pressurizer level	4.08 ± 0.1 m	4.08 m	4.08 m	4.08 m
reactor coolant system mass	1960 kg	1948 kg	1948 kg	1948 kg
secondary side pressure (per SG)	6.91 ± 0.04 MPa	6.77 MPa	6.77 MPa	6.75 MPa
steam generator level (per SG)	13.45 ± 0.05 m	13.41 m	13.18 m	13.45 m
feedwater temperature	491.1 ± 2.0 K	491.0 K	491.0 K	491.0 K
secondary coolant mass (per SG)	820 ± 30 kg	820 kg	804 kg	800 kg

The main sequence of events is shown in Table 2. As can be seen the RELAP5 calculation using standard BETHSY input model is in a better agreement with the experiment in the initial phase than TRACE 1D calculation using converted model, while in the later part the TRACE 1D model was better than RELAP5. The timing for TRACE 3D calculation is in a good agreement during the whole transient time. The time sequence of events mostly depends on the break flow. For RELAP5 original Ransom-Trapp break flow model the values of 0.8, 1.0 and 1.1 were used for subcooled, two phase and superheated discharge coefficients, respectively. For TRACE 1D break model the values of 1.0 and 1.1 were used for subcooled and two phase discharge coefficients, respectively. For TRACE 3D break model the value of 0.9 was used for subcooled and two phase discharge coefficient. The values of break discharge coefficients for TRACE calculations were selected after some sensitivity studies and the wish was to use the values as close as possible to the default values. However, decreasing of discharge coefficients delays the ultimate procedure initiation. Our goal was to as closely as possible to match the start of ultimate heat procedure, as this greatly influence primary pressure, which further determines the actuation of accumulators and low pressure injection system.

Table 2 Main sequence of events for BETHSY 9.1b test

Events	**Time (s)**			
	Measured	**RELAP5**	**TRACE 1D**	**TRACE 3D**
Break opening	0	0	0	0
Scram signal (13.1 MPa)	41	31	21	28
Safety injection signal (11.9 MPa)	50	54	35	51
Core power decay start (17 s after scram)	58	48	38	45
Auxiliary feedwater on (30 s after SI signal)	82	84	65	83
Pump coastdown start (300 s after SI signal)	356	354	335	353
End of pump coastdown	971	969	950	970
Start of the first core level depletion	1830	2020	1820	N.A.
Start of second core uncovery	2180	2130	2183	2091
Ultimate procedure initiation	2562	2508	2573	2614
Accumulator injection starts (4.2 MPa)	2962	2880	2930	2974
Primary mass inventory is minimum	2970	2880	2932	2976
Maximum core clad heatup	3053	3009	3002	2997
Accumulator isolation (1.5 MPa)	3831	3865	3957	3833
Low pressure injection system start (0.91 MPa)	5177	5235	5330	5075

In Figures 4 to 8 are shown the main variables. The break mass flow affects the core water inventory and heat transfer. The heat removal from the core determines the time when the maximum heater rod temperature reaches the setpoint to initiate ultimate procedure (i.e., 723 K). Ultimate procedure actions drive the primary system response, through depressurization the secondary system. Finally, primary pressure determines actuation and closure of accumulators and start of low pressure injection system.

In Figure 4 the break flow and integrated break mass flow are shown. None of the calculations perfectly match the break flow (see Figure 4(left)). In the first part of transient the TRACE 1D and TRACE 3D calculation are similar. However in the second part of transient TRACE 3D calculation better agrees with the measurement than TRACE 1D calculation. Also, no spikes in break flow are present in TRACE 3D calculation as in the case of TRACE 1D calculation. In general the agreement is satisfactory as shown in Figure 4(right). TRACE 1D and RELAP5 integrated break flows are practically the same until accumulator injection, while TRACE 3D is a bit lower. During accumulator injection TRACE 1D and TRACE 3D are better than RELAP5, while during low pressure injection period the slightly higher secondary pressure calculated by TRACE 1D causes lower injection flow and therefore also lower break flow than RELAP5, while TRACE 3D slightly underpredict the secondary pressure, resulting in higher break flow. The pressurizer and steam generator no. 1 pressure are shown in Figure 5. Due to selected break discharge coefficients the timing of pressure drop of pressurizer pressure (Figure 5(left) is better for TRACE calculations than for RELAP5 calculation. On the other hand, the steam generator no. 1 pressure is better predicted by TRACE in the first part, while in the second part the RELAP5 was closer to the measured values. In the period before ultimate procedure initiation the pressure in all calculations is constant, because in the experiment the pressure was controlled to be constant at 6.91 MPa.

In Figure 6 are shown core inlet and outlet temperature. For core inlet temperature shown in Figure 6(left) the best agreement with measured data was obtained for TRACE 3D calculation and for the core outlet temperature shown in Figure 6(left) for TRACE 1D calculation. The calculated temperatures of core outlet temperature are liquid temperature, while measured value is two-phase mixture temperature.

The maximum heater rod temperature and accumulator pressure are shown in Figure 7. The heater rods start to heatup when the core starts to uncover, as it is shown in Figure 7(left). TRACE 3D calculation has very good timing, while the peak cladding temperature is overpredicted, while in the case of TRACE 1D is underpredicted. For quenching the rod the primary depressurization was needed to enable accumulator injection. Figure 7(right) shows the accumulator pressure drop due to discharging. TRACE 3D calculation is in the best agreement with the experimental data. During accumulator injection the core level recovers. After accumulator injection is terminated, the primary system mass (see Figure 8(left)) start to decrease again until the low pressure injection starts as shown in Figure 8(right). Due to the slightly higher primary pressure prediction in TRACE 1D calculation the injection started a bit later and the injected flow is also lower. Finally, Figure 9 shows cross-over leg no. 1 downflow and upflow side differential pressure. None of the calculations perfectly agree with experimental data, being TRACE 1D in the best qualitative agreement.

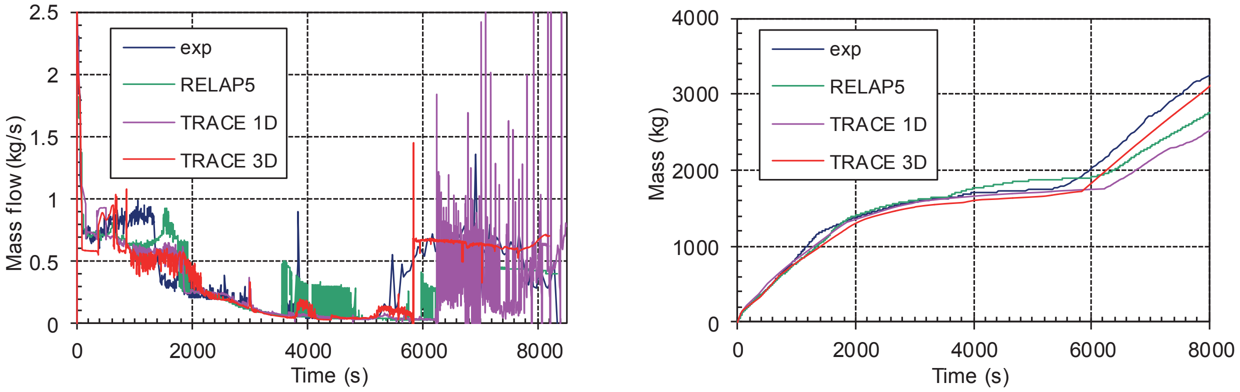

Figure 4: Break mass flow (left) and integrated break mass flow (right)

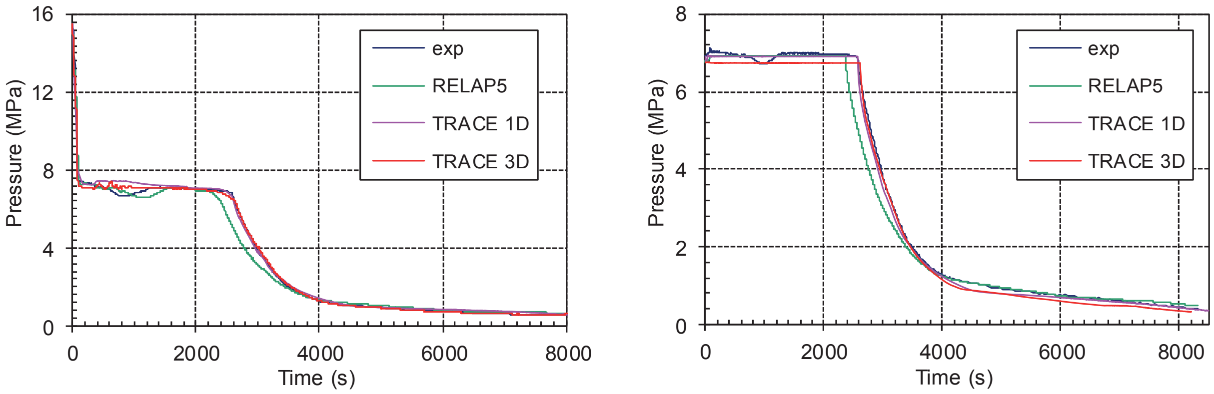

Figure 5: Pressurizer pressure (left) and steam generator no. 1 pressure (right)

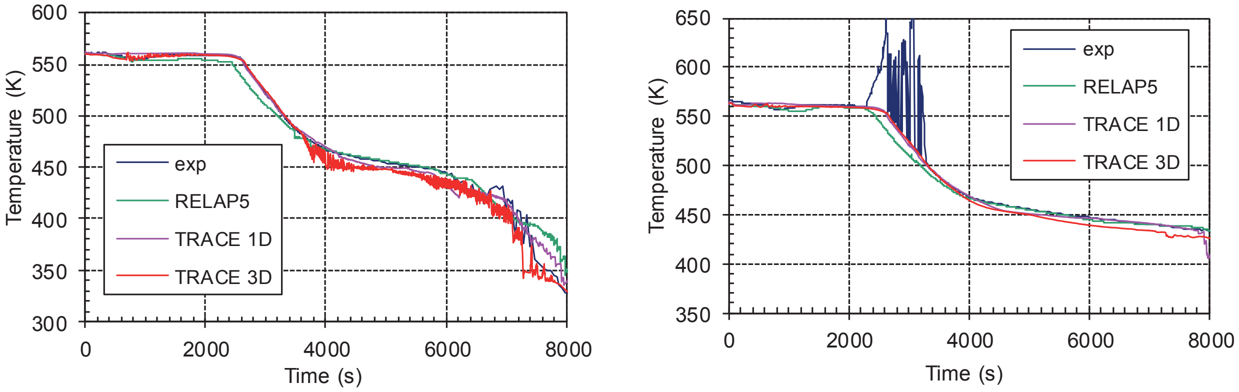

Figure 6: Core inlet (left) and outlet (right) temperature

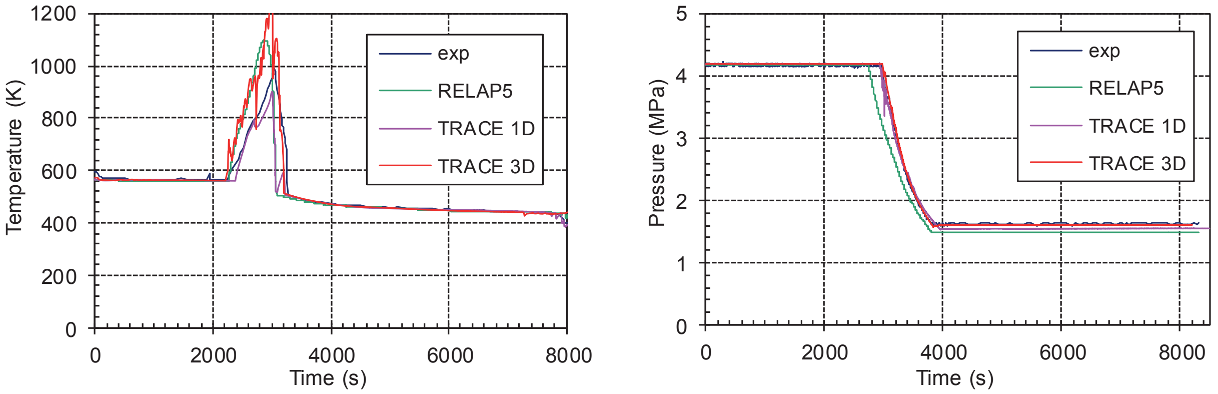

Figure 7: Maximum heater rod surface temperature (left) and accumulator pressure (right)

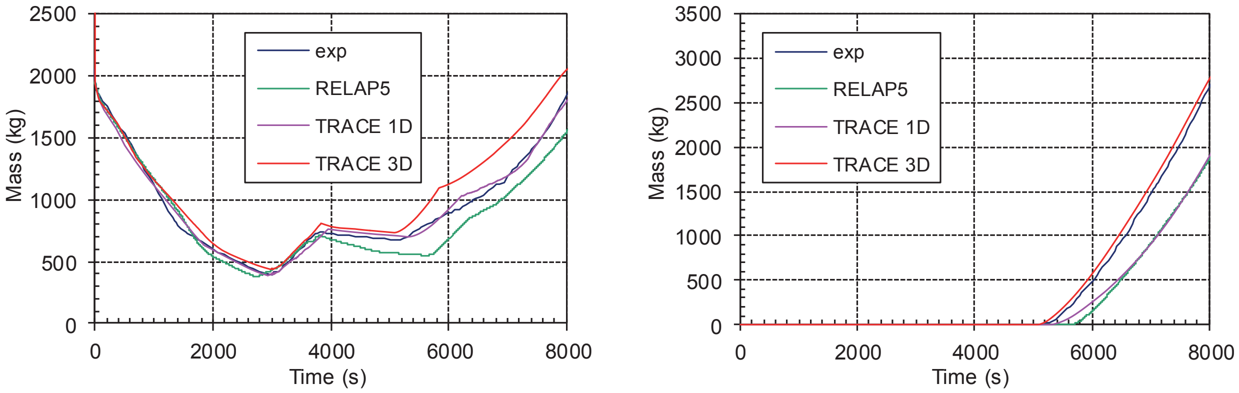

Figure 8: Primary mass inventory (left) and integrated low pressure injection system mass (right)

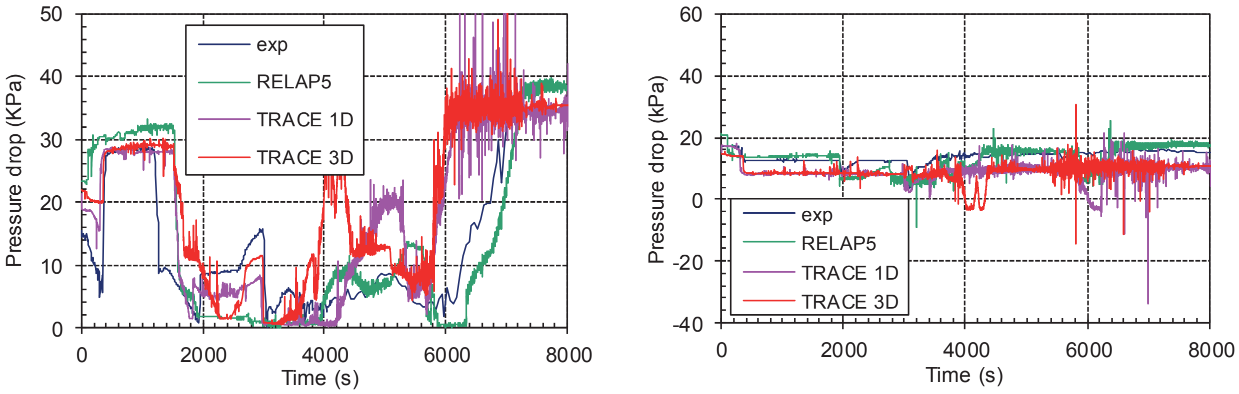

Figure 9: Cross-over leg no. 1 downflow (left) and upflow (right) side differential pressure

3.2 Discussion

The results show that in general the RELAP5 and TRACE 1D calculation are comparable, being TRACE 1D slightly better. One reason may be that in the facility the phenomena were mostly one dimensional. For RELAP5 calculations performed by different versions [4] it has been shown, when the same input deck has been used used, that the results obtained by RELAP5/MOD2 code were comparable to the results obtained by the latest RELAP5/MOD3.3 Patch 4 code. This study showed that converted TRACE input model required some adaptations, before correct timing of events was obtained. The difficulties were especially by BRANCH components of RELAP5 which were not properly converted by SNAP (normally to PIPE components). Such PIPE components in TRACE had to be replaced by TEE components manually (e.g. break location, accumulator injection location, steam generators). It was proved that through SNAP conversions some 90% of conversion is done and that manual corrections are unavoidable. Nevertheless, steady state calculation can be pretty quickly achieved by automatic SNAP conversion and BRANCH components converted to TRACE do not cause difficulties.

Introducing 3D vessel component for pressure vessel requires manual work. It was shown that further improvement was obtained for some variables. Nevertheless, the heater rod temperatures were very high and this should be investigated in the future. One difficulty was, that by setting the flow area fraction in the vessel, the desired core bypass flow could not be achieved. Therefore the core bypass area fraction was set to zero, i.e. no bypass flow was modeled. Also, the maximum heater temperature depends very much on the break discharge coefficients. For example, the change of two phase discharge coefficient from 0.90 to 0.85 the maximum temperature was few hundreds K lower, what requires some further investigation. Nevertheless, the 3D core modeling qualitatively matches the experimental temperatures as shown in Figure 10. The outer core temperatures were higher than the inner core temperatures. Also, it should be noted that the given measured temperatures are from inner part of the core and that quantitative agreement of inner ring heater rod temperatures is satisfactory. This clearly demonstrates the benefits of 3D modeling.

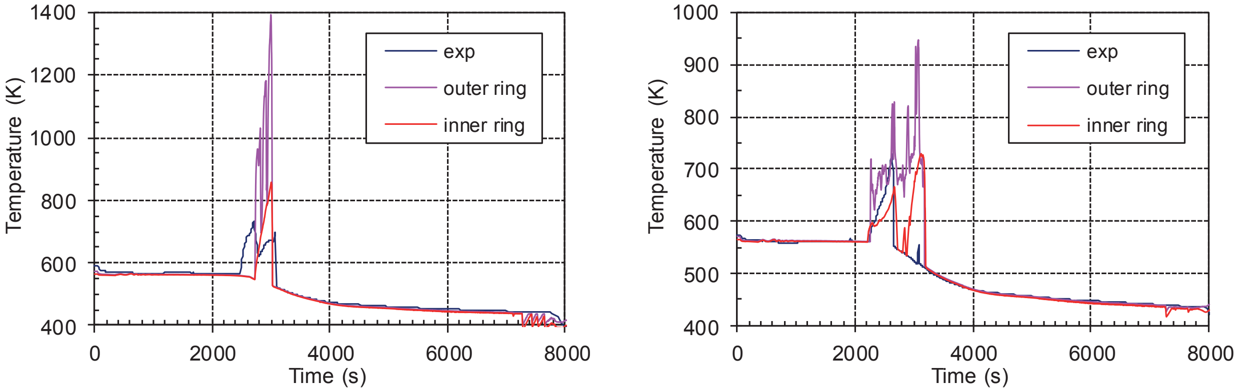

Figure 10: Comparison between TRACE 3D calculation and experimental data for heater rod surface temperature in the middle (left) and at the top of the core (right)

4 CONCLUSION

The BETHSY 9.1b test, which is 5.08 cm equivalent diameter cold leg break without high pressure safety injection and with delayed ultimate procedure, was simulated by RELAP5/MOD3.3 Patch 4 and TRACE V5.0 Patch 1 computer codes. The TRACE 1D input model was obtained by SNAP conversion of RELAP5 input model and several specific adaptations. The TRACE 3D pressure vessel model was build manually. In general, all presented code calculations were in good agreement with the BETHSY 9.1b test data. The TRACE 1D calculation results are comparable to RELAP5 calculated results, being TRACE 1D slightly better. Finally, the TRACE 3D calculation is slightly better than TRACE 1D calculation. One reason is that the results are comparable because of already good agreement of RELAP5 calculation and the TRACE calculation using converted input model from REALP5 input model. The other reason may be that in the facility the phenomena were mostly one dimensional (for example, external downcomer was used for reactor vessel modeling). However, when 3D behavior of the heater rod temperatures was investigated, the advantage of three dimensional treatment was clearly demonstrated.

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