Published in: 4th International Symposium on Safety and Reliability Systems of PWR’s/VVER’s.
May 14-17, 2001, Brno, Czech Republic

Investigations of Natural Circulation Instabilities in VVER-type Reactors at LOCA Conditions

F. Schäfer, Research Center Rossendorf, POB 510119,
D-01314 Dresden, Germany

Abstract

An important component of nuclear safety research is the analysis of accident scenarios in nuclear power plants with complex thermohydraulic computer codes. In the presented work the ATHLET code was used for calculations of small and intermediate loss of coolant accident experiments, which were performed at the Hungarian test facility PMK-2.

Loss of coolant accidents (LOCA’s) are characterized by a rapid primary pressure decrease in the early phase of the transient. After pump coast down natural circulation becomes the dominant decay heat removal mechanism. Boiling in the reactor core leads to formation of two-phase flow conditions in the primary circuit. At these conditions different types of two-phase flow instabilities can appear. Such instabilities can disturb the decay heat removal from the reactor core.

The aim of the presented calculations is to investigate whether the code ATHLET is capable of modelling natural circulation phenomena in VVER 440-type reactors. It could be shown, that ATHLET can calculate the accident behaviour in good agreement with the experimental data. All significant phenomena and especially the different types of instabilities are calculated very well. Calculations for a VVER-reactor show that the instabilities can also appear in a real plant.

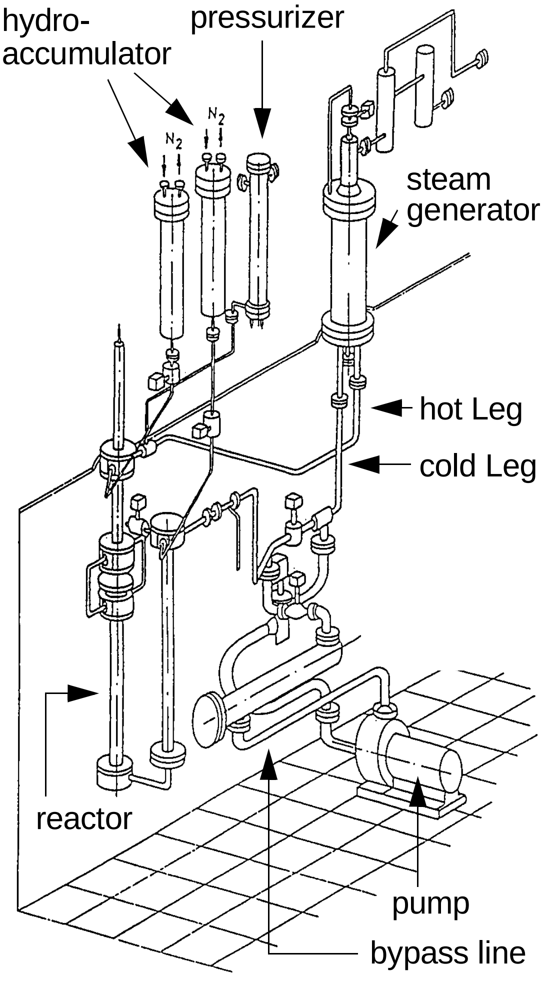

Fig. 1: Axonometric view of PMK-2

1 The PMK-2 Test Facility

The PMK-2 test facility (see Fig. 1) is a full-pressure, volume-scaled model of the Paks Nuclear Power Plant. The facility was constructed by the KFKI Atomic Energy Research Institute Budapest and is mainly designed to investigate processes following small and medium size breaks in the primary circuit and to study the natural circulation behavior of VVER-440 type reactors. The 6 loops of the plant are modelled by a single active loop with a scaling ratio of 1:2070. The core model is equipped with a electrically heated 19-rod bundle.

The steam generator consists at the primary side of a hot and cold collector and 82 heat transfer tubes. The main coolant pump is installed in a bypass line. During steady state operation circulation takes place through the bypass line. Pump trip modelling is achieved by controlling the pump flow rate with a valve. After pump coast down the bypass line is seperated from the loop.

2 Thermohydraulic Model

The presented calculations were performed with ATHLET Mod 1.1 Cycle A and Cycle C. For modelling the thermofluid network the five equation model of ATHLET is used. In most of the control volumes the flooding based drift model is applied and the one dimensional steady state critical discharge model is used for calculating the break flow. Before starting the transient, a steady state calculation at stationary boundary conditions is performed. In this way the stationary mass flows, the pressure differences and the heat losses are adjusted. The initiation of power scram, pump coast down and emergency core cooling systems is controlled by the primary pressure. The time dependence of the reactor power is assumed according to the decay heat curve. Fig. 2 shows the measurement positions at the PMK-2 test facility.

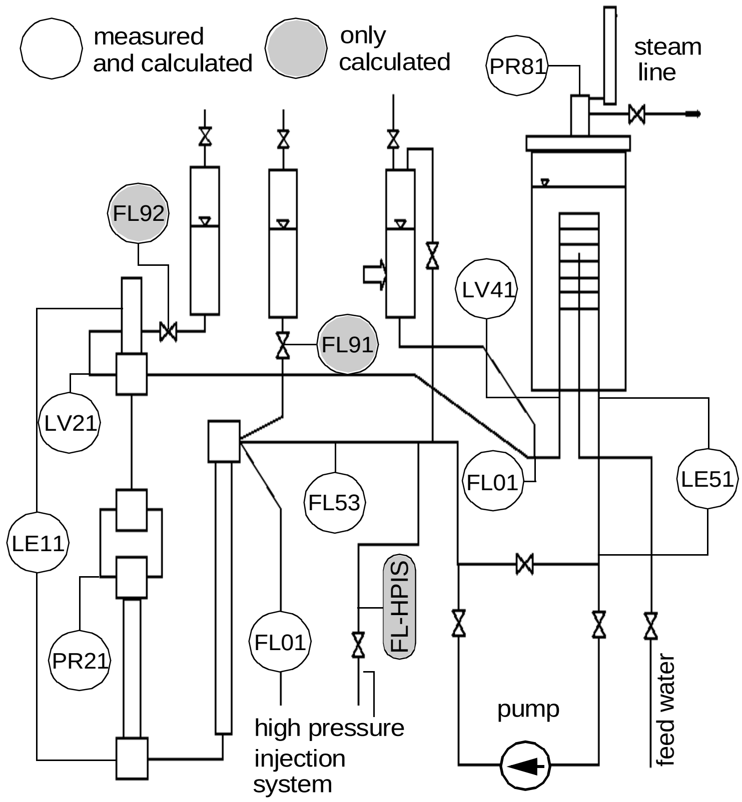

Fig. 2: Measurement positions at PMK-2

3 Experiments

At the KFKI Atomic Energy Research Institute Budapest a series of LOCA experiments were performed. Natural circulation instabilities could be detected in 3 different experiments.

These experiments are characterized as follows:

Cold leg break (CLB): small break in the upper head of the downcomer (d = 1 mm) with injection from the high pressure injection system and without injection from the hydroaccumulators.

Cold leg break with primary bleed: same initial conditions as in the cold leg break, additionally an accident management measure is realized by opening the pressurizer safety valve.

Surge line break (SLB): break in the pressurizer surge line (d = 5 mm) with injection from the hydroaccumulators and the high pressure injection system.

All 3 experiments were started at nominal operating parameters. With respect to the scaling ratio the reactor power, primary and secondary pressure and the mass flows corresponds to the nominal values at Paks NPP.

4 Results

4.1 Cold leg break

The experiment starts with the break initiation at t=0 s and simultaneously the steam generator (SG) is isolated by closing the feed water and steam lines. Opening the break valve results in a fast decrease of the primary pressure (Fig. 3). Due to the pressure decrease boiling starts in the reactor core. In this period the natural circulation is interrupted due to the effect of the hot leg loop seal (Fig. 4).

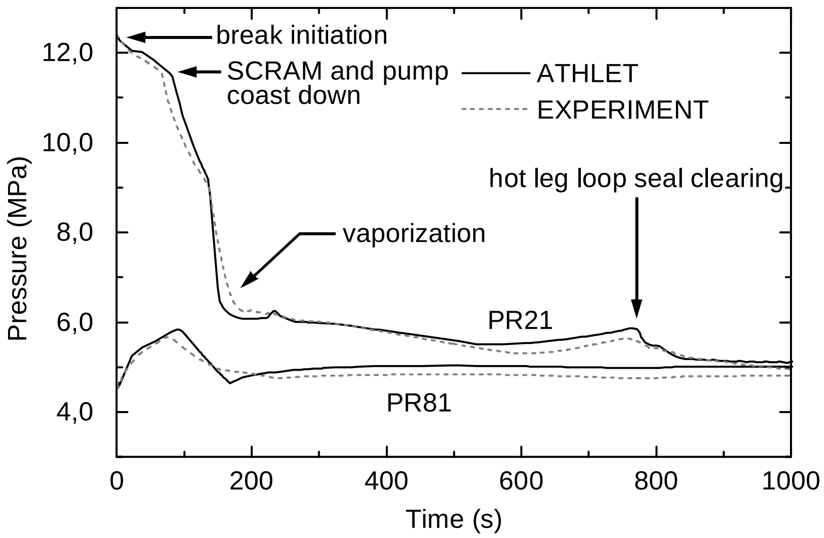

Fig. 3: Primary (PR21) and secondary pressure (PR81)

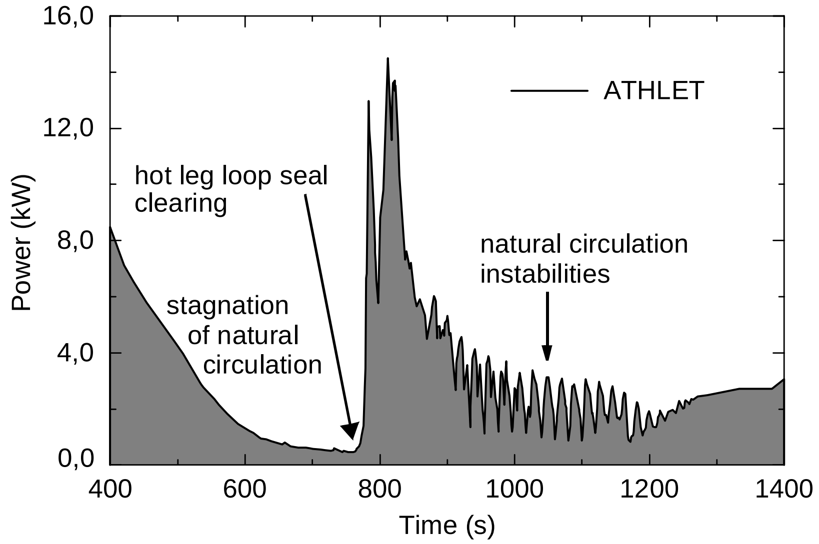

Fig. 4: Steam generator power during the hot leg loop seal clearing

At t=760 s the level in the inclined part of the hot leg reaches a minimum. The steam generated in the core enters the SG hot collector and the loop seal clearing takes place. From 760 s to 1250 s both calculation and experiment show oscillations with a period of appr. 20 s (Fig. 5). The results of the calculation show that this kind of natural circulation instabilities are caused by vaporization and condensation effects in the hot leg loop seal, reactor model and SG inlet. As a consequence of condensation in the SG inlet the primary pressure decreases. The steam flow from the reactor to the SG leads to an increase of the mass flow (FL53) and also the reactor level increases. The rise of the reactor level leads to a reduced void fraction at the reactor outlet and as a result there is less condensation in the SG. The phase-shift between void fraction at reactor outlet (LV21) and SG inlet (LV41) amounts to 180 degrees. When the primary pressure reaches a local minimum, for a short period the mass flow rate is negative. The calculation shows that there is a fluid mass flow directed from the SG inlet to the hot leg. This fluid mass flow and the rising water level in the reactor leads to a refilling of the hot leg loop seal from both ends. Once more the primary pressure increases and the described process is repeated periodically.

Afterwards the reactor level decreases, steam from the hot leg enters the SG cold collector and the level in the SG cold collector starts to drop. The level decrease in both reactor model (LE11) and cold leg (LE51) is accompanied by oscillations (Fig. 6). The oscillations are initiated by the decreasing cold leg mass flow with a flow reversal in the lower plenum and the downcomer. That means, there is a mass flow from the reactor and also from the SG cold collector towards the break. The phase-shift between both mass flows amounts to 180 degrees and the resulting mass flow leads to periodical changes in the break flow. An increasing break flow leads to a faster decrease of the levels (LE11 and LE51) and vice versa.

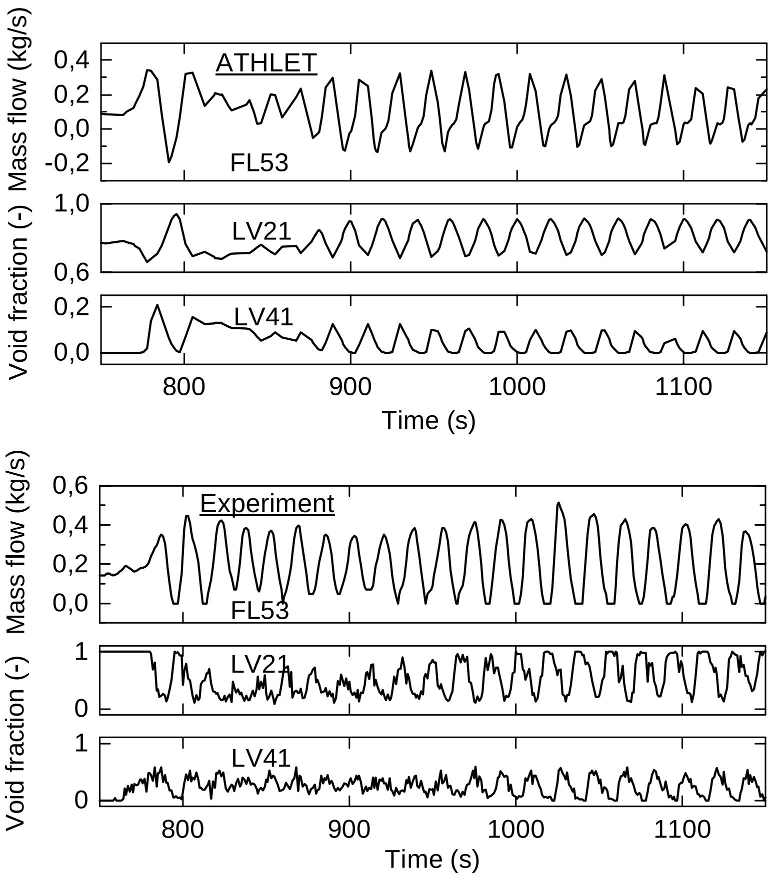

Fig. 5: Instabilities during the hot leg loop seal clearing in measured and calculated mass flow and void fraction

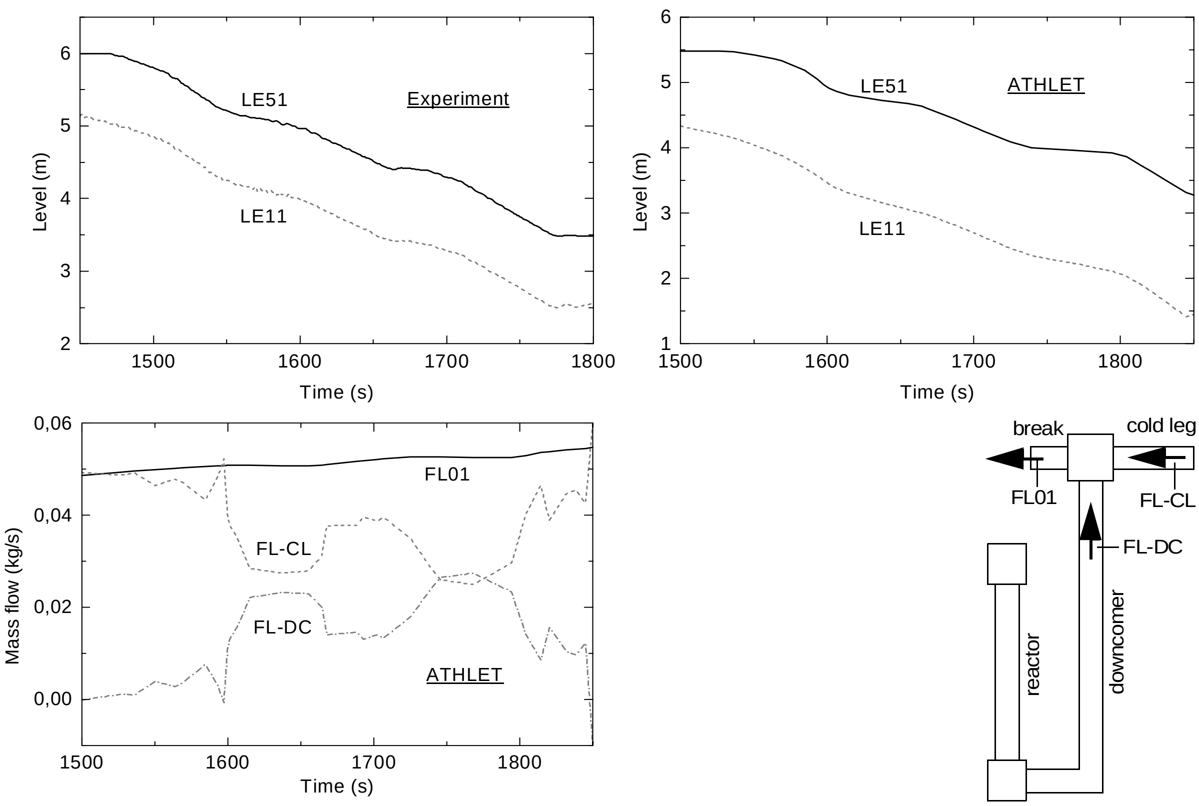

Fig. 6: Natural circulation instabilities in the reactor model and in the cold leg before the cold leg loop seal clearing starts

4.2 Cold leg break with primary bleed

In general the course of events corresponds to the cold leg break experiment. Additionally an accident management measure is realized by manual opening of the pressurizer safety valve at t=643 s. The aim of this accident management measure is to prevent a dry out in the core. Due to the additional depressurization the primary pressure decreases faster and the natural circulation instabilities during the hot leg loop seal clearing lasts only from t=750 s to t=950 s (Fig. 7).

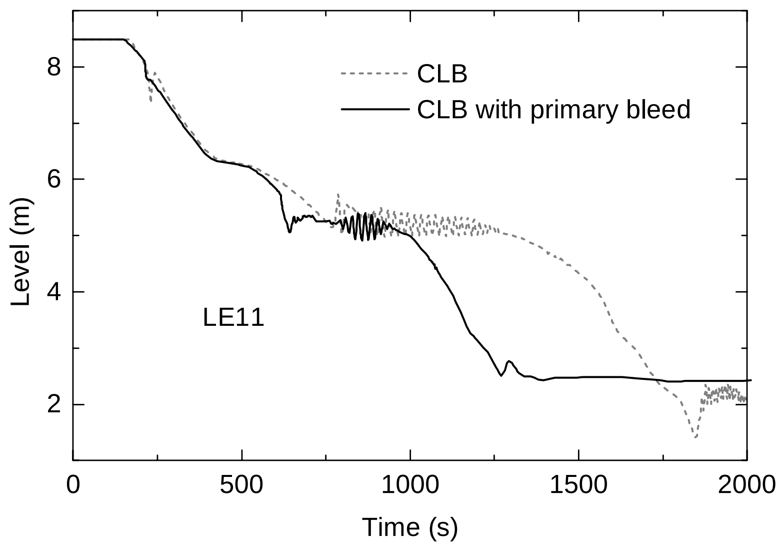

Fig. 7: Instabilities in the reactor level (cold leg break and cold leg break with primary bleed) - ATHLET

4.3 Surge line break

The SLB experiment starts with initiation of the break valve at t=0 s. Simultaneously the SG is isolated by closing the feed water line and the steam line. The break is located in the hot leg at the connection between hot leg and surge line. In the experiment the high pressure injection system (FL-HPIS) and the hydroaccumulators (FL91/92) are activated. The whole transient lasts about 1265 s. Due to a fault in the experimental scenario, a certain amount of nitrogen was injected from the accumulator connected with the upper part of the downcomer.

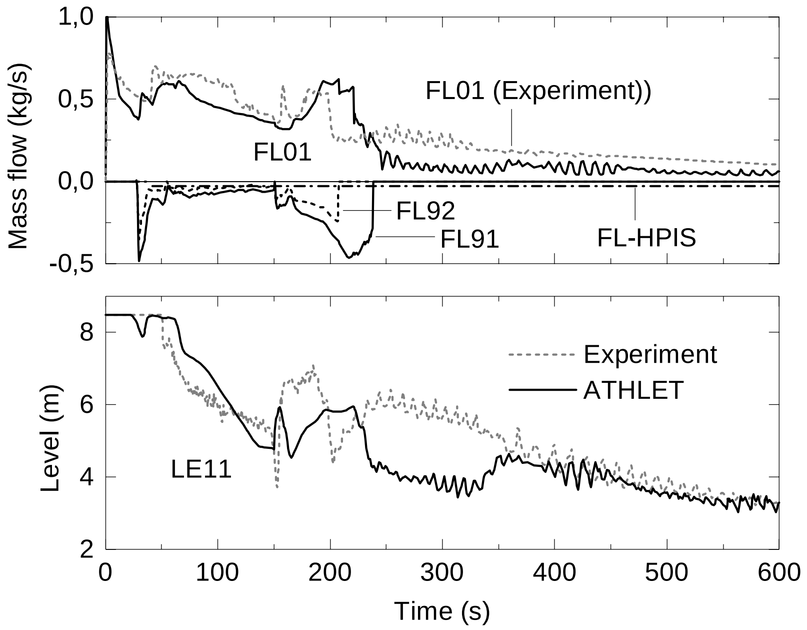

Fig. 8: Instabilities in reactor level (LE11) and break flow (FL01) and the injected mass flows from the emergency core cooling systems (FL-HPIS, FL91, FL92)

Due to the break the pressure decreases very fast in the early phase of the experiment. Already at t=1 s the reactor scram and the high pressure injection system are initiated and at t=3 s the pump coast down starts. The coolant vaporizes at first in the hot leg loop seal and immediately afterwards in the reactor and SG inlet. At t=25 s the primary pressure reaches the setpoint of hydroaccumulator injection. Therefore the vaporization in the hot leg is temporarily stopped. Due to boiling in the core the pressure decrease stagnates and the injection from the hydroaccumulators is reduced (FL91/92, Fig. 8). In this period the injected water in the upper plenum flows only towards the hot leg and the break mass flow (FL01) increases. The effect of countercurrent flow limitation in the upper plenum lasts up to 160 s. The injection from the hydroaccumulators is stopped at t=205 s (upper plenum, FL92) and t=235 s (downcomer, FL91). At the end of the hydroaccumulator injection (FL91) nitrogen is injected into the upper part of the downcomer. The effect of this nitrogen bubble can be seen in the reactor level. In the experiment LE11 rises again. In the ATHLET calculation the nitrogen injection was not calculated and so the reactor level further decreases (Fig. 8). If the hydroaccumulator injection has stopped the coolant in the hot leg vaporizes again and the SG primary side is filled with steam.

Two kinds of natural circulation instabilities can be observed in the further course of the transient. At t=200 s instabilities in the hot leg loop seal occur with a period of approximately 10 s. These oscillations are caused by periodical changes in the break flow (FL01). At the break position a transition regime between water, two-phase and steam flow can be observed, which is coupled with periodical changes in the reactor level. At t=350 s the void fraction at reactor outlet reaches 100 % and the instabilities in the hot leg are stopped. The unstable behaviour in this period is correctly modelled by the ATHLET calculation (Fig. 8).

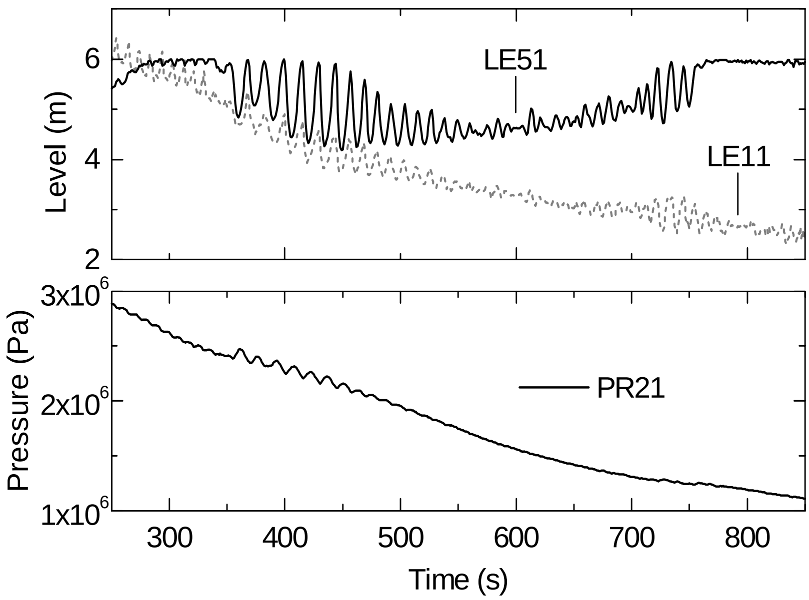

Fig. 9: Instabilities in the cold leg (LE51), reactor level (LE11) and primary pressure (PR21) - Experiment

At t=350 s the primary loop changes again to an unstable state (Fig. 9). Due to vaporization in the cold leg, two-phase mixture is pushed into the SG cold collector. In this period the primary pressure is lower than the secondary pressure. As a result the two phase mixture in the SG cold collector will be vaporized and the cold collector level drops down. Due to vaporization in the cold leg the mixture level in the SG cold collector rises again and the process is repeated periodically with a period of 15 s. The calculation fails to predict this kind of instabilities. Possibly a reason for these deviation is the influence of the injected nitrogen.

4.4 Calculations for a VVER-440 reactor

In case of the cold leg break experiment the transferability of the experimental results was examined for the original reactor plant. Therefore ATHLET calculations were carried out with a VVER-440 data set adapted to the experimental scenario.

As the comparison between experimental data and calculations for the experiment and original plant shows, all the important thermal-hydraulic phenomena were correctly modelled by ATHLET for the VVER-440 reactor. The processes connected with the hot leg loop seal clearing, particularly the natural circulation instabilities, can be also observed in the calculation for the original plant, see Fig. 10.

The longer period of the instabilities in the VVER-440 calculation is a result of the lower steam mass flow in the hot leg, compared to the scaled value of the test facility. The lower steam mass flow is caused by a lower evaporation rate in the reactor core due to a greater subcooling at the reactor inlet.

Conlusions

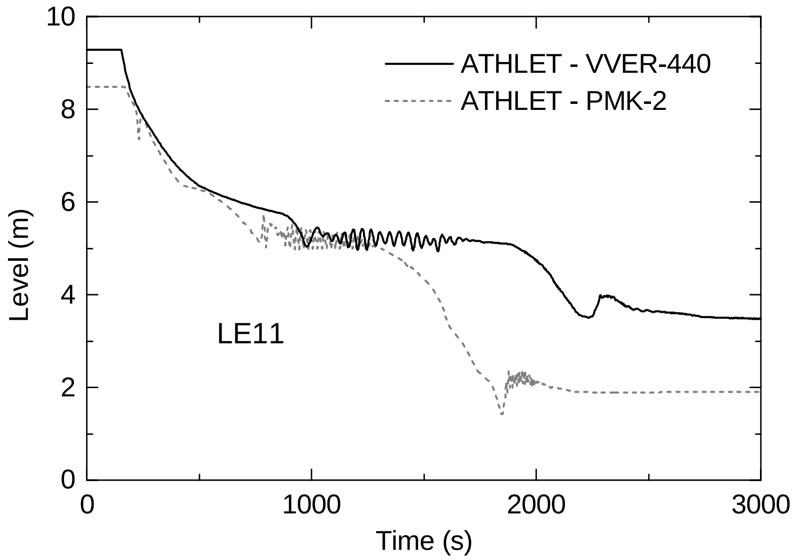

Fig. 10: Instabilities in the reactor level (ATHLET calculation for PMK-2 and VVER-440 reactor)

With the help of the presented calculations it could be shown, that ATHLET is able to calculate the accident behaviour in a good agreement with the experimental data. All significant phenomena, such as hot and cold leg loop seal clearing, stagnation of the natural circulation, phase and mass separation along the facility and especially the natural circulation instabilities are calculated very well. In some cases the ATHLET calculation provide the more detailed information required to clarify the complex processes connected with the different kinds of instabilities. The calculations for a VVER-440 reactor show that the instabilities can also appear in a real plant.

References

[1] Description of the PMK-NVH Facility
KFKI Atomic Energy Research Institute Budapest, 1990

[2] L. Perneczky, G. Ézsöl, L. Szabados:
1% Cold Leg SBLOCA Analysis on PMK-NVH Facility
Central Research Institute for Physics, Budapest, 1990

[3] Gy. Ézsöl, A. Guba, L. Perneczky, H.-M. Prasser, F. Schäfer, E. Krepper:
1% Cold leg break experiment on PMK-2 - Test results and computer code analysis
Forschungszentrum Rossendorf e.V., Report FZR-76, March 1995

[4] Gy. Ézsöl, A. Guba, H.-M. Prasser, F. Schäfer:
Small Cold Leg Break Experiment on PMK-2
Annual Meeting on Nuclear Technology, Nürnberg 16.-18. Mai 1995, Proceedings. P.119-122

[5] Gy. Ézsöl, A. Guba, L. Perneczky, E. Krepper, H.-M. Prasser, F. Schäfer:
Simulation of a Small Cold Leg Break Experiment at the PMK-2 Test Facility Using the RELAP5 and ATHLET Codes.
Nuclear Technology, Vol.118, May 1997