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6

Primary to Secondary Leakage at PSB-VVER Test Facility, Simulated by CATHARE 2 Code

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1. Introduction

The current analysis was carried out in the framework of the international PHARE project on code assessment and validation with participation of IRSN-France, GRS-Germany, NRI-Czech republic and EREC-Russia. Overall objectives of this project are utilization and transferring of methodologies for computer codes validation using available experimental data of VVER test facility.

The experiment "Primary to Secondary Leakage" (PRISE) was performed by EREC at PSB-VVER test facility. It replicates an accident on VVER-1000 with an equivalent diameter of 100 mm for the leak size, which corresponds to a break size of 1.4%. The initial event of the experiment is a leakage from primary to secondary side as a result of a cover break of a hot steam generator collector. This test provides the data required to perform an analysis with the thermal-hydraulic computer code CATHARE: initial and boundary conditions, transient scenario, experimental results.

2. PSB-VVER test facility

The PSB-VVER facility is a large-scale integral test facility, which structure is similar to that of the primary circuit of VVER-1000 nuclear power plant (NPP). It is scaled 1:1 in height and 1:300 in volume and power.

The facility consists of a reactor model, four loops, four steam generators, a pressurizer (PRZ) and an emergency core cooling system (ECCS). The reactor model comprises five elements: lower plenum (LP), core simulator (CS), external core bypass (BP), upper plenum (UP) and external downcomer (DC). Each loop includes a circulation pump (MCP), a steam generator (SG), and hot and cold legs (HL and CL). Special lines (primary to secondary leakage system) connect the upper part of SG #4 headers to the steam generator secondary side, which allows simulation of both hot and cold SG collectors break. MCPs are installed on CLs. They can operate in two-phase flow and have a motor speed control system (Melikhov et al., 2003).

The PRZ is a vessel, connected to one of the loop HL through a surge line. It operates similarly to the reference NPP one, controlling primary pressure. It is equipped with a relief valve, a spray line for pressure decrease and an electrical heater – installed in the vessel lower part – for pressure increase. In this scenario, PRZ is connected to loop #2.

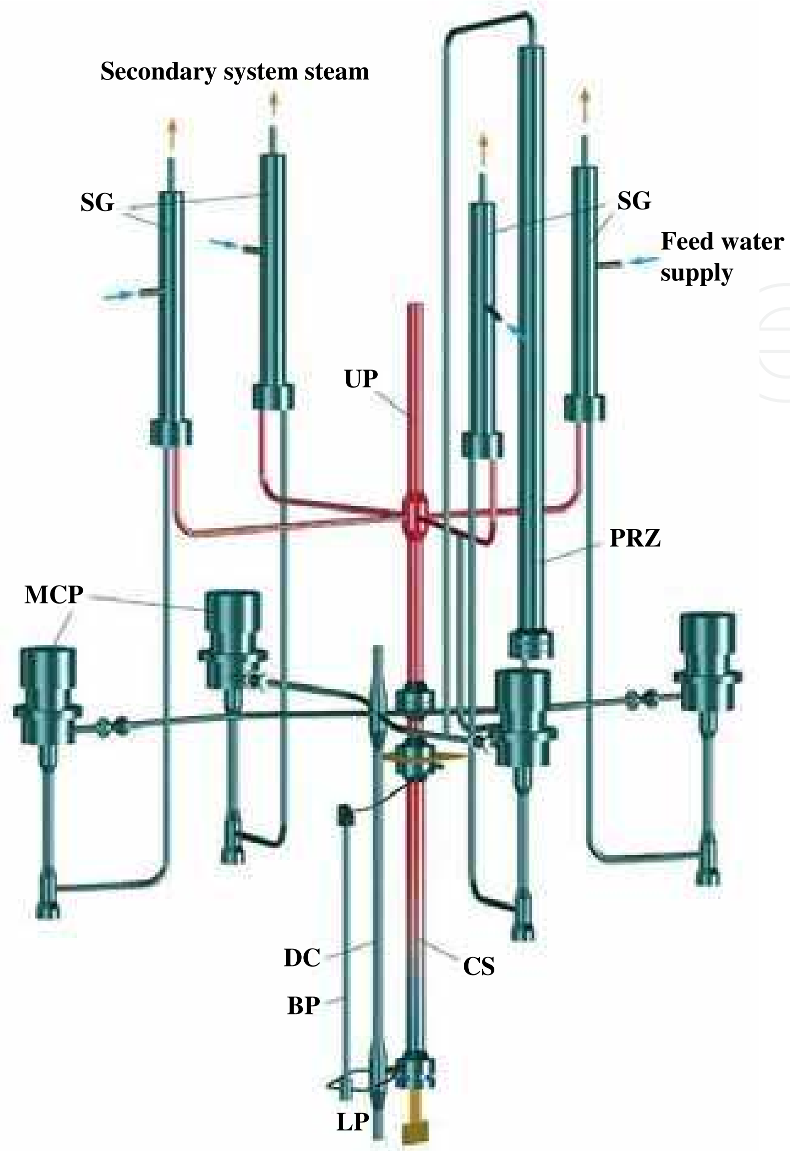

Fig. 1. General view of PSB-VVER facility

ECCS of the facility includes three subsystems: a passive system, a high pressure active system (HPSI) and a low pressure active system (LPSI). The passive system consists of four hydroaccumulators (ACCUs) connected in pairs to the downcomer inlet chamber and to the upper plenum outlet chamber. Both active ECCS are simulated by a proper delivery of cold water into hot and cold legs of loops #1, #3 and #4, from a feed water system.

The core simulator is a bundle of 168 fuel rods (FRs) and one central non-heated tube, placed in a regular hexagonal channel. These FRs are electric resistance heating rods, with a uniform power profile along the height. FRs and central tube are grouped along a triangular lattice. Along bundle height, 17 spacer grids are welded to the central tube. The bypass connects the lower plenum with the upper plenum. Its walls are heated directly by electric power supplies.

Heat is removed from primary circuit using steam generators. Each SG consists of a vertical vessel with two vertical headers inside (hot and cold collectors), interconnected with 34 helical tubes. Thus, the heat-exchanging surface of SG model is a slightly inclined helical bundle of 34 tubes.

Secondary circuit of the facility is designed as an open loop. Feed water is supplied to steam generators through annular header. Flow rate of feed water is regulated with control valves. Steam from each SG flows through steam discharge lines to a common header and then to a special process condenser. An atmospheric steam dump system (ADS) is connected to each SG.

The test facility is equipped with advanced data acquisition and process control systems. The latter controls the experiment on PSB-VVER facility.

3. CATHARE 2 computer code

CATHARE (Code for Analysis of Thermal-Hydraulics during an Accident of Reactor and safety Evaluation) is an advanced, two-fluid, thermal-hydraulic code. It is developed in France by the French Atomic Energy Commission (CEA), Electricité de France (EDF), Areva NP and IRSN.

CATHARE is designed to perform best-estimate calculations of accidents in pressurized water reactor, including VVER. Specific modules have also been implemented to allow modeling of other reactors like boiling water reactors or gas cooled reactors. CATHARE is limited to transients during which no severe damage occurs to fuel rods; more precisely, fuel ballooning and clad rupture are assumed not to have major effect on water flow in the reactor core. Its range of application covers all loss-of-coolant accident (LOCA), all degraded operating conditions in steam generators secondary systems, following ruptures or system malfunctions (Barre & Bestion, 1995).

CATHARE has a modular structure with five main modules: 1D axial module for pipes, tubes or channels where velocity has a preferential direction; 0D volume module for vessels or plenums where fluid is not channeled in a preferential direction of flow and where inertial forces are negligible compared with gravity; 3D module; boundary condition module; double-ended break module. Each 0D module is divided in two sub-volumes. Any kind of hydraulic circuit may be represented by a set of modules, which are connected by junctions. Hydraulic elements (axial, volume and 3D modules) can be connected to multi-layer walls. The heat exchange between one primary and several secondary circuits, via heat exchangers, can be calculated. Other gadget sub-modules are available to represent local changes to standard thermal hydraulic equations: hydroaccumulator; valve; 0D pump, using homologous curves of head and torque; break; heat and/ or mass sources; heat and/ or mass sinks; etc.

These modules allow to take into account any two-phase flow behavior. Thus, mechanical and thermal non-equilibrium, as well as all flow and heat transfer regimes, are described: stratified and co- or counter-current flow; critical flow and heat flux; reflooding; natural and forced convection; subcooled and saturated nucleate boiling; film boiling and condensation; etc. In particular, a flooding counter-current flow limitation (CCFL) is modelled (Sabotinov, 1997).

Two-phase flows are described using a two-fluid six-equation model. These equations represent conservation of mass, energy and momentum, for separate processing of liquid and steam. The presence of one to four non-condensable gases can be taken into account by one to four additional transport equations. This system of equation is closed by a complete set of momentum, mass and energy transfer laws for exchange at liquid/ steam interfaces or at walls. Specific models are also available to represent fuel rods thermomechanics, core neutronics, reflooding, etc. (Bazin & Pellissier, 2006).

The mass and energy balance equations are of primary form whereas the momentum equations are of secondary form. The six main variables are pressure, liquid enthalpy, gas enthalpy, void fraction, liquid velocity and gas velocity and, if it exists, up to four non-condensable mass fraction. In 0D modules, two energy and mass balance equations are written for each sub-volume (inertia is neglected). The main variables (except velocity) are then calculated for each sub-volume, as well as the separation level elevation between the two sub-volumes. In 3D modules, the momentum equation is written in all three directions.

The numerical choices are finite volume discretisation with structured mesh, first order discretisation in space and time, staggered spatial mesh and donor cell principle. Time discretisation is fully implicit (semi-implicit for 3D) and enables solution stability to be achieved over a broad range of time step values. The maximum time step is up to the user and depends on the problem being solved. A non-linear system is thus obtained, solved using the Newton-Raphson iterative method.

4. Test specification

4.1 Facility configuration

The pressurizer is connected to loop #2. Two lines of HPSI are connected to the cold legs of loops #3 and #4. Two lines of LPSI are connected to the hot and cold legs of loops #3 and #4. The two other active ECCS lines are disconnected. All ACCUs are enabled: ACCUs #1 and #3 are connected to the UP outlet chamber while ACCUs #2 and #4 are connected to the DC inlet chamber.

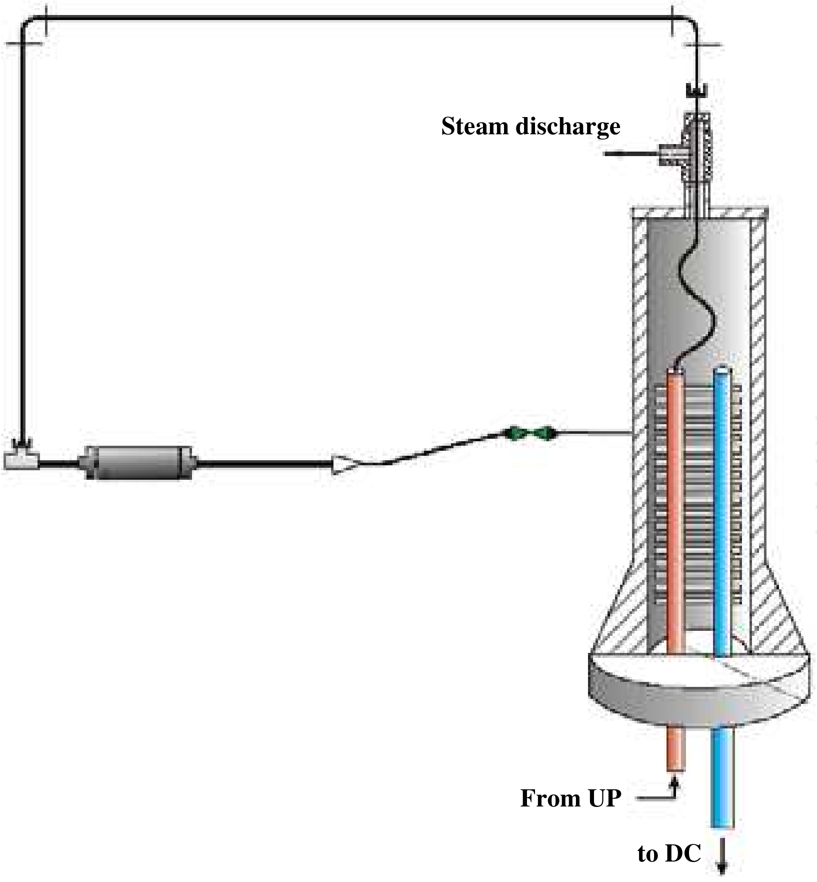

Fig. 2. Primary to secondary leakage system

Level in SGs under steady-state conditions is maintained by means of pulsed supply of feed water with a temperature of about 220°C. Atmospheric steam dumping systems are connected to each SG. In each ADS line, a throttle of 50 mm long by 12.1 mm inner diameter is installed. The opening/ closing of ADS are set to 7.16/ 6.28 MPa.

The leakage simulation system connects the top of the SG #4 hot header to the steam generator secondary side (figure 2). In this connecting branch, a throttle of 56 mm long by 5.8 mm inner diameter is installed.

4.2 Initial conditions

Initial conditions of the experiment (Elkin et al., 2005) with respective results of the steady-state calculation by CATHARE are presented in table 1.

Parameters	Experiment	Calculation
Primary circuit		
Core simulator power, kW	1507	1507
Bypass power, kW	15.0	15.0
Loop-1 flow rate, kg/ s	10.45	10.45
Loop-2 flow rate, kg/ s	10.41	10.41
Loop-3 flow rate, kg/ s	10.39	10.39
Loop-4 flow rate, kg/ s	10.15	10.15
Pressure at CS outlet, MPa	15.74	15.65
Coolant temperature at DC inlet, °C	280	281
Coolant temperature at UP inlet, °C	291	288
Collapsed level in PRZ, m	6.71	6.69
Secondary circuit		
Pressure in SG-1, MPa	6.28	6.32
Pressure in SG-2, MPa	6.30	6.32
Pressure in SG-3, MPa	6.33	6.31
Pressure in SG-4, MPa	6.29	6.32
Collapsed level in SG-1, m	1.70	1.70
Collapsed level in SG-2, m	1.71	1.71
Collapsed level in SG-3, m	1.70	1.70
Collapsed level in SG-4, m	1.69	1.69
Hydroaccumulators		
Pressure in ACCU-1, MPa	5.88	5.88
Pressure in ACCU-2, MPa	5.87	5.87
Pressure in ACCU-3, MPa	5.87	5.87
Pressure in ACCU-4, MPa	5.90	5.90
Collapsed level in ACCU-1, m	4.84	4.84
Collapsed level in ACCU-2, m	4.84	4.84
Collapsed level in ACCU-3, m	4.84	4.84
Collapsed level in ACCU-4, m	4.86	4.86

Table 1. Initial conditions

4.3 Boundary conditions and scenario

The experiment starts with the opening of an isolation valve in the break line.

PRZ heater power is regulated depending on the pressure in UP according to a specified law. When collapsed level in PRZ reaches 2.33 m, its heater power is switched off.

When the level of affected steam generator (SG #4) reaches 1.77 m, a signal is given to close the valve of the steam discharge line of this SG – and then to isolate it from intact SGs – with a delay of 2 s. The valve is completely closed in 11.3 s.

When the pressure in UP reaches 13.7 MPa, a scram signal is simulated, which leads to four actions. Firstly, core and bypass power start to reduce, according to a specified law, with a delay of 5.6 s. Secondly, a command to close the feed water valve of SG #4 – and then to stop feed water supply to this SG – is given with a delay of 4.6 s. The valve is completely closed in 2 s. Thirdly, level in intact SGs is maintained at 1.67 m by operation of emergency feed water pumps. These pumps are actuated with a delay of 2 s. The temperature of emergency feed water is 150°C, and the maximum flow rate is 67 g/ s. Fourthly, the valve that controls steam removal from SGs is closed in 16.6 s.

When the difference between the saturated temperature of primary circuit and the maximal coolant temperature in hot legs of primary loops reaches 10°C, a signal to stop MCPs is given with a delay of 17 s. MCPs are completely stopped in 232 s.

The opening/ closing of ADS are set to 7.16/ 6.28 MPa. ADS in SG #1, #2 and #3 operates according to pressure in SG #2 secondary side, while ADS in SG #4 operates according to pressure in SG #4 secondary side. After the first opening of ADS in affected steam generator (SG #4) a seizure is simulated and then this ADS remains in fully open position until the end of the transient.

When the UP pressure drops below 10.8 MPa, cooling water from HPSI is supplied to the cold leg of loops #3 and #4 with a delay of 1 s. HPSI flow rate is regulated depending on the pressure in UP, according to a specified law.

On decreasing the primary pressure below the set point of ACCUs actuation (5.9 MPa), they start to supply water to the primary circuit. When the level in ACCU falls down to 0.45 m, they are isolated from primary circuit by closing a valve.

When the UP pressure drops below 2.5 MPa, cooling water from LPSI is supplied to the cold and hot legs of loops #3 and #4. LPSI flow rate is regulated depending on the pressure in UP, according to a specified law.

When the total volume of water injected into primary circuit through HPSI and LPSI reaches 0.33 m3, a signal to stop HPSI and LPSI injections is given with a delay of 10 s (simulation of water tank emptying).

The experiment is terminated when the maximal FR cladding temperature reaches 300°C.

5. Transient calculation

5.1 Modeling of PSB facility by Cathare 2

An input data deck (IDD) for LOCA calculations of PSB-VVER test facility has been developed for the code version CATHARE 2 V2.5_1. It is based on IDD of PSB-VVER developed for the version CATARE 2 V1.3_1 for natural circulation calculation system (Melikhov et al., 2004). The geometrical information of the test facility is checked against the information provided by EREC in the framework of an OECD project. The basic IDD has been modified for the specific initial and boundary conditions of the PRISE experiment.

Nodalization scheme of the primary circuit includes four loops. The core vessel is modeled by a lower plenum, an average core channel, with 21 axial segments (168 fuel rods), a core bypass, an upper plenum and an external downcomer. The models of the LP, UP and DC consist of volume and axial elements connected by junctions.

The pressurizer consists of a volume with internal wall, modeling the heaters. It is connected to loop #2.

For the SGs modeling, a multitube approach is applied as for PACTEL experimental facility (Sabotinov, 1993), (Sabotinov, 2005). The 34 heat exchange tubes of each SG are presented as 3 axial elements, located at different horizontal elevations (high, middle and low tube bundles). Each axial element is divided into 26 segments.

The SG secondary side is presented by a recirculation model. It consists of one axial and one volume element, connected to the steam discharge lines. The latter also consist of volume and axial elements, with a unique pressure boundary condition at the outlet. Each SG feed water is modeled by a source.

HPSI and LPSI are modeled by sources, connected to the hot and cold legs of loop #3 and #4. Each ACCU is modeled by an accu gadget: ACCUs #1 and #3 are connected to UP, while ACCUs #2 and #4 are connected to DC.

Each ADS is represented by a sink gadget, connected to the steam discharge line of the SG.

The primary to secondary leak is modeled by a pressure boundary condition with sonic blocking at the top of the hot collector of SG #4 in the primary side, and a source in the secondary side.

The CATHARE model of PSB-VVER primary circuit is presented in figure 3. Loop #1 is not represented.

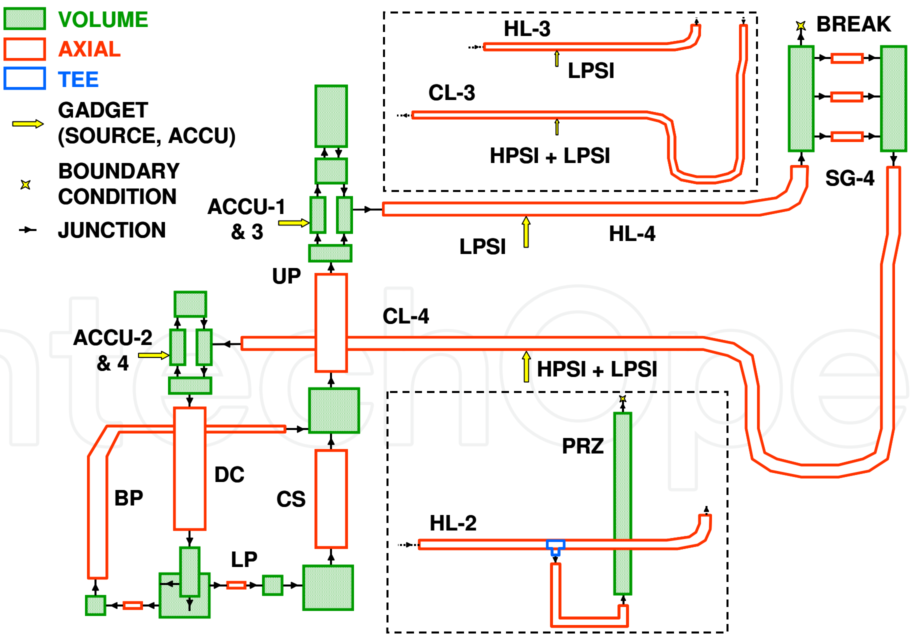

Fig. 3. CATHARE model for primary circuit

The primary circuit nodalization consists of 55 hydraulic modules (28 axial, 24 volume and 3 boundary condition elements) for a total scalar meshes number of 1279. The secondary circuit nodalization consists of 30 hydraulic modules (16 axial, 13 volume and 1 boundary condition elements) for a total scalar meshes number of 488.

5.2 Steady state calculation

In order to achieve nominal conditions the following regulators are used in the IDD: regulation of primary flow rates in the 4 loops by MCPs speed variation; regulation of the SGs level by source of water; regulation of the equilibrium between steam and feed water flow rates; regulation of the nominal PRZ level by source of water; regulation of primary side pressure by the PRZ heaters.

The steady state has been calculated for 3000 s. The last 500 s, the regulators were switched off in order to check that the parameters remain constant. Values of main parameters, obtained at the end of the steady state, are presented in table 1, where they are compared with experimental initial parameters (Elkin et al., 2005).

5.3 Transient calculation results

The calculation is carried out until the maximal FR cladding temperature reaches 300°C. This happened at t = 12645 s. The calculation took 4 hours and 30 minutes on PC bi-processor Intel with 3.6 GHz under Windows XP operating systems.

A large number of sensitivity calculations have been performed, regarding different modeling and CATHARE options:

- different modeling of the primary to secondary leak;
- variation of the hydraulic resistance of the break line in order to evaluate the break flow and the primary pressure;
- variation of the discharge coefficient of the atmospheric steam dump system (ADS) in order to predict correct secondary pressure evolution of SG #4;
- with and without CCFL model between core and upper plenum with sensitivity study on the CCFL parameters to evaluate the influence on the core cooling;
- modeling of the SG level regulation with constant or impulse feed water supplies (negligible effect);
- different heat loss coefficients in the SG for better prediction of the SG secondary pressures.

The steady state provides the initial conditions of the transient. A comparison of calculated and experimental (Elkin et al., 2005) times of occurrence of main events is presented in table 2.

Event		Time (s)	
		Experiment	Calculation
1	Leakage opening	0	0
2	Signal for steam line closing in SG-4 (SG-4 level > 1.77 m)	4.3	4.0
3	Beginning of steam line closing in SG-4 (event #2 + 2 s)	6.3	6.0
4	Complete steam line closing in SG-4 (event #3 + 11.3 s)	17.6	17.2
5	Scram signal, begin of intact SGs isolation (press. in UP < 13.7 MPa)	26.9	21.8
6	Actuation of emergency feed water pumps (event #5 + 2 s)	28.9	23.8
7	Beginning of feed water closing in SG-4 (event #5 + 4.6 s)	31.5	26.4

Event		Time (s)	
		Experiment	Calculation
8	Switching off of PRZ heaters (PRZ collapsed level < 2.33 m)	32.0	27.8
9	Start of core and bypass power reduction (event #5 + 5.6)	32.5	27.4
10	Opening and seizure ADS of SG-4 ADS (press. in SG-4 > 7.16 MPa)	32.5	25.3
11	Complete feed water closing in SG-4 (event #7 + 2 s)	33.5	28.4
12	Stopping of SG-1, 2 and 3 steam discharge (event #5 + 16.6 s)	43.5	38.4
13	PRZ emptying	50.0	42.6
14	Pressure in UP < 10.8 MPa	62.0	54.0
15	Start of HPSI injection (event #14 + 1 s)	63.0	55.5
16	Primary coolant reaches a subcooling of 10°C	66.5	63.5
17	Start of MCPs coast down (event #16 + 17 s)	83.6	80.6
18	Complete switching off of MCPs (event #17 + 232 s)	289	313
19	Start of ACCU-1 injection Start of ACCU-2 injection Start of ACCU-3 injection Start of ACCU-4 injection (primary pressure < ACCU pressure)	617 617 617 617	635 636 637 627
20	Pressure in the primary side is lower than in the secondary one	416	444
21	Volume of water injected in primary circuit by HPSI > 0.33 m^3	888	861
22	Stop of HPSI injection (event #21 + 10 s)	898	872
23	Stop of ACCU-1 injection Stop of ACCU-2 injection Stop of ACCU-3 injection Stop of ACCU-4 injection (ACCU level < 0.45 m)	4600 4675 4615 4620	6108 6105 6109 6110
24	Start of the first bundle heat up	8521	-
25	First loop seal clearing	8635	-
26	Start of the second bundle heat up	12208	12400
27	Stop of experiment	12425	12645

Table 2. Chronology of main events

The leak flow is very specific in PRISE compared to leakages from primary or secondary circuit to the ambient atmosphere. Secondary pressure is higher than atmospheric pressure, so the ratio between the pressure at break upstream and downstream is lower in the first case. Thus, in PRISE, critical flow is observed at the very beginning of the accident, whereas the sonic flow remains a long period of time in case of a leakage to atmosphere.

Due to the leak, the primary pressure is decreasing (figure 4), which leads to the actuation of the scram signal at 21.8 s (UP pressure < 13.7 MPa).

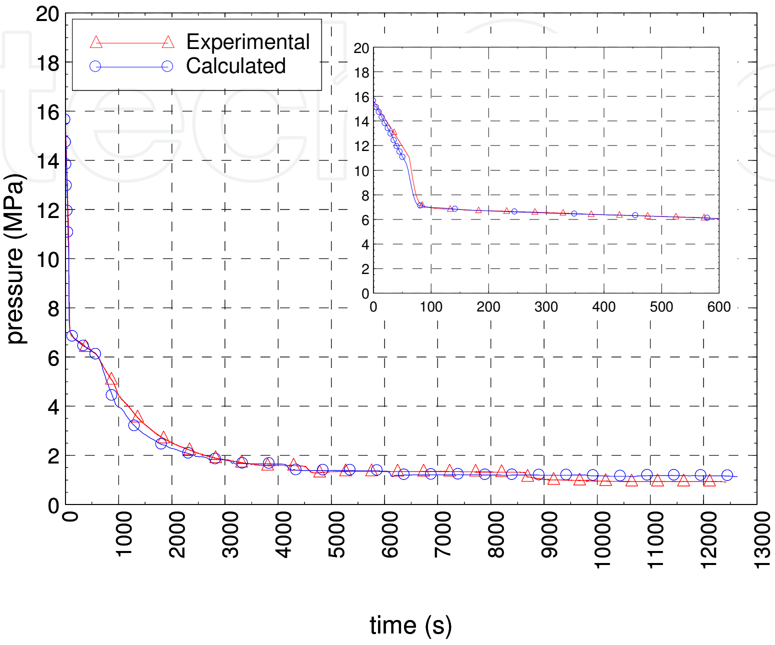

Fig. 4. Pressure in the UP (hot leg connection area)

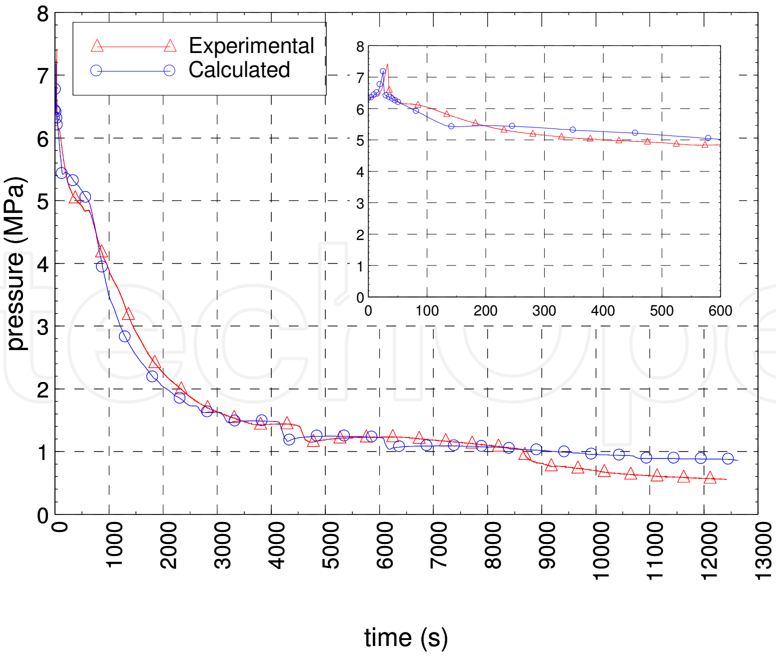

Fig. 5. SG-4 secondary pressure

The power in the core simulator and bypass heaters starts to decrease according to the specified law with a delay of 5.6 s after the scram signal. On the secondary side, the valve that controls steam removal from steam generators begins to close. Feed water supplies of intact SGs are switched to the emergency feed water, with a delay of 2 s, while feed water supply to broken SG is closed.

The pressure and the water level in the broken SG (SG #4) rapidly increase from 6.31 to 7.16 MPa. So that the signal for steam line closing, due to SG high level (> 1.77 m), is given at 4.0 s (4.3 s in the experiment). Complete steam line closure occurs at 17.2 s. (17.6 s measured).

At 25.3 s, the pressure in the broken steam generator (SG #4) reaches 7.16 MPa (figure 5), then opening and seizure of ADS in open position occurs.

In the intact SGs, the pressure also increases but do not reaches the set point for ADS opening (figure 6).

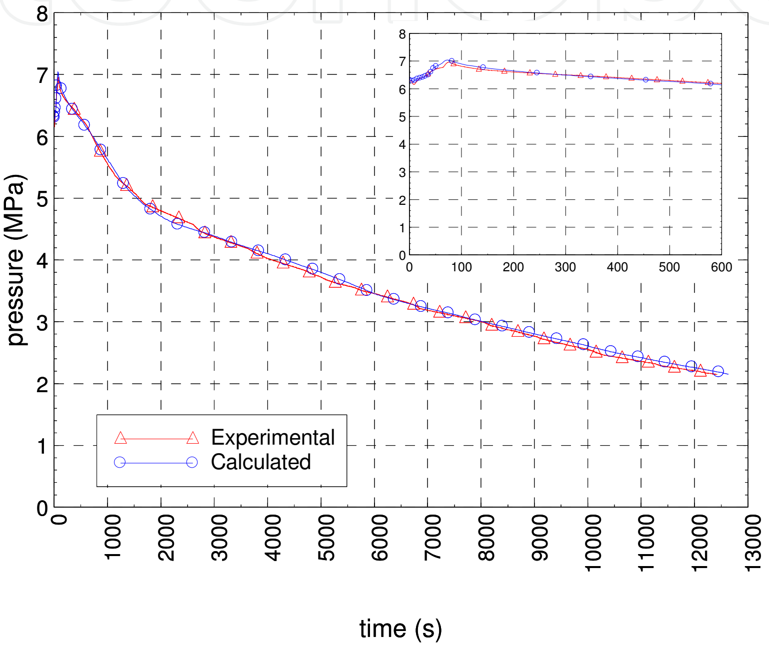

Fig. 6. SG-2 secondary pressure

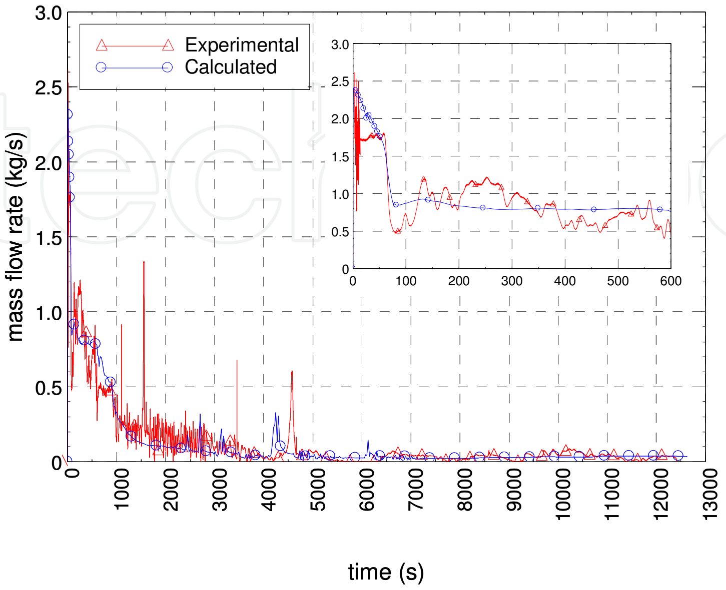

Fig. 7. Break line flow rate

The calculated leak flow reaches the maximal value of 2.4 kg/ s at the very beginning of the transient (figure 7). It can be compared with the experimental value of 2.6 kg/ s.
According to EREC specialists, one shall consider that the two-phase flow rate measurements must be used with care, comparing them with the calculated mass ejected through the break. More reliable is the comparison of the rejected masses (figure 8).

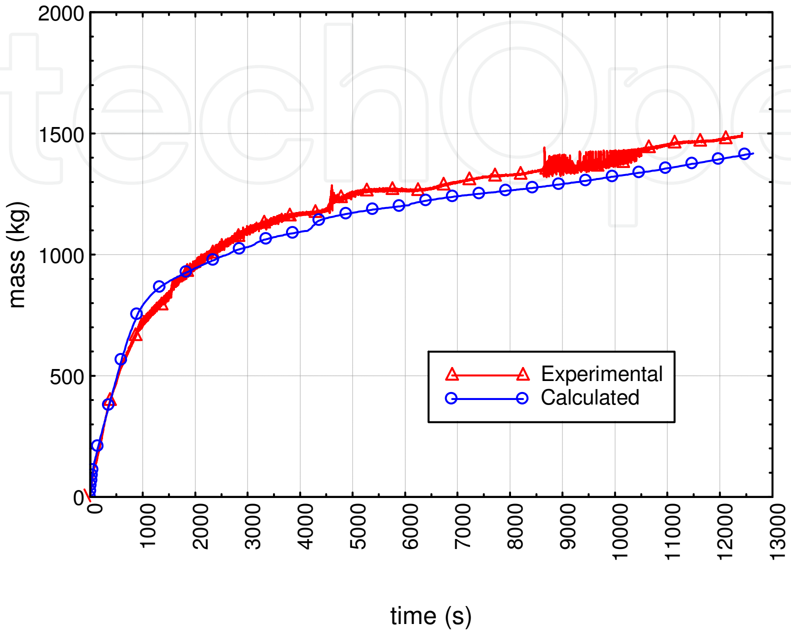

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Fig. 8. Mass of coolant ejected through the break

The pressurizer level rapidly decreases due to the leak from primary circuit. Pressurizer heaters are switched off at 27.8 s. (PRZ level < 2.33 m). The PRZ is completely empty at 42.6 s (50 s in the test).

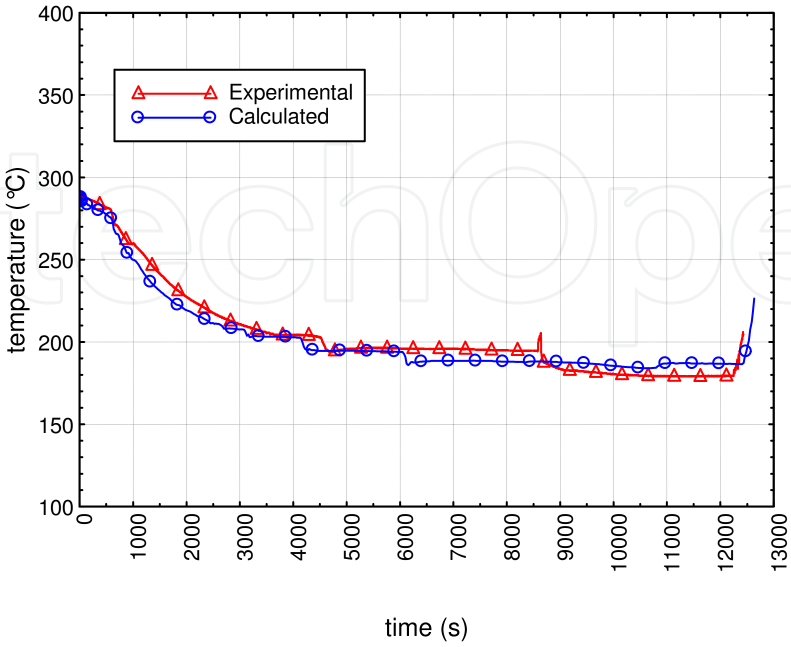

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Fig. 9. Coolant temperature in the UP lower part

At 63.5 s (66.5 s in the experiment) the primary coolant reaches a sub-cooling of 10°C and the main circulation pumps starts coast down, with a delay of 17 s, according to a specified law. The coolant temperature in the upper plenum lower part – at core outlet – is shown in figure 9.
After pressure in primary circuit decreases below 10.8 MPa at 54 s, HPSI pumps start to inject water into the cold legs of loops #3 and #4. The injection lasts until 861 s (888 s in the experiment) when the storage tank is empty (0.33 m3). The LPSI does not start because the tank is already empty when reaching the actuation set point of 2.5 MPa.
Further decrease of primary pressure causes hydroaccumulators injection at 627-635 s (primary pressure < ACCU pressure set point). The ACCU injection is sufficient to compensate the loss of the coolant through the break. The primary mass inventory stabilizes until the end of ACCU injection (injection stops when the ACCU level decreases below 0.45 m). The behavior of ACCU #1 is shown in figure 10.

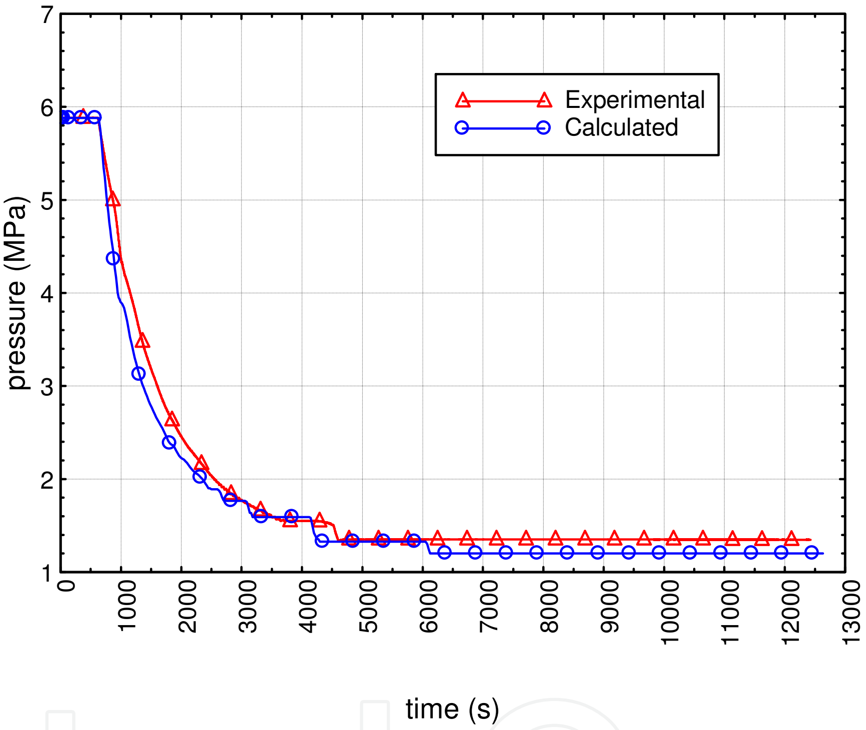

Fig. 10. Pressure in ACCU-1

At 444 s (416 s in the experiment) the pressure in the primary side decreases below the secondary pressure in SG #1, #2 and #3. The heat exchange between primary and secondary circuit is different in the intact and broken steam generators. In the broken SG, heat is transferred from the primary side to the SG and then released through ADS, whereas in the intact SGs, reversed heat flow occurs and they are cooled down by the primary side and the heat losses.
After the stop of ACCUs injection, primary mass inventory continually decreases, core void fraction increases and finally heat up of the upper part of the fuel bundle occurs. Figure 11 shows the bounding fuel cladding temperature in the core: i.e. at each time step, the maximum fuel cladding temperature in the whole core is considered.
In the experiment, a small core heat up (t = 270°C) can be observed at 8638 s, which is not predicted by CATHARE code. The second fuel simulator heat up is rather well predicted by

CATHARE. It starts at 12400 s in the calculation (12208 s in the experiment). The experiment and the calculation finish when the fuel cladding temperature reaches 300°C.
The differential pressure in the core is represented in figure 12.

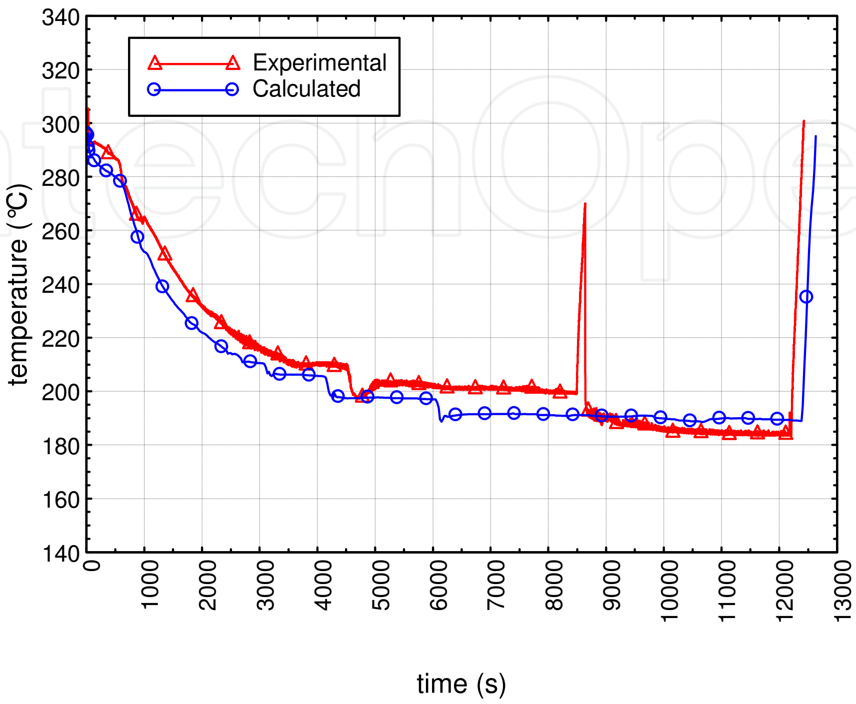

Fig. 11. Bounding fuel cladding temperature

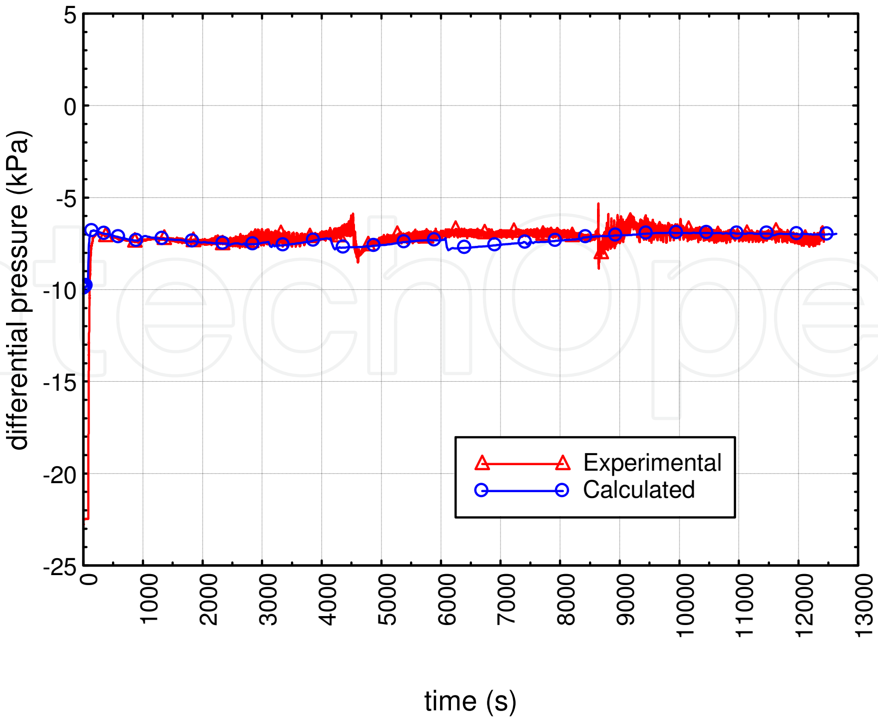

Fig. 12. Differential pressure in core

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Differential pressure in the upper plenum is shown in figures 13 and 14.

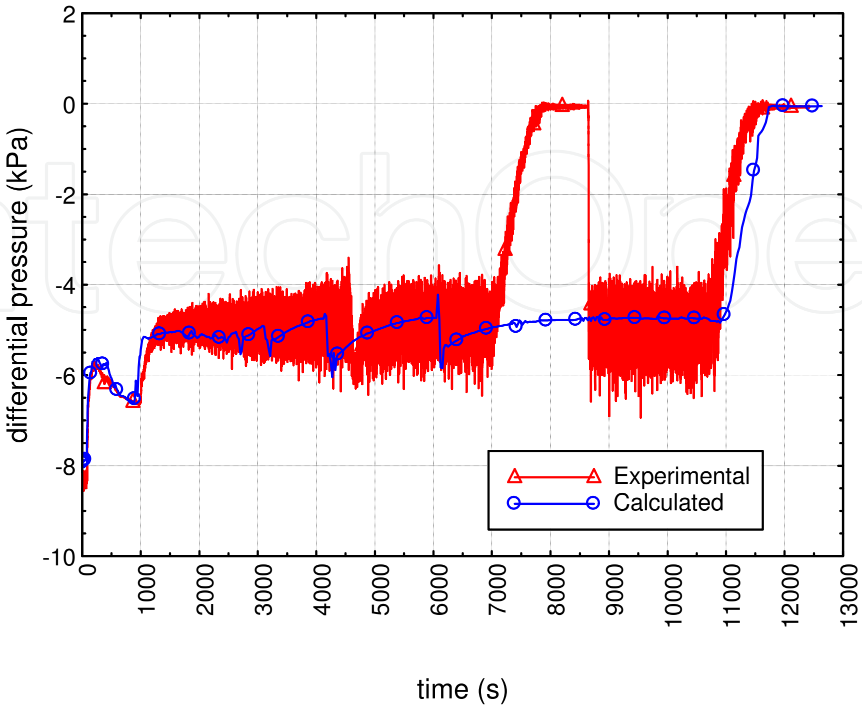

Fig. 13. Differential pressure in the UP lower part

Figures 15 and 16 illustrate respectively the calculated fuel cladding temperature and void fraction in the core as function of time and axial position.

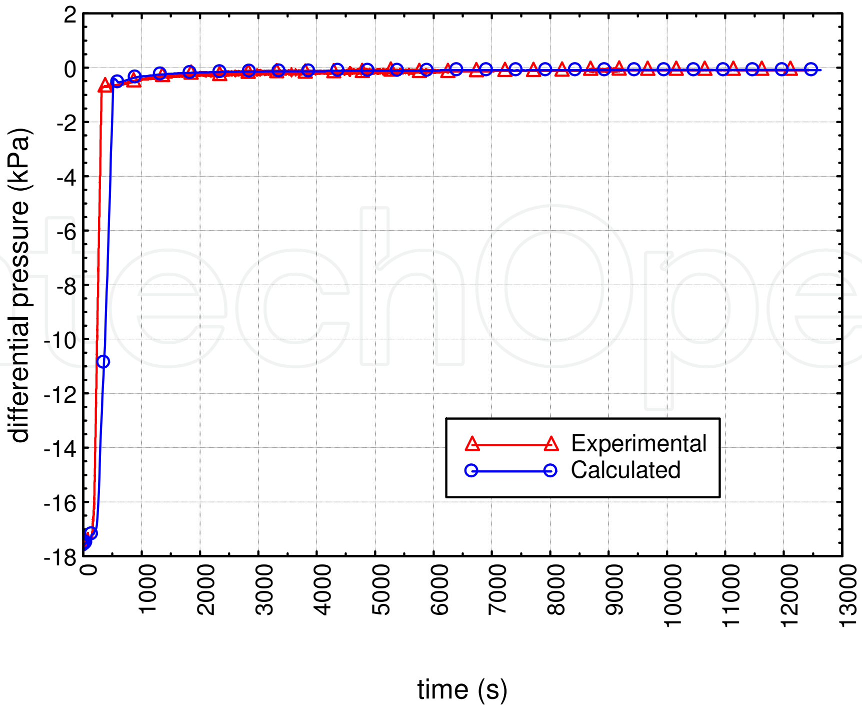

Fig. 14. Differential pressure in the UP upper part

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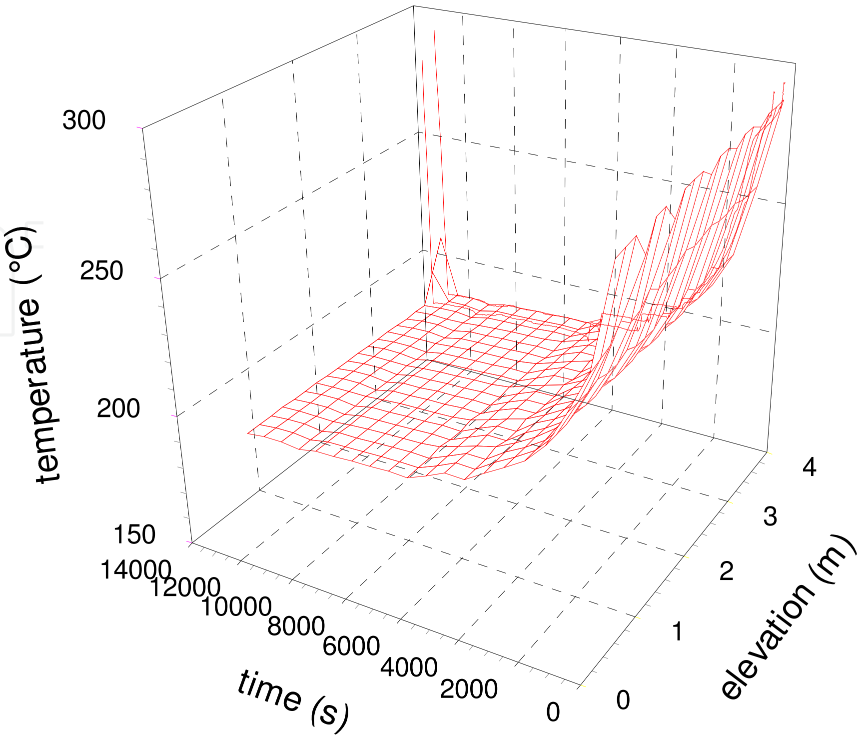

Fig. 15. Fuel cladding temperature

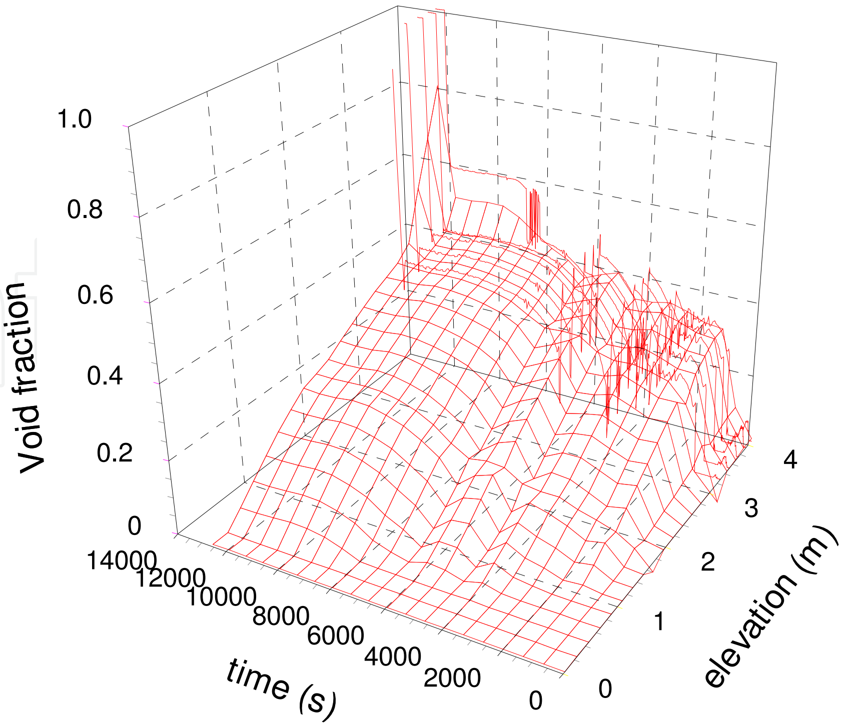

Fig. 16. Void fraction in the core

6. Conclusion

Comparison between calculated and experimental results shows good prediction of the basic physical phenomena and parameters such as primary and secondary pressures, temperatures, loop flows, etc.

Discrepancies appear in some differential pressures and loop seal clearance is delayed. Some overprediction of primary mass inventory can be observed.

The final core heat up is in good agreement with the experiment.

7. Acronyms

ACCU	Hydroaccumulator
ADS	Atmospheric Steam Dump System
BP	Core Bypass
CCFL	Counter-Current Flow Limitation
CL	Cold Leg
CS	Core Simulator
DC	Downcomer
ECCS	Emergency Core Cooling System
FR	Fuel Rod
HL	Hot Leg
HPSI	High Pressure Safety Injection
IDD	Input Data Deck
LOCA	Loss of Coolant Accident
LP	Lower Plenum
LPSI	Low Pressure Safety Injection
MCP	Main Circulation Pump
NPP	Nuclear Power Plant
PRISE	Primary to Secondary Leakage
PRZ	Pressurizer
PSB	Polnomasshtabnyi Stend Besopasnosti (Fullscale Safety Mock-up)
PWR	Pressurized Water Reactor
SG	Steam Generator
UP	Upper Plenum
VVER	Vodo-Vodianoi Energeticheskii Reaktor (Russian designed PWR)

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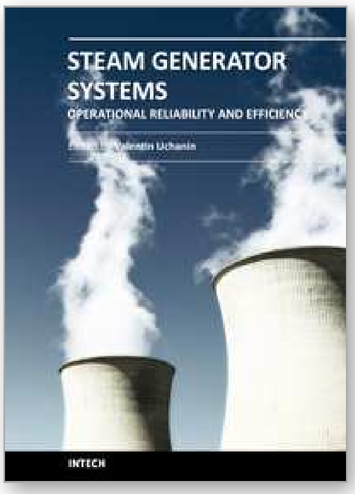

Steam Generator Systems: Operational Reliability and Efficiency
Edited by Dr. Valentin Uchanin

ISBN 978-953-307-303-3
Hard cover, 424 pages
Publisher InTech
Published online 16, March, 2011
Published in print edition March, 2011

The book is intended for practical engineers, researchers, students and other people dealing with the reviewed problems. We hope that the presented book will be beneficial to all readers and initiate further inquiry and development with aspiration for better future. The authors from different countries all over the world (Germany, France, Italy, Japan, Slovenia, Indonesia, Belgium, Romania, Lithuania, Russia, Spain, Sweden, Korea and Ukraine) prepared chapters for this book. Such a broad geography indicates a high significance of considered subjects.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Luben Sabotinov and Patrick Chevrier (2011). Primary to Secondary Leakage at PSB-VVER Test Facility, Simulated by CATHARE 2 Code, Steam Generator Systems: Operational Reliability and Efficiency, Dr. Valentin Uchanin (Ed.), ISBN: 978-953-307-303-3, InTech, Available from: http://www.intechopen.com/books/steam-generator-systems-operational-reliability-and-efficiency/primary-to-secondary-leakage-at-psb-vver-test-facility-simulated-by-cathare-2-code

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