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POST-TEST ANALYSIS OF TWO ACCIDENT MANAGEMENT EXPERIMENTS PERFORMED AT THE BETHSY TEST FACILITY USING THE CODE ATHLET

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ABSTRACT

In the framework of the external validation of the thermal-hydraulic code ATHLET, which has been developed by the GRS, post test analyses of two experiments were done, which were performed at the french integral test facility BETHSY. During the experiment 5.2 C the complete loss of steam generator feedwater was simulated. The depressurization of the primary circuit and high pressure injection is assumed as an emergency measure. During the experiment 9.3 the break of a steam generator U-tube is simulated. The failure of the high pressure injection is assumed. As accident management measures, the depressurization of the steam generator secondary sides and finally of the primary circuit by opening of the pressurizer valve were investigated. The results show, that the code ATHLET is able to describe the complex scenario in good accordance with the experiment. For both tests the safety related statement could be reproduced.

THE BETHSY TEST FACILITY

The BETHSY-test facility is a 1:100 scaled thermal-hydraulic model of a 900 MW(el) pressurized water reactor (FRAMATOME). The test facility is mainly designed to investigate various accident scenarios and to provide an experimental data base for code validation and for the verification of accident management measures. In the test facility, the three identical loops of the primary circuit are modelled with a volume scaling ratio of 1:100 with retaining the original heights, [1], [2]. Each primary loop is equipped with a vertical steam generator. The maximum pressure on the primary side is 17.2 MPa and on the secondary 8.0 MPa. Figure 1 illustrates the structure of the primary circuit with the reactor model, the hot and cold leg, the pressurizer and the steam generator. The indicated levels are related to the lower part of the heater rods in the reactor core.

THE THERMAL-HYDRAULIC CODE ATHLET

The thermal–hydraulic computer code ATHLET (Analysis of Thermal-hydraulics of Leaks and Transients) is being developed by the Gesellschaft für Anlagen– und Reaktorsicherheit (GRS) for the analysis of anticipated and abnormal plant transients, small and intermediate leaks as well as large breaks in light water reactors [3]. The code is composed of several basic modules (Thermo-fluiddynamics, Heat Transfer, Heat Conduction and Neutron Kinetics) for the calculation of the different phenomena involved in the operation of a light water reactor. ATHLET provides a modular network approach for the representation of a thermal-hydraulic system. A given system configuration can be simulated by connecting of basic fluiddynamic elements (objects). Several object types are available, each of them applying for a certain fluiddynamic model (pipe objects, branch objects and special objects used for components with complex geometry). For the presented calculations the code version MOD 1.1 Cycle D was used.

THE BETHSY TEST 5.2 C

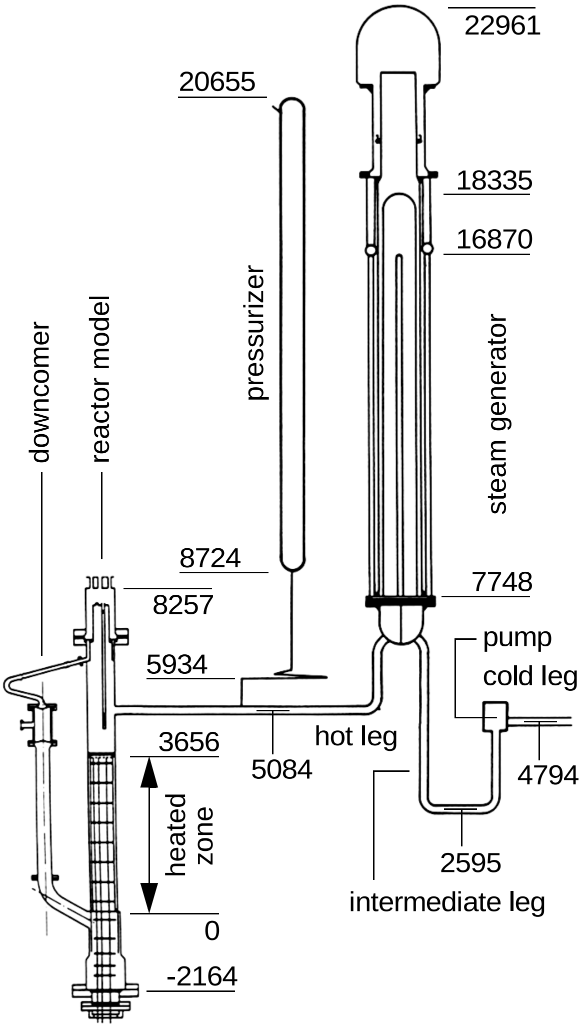

Figure 1. The BETHSY Test Facility (single loop and reactor model)

The BETHSY experiment 5.2 C investigates accident management procedures in case of a total loss of feedwater at the steam generator secondary side [4]. In such an accident the emergency cooling of the reactor core, the behaviour of the steam generators in case of dryout, and the long time behaviour of the test facility are of particular interest.

Table 1 gives a comparison of measured and calculated times of the main events in the transient. With the initiation of the transient the reactor power was reduced and the secondary pressure was controlled at 7.03 MPa (turbine bypass mode). The safety injection (SI) signal is triggered when two steam generator levels drop below 3 m. Simultaneously, the pump coast down and the HPSI were initiated. The feed and spill mode starts when the primary pressure reaches the setpoint of 16.3 MPa. In this mode the primary pressure remains constant by a controlled depressurization via the pressurizer relief valve. The steam lines at the steam generator secondary side were isolated 300 s after the SI-signal and the secondary pressure was controlled at a constant value of 7.17 MPa. 1800 s after the SI-signal the feed and bleed mode

Table 1: Measured and calculated course of the transient during test 5.2 C

Phenomena	Experiment	Calculation
Start of Experiment		
Total loss of feedwater	0 s	0 s
Reactor SCRAM	0 s	0 s
Turbine bypass mode (7.03 MPa controlled)	0 s	0 s
2 Steam generator levels < 3m		
SI Signal	788 s	752 s
Start of pump coast down	793 s	760 s
Start of HPSI	799 s	760 s
Primary pressure = 16.3 MPa		
Regulation of primary pressure	1033 s	956 s
300 s after Safety Injection Signal		
Isolation of SG steam lines and regulation of secondary pressure (7.17 MPa)	1095 s	1088 s
1800 s after Safety Injection Signal		
Full opening of pressurizer relief valve	2593 s	2588 s
Primary pressure = 4.2 MPa		
Start of accumulator injection	4450 s	4393 s
Primary pressure = 1.5 MPa		
End of accumulator injection	8278 s	8735 s
Primary pressure = 1.0 MPa		
Start of LPSI	8815 s	8975 s
End of transient	10025 s	10050 s

was initiated by fully opening the pressurizer relief valve. The injection from the hydroaccumulators was started at a primary pressure of 4.2 MPa and the injection was stopped at 1.5 MPa. At the end of the transient the LPSI starts at a setpoint pressure of 1.0 MPa.

ATHLET CALCULATIONS OF THE BETHSY TEST 5.2 C

The input deck models the three loops of the test facility in detail and consists of 87 thermofluid objects with a total amount of 504 control volumes. In all control volumes the five-equation

Table 2: Initial conditions for Test 5.2

Power	1.094 MW
Primary pressure	14.49 MPa
Pressurizer level	4.43m
Core inlet temperature	286.5 ^{o}C
Core outet temperature	287.9 ^{o}C
Downcomer mass flow	150.9 kg/s
Secondary pressure	6.92 MPa
Secondary level	5.8 m
Feedwater mass flow	0.24 m
Steam generator inventory	324.0 kg

model with separate conservation equations for liquid and vapour mass and energy and a mixture momentum equation was applied. The one-dimensional critical discharge model (CDR1D) was used to model the depressurization of the primary circuit via the pressurizer relief valve. For the calculation of the mass flows at the steam generator secondary side the homogeneous isentropic equilibrium model (Moody-model) was applied.

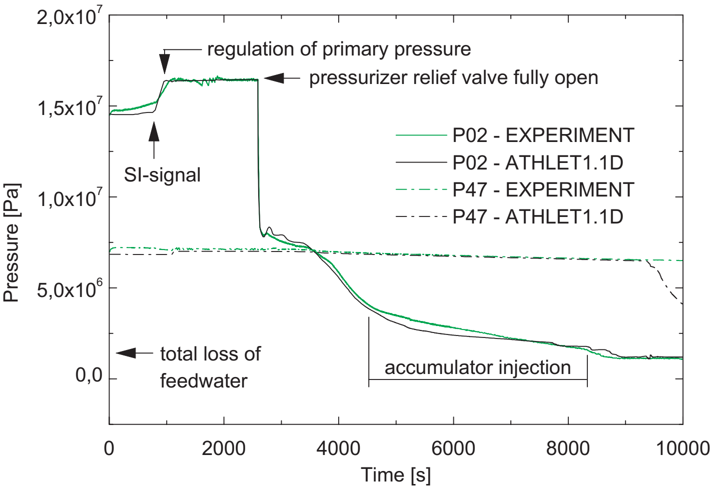

Figure 2. Primary (P02) and secondary (P47) pressure - experiment and calculation

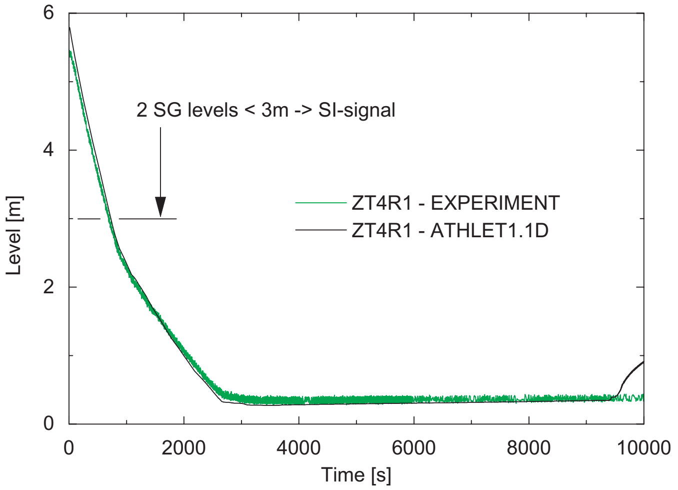

Figure 3. Measured and calculated level in steam generator 1 (ZT4R1)

At the BETHSY test facility the maximal core power is limited to 10 % of the nominal power. Therefore, the experiment starts with already reduced mass inventory at the secondary side. Table 2 gives the measured initial values for this test. The steam generator levels were adjusted in a steady state calculation from the nominal value of 12.7 m to the initial value of 5.76 m for the transient. In the ATHLET calculation, the various hardware actions are modelled with special GCSM signals (General Control and Simulation Module) depending on the system pressure, the filling levels and the problem time. For the calculation of the ECC mass flows the pressure dependence of the HPSI and LPSI mass flows was considered.

The first stage of the transient is mainly characterized by the processes at the steam generator secondary side. Due to the total loss of feedwater the secondary coolant will be vaporized and the SG levels decrease uniformly very fast (see Figure 3 for SG1). At t=752 s (788 s in the experiment) all three SG levels drop below the setpoint of the SI-signal (3 m). At the same time the pump coast down and the HPSI are initiated (Figure 2 and Figure 6). The rapid decrease of the SG levels leads to a reduced heat transfer from the primary to the secondary side and the primary pressure increases up to the setpoint of 16.3 MPa (Figure 2). In this way the primary pressure regulation via the pressurizer relief valve is initiated at t=956 s (1033 s in the experiment).

The depressurization of the primary system starts 1800 s after the safety injection signal by fully opening the pressurizer relief valve. Immediately after the full opening, the primary pressure decreases very fast from 16.3 MPa to 8 MPa. Due to this pressure decrease the mass flow from the HPSI is increased by a factor of about 2.7 (Figure 6). At the same time vaporization can be observed in the hot and also in the cold leg. Up to about 2590 s the pressurizer is continuously filled with water. When depressurization starts the level decreases again (Figure 4). The mass flow and void fraction in the pressurizer vent line and the general behaviour of the pressurizer level are calculated very well by ATHLET. Most of the hardware actions in the calculation are initiated by the primary pressure and the problem time. Due to the good agreement between the measured and calculated pressure the general course of the calculated transient shows no significant deviations. Approximately 2000 s after primary depressurization the mass flow and void fraction in the pressurizer vent line oscillate very strong (see Figure 5). These oscillations are a consequence of a feedback between the mass flow in the vent line and the pressure gradient in the pressurizer. The nature of these oscillations was investigated by D. Lucas and H.-M. Prasser [5]. The period of the oscillations is determined by the length of the vent line. The oscillations are calculated very well by ATHLET (Figure 5).

The primary pressure reaches the setpoint for the accumulator injection at t=4393 s (4450 s in the experiment).

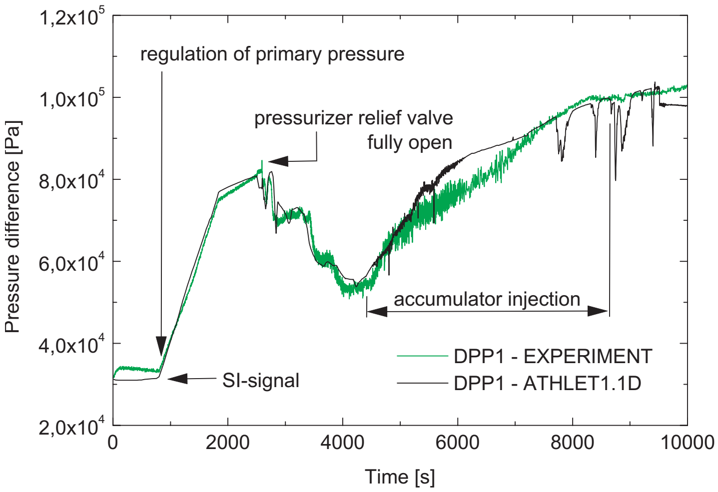

Figure 4. Pressure difference in the pressurizer (DPP1) - experiment and calculation

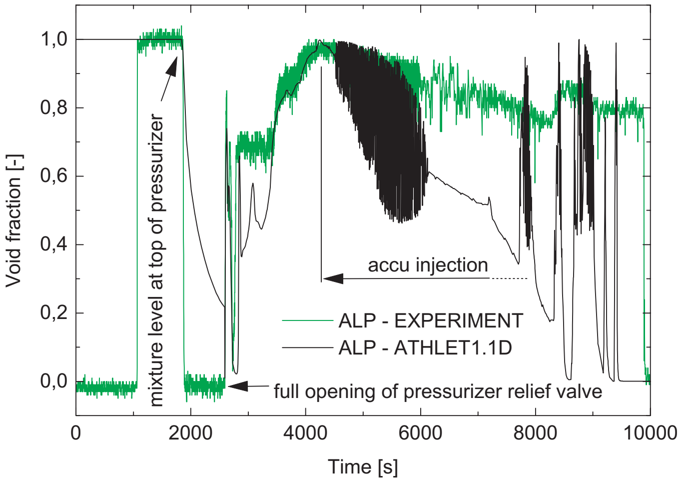

Figure 5. Void fraction upstream from the pressurizer relief valve (ALP)

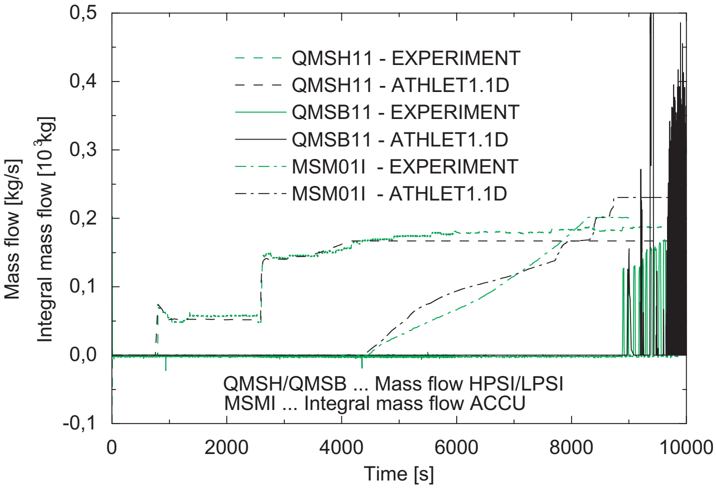

Figure 6. Mass flows and integral mass flow from the ECC injection into loop 1

The accumulator injection depends on the primary pressure. In the first time the cold water flow leads to condensation of steam (e.g. in the upper plenum). The pressure decrease is overestimated by ATHLET (Figure 2). The lower primary pressure leads to a forced accumulator injection. In the further course of the transient the injected mass flow decreases slightly but the integral injected mass is higher than in the experiment (Figure 6). The hydroaccumulator injection leads to an increase in the reactor and pressurizer coolant levels from 4500 s up to 8735 s (8278 s in the experiment). The calculated primary pressure at the end of the accumulator injection is a little higher than in the experiment. For this reason the start of the LPSI, which is initiated by a primary pressure of 1.0 MPa, is calculated with a 160 s delay. The LPSI mass flow is controlled by the primary pressure. In contrast to the experiment the calculated mass flow shows unrealistically strong oscillations, which result in a significant extension of CPU time.

The evaluation of the calculated results shows that all main phenomena can be calculated in a good agreement with the experiment. Resulting from various calculations it should be noticed that the quality of the results strongly depends on the heat losses of the facility, which were partly compensated by the trace heating. This trace heating was changed several times in the experiment to compensate the changing heat losses. The scenario very strongly depends on the course of the primary pressure, which is very sensitive influenced by the heat losses. Therefore exact modelling of the resulting heat losses influences the course of the whole transient.

THE BETHSY TEST 9.3

Steam generator tube ruptures are Small Break Loss Of Coolant Accidents which allow a primary to secondary system flow and may result in a release of radioactive products to the atmosphere. The measures during such an accident situation are therefore first the isolation of the damaged steam generator, then the mass flow cancellation through the break by balancing the primary and damaged steam generator pressure while cooling the primary side with the atmospheric steam dumps of the intact steam generators. Finally the primary mass inventory can be controlled by the safety injection system (high pressure injection, accumulators and low pressure injection) and the reactor state will be shifted to stable residual heat removal conditions.

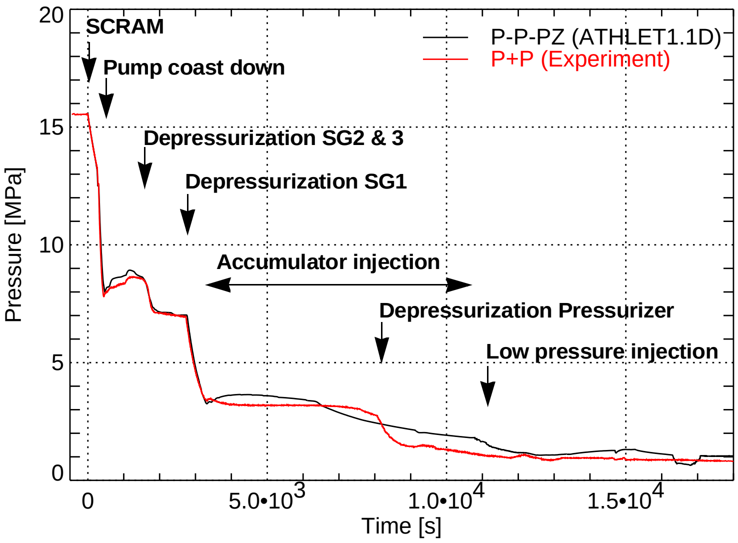

Figure 7. Measured and calculated primary pressure and actions (see Table 3)

The simultaneous failure of the high pressure safety injection and auxiliary feedwater systems is a Beyond Design Basis Accident, which leads to core heat up,

Table 3: Scenario and observed thermal-hydraulic events during the test 9.3

Action	Condition	Time [s] (Exp.)	Thermal-hydraulic event	Time [s] (Calc.)
U-tube rupture		0	Fast decrease of P+P*	0
SCRAM SG Isolation	P+P* < 12.9 MPa	273	Increase of secondary pressure until safety valves opens	265
Safety injection signal = tSI	P+P* < 11.9 MPa	309	Stop of feedwater supply	313
Pump coast down	core outlet saturation margin < 10 K	391	steam in hot legs and upper plenum P+P* increasing Natural circulation	418
Atmospheric steam dump of the intact SG2 & SG3	t SI+ 1200 s	1509	Decrease of primary pressure to the level of secondary pressure	1513
		1659	Interruption of mass flow in SG1 heat removal only via SG2 & SG3	1700
		1810	Break flow cancellation	1900
		1860	recovery of core outlet saturation margin	2005
Atmospheric steam dump of the damaged SG1	LE SG2** < 2 m LE SG3** < 2 m	2728	primary heat removal via SG1	2775
Accumulator injection	P+P* < 4.28 MPa	3058		3130
		3260	Boiling in primary circuit --> stabilization of P+P* at 3.2 MPa stagnation of accumulator injection	3330
Depressurization of the pressurizer	LE SG1** < 2 m	8065	Fast decrease of P+P* enhanced accumulator injection	10947
		10600	Accumulator empty	11160
Low pressure injection	P+P* < 1.75 MPa	11720		12725
		17700	stable heat removal conditions	16700

*	P+P	Primary Pressure
**	LESGI	Collapsed level in steam generator I

if no additional measures are taken. During the test 9.3 the efficiency of both the steam generator atmospheric steam dump and the depressurization of the primary circuit via the pressurizer relief valve is investigated, [6]. In Table 3 the test scenario is described and the observed thermal-hydraulic phenomena are listed. Figure 7 shows the calculated and the measured primary pressure and the times of the main safety related actions listed in Table 3. During the test the following phenomena are observed, which have to be modelled by the code simulation [7]:

- natural circulation
- asymmetric loop behavior concerning the heat removal from the primary circuit break flow
- mixture level and entrainment of the steam generator secondary side
- emergency core cooling: mixing and condensation
- heat transfer in the covered core
- heat transfer at steam generator primary and secondary side
- surgeline and pressurizer thermal-hydraulics

ATHLET CALCULATIONS OF THE BETHSY TEST 9.3

Table 4: Initial condistions of test 9.3

Power	2.867 MW
Primary pressure	15.54 MPa
Pressurizer level	3.81m
Core inlet temperature	286.9 °C
Core outet temperature	291.6 °C
Downcomer mass flow	143.4 m/s
Secondary pressure	6.88 MPa
Secondary level	12.63 m
Feedwater mass flow	0.57 m
Steam generator inventory	726.0 kg

Table 4 presents the initial conditions of the test. Figure 7 shows the fast decrease of the primary pressure at the beginning of the test. Steam occurs in the primary circuit when the pumps are switched off. The primary pressure increases slightly at a level of 8 to 9 MPa. The safety injection signal at 11.9 MPa automatically shuts down the steam generator main feedwater systems (see Table 3). 1200 s after the failure of the high pressure injection, the depressurization of the secondary sides of the two intact steam generators was started (see Figure 8). The primary pressure decreases slightly below the secondary pressure of the damaged steam generator. Consequently an inversion of the break mass flow was observed (see Figure 9). For a short time the saturation margin of the core outlet was recovered.

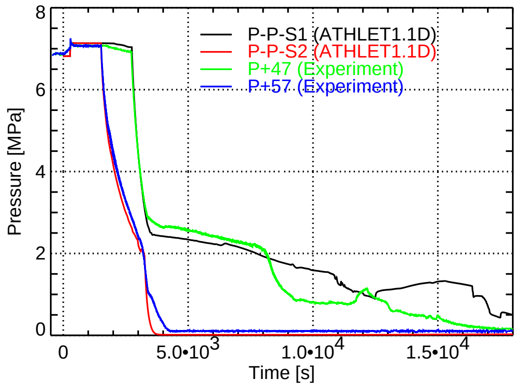

Figure 8. Secondary pressure in SG1 (damaged) and SG2 (intact, identical to SG3)

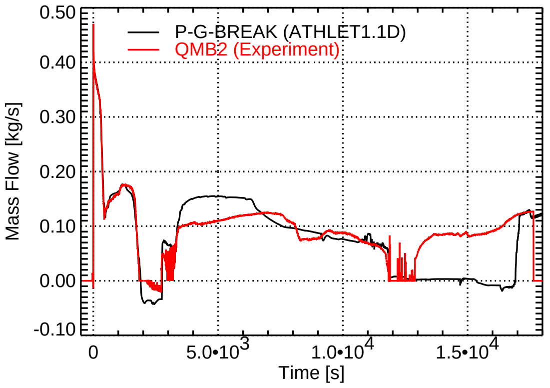

Figure 9. Break mass flowAccumulator inventory

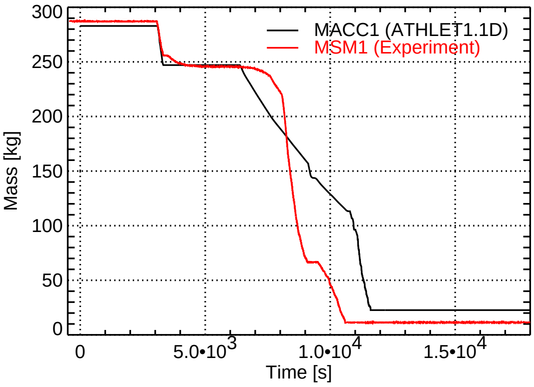

Figure 10.Accumulator inventory

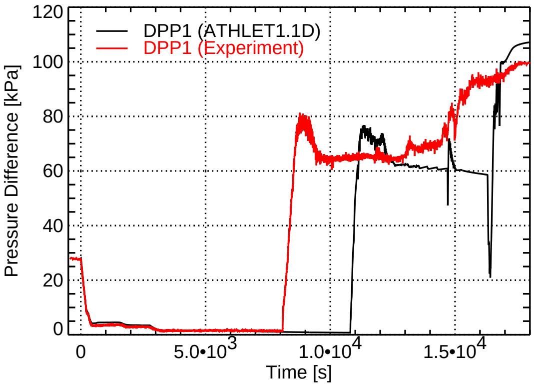

Figure 11.Pressure difference in the pressurizer

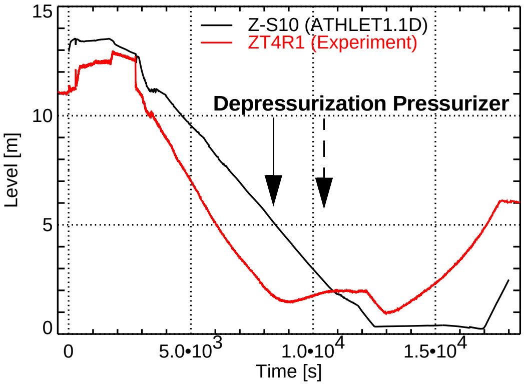

Figure 12.Collapsed level of the damaged steam generator secondary side

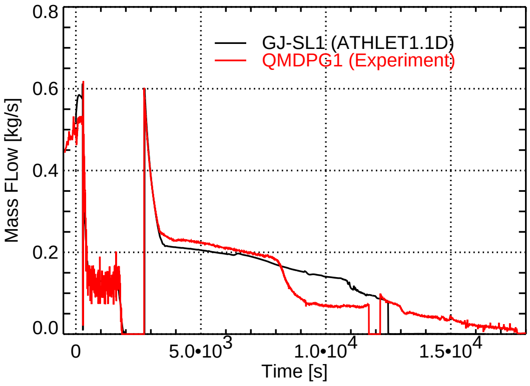

Figure 13.Steam mass flow from the damaged steam generator

When the collapsed levels of the secondary sides of the intact steam generators dropped below the 2 m limit, the damaged steam generator was depressurized too. At the same time the primary mass flow in the two intact steam generators is breaking down. Then all residual heat of the primary circuit was removed via the damaged steam generator. The break flow is again directed from the primary to the secondary side. The primary pressure decreased below the setpoint of the accumulator injection. Figure 10 shows, that the process of the accumulator injection was modelled with good agreement to the experiment.

Figure 12 shows deviations between the measured and the calculated secondary collapsed level for the damaged steam generator. During this scenario the secondary side is simultaneously filled through the break and depleted by the steam dump. The atmospheric dump mass flow up to a problem time of about 8000 sec was calculated in good agreement to the experiment (see Figure 13) whereas the calculated break flow at this period is too high (see Figure 9). For the assessment of the break mass flow calculation not only the leak model, but also by the thermal-hydraulic conditions near the break during this period have to be taken into account. Figure 14 shows the void fractions at this time in the primary and secondary components of the damaged steam generator. The secondary side will be depleted by the depressurization. At a certain level the heat

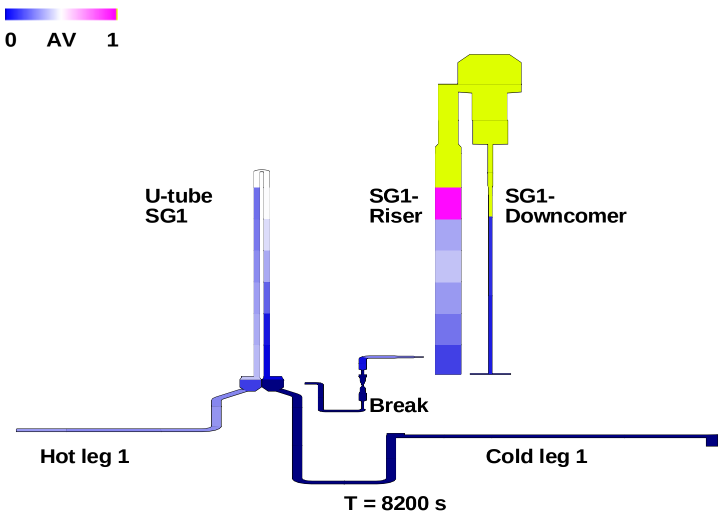

Figure 14.Void fractions at the primary and secondary side of the damaged steam generator

sink of the first steam generator gets low. Figure 14 shows the situation, when even steam occurs at the primary side at the top of the U-tubes. The primary fluid flow will be interrupted. These processes are very complex and are very hard to model by an 1D-system code like ATHLET.

In the test after 8065 sec the collapsed level of the damaged steam generator dropped below 2 m. Efforts for residual heat removal had to be made quickly to reach the threshold of low pressure injection. Therefore the pressurizer valve was opened, which lead to a further drop of the primary pressure (see Figure 7) and an increased accumulator injection (see Figure 10). Because of the too high calculated level of the damaged

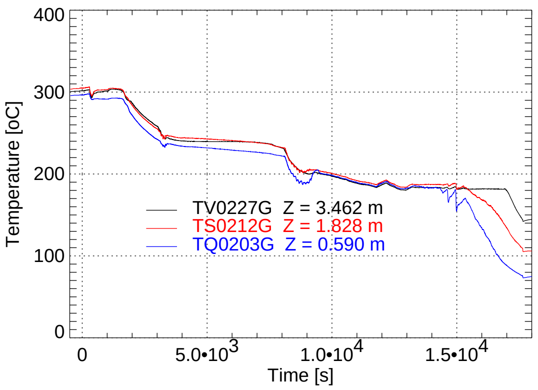

Figure 15.Measured rod cladding temperature at different heights

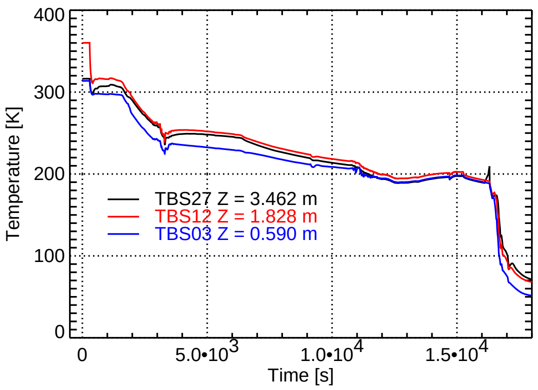

Figure 16.Calculated rod cladding temperatures at different heights

steam generator (see Figure 12), the opening of the pressurizer dump valve was calculated about 2000 sec too late (see Table 3, Figure 11). Also the increasing pressure difference in the pressurizer, which is a measure for the pressurizer collapsed level, was modelled with good accordance to the experiment up to the low pressure injection apart from the too late opened dump valve (see Figure 11). At 11720 s the setpoint for the low pressure injection was arrived and stable heat removal conditions were established. Neither in the test nor in the calculation heating up of the rod cladding temperatures were observed (see Figure 15 and Figure 16).

SUMMARY AND CONCLUSIONS

In both ATHLET calculations most of the thermal-hydraulic phenomena could be modelled with a rather good agreement to the experimental results.

For the test 5.2c the quality of the calculations strongly depends on the modelling of the heat losses, which were partly compensated by the trace heating at the test facility. In the calculation most of the hardware actions are controlled depending on the system pressure, which is strong influenced by the heat losses.

A total loss of feedwater accident is characterized by a fast decrease of the steam generator levels, a reduced primary to secondary heat transfer and a pressurization of the primary side. In such an accident the primary pressure can be reduced by accident management measures. The accident can be controlled by primary bleed via the pressurizer relief valves and primary feed with the ECC systems.

During the calculations for the test 9.3 deviations from the experimental results occurred concerning the break mass flow during the depressurization of the damaged steam generator. Difficulties arose in particular to model the processes near the break, when at the same time the secondary relief valve opens.

At a failure of both the high pressure injection and the auxiliary feedwater system the atmospheric steam dump first of the intact, then of the damaged steam generators and finally the depressurization of the primary circuit via the pressurizer valve, can avoid any heat up of the rod cladding temperatures.

From the safety point of view the main statement of the tests could be confirmed by the calculations.

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