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Analysis, by Relap5 code, of Boron Dilution Phenomena in a Small Break Loca Transient, performed in PKL III E 2.2 Test

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ABSTRACT

The present work is finalized to investigate the E2.2 thermal-hydraulics transient of the PKL III facility, which is a scaled reproduction of a typical German PWR, operated by FRAMATOME-ANP in Erlangen, Germany, within the framework of an international cooperation (OECD\SETH project). The main purpose of the project is to study boron dilution events in Pressurized Water Reactors and to contribute to the assessment of thermal-hydraulic system codes like Relap5.

The experimental test PKL III E2.2 investigates the behavior of a typical PWR after a Small Break Loss Of Coolant Accident (SB-LOCA) in a cold leg and an immediate injection of borated water in two cold legs. The main purpose of this work is to simulate the PKL III test facility and particularly its experimental transient by Relap5 system code. The adopted nodalization, already available at Department of Nuclear Engineering (DIN), has been reviewed and applied with an accurate analysis of the experimental test parameters. The main result relies in a good agreement of calculated data with experimental measures for a number of main important variables.

1 INTRODUCTION

Several organizations (EURATOM, FRAMATOME, OECD) are interested in boron dilution events in Pressurized Water Reactor (PWR) in the context of reactor safety research.

During some typical accidents, unborated or low-borated water slugs could enter the core region leading to local criticality and power excursion. In last years, the interest has been focused on the accumulation of low-borated water consequently to a refilling after reflux condenser conditions following a Small Break-Loss Of Coolant Accident (SB-LOCA) in the primary system of a PWR.

In order to investigate these phenomena, Organization for Economic Co-operation and Development (OECD) set up a project, named SETH (SESAR Thermal Hydraulics), with the main purpose of simulate the boron dilution events in the PKL test facility.

PKL facilty [1], operating in Erlangen, Germany, is a scaled model of Philippsburg 2 nuclear power plant, a 1300 MW PWR of KWU. The facility models the entire primary system and the main parts of secondary system. All the elevation are scaled 1:1, volumes, power and mass flows are scaled 1:145. Core power is supplied by 314 electrically heated rods for a maximum power of 2.5 MW.

In this work attention is focused on the PKL III E2.2 test which simulates a break in a cold leg with a contextual high pressure injection in two cold legs and a secondary system cooling rate of 100 K/h. The transient has been analyzed exploiting the experimental data provided by FRAMATOME ANP and the system code RELAP5/mod 3.3 [2].

The results of the test simulated by RELAP5 are compared with the experimental ones and represent an element for the code assestment.

2 PKL III FACILITY AND E2.2 TEST

2.1 PKL III Facility

PKL III test facility, represented in figure 1, models the essential parts of a PWR. The most important components are:

- Reactor Pressure Vessel (RPV);
- 4 loops, each endowed with a circulation pump (RCP);
- 4 steam generators;
- 1 pressurizer;
- 1 external downcomer, constituted by an anular downcomer, coaxial with the upper plenum, and two downcomer tubes which connect the anular downcomer to the lower plenum.

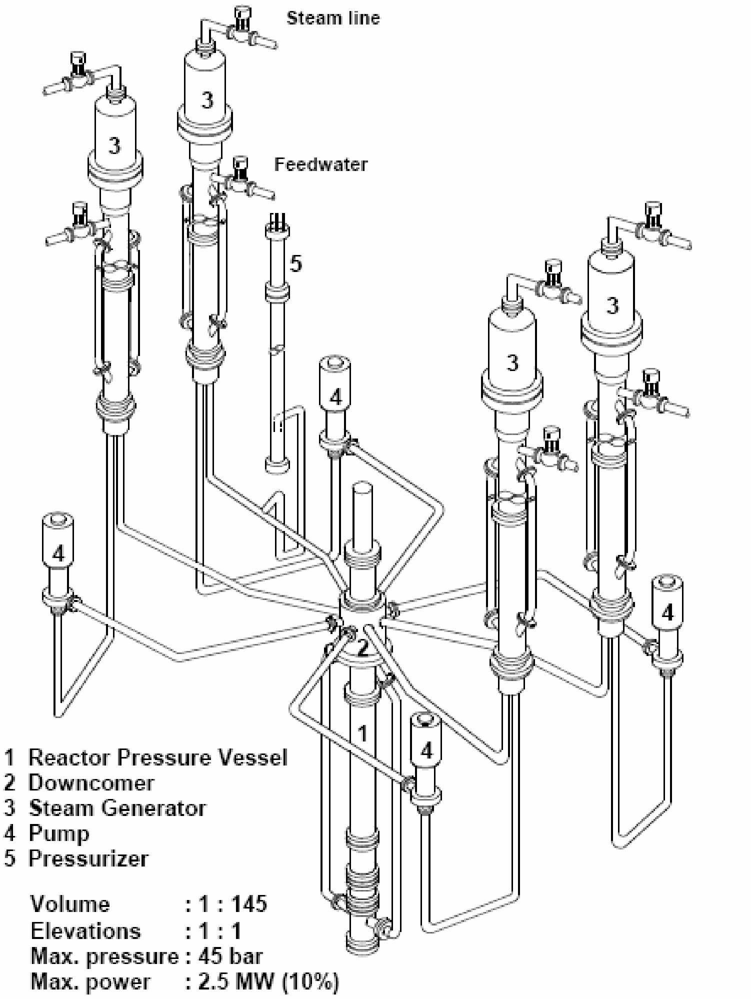

Figure 1: PKL III Test Facility

2.2 The test E2.2

The test E2.2 [3,4], performed in december 2002 in Erlangen, simulates a SB-LOCA with the following main boundary conditions:

- break (32 cm^2/145) in the cold leg of loop 1, between RCP and RPV;
- all 4 steam generators running down at a cooling rate of 100 K/h;
- active High Pressure Injection Systems (HPIS) in loop 1 and 2;
- active Low Pressure Injection Systems (LPIS) in loop 1 and 2 when pressure in Reactor Coolant System (RCS) drops below 10 bar for the first time.

The test initial conditions are established in two phases: a pre-conditioning phase and a conditioning phase. The first one is performed to reach a steady state condition before the conditioning phase.

At the end of the pre-conditioning phase (subcooled natural circulation):

- the primary system is completely filled with 2300 kg of water with a homogenous boron concentration of 1000 ppm;
- the heater rods supply a constant power of 530 kW;
- pressure in RCS is about 42 bar and the core outlet temperature is 250 °C (3°C of subcooling);
- heat is removed by natural circulation in all 4 loops;
- main steam pressure is about 28 bar.

The conditioning phase initiates 6450 s before test start (t=0) by insulating the main steam line with the purpose of increasing the pressure in secondary side to reduce the primary to secondary temperature difference. This induces saturated conditions at core outlet and consequently an increasing pressure in RCS. When the RCS pressure reaches 44 bar (t=-5270 s), the break in cold leg 1 is opened and the pressure difference between primary and secondary falls down to 1-2 bar. The level in RPV drops rapidly reaching the Reactor Coolant Line (RCL), while U-tubes of the Steam Generators (SGs) and pressurizer completely empty.

At t=-4430 the main steam line is opened again so the primary pressure reaches about 40 bar. The pressure of secondary system is controlled at about 39.4 bar in order to decrease the natural circulation in RCS.

When the coolant inventory is about 1170 kg (t=-3950 s), the break is closed and the primary system remains in reflux-condenser conditions for 3240 s. At the end of this phase, 200 kg of condensate are formed per loop and low-borated water is accumulated in loop seals. At t=-710 s a high pressure injection in cold legs 1 and 2 begins at a reduced flow rate in order to avoid rapid condensation which could cause high mass flows in RCS, and therefore mixing processes between low-borated and high-borated water. At the end of this phase, the mass inventory is about 1440 kg.

At t=0 the test starts with the opening of the break in cold leg 1, the injection by HPIS in cold legs 1 and 2 of a flow rate of about 1 kg/s and the cooldown of the SGs at 100 K/h. At start time, the facility is in those conditions experienced by a PWR after about half an hour from the onset of a SB-LOCA accident.

At the beginning, the mass flow which goes out through the break is greater than the mass flow injected by HPIS. The coolant inventory has a minimum at about 1200 s, than return to increase owing to a decreasing RCS pressure and an increasing flow rate injected.

When RCS pressure drops below 10 bar, LPIS is activated in cold leg 1 and 2, it is switched off again when the same pressure rise again above 10 bar.

At t=5980 s the HPIS is switched off and the test is considered ended at t=8430 s, when the RCS and the secondary side pressures are about equal to external pressure.

3 PKL MODEL

The PKL III test facility has been nodalized at the DIN to obtain a finite-volume model to be used in input for the RELAP5 analysis. The nodalization of RPV is shown in figure 2, while the ones of loop 2, pressurizer and secondary system are represented in figure 3.

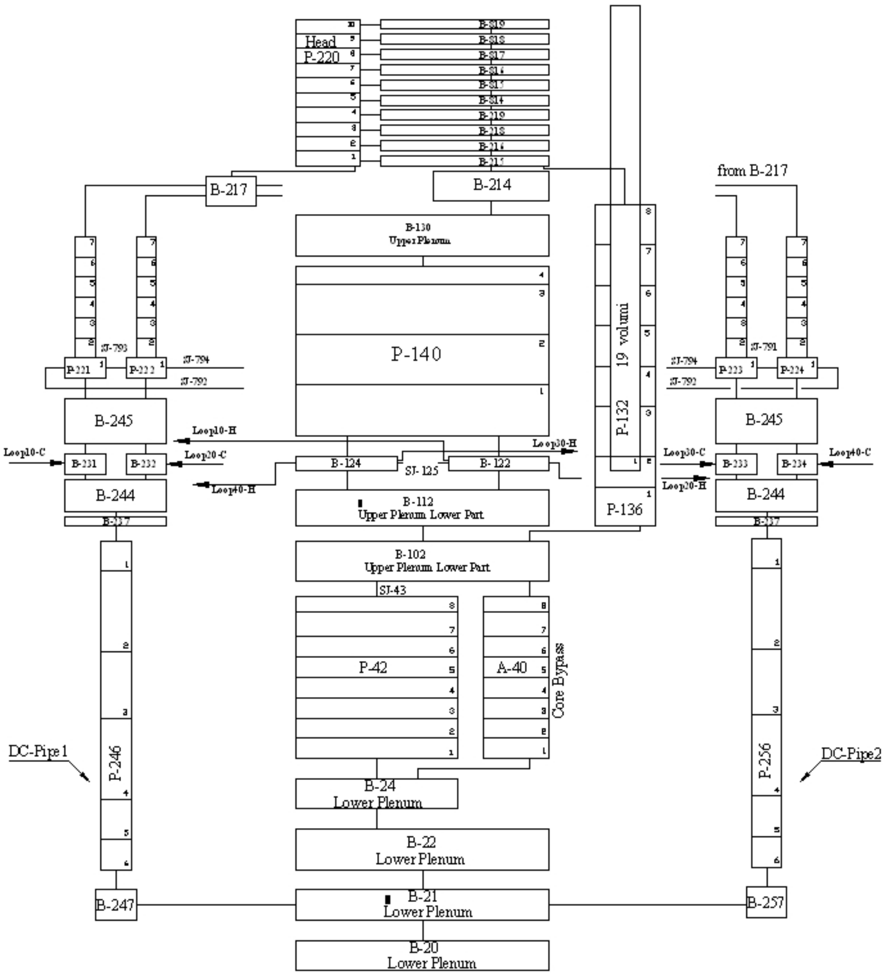

Figure 2: RELAP5 noding diagram of PKL III vessel

The RPV is modeled by 49 volumes, eventually divided in sub-volumes. The core region is modeled with a pipe and an annulus which simulates the anular gap. The anular downcomer is modeled by 7 volumes. The coolant flowing through the 4 cold legs is distributed to 4 different volumes, it is then mixed into a single volume and re-separated in the 2 downcomer pipes.

The U-tubes in SGs are 28 for each loop in the facility and they have 7 different elevations. They are modeled in input with 3 tubes having 3 different heights respecting elevations vs volumes and the real heat-exchange surface.

This simulation shows that RELAP5 has serious difficulties when drawn equal and parallel components. Cause numerical instability, in some conditions, two equal pipes with the same start volume and the same end volume have different behavior.

In order to reproduce accurately the test facility a check of volumes vs elevations, thermal losses, masses and pressure losses was performed. The volume of each hydraulic component was related with its elevation and the result was compared to the corresponding experimental data (figure 4) [5,6,7]. The thermal losses were calculated by code at steady state and they have been compared with experimental data in the same boundary conditions. The results of this comparison show that the input realistically models the test facility.

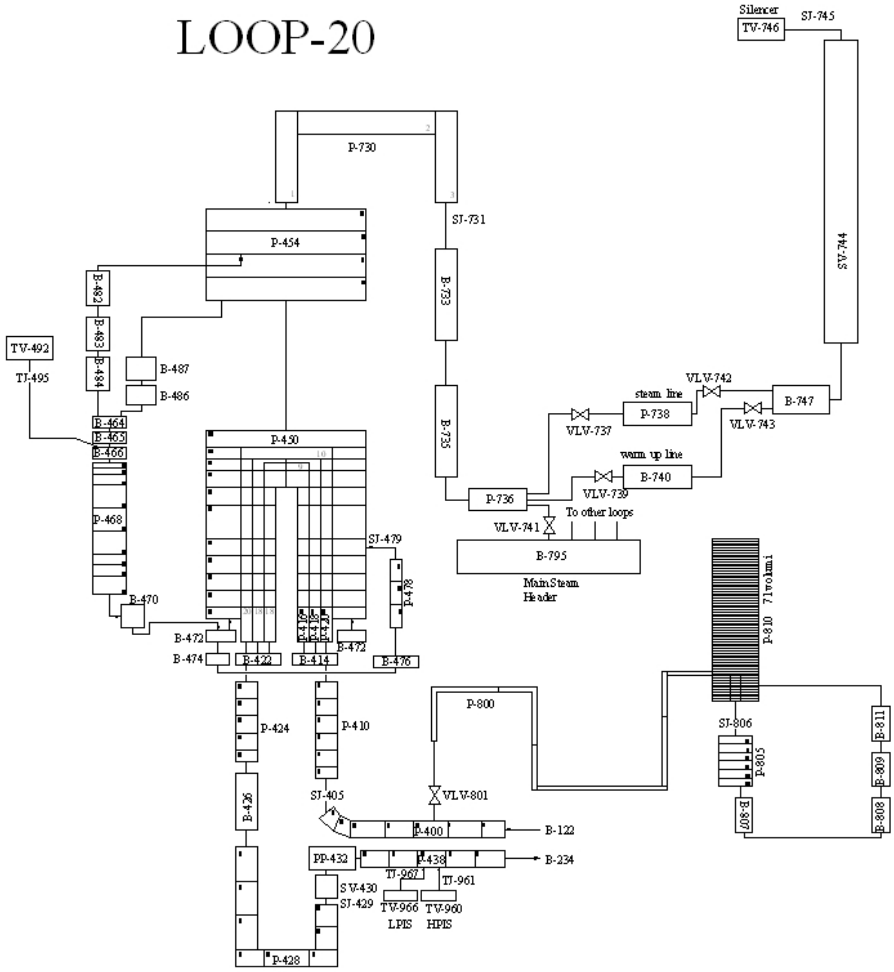

Figure 3: RELAP5 noding diagram of PKL III loop 2, pressurizer and secondary system

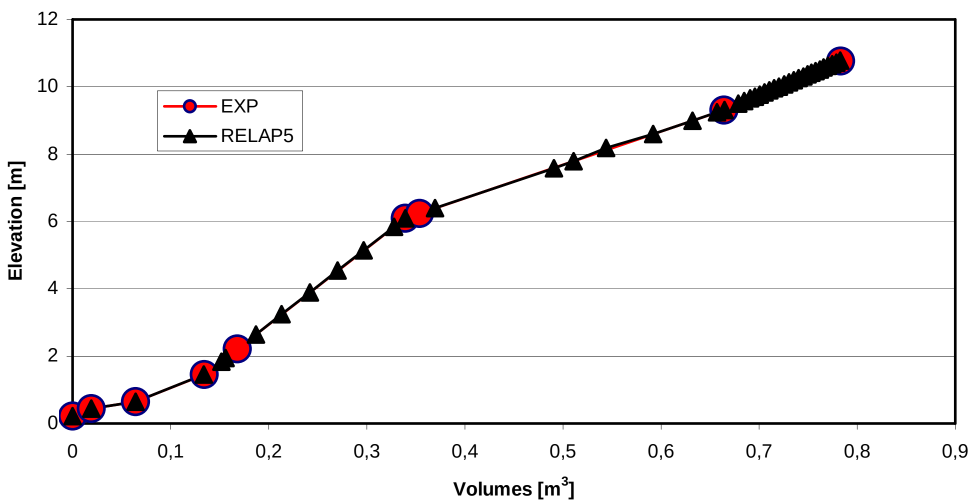

Figure 4: Comparison between experimental and adopted values for the elevations vs volumes distribution in PKL III rod bundle vessel

4 RELAP5 THERMAL-HYDRAULIC ANALYSIS

The boundary conditions for the test PKL III E2.2 were set in the input. The steady state has lasted for 10000 s and all the initial conditions for the start of the conditioning phase were encountered with sufficient accuracy.

At t=-6450 s the main steam line is closed so the secondary system pressure rise to 39.4 bar and the primary system pressure slowly increases its value up to 44 bar. It happens 5270 s before the test start, like as the experimental test. The secondary pressure is controlled at 39.4 bar by a system of logical trips up to the start of the test.

This phase stops when the coolant inventory reaches the value of 1170 kg. It happens, in accordance with the experimental test, about 3950 s before the start of the test. Also the pressurizer level respects the behavior shown in the experimental test during the conditioning phase.

710 s before the start of the test, the trip which controls the HPIS is activated, a flow rate of 0.4 kg/s enters the system and the steam in cold legs condensates more rapidly than in the experimental case.

At t=0 the test starts: the break is opened and the coolant flows through the break without critical flow phenomena even if the Henry-Fauske model has been foreseen at this junction. Friction caused by the break dominates the mass flow exiting from the system. At about the same time starts the heater rod power reduction, the cooldown of the SGs and the high pressure injection at the flow rate of about 1 kg/s. Since this time, the pressure of the secondary system follows the saturation pressure driven by cooldown.

In Table 1 a comparison is represented between some of the main claculated results and experimental measures at the start of the test.

The mass inventory has the same behavior as shown in the experimental case, reaching the minimum value (about 1250 kg) about 1200 s after the start of the test and the maximum value (about 2880 kg) when the HPIS is switched off.

Table 1: Comparison between calculated and experimental data at the start of the test

	Experimental	Relap5	Error %
Coolant inventory, kg	1440	1441	0.07
Boron concentration in the loop seal, ppm	<50	50-60	
Heater rods power, kW	530	530	0
Primary pressure, bar	40.5	40.53	0.07
Core outlet temperature, °C	251	251.6	0.2
Pressurizer fluid temperature, °C	251	251	0
Pressurizer level, m	1.1	1.06	3,6
Blowdown at break, kg/s	1.1	1.1	0
Main steam pressure, bar	39.4	39.8	1
Main steam temperature, °C	249	249	0
Collapsed level in SGs, m	12.2	12.25	0.4
Feedwater temperature, °C	110-120	110	

The primary system pressure goes down to the value of 10 bar with the same path than in the experimental transient. When this time comes, the trip that controls the LPIS is activated so the pressure rises again reaching a maximum value of 24.5 bar, slightly higher than in experimental data. A sensitivity analysis shows that this discrepancy is probably due to some spurious condensation processes foreseen by the code during the primary system pressure rise, approximately 3500 s after the start of the test, as well as to the approximation in the HPIS mass flow rate-pressure law dependence. For the same reason, the pressurizer level, during this phase, reaches a value greater than in experimental case.

The minimum value of boron concentration is about 500 ppm and is measured at RPV inlet in cold leg 3 after the start of the natural circulation. In the RELAP5 analysis it is reached in the same loop and conditions but its value is about 700 ppm.

At t=5980 s after start of the test the trip which controls the HPIS is switched off so the primary pressure goes down to the external value due to the draining of the system.

In figures 5-6 the graphs of the primary pressure and of the pressurizer level are shown [8].

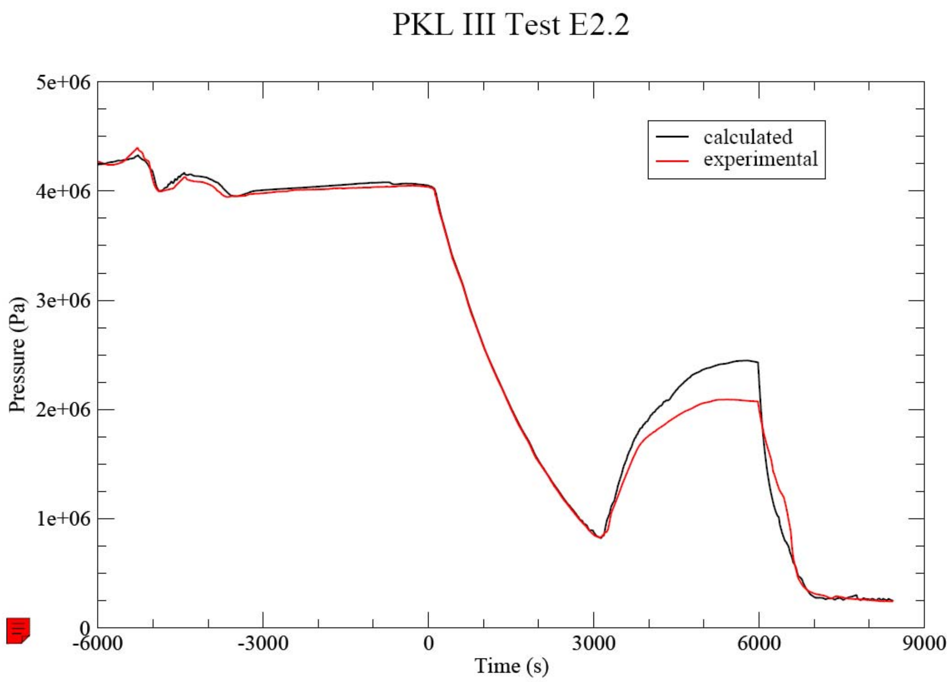

Figure 5: E2.2 experiment and analysis results for pressurizer pressure

CONCLUSIONS

The simulation results show a good agreement with the experimental data for a number of main important variables as the primary system pressure, the level in RPV, pressurizer and SGs and the value of mass flow in core.

The steady state and the conditioning phases are reproduced with a satisfying accuracy and their simulation gives pretty much the same initial conditions than in the experimental test.

More accurate studies of condensation processes in this transient could improve the simulation results during the phase in which the pressure rises rapidly, after the LPIS intervention.

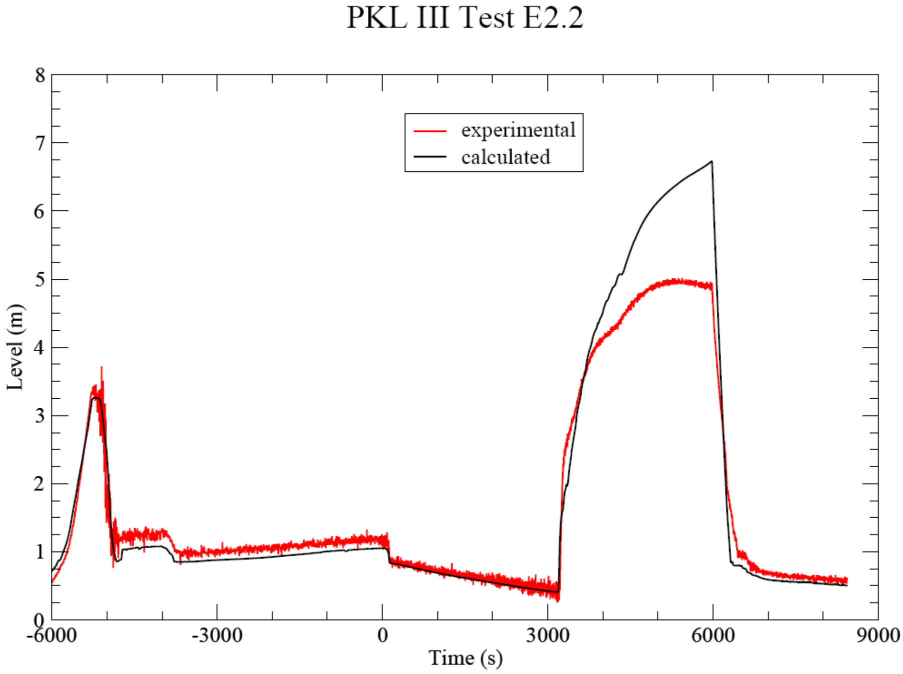

Figure 6: E2.2 experiment and analysis results for pressurizer collapsed level

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