NUREG/IA-0530

International Agreement Report

Analysis with TRACE Code of PKL III Tests G1.1 & G1.1a. Study on Heat Transfer Mechanisms in the SG in Presence of Nitrogen, Steam and Water as a Function of the Primary Coolant Inventory in Single Loop Operation

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ABSTRACT

The goal of this report is to explain the main results obtained in the simulations performed with the consolidated thermal-hydraulic code TRACE regarding tests PKL III G1.1 and G1.1a. The G1 test series focused on the occurrence of boron dilution processes following the loss of Residual Heat Removal System (RHRS) during ¾-loop operation (primary circuit still closed). Main objective was to provide a data basis for thermal-hydraulics codes for a better understanding of the heat transfer mechanisms in the Steam Generator in presence of Nitrogen, steam and water in the U-tubes and of the coolant transport phenomena observed inside the U-tubes. The main goal of this report is to analyse the capacity of TRACE V5.0p2 code to precisely simulate thermal stratification and natural circulation of both single and biphasic fluxes inside the whole primary circuit.

FOREWORD

Thermalhydraulic studies play a key role in nuclear safety. Important areas where the significance and relevance of TH knowledge, databases, methods and tools maintain an essential prominence, are among others:

- assessment of plant modifications (e.g., Technical Specifications, power uprates, etc.);
- analysis of actual transients, incidents and/or start-up tests;
- development and verification of Emergency Operating Procedures;
- providing some elements for the Probabilistic Safety Assessments (e.g., success criteria and available time for manual actions, and sequence delineation) and its applications within the risk informed regulation framework;
- training personnel (e.g., full scope and engineering simulators); and/or
- assessment of new designs.

For that reason, the history of the involvement in Thermalhydraulics of CSN, nuclear Spanish Industry as well as Spanish universities, is long. It dates back to mid 80's when the first serious talks about Spain participation in LOFT-OCDE and ICAP Programs took place. Since then, CSN has paved a long way through several periods of CAMP programs, promoting coordinated joint efforts with Spanish organizations within different periods of associated national programs (i.e., CAMP-España).

From the CSN perspective, we have largely achieved the objectives. Models of our plants are in place, and an infrastructure of national TH experts, models, complementary tools, as well as an ample set of applications, have been created. The main task now is to maintain the expertise, to consolidate it and to update the experience. We at the CSN are aware on the need of maintaining key infrastructures and expertise, and see CAMP program as a good and well consolidated example of international collaborative action implementing recommendations on this issue.

Many experimental facilities have contributed to the today's availability of a large thermal-hydraulic database (both separated and integral effect tests). However there is a continuous need for additional experimental work and code development and verification, in areas where no emphasis have been made along the past. On the basis of the SESAR/FAP[1] reports "*Nuclear Safety Research in OECD Countries: Major Facilities and Programmes at Risk" (SESAR/FAP, 2001)* and its 2007 updated version "*Support Facilities for Existing and Advanced Reactors (SFEAR) NEA/CSNI/R(2007)6"*, CSNI is promoting since the beginning of this century several collaborative international actions in the area of experimental TH research. These reports presented some findings and recommendations to the CSNI, to sustain an adequate level of research, identifying a number of experimental facilities and programmes of potential interest for present or future international collaboration within the nuclear safety community during the coming decade. The different series of PKL, ROSA and ATLAS projects are under these premises.

CSN, as Spanish representative in CSNI, is involved in some of these research activities, helping in this international support of facilities and in the establishment of a large network of international collaborations. In the TH framework, most of these actions are either covering not

[1] SESAR/FAP is the *Senior Group of Experts on Nuclear Safety Research Facilities and Programmes* of NEA Committee on the Safety of Nuclear Installations (CSNI).

enough investigated safety issues and phenomena (e.g., boron dilution, low power and shutdown conditions, beyond design accidents), or enlarging code validation and qualification data bases incorporating new information (e.g., multi-dimensional aspects, non-condensable gas effects, passive components).

This NUREG/IA report is part of the Spanish contribution to CAMP focused on:

- Analysis, simulation and investigation of specific safety aspects of PKL/OECD ROSA/OECD and ATLAS/OECD experiments.
- Analysis of applicability and/or extension of the results and knowledge acquired in these projects to the safety, operation or availability of the Spanish nuclear power plants.

Both objectives are carried out by simulating the experiments and conducting the plant application with the last available versions of NRC TH codes (RELAP5 and/or TRACE).

On the whole, CSN is seeking to assure and to maintain the capability of the national groups with experience in the thermalhydraulics analysis of accidents in the Spanish nuclear power plants. Nuclear safety needs have not decreased as the nuclear share of the nation's grid is expected to be maintained if not increased during next years, with new plants in some countries, but also with older plants of higher power in most of the countries. This is the challenge that will require new ideas and a continued effort.

Rosario Velasco García, CSN Vice-president

Nuclear Safety Council (CSN) of Spain

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EXECUTIVE SUMMARY

This report presents the main results obtained with the NRC consolidated code TRACE for the simulation of OECD/NEA PKL-2 project test G1.1 and G1.1a conducted at the Primärkreislauf-Versuchsanlage (primary coolant loop test facility) PKL. This facility is owned and operated by AREVA NP and is located in Erlangen, Germany. The PKL-III G test program investigates safety issues relevant for current pressurized water reactor (PWR) plants as well as for new PWR design concepts, focusing on complex heat transfer mechanisms in the steam generators and boron precipitation processes under postulated accident situations. Specifically, the first test series G1 focused in systematically investigating the heat transfer mechanisms in the steam generators in the presence of nitrogen, steam and water, with two experiments being conducted: G1.1 (one loop configuration) and G1.2 (two loop configuration).

The PKL facility models the entire primary side and significant parts of the secondary side of a pressurized water reactor at a height scale of 1:1, with volumes, power ratings and mass flows being scaled with a ratio of 1:145. The experimental facility consists of four primary loops with circulation pumps and steam generators (SGs) arranged symmetrically around the reactor pressure vessel (RPV). The investigations carried out in this facility encompass a very broad spectrum, from accident scenario simulations with large, medium, and small breaks, over the investigation of shutdown procedures after a wide variety of accidents, to the systematic investigation of complex thermal-hydraulic phenomena, having been in operation since 1977.

The objective of this document is to compare code predictions with experimental data obtained during the PKL tests G1.1 and G1.1a in order to establish TRACE's capability to model heat transfers at atmospheric pressure in presence of nitrogen (modelled as air in the TRACE model, due to its similarity with pure nitrogen), water and steam in the U-tubes and the coolant transfer phenomena inside the U-tubes observed in previous tests, as well as assessing TRACE code precision. As a secondary objective, this report assesses TRACE capability to correctly predict boron concentration variations during several consecutive evaporations and condensations of primary coolant liquid.

During all tests, the pressurizer (PRZ) was permanently isolated from the primary circuit, thus not being part of the primary side volumes.

Prior to the transient phase start, a conditioning phase was conducted, in order to achieve the initial test conditions and the initial inventory status. The preliminary test phase started with a complete filling with subcooled water at a homogeneous boron concentration of 2000 ppm and ambient pressure. In which loop 1 was filled in tests G1.1 and G1.1a. Then proceeding with a slow drain of the primary inventory down to ¾-loop, approximately 1060 kg of residual inventory for G1.1 and G1.1a, coupled with a constant feed of N_2 to the primary circuit via the PRZ valve station, thus replacing the void volumes resulting from the drainage. After completing the decrease of primary coolant inventory, rod bundle power was decreased to 200 kW in order to simulate the decay heat in the core, accounting to 0.6% of full load thermal power, including compensation for heat losses. After fixing core thermal power, the system remains under this conditions enough time to reach the steady-state conditions. During this time, core power is removed from the system using the residual heat removal system (RHRS).

Start of test (SOT) begin with the shut-down of RHRS, it causes:
> Heat-up of core inventory.
> Start of steam formation in the core (approximately 10 min after shut-down of RHRS).

> Frothing of core inventory.

Both tests were started at steady state conditions at Start Of Test (SOT) with stationary conditions and ¾-loop with the RHRS engaged. Throughout the tests, the secondary pressure was controlled at 2 bars by the Main Steam Relief Valve (MSRV). Reduction and increase of inventory was accomplished via lower plenum drain line and injection lines into the lower section of the DownComer-pipes (DC-pipes). In this way, the additional coolant was injected into the subcooled fluid, not into steam volumes. Thereby, the steam condensation (and heat transfer in the U-tubes) was left undisturbed by draining/replenishment procedures.

ACKNOWLEDGMENTS

The thermal-hydraulic and nuclear engineering group of the UPV is indebted to the management board of the PKL III project and to the people of the Thermal-Hydraulics Safety Research Group.of AREVA. The authors are grateful to the CSN, who financed this study and help to develop this report. We also thank to the “Grupo de Análisis Dinámico de Sistemas Energéticos del Instituto de Técnicas Energéticas de la Universidad Politécnica de Cataluña”, who provided the TRACE model of the PKL III facility and many interesting suggestion on the improvement of the model.

ABBREVIATIONS AND ACRONYMS

B	Boron ([B]: boron concentration, ppm)
CCFL	CounterCurrent Flow Limitation
CI	Coolant Inventory
CL	Cold Leg
CM	Coolant Mass
COMBO	Continuous Measurement of Boron Concentration
CSN	Spanish Nuclear Regulatory Commission
CVCS	Chemical/Volume Control System
Δp	Pressure difference in bar, Pa
DC	Downcomer
DCT	Downcomer Tube/pipe
DCV	Downcomer Vessel
EOT	End Of Test
HL	Hot Leg
ITF	Integral Test Facility
LOCA	Loss of Coolant Accident
$\dot{m}$	Mass flow in kg/s
max	Maximum
MCP	Main Coolant Pump
min	Minimum
MS	Main Steam
MSRV	Main Steam Relief Valve
NC	Natural Circulation
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plants
OECD	Organization for Economic Cooperation and Development
p	Pressure in bar, Pa
PCI	Primary Coolant Inventory
P	Power in kW
PKL	Test facility, (German acronym for “Primärkreislauf”, means: primary circuit)
prim	Primary
PRZ	Pressurizer
PS	Pump Seal
PWR	Pressurized Water Reactor
ρ	Density in kg/m^3
RC	Reflux-Condenser
RCL	Reactor Coolant Line
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System
RPV	Reactor Pressure Vessel
sec	Secondary
SG	Steam Generator
SOT	Start Of Test
STP	Standard Temperature and Pressure conditions
t	Time in s
T	Temperature in °C, K
TRACE	TRAC-RELAP Advanced Computational Engine

UNESA	Asociación Española de la Industria Eléctrica
UPTF	Upper Plenum Test Facility

1 INTRODUCTION

The present study was performed as a contribution to the OCDE international collaborative research project PKL. The Spanish contribution was coordinated by the Spanish Nuclear Regulatory Commission (CSN) with the contribution of the Spanish Electricity Producers Association (UNESA). A consortium formed by the CSN, several Spanish Technical Universities and UNESA developed the Spanish participation in the project that was coordinated by the CSN and a steering committee.

The PKL facility is owned and operated by AREVA NP and is located in Erlangen, Germany. The analysis of the experiments PKL G1.1 and G1.1a with the TRACE code were assigned to the "thermal-hydraulics and nuclear engineering group" of the Polytechnic University of Valencia. The PKL tests have been performed in the Primärkreislauf-Versuchsanlage (primary coolant loop test facility) PKL. The TRACE code employed to perform the simulation was the Version 5.0p2 and the SNAP interface version the 2.0.4.

The Tests G1.1 and G1.1a consist of several stages. The test conditions and the initial inventory status were arranged in the course of the preliminary test phase. The test results and perceptions drawn from tests E3.1 and F2.2 were taken as a basis for the choice of the initial and boundary conditions employed in tests G1.1 and G1.1a.

The preliminary test phase started with a complete filling with subcooled water at a homogeneous boron concentration of 2000 ppm and ambient pressure (p_{prim}~1 bar) of the loop 1 for tests G1.1 and G1.1a. The slow drain of the primary inventory down to ¾-loop (approximately 1060 kg for tests G1.1 and G1.1a was attended by a constant feed of N_2 to the primary circuit via the PRZ valve station, thereby replacing the void volumes emerging from the drainage. The volume of N_2 fed to the primary circuit was approximately 0.6 m³ at STP for G1.1 and G1.1a.

After the decrease of the primary inventory, the rod bundle power was set to 200 kW (simulation of the decay heat in the core, resembling 0.6 % of full load thermal power, inclusive compensation for heat losses) and kept constant. Until start of test, the core power was removed from the primary circuit via the residual heat removal system engaged in loop 1.

The tests begin with the shut-down of the RHRS. This shut-down causes the heat-up of core inventory and consequently the start of steam formation in the core (approximately 10 minutes after shut-down of RHRS) and the frothing of core inventory.

In test G1.1, after a time to reach the steady state, a reduction of primary coolant inventory to establish a swell level in the SG inlet chamber below the tube sheet is done. This established a heat transfer mode in the U-tubes similar to Reflux-Condenser (RC) operation, with active and passive heat transfer zones. After that a gradual increase of the primary inventory after establishment of (quasi-) steady state conditions. Test G1.1a only that last gradual increase of inventory is carried out.

Heat transfer to the secondary side leads to a temperature and pressure increase on the secondary side. The secondary side of the active loop was kept constant at 2 bars pressure and 12.2 m fill level via MSRV and feedwater injection. Reduction and increase of inventory was accomplished via lower plenum drain line and injection lines into the lower section of the DC-pipes. In this way, additional coolant was injected into already subcooled fluid and not into steam volumes. Thereby, the steam condensation (and heat transfer in the U-tubes) was left undisturbed by draining/replenishment procedures.

The goal of this work is to compare the experimental results with the predictions of the TRACE code and to analyse the set of phenomena that take place at the primary and secondary sides of the Steam Generator (SG). Special emphasis is devoted to the analysis and comparison of the code results and the experimental data.

This study has been divided into four sections: section 1 is a general introduction, section 2 is a description of PKL facility, test series G.1.1 and G1.1a, and the applied boundary conditions, section 3 deals with the study of the transient sequence and the comparison of TRACE results for the main physical magnitudes versus the experimental data and section 4 is devoted to present the final conclusions.

2 INITIAL AND BOUNDARY CONDITIONS

2.1 Description of the PKL Facility

The integral test facility PKL (Figure 2-1), which is operated at the Technical Center of Framatome ANP, is a mock-up of a 1300MW class PWR (Kremin, Limprecht et al., 2001). It is used for research into the behavior of the thermal-hydraulic system under accident situations with and without loss of coolant. The test facility simulates the entire primary side with four loops and the essential parts of the secondary side. In view of the importance of gravity during accident situations, all elevations of the test facility correspond to actual reactor dimensions. The overall volume and power scaling factor is 1:145. In order to account for important phenomena in the hot legs such as flow separation and counter current flow limitation, the design of the hot leg bases on the conservation of the Froude number whereas also the results of the experiments in the 1:1 scaled UPTF were taken into consideration.

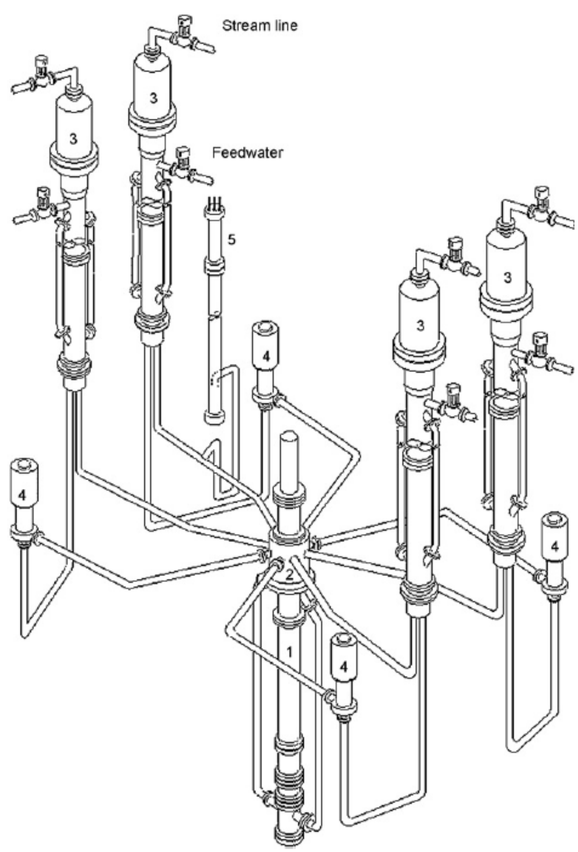

Figure 2-1 PKL Facility. (1) Reactor Pressure Vessel; (2) Downcomer; (3) Steam Generator; (4) Pump; (5) Pressurizer. Volume: 1:145; Elevations: 1:1; Max. Pressure: 45 Bars; Max. Power 2.5MW

The reactor core and the steam generators are simulated as a “section” from the actual system, in other words, full-scale rods and U-tubes are used. The number of rods and tubes has been scaled. The reactor pressure vessel has been modeled by scaling the cross sectional area preserving the full height of the core and the upper and lower plenum. The core is modeled by a bundle of 314 electrically heated rods with a total power of 2.5MW corresponding to 10% of the scaled nominal power. The reactor pressure vessel (RPV) downcomer is modeled as an annulus in the upper region and continues as two stand pipes connected to the lower plenum. This configuration provides symmetrical connection of the four cold legs to the RPV, reliable determination of flow rates, preservation of frictional pressure losses and does not unacceptably distort the volume/surface ratio. The symmetrical arrangement of the four loops around the RPV means that the requirement for identical piping lengths and hence recirculation period is fulfilled. This configuration enables the individual effects of multiple system failures to be studied as well as other events. Experiments on the behavior of a 3-loop (2-loop) plant can also be conducted by simply isolating one (two) loop(s).

Each of the primary-side loops contains active coolant pumps which are equipped with speed controllers to enable any pump characteristics to be simulated. The four fully scaled steam generators are equipped with prototype tubing (diameter, wall thickness, differing lengths) and tube sheet.

By preserving the frictional pressure losses in the steam generators and in the core region, the integral pressure loss for the entire primary system is also very similar to that of the actual plant. The maximum operating pressure of the PKL facility is 45 bars on the primary side and 60 bars on the secondary. This allows simulation over a wide temperature range.

PKL is also equipped with all relevant safety and operational systems on both the primary and secondary side. On the primary side the following are all simulated: four independent high- and low-pressure safety injection systems connected to both the hot and cold legs, the residual heat removal system, eight accumulators, the pressurizer pressure control system and the chemical and volume control system. On the secondary side, the feedwater system, the emergency feedwater system and the main steam lines, with all control features of the original systems are modeled. For the realistic simulation of secondary-side bleed-and-feed procedures, special care was taken to correctly model the feedwater lines and the feedwater tank with respect to the volume (1:145), the elevations (1:1) and the friction losses (1:1). All these features allow the simulation of a wide spectrum of accident scenarios involving the interaction between the primary and secondary side in combination with various safety and operational systems.

The facility is extensively instrumented with more than 1300 measuring points. Besides conventional measurements (temperature, pressure, etc.), two-phase flow measurements can also be made. In addition, for the test series PKL III E, F and the current series PKL III G, special devices for the detection of boron concentration were installed.

To summarize, the PKL facility is a full-height Integral Test Facility (ITF) that models the entire primary system (four loops) and most of the secondary system (except for turbine and condenser) of a 1300-MW PWR.

The facility includes:
- Reactor Coolant System (RCS)
- Steam Generators (SG’s)
- The interfacing systems on the primary and secondary side and the break.

The RCS includes:
- The upper head plenum, which is cylindrical, full-scale in height and 1:145 in volume.
- The upper plenum, full-scale in height and scaled down in volume.

- The upper head bypass, represented by four lines associated with the respective loops to enable detection of asymmetric flow phenomena in the RCS (e.g., single-loop operation).
- The reactor core model, consisting of 314 electrically heated fuel rods and 26 control rod guide thimbles. The maximum electrical power of the test bundle is 2512 kW.
- The reflector gap, located between the rod bundle vessel and the bundle wrapper (the barrel in the real plant).
- The lower plenum, containing the 314 extension tubes connected with the heated rods. The down-comer pipes are welded on the lower plenum bottom in diametrically opposite position. Two plates are located in this zone: the Fuel Assembly Bottom Fitting and the Flow Distribution Plate.
- The down-comer modeled as an annulus in the upper region and continues as two stand pipes connected to the lower plenum. This configuration, as already mentioned above, permits symmetrical connection of the 4 Cold Legs (CL) to the RPV, preserves the frictional pressure losses.
- The (four) hot legs, designed taking into account the relevance of an accurate simulation of the two phase flow phenomena, in particular CounterCurrent Flow Limitation (CCFL), in the hot leg piping as in the reactor.
- The (four) cold legs, connecting the SG to the Main Coolant Pump (MCP) through the loop seal and the MCP to the DownComer (DC) vessel. The hydrostatic elevations of the loop seals are 1:1 compared with the prototype NPP.
- The (four) MCP, which are vertical single-stage centrifugal pumps.
- The PRZ, full-height and connected through the surge line to the hot leg #2.
- The SG primary side, modeled with vertical U-tube bundle heat exchangers like in the prototype NPP. The scaling factor has been preserved by reducing the number of tubes (28 tubes with seven different lengths).
- The SG (secondary side) is constituted by the tube bundle zone, seal welded hollow fillers (below the shortest tubes), the DC (with the upper zone annular containing the FW ring, the central zone modeled by two tubes outside of the SG housing and the lower zone with annular shape) and the uppermost part of the SG that models the steam plenum.

2.2 Stationary Initial Test Conditions and Test Phase

2.2.1 Conditioning Phase

The SNAP interface version used to launch TRACE simulations was the 2.0.4 and the code employed to perform the simulations was the TRACE Version 5.0p2.
The TRACE 1-D model of the PKL III E2.2 test conditions (developed by “Grupo de Análisis Dinámico de Sistemas Energéticos del Instituto de Técnicas Energéticas de la Universidad Politécnica de Cataluña”) is the employed as a starting point. Therefore, first step is to deal with the evolution from E2.2 test conditions to the initial G1 test series conditions. Table 2-1 presents the main characteristics of tests E2.2 and G1.1-1.1a.

Table 2-1 E2.2 vs. G1.1 Test Conditions

Test	E2.2	G1.1-G1.1a
Primary Pressure (bar)	42	≈1
Secondary Pressure(bar)	28	≈1
Rod Bundle Power (kW)	530	≈200
Coolant Inventory (kg)	2250	1060
Boron Concentration (ppm)	1000	2000

As can be seen from Table 2-1, test conditions of E2.2 and G1.1 are quite different, so thoroughgoing work has been needed to reach the initial G1.1 and G1.1a test conditions. Besides, not only the previous differences shown in Table 2-1 were present: mass flow rates, temperatures, pressures, extraction and injection events, valves adjustment, control systems and many other elements have been modeled or modified. After having achieved the initial steady state, initial G1.1 and G1.1a test conditions, the pre-test phase is ended. Test phase can begin, this phase starts with the shut-down of the RHRS, this sudden lock of the RHRS produces a quick rise of core temperature. Figures 2-2 and 2-3 present the sudden rise of experimental temperature and the simulated with TRACE respectively, a big difference in the temperature evolution can be appreciated. Whereas the experimental temperatures of the whole core evolves with almost the same temperature passed a few time period, in the TRACE simulations each cell of the core evolves in a different way, i.e., thermal stratification continues. That is, as core elevation increases the temperature increases too, lower cells are colder than the higher ones. That phenomenology is produced by the own model design, one dimensional components are not able to reproduce mixing processes in natural circulation regime. With the aim of increase the mixing processes a collection of small by-passes (3% of the core average flow area) have been introduced among the different core cells and with the adjacent components. The simulation results to G1.1 test are shown in Figure 2-4. As can be appreciated a much better mix is achieved, then, after having reached a suitable mixing in the core, it is considered that an appropriate model is developed, so the whole test phases run is simulated for both test conditions.

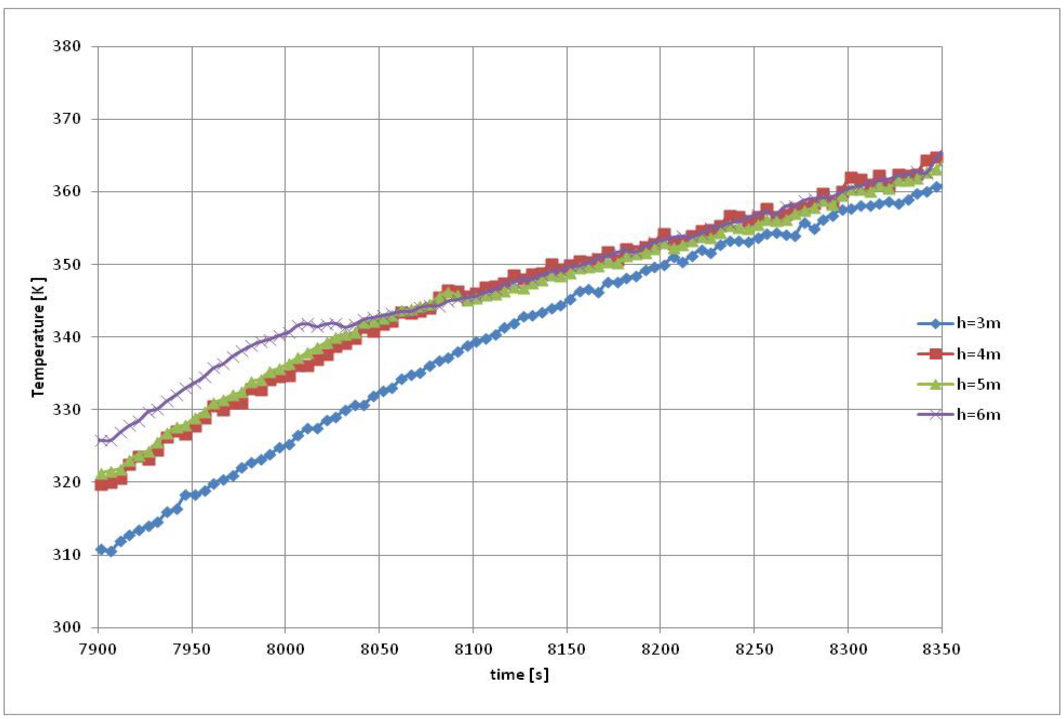

Figure 2-2 Test G1.1, Experimental PKL Core Temperature Evolution (MST 612, 574, 575 & 576 Respectively) from Shut-Down of RHRS to the First Extraction

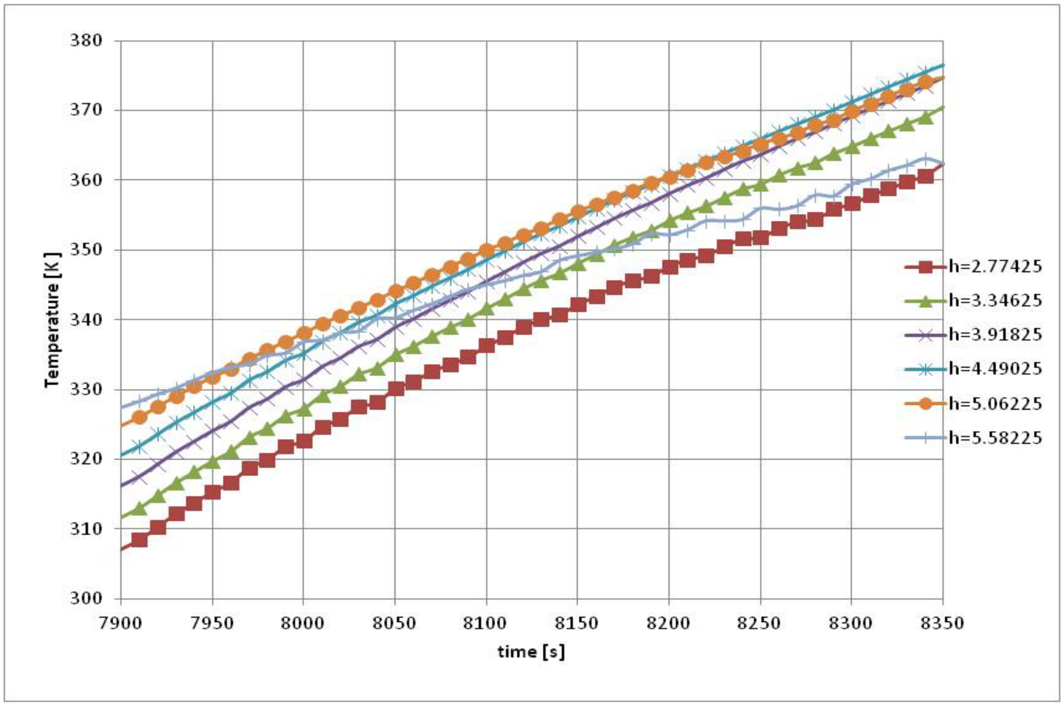

Figure 2-3 Test G1.1, TRACE Core Temperature Evolution (Pipe 120) from Shut-Down of RHRS to the First Inventory Extraction

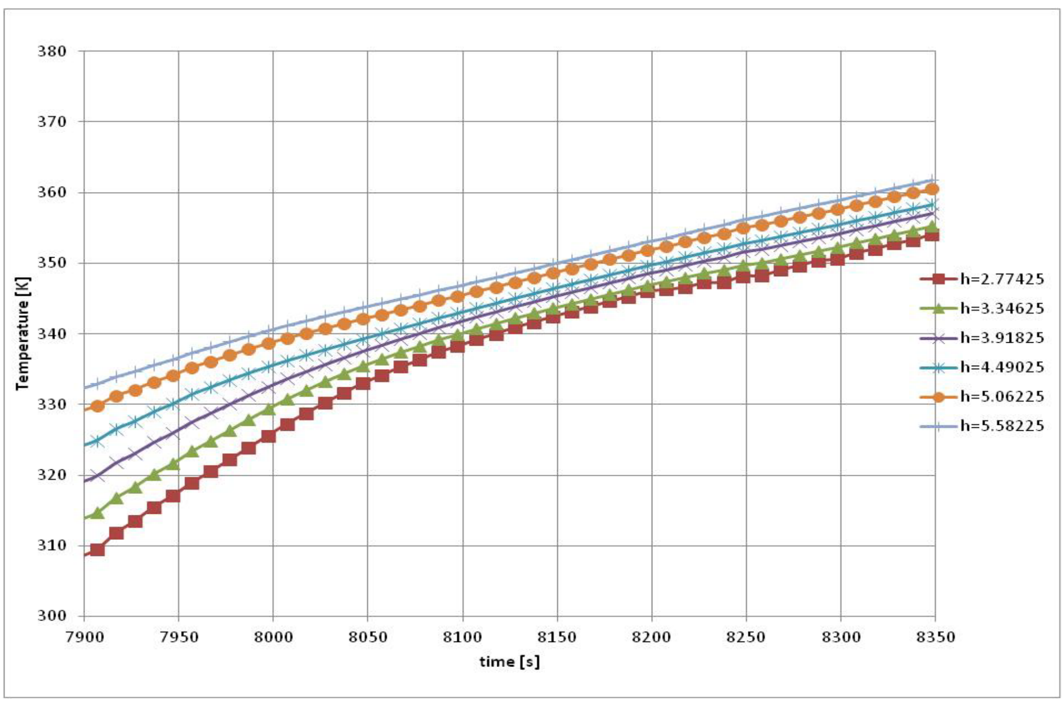

Figure 2-4 Test G1.1, TRACE Core Temperature Evolution (Pipe 120) from Shut-Down of RHRS to the First Inventory Extraction with By-Passes

2.2.2 Initial Test Conditions

The test conditions and the initial inventory status were arranged in the course of the above section, the conditioning phase. Two temporal scales are defined in the present tests, the general time scale which begins at the preliminary test phase and the after start of test scale (SOT) which selects as t = 0 the beginning of the test phase, in the hole document all figures are referred to the general time scale.

The test results and perceptions drawn from E3.1 and F2.2 were taken as a basis for the choice of the initial and boundary conditions employed in test G1.1. The preparative procedures listed hereafter have been almost similar in both test runs G1.1 and G1.1a.

The preliminary test phase started with a complete filling of the entire loop 1 with subcooled water at a homogeneous boron concentration of 2000 ppm and ambient pressure (p_{prim} ~ 1 bar). The slow drain of the primary inventory down to ¾-loop (approximately 1060 kg of residual inventory) was attended by a constant feed of N_2 to the primary circuit via the PRZ valve station, thereby replacing the void volumes emerging from the drainage. The volume of N_2 fed to the primary circuit was approximately 0.6 m³ at Standard Temperature and Pressure conditions (STP) in both test runs.

After the decrease of the primary inventory, the rod bundle power was set to 200 kW (simulation of the decay heat in the core, resembling 0.6 % of full load thermal power, inclusive compensation for heat losses) and kept constant. Until start of test, the core power was removed from the primary circuit via the residual heat removal system engaged in loop 1.

These initial conditions were the operating ones prior to the start of test, SOT. Table 2-2 and Figure 2-5 present this test initial facility configuration, the initial test conditions to G1.1 and G1.1a (both tests runs were identical).

Some differences has been found between the stated conditions at PKL III G1.1 Quick Look Report (Schollenberger, 2009) and the real measured experimental tests conditions at the SOT, all of them are reported in Table 2-3.

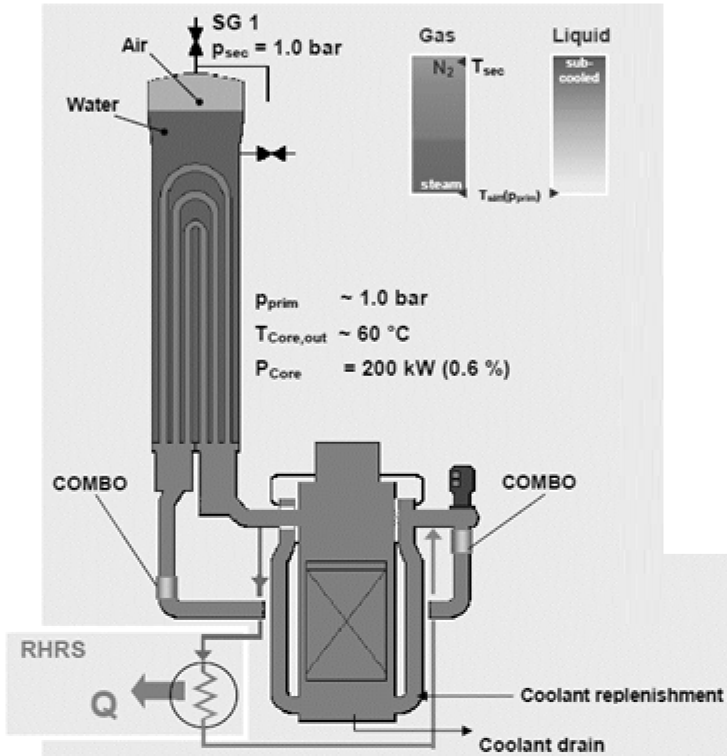

Figure 2-5 Initial (SOT, t=0) Test Facility Configuration for Both Tests Run

Table 2-2 Initial Conditions for Test G1.1 and G1.1a

Primary side	
General conditions of flow and heat transfer	Cold shutdown conditions. No flow. Loops 1 filled with water up to ¾-loop, N_2 above. Remaining 3 loops isolated by blank flange close to RPV outlet/inlet. RHRS active in loop 1.
Coolant inventory	1060 kg (PRZ isolated)
Boron concentration	2000 ppm
Heater rod bundle power	200 kW
Pressure	≈ 1 bar (atmospheric pressure)
Fluid temperature at core outlet	≈ 333 K
Subcooling at core outlet	≈ 40 K
Pressurizer fluid temperature	PRZ isolated throughout the whole test
Pressurizer level	
Flow conditions	No flow
Secondary side	
Secondary pressure in SG (remaining SGs not in operation)	≈ 1 bar (atmospheric pressure), MSRV closed
Secondary temperature in SG 1	≈ 298 K
Water levels in SG 1	≈ 12.2 m (air above)

Table 2-3 Initial Tests Condition, Stated vs. Real Experimental Tests Conditions

	Stated Conditions	**Test Conditions (G1.1)**	**Test Conditions (G1.1 a)**
General conditions of flow and heat transfer	Cold shutdown conditions. No flow. Loop 1 primary filled with water up to ¾-loop, N_2 above. Remaining 3 loops isolated by blank flange close to RPV outlet/inlet. RHRS active in loop 1.	Almost no flow, with only slight variations at SG1 Outlet (0.1 kg/s around SOT). 20% of Loop 1 filled with water, N_2 above. Everything else as stated.	No flow. 20% of Loop 1 filled with water, N_2 above. Everything else as stated.
Coolant inventory	1060 kg (PRZ isolated)	No data	No data
Boron concentration	2000 ppm	2000 ppm	2145 ppm
Heater rod bundle power	200 kW	223 kW	181 kW
Pressure	~ 1 bar (atmospheric pressure)	0.94 bar	1 bar
Fluid temperature at core outlet	~ 60 °C	61.7 °C	64.7°
Subcooling at core outlet	~ 40 K	~ 37 K	31.7 K
Pressurizer fluid temperature	PRZ isolated throughout the whole test	As stated	As stated
Pressurizer level			
Flow conditions	No flow	No flow	No flow

2.2.3 Tests Run Conditions

Both runs of test G1.1 were started at steady state conditions at SOT time scale t = 0 with the initial conditions described in the above tables (see Table 2-4 and Figure 2-5). Both test runs (G1.1, G1.1a) started from ¾-loop with the RHRS engaged. The tests start with the shut-down of RHRS. As a consequence, a heat-up of core inventory is produced, starting the steam formation in the core after approximately 10 minutes after the shut-down and consequently the frothing of the core inventory.

In test G1.1 a reduction of primary coolant inventory is caused in order to establish a swell level in the SG inlet chamber below the tube sheet. This established a heat transfer mode in U-tubes similar to RC operation, with active and passive heat transfer zones. After that reduction of the primary coolant inventory a gradual increase is carried out. Previously to the coolant inventory increase a (quasi-) steady state conditions have been establishment. During the whole test run heat transfer to the secondary side leads to a temperature and pressure increase on the secondary side. But the secondary side of loop 1 was kept constant at 2 bars pressure and 12.2 m fill level via the main steam relief valve (MSRV) and feed water injection. The procedure returned a sequence of phases at steady-state operating conditions.

In test G1.1a the same procedure as in test G1.1 is carried out. The only difference is that not reduction of primary coolant inventory is caused and, as consequence, a rising of the swell level into the SG U-tubes is reached. After the establishment of (quasi-) steady state conditions a gradual increase of the primary inventory is executed. As happened in test G1.1, the procedure returns a sequence of phases at steady-state operating conditions. Test run G1.1a serves as the extension of the sequence of steady state points acquired in run G1.1 by two additional points.

Reduction and increase of inventory was accomplished via lower plenum drain line and injection lines into the lower section of the DC-tubes. In this way, additional coolant was injected into already subcooled fluid and not into steam volumes. Thereby, the steam condensation (and heat transfer in the U-tubes) was left undisturbed by draining/replenishment procedures.

In Tables 2-4 and 2-5 there are chronologically displayed the changes of coolant inventory and significant events during test phase for the PKL III facility in the course of both tests, G1.1 and G1.1a. Figures 2-6 and 2-7 present the evolution of the main parameters.

Table 2-4 Test run G1.1: Changes of Coolant Inventory and Significant Events

General Time [s]	Time after SOT [s]	Measures / Events	Primary coolant inventory [kg] +/- 20kg
0		Preliminary Test Phase	1060
7900	0	Start of Test (SOT)	1060
8340	440	Star of Coolant Drain with 0.219 kg/s	1060
10120	2220	End of Coolant Drain	670
23750	15850	Start of Coolant Injection with 0.06433 kg/s	670
25460	17560	End of Coolant Injection	780
27060	19160	Start of Coolant Injection with 0.0613 kg/s	780
28610	20710	End of Coolant Injection	875
34960	27060	Start of Coolant Injection with 0.06322 kg/s	875
35830	27930	End of Coolant Injection	930
45620	37720	Start of Coolant Injection with 0.0633 kg/s	930
46410	38510	End of Coolant Injection	980
49220	41320	Start of Coolant Injection with 0.06587 kg/s	980
50890	42990	End of Coolant Injection	1090
53400	45500	Start of Coolant Injection with 0.0666 kg/s	1090
53700	45800	Increase of Injection Rate to 0.1298 kg/s	1110
55010	47110	End of Coolant Injection	1280
57150	49250	Start of Coolant Drain with 0.703 kg/s	1280
57520	49620	End of Coolant Drain	1020
58890	50990	End of Test (EOT)	1020

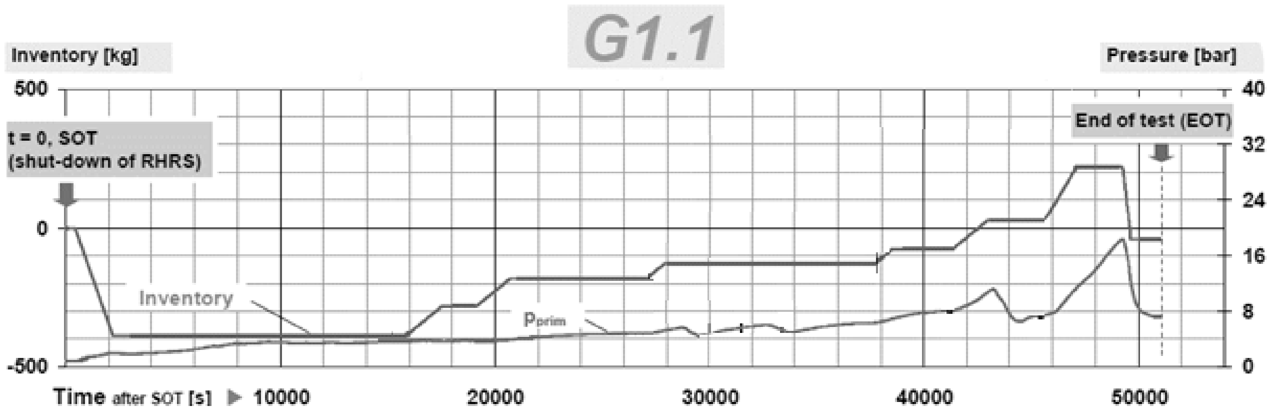

Figure 2-6 Evolution of Main Parameters (Inventory, Primary Pressure)

Table 2-5 Test run G1.1a: Changes of Coolant Inventory and Significant Events

General Time [s]	Time after SOT [s]	Measures / Events	Primary coolant inventory [kg] +/- 20kg
0		Preliminary Test Phase	1060
5600	0	Start of Test (SOT)	1060
33760	28160	Star of Coolant Injection with 0.0623 kg/s	1060
35525	29925	End of Coolant Injection	1170
37900	32300	Start of Coolant Injection with 0.128 kg/s	1170
39385	33785	End of Coolant Injection	1360
47830	42230	Start of Coolant Injection with 0.0556 kg/s	1360
48820	43220	Increase of Injection Rate to 0.1452 kg/s	1410
49130	43530	End of Coolant Injection	1455
50140	44540	Start of Coolant Injection with 0.0633 kg/s	1455
50535	44935	End of Coolant Injection	1480
51045	45445	Start of Coolant Drain with 0.3062 kg/s	1480
52580	46980	End of Coolant Drain	1010
53720	48120	Start of Coolant Drain with 0.275kg/s	1010
55285	49685	End of Coolant Drain	580
57370	51770	End of Test (EOT)	580

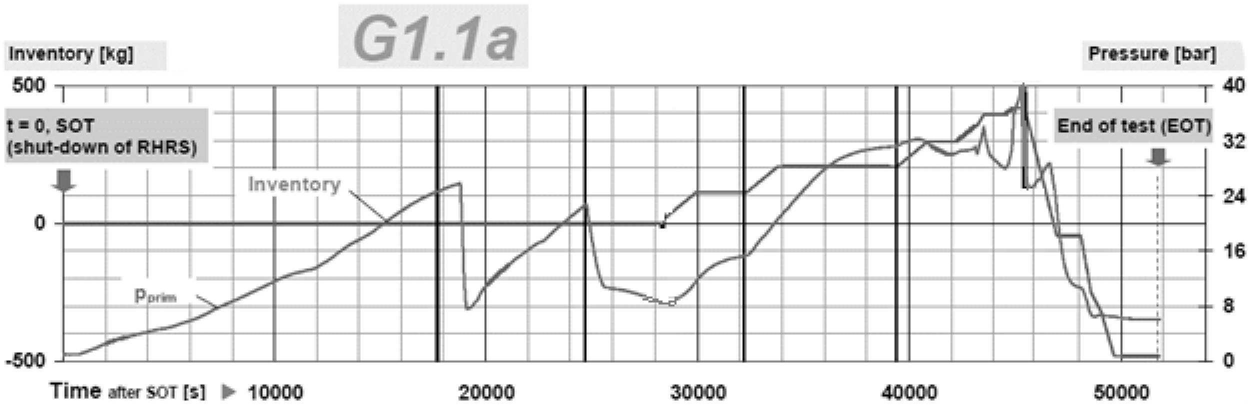

Figure 2-7 Evolution of Main Parameters (Inventory, Primary Pressure)

Some differences has been found between the stated conditions at PKL III G1.1 Quick Look Report and the real measured experimental tests conditions during the tests run, all of them are presented in next figures. Figure 2-8 presents the variation of the rod bundle power during test run.

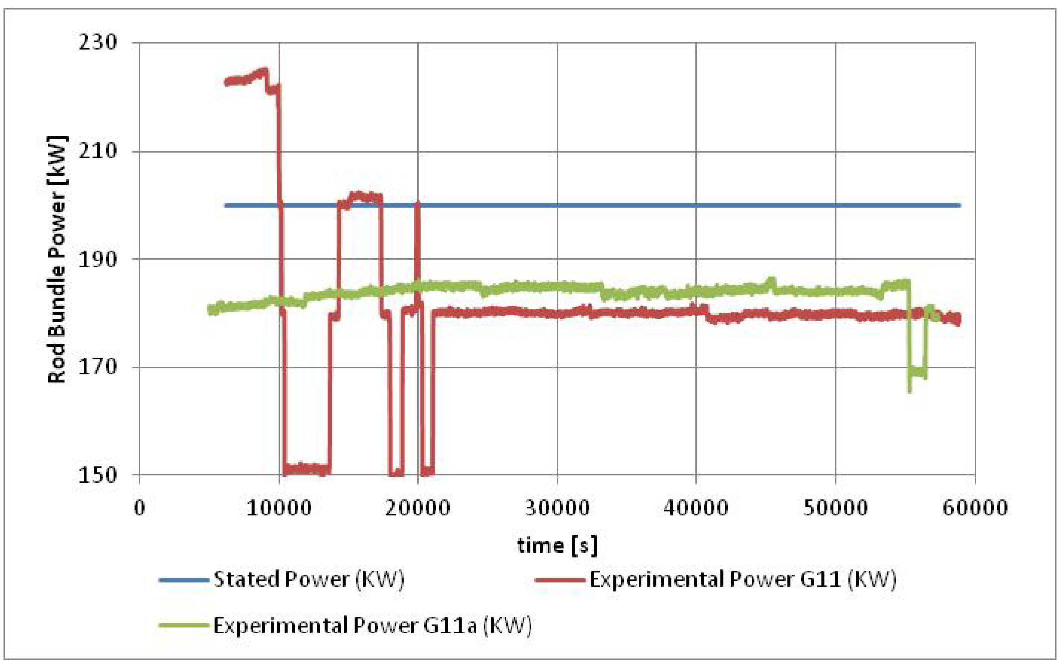

Figure 2-8 Rod Bundle Power Variation vs. Time Throughout G1.1 and G1.1a Tests Run (MST 2713) and the Stated at Quick Look Report

Refilling of coolant inventory is stated to be made by injection of “cold” water with [B] = 2000 ppm into lower parts of both RPV DC-pipes, the temporal evolution of this injection temperature is presented in Figure 2-9.

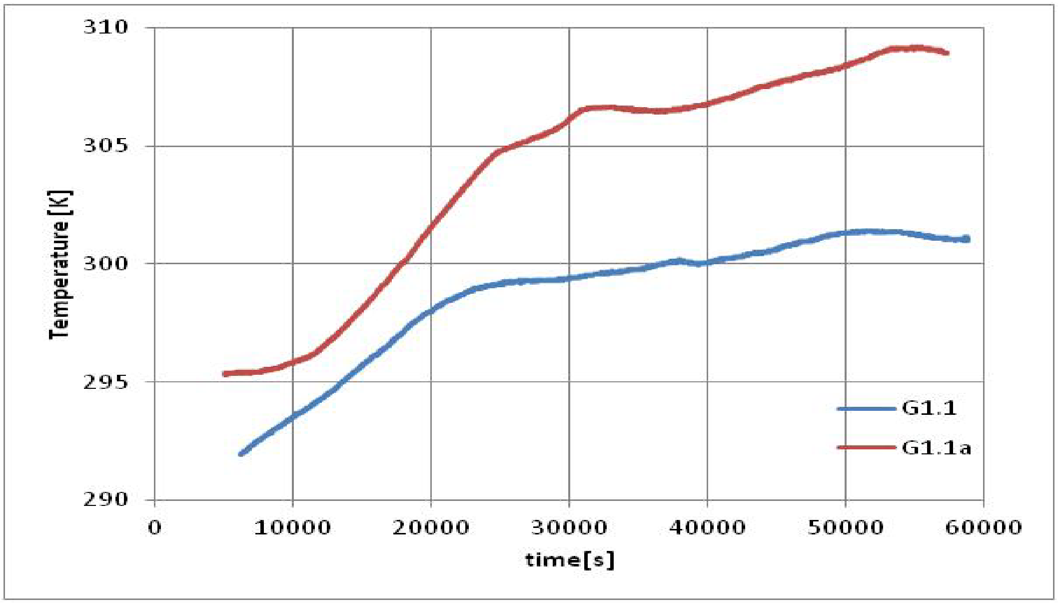

Figure 2-9 Coolant Inventory Replenishment Temperature vs. Time along G1.1 and G1.1a Tests Run (MST 1830)

Secondary feed water system is stated in Quick Look Report to be at 298 K for the whole tests run, whereas the experimental data shows temperature changing constantly in every single test, see Figure 2-10.

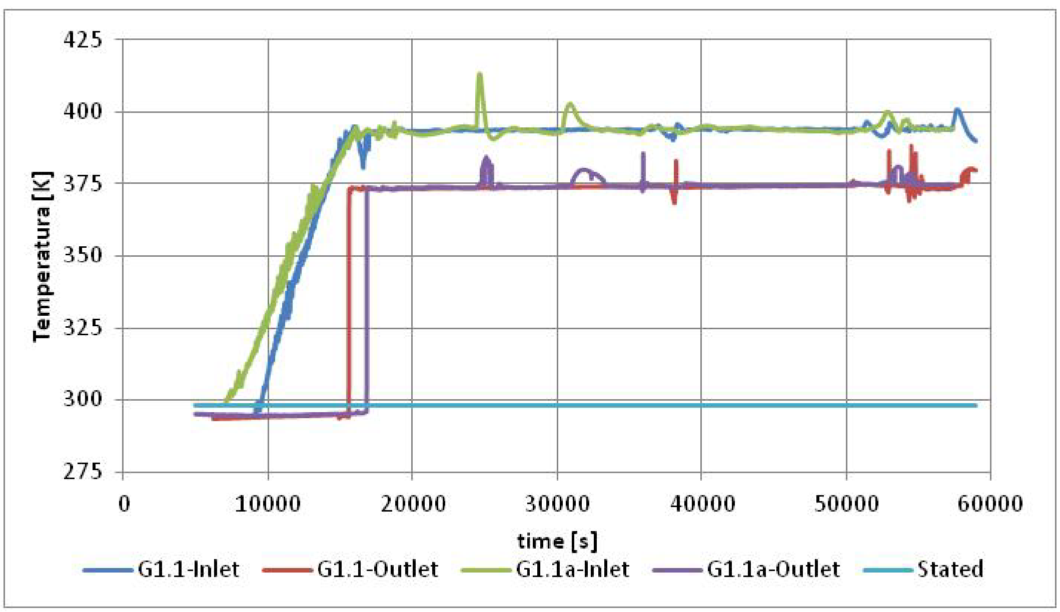

Figure 2-10 Water Temperature of the Steam Generator Secondary Side vs. Time Throughout G1.1 and G1.1a Tests Run (inlet MST 817 & outlet 835) and the Stated at Quick Look Report

3 TEST RESULTS AND COMPARISON WITH TRACE

This section is devoted to review the main experimental results and to discuss the results obtained with the TRACE code, it has been divided into two parts, one for each test run.

3.1 G1.1 Test Phase Results

The comparison of the main characteristics curves between the experimental PKL measurements facility and TRACE simulation results to G1.1 are presented in the next paragraphs. First graphic presented is the comparison of experimental data versus TRACE simulation results for vessel liquid level. Next figures presented are the comparative temperature curves in the most significant components, such are the core, downcomer, lower plenum, hot line, steam generator and cold leg. Finally the pressure curve in the upper plenum is presented.

Figure 3-1 shows the comparison between experimental PKL facility data and TRACE calculations of the water level in the vessel. The calculations performed by TRACE provide a quite good correlation of the water level into the vessel, although, in some periods of the transient the level calculated differs from the experimental data, for instance, the initial decrease in level at the end of first extraction is more pronounced in the experimental test and besides the fluctuations in the simulation are more marked.

The core experimental temperature data versus TRACE simulated core temperature results are presented in Figure 3-2. Both temperatures evolve in a similar way until the second 15000-16000 approximately, with an abrupt initial increase caused by the shut-down of the RHRS. From that moment on, the increase in the TRACE simulation temperature is bigger than the measured in the experimental facility. At about 20000 seconds the temperature of the TRACE simulation stabilizes among 430-450 K approximately, whereas the experimental values keep its slow rise. At approximately 50000 seconds the simulation temperature is reached by the experimental. The quick drainage at the end of the test produce a sharp increase in the core temperature, it is much more appreciable in the experimental results than in the TRACE simulation results.

Figure 3-3 presents the experimental lower plenum temperature versus the TRACE simulated. The obtained temperature with the simulation increases gradually and after approximately 20000 seconds stabilizes until approximately 50000 seconds where decreases sharply and with the final drainage process, increases quickly. Whereas experimental values increases sharply at the beginning, but present a several abrupt falls followed by abrupt recovers, maintaining its slow increase until approximately 51000 seconds where as an abrupt fall down which recovers partially. These abrupt falls and recovers has not theoretical explanation, it might be caused by the sudden close and open of a valve or another transient effect.

The comparison among the different downcomer temperatures are presented in Figure 3-4. All four TRACE simulation temperatures evolve in a similar way, initial abrupt increase, with a subsequent stabilization and ending with a sharp decrease that partially recovers, caused by the final drainage event. Whereas the experimental measures of the top and middle downcomer areas increases less than the simulated, the middle area increases even slowly in the first 35000 seconds approximately, whereas in the bottom area nothing happens until almost the end of the test, where a small increase in temperature appear.

As far as hot leg temperatures concerns (see Figure 3-5), we can say that evolve in a very similar way than the core temperature, Figure 3-2.

Figure 3-6 presents the steam generator inlet level measurements. The experimental values remain in cero until 30000 seconds approximately whereas the TRACE simulation starts its increase at approximately 10000 seconds. During both test run, there are big level fluctuations. But in the experimental measures, when starts its increase, there are bigger peaks than in the TRACE simulation but maintaining its upward trend, whereas in the simulation the level stabilizes among 4 and 7 meters approximately.

Values of the steam generator temperature are presented in Figure 3-7. A sudden initial temperature rise in both cases takes place, much more marked in the experimental measures, followed by an almost flat profile, but with wide fluctuations, greater in the TRACE simulation results.

The cold leg temperatures are presented in Figure 3-8. TRACE simulation present a sudden increase from about 15000 to 20000 seconds, increasing from 300 to 400 K, followed by a gradual decrease until the stabilization at about 330-340 K. Whereas, for the experimental measures of the CL pipe this abrupt increase is similar, but it is followed by an almost constant increase not decrease as in the simulated by TRACE. The other two CL temperature measures remain constant, until approximately 22000 seconds to the inlet pump and 36000 seconds to the pump seal. Both of them are followed by a sharp increase until the CL pipes values is reached, then all of them evolve with a progressive increase, ending with an abrupt decrease approximately 51000 seconds.

Figure 3-9 represent the upper plenum pressure evolution for both cases, the TRACE simulation and experimental measures. A pressure increase is produced at 7900 seconds, caused by the shut-down of the RHRS, but in a different way in each case. The experimental measures present an almost steady increase until approximately 50000 seconds, from the initial approximately atmospheric pressure to 11 bars. In that moment a sudden pressure decrease appears, from 11 to 6 bars, followed by an abrupt increase from the previous 6 bars to 18. The test ends with another sudden pressure fall down. The TRACE simulation presents a bit more accentuated pressure increase than the experimental one, reaching 10 bars at 20000 seconds approximately. That increase is followed by several sudden pressure decreases from 10 to 6 bars, among 20000 and 30000 seconds. After that, the pressure fluctuations continue, but with lower amplitude, these fluctuations continue until 50000 seconds approximately. The test ends with a pressure increase and a sudden fall down.

Figure 3-10 presents the experimental boron concentration evolution versus the simulated with TRACE code. Up to 15000 seconds both evolve in a similar way, however from this point on it does not happen in this way. Whereas the simulation shows a sharp decrease from the initial value of 2000 ppm to about 1000 ppm, at 20000 seconds approximately, growing up to 1700 ppm from this point to the 25000 seconds. For its part, the experimental curve remains practically constant at the 2000 ppm. Although, at this point the experimental curves evolves differently for the measurements below the SG and those made below the pump. First measure presents three sharp decreases, falling until 0 ppm, all of them followed by sharp recoveries, reaching all of them the 2000 ppm, ending with another sharp decrease until 1250 ppm, followed by a new recovery again, finally the experiment ends in the vicinity of the 2000 ppm. Whereas the second experimental curve has a less pronounced decrease and maintaining at all the time its downward trend. However, for the simulation curve has a slight fall from the above 25000 seconds until the 50000, reaching concentrations until about 1000 ppm, ending with a sharp recovery until 1500 ppm followed by a fall to finish in the 1250 ppm. These decreases and boron concentration peaks do not coincide with any particular event (extractions or injections), but in any case the falls could be attributed to the strong initial extraction by applying a lag, while the recovery would be due to subsequent injection events performed, in this case being smoother, process takes place in several stages.

Regarding the comments on the TRACE simulation results vs. the PKL experimental measurements it can start by saying that, although up to approximately 15000 seconds, the main experimental measurements and the obtained into the simulation are similar, such are temperatures and pressures in the vessel region. From this point on, there are a major break between experimental values and the results obtained from the simulation. Even though quite good results, beyond the aforementioned point, are obtained for the temperature values of several variables, such are the lower plenum, the SG and HL, but not so happens for the temperatures in the downcomer and CL, the upper plenum pressures and the SG levels. The main conclusion that can be drawn is the fact that the experimental curves and the TRACE simulations are very different, namely, the model cannot simulate the experimental conditions.

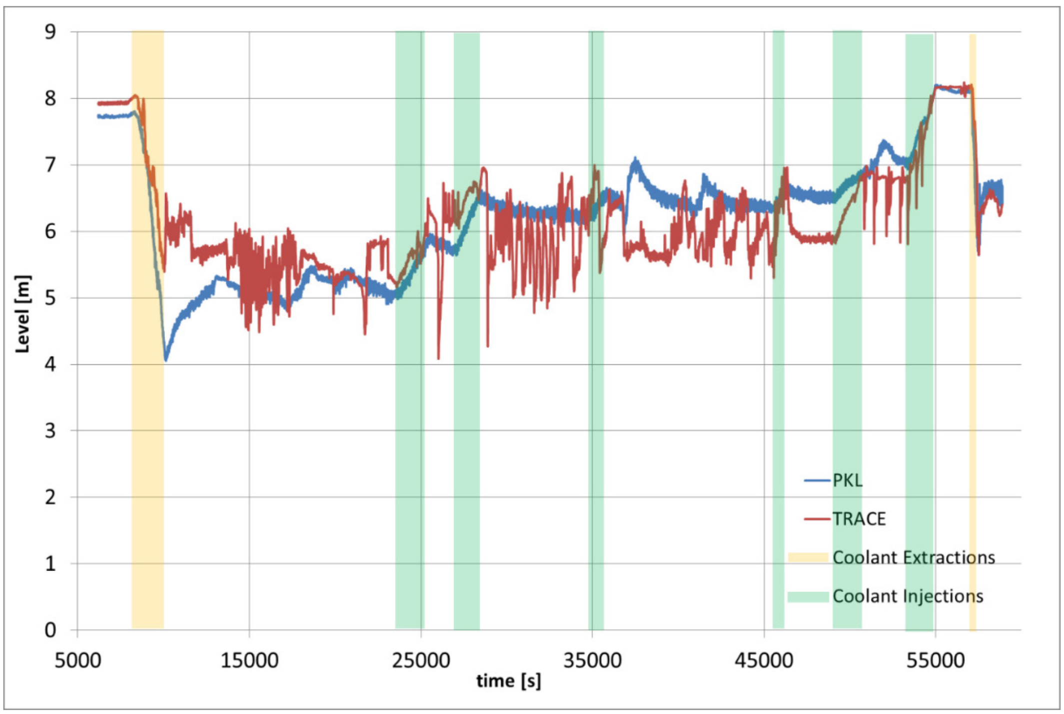

Figure 3-1 Test G1.1, Vessel Level of PKL Facility (MST 45) vs. TRACE Simulation

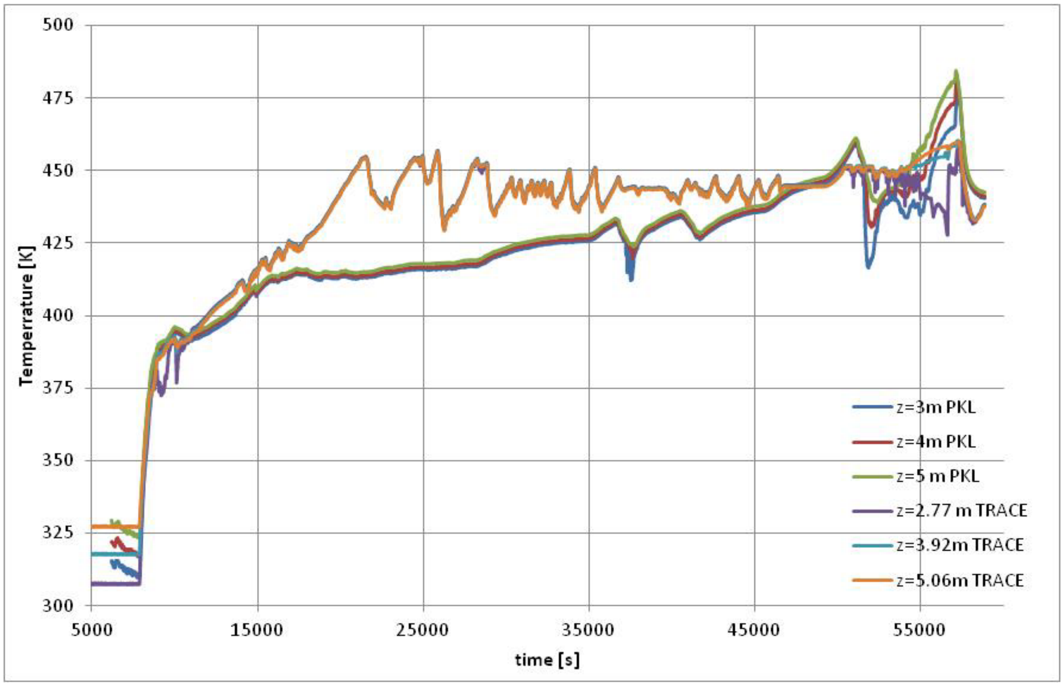

Figure 3-2 Test G1.1, Core Temperature of PKL Facility (MST 612, 574 & 575 Respectively) vs. TRACE simulation (Pipe 120, cells 2, 4 & 6 Respectively)

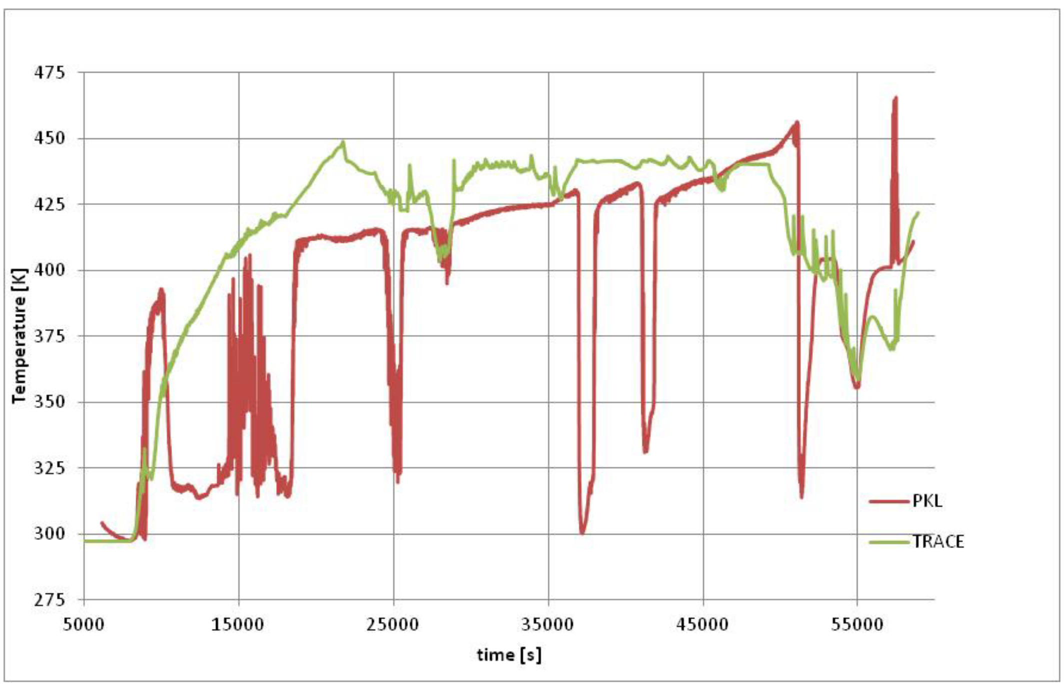

Figure 3-3 Test G1.1, Lower Plenum Temperature of PKL Facility (MST 636) vs. TRACE Simulation (Plenum 110)

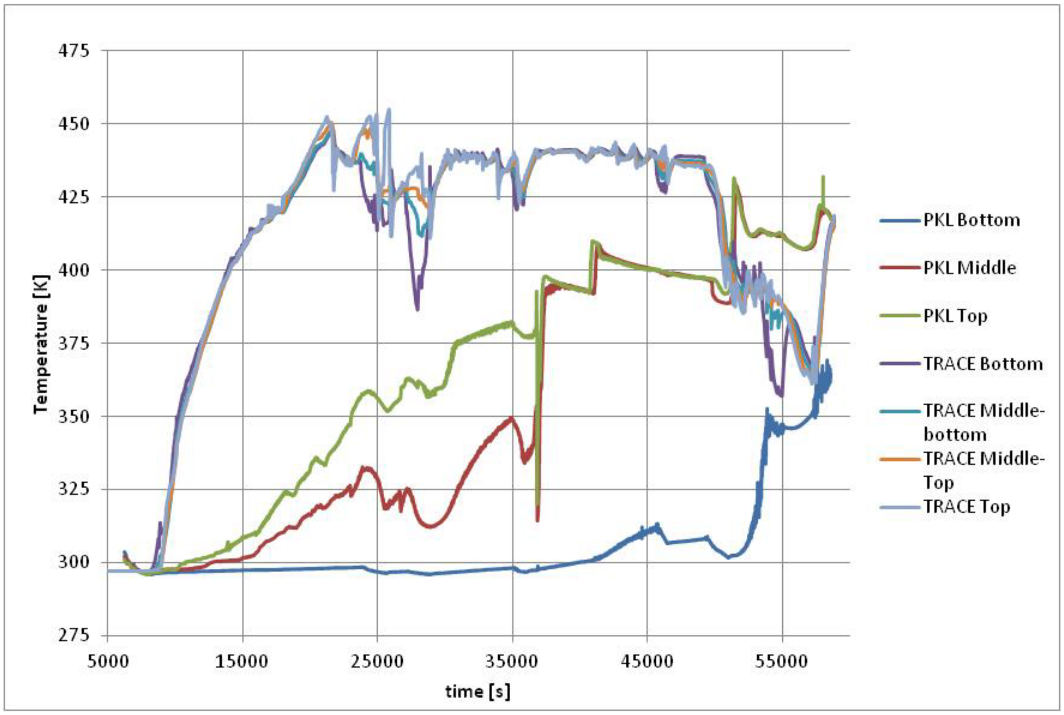

Figure 3-4 Test G1.1, Downcomer Temperature of PKL Facility (MST 1153, 1155 & 1157 Respectively) vs. TRACE Simulation (Pipe 104, cells 4 to 1 Respectively)

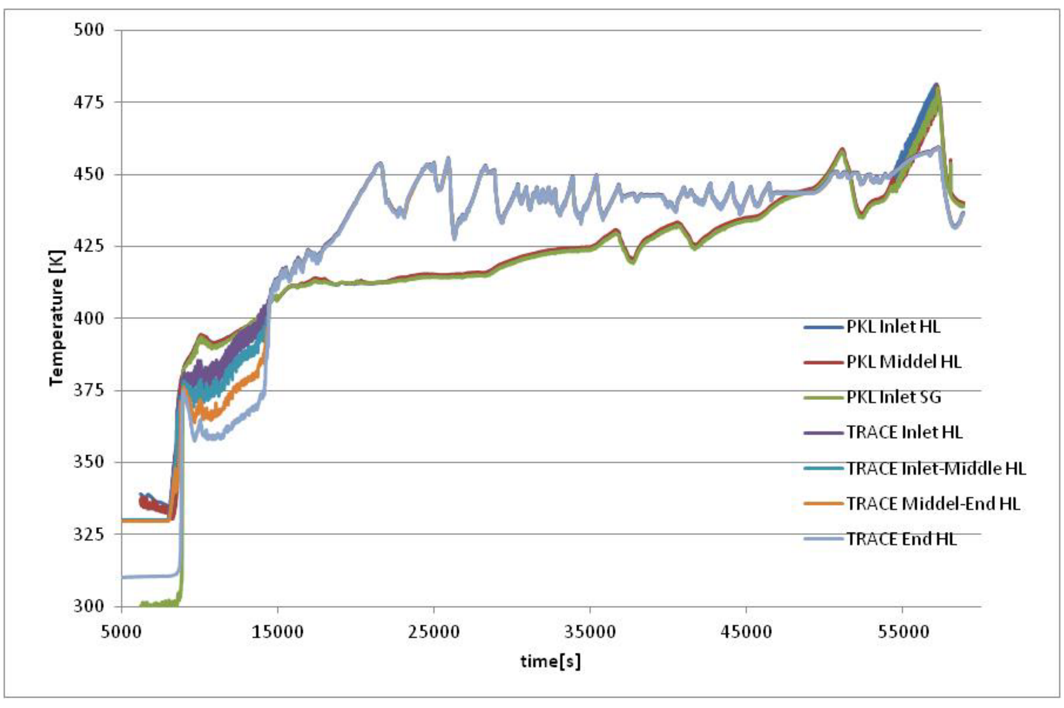

Figure 3-5 Test G1.1, Hot Leg Temperature of PKL Facility (MST 1167,1170 & 1194 vs. TRACE Simulation (Pipe 210 Inlet GV, Cells 1-4)

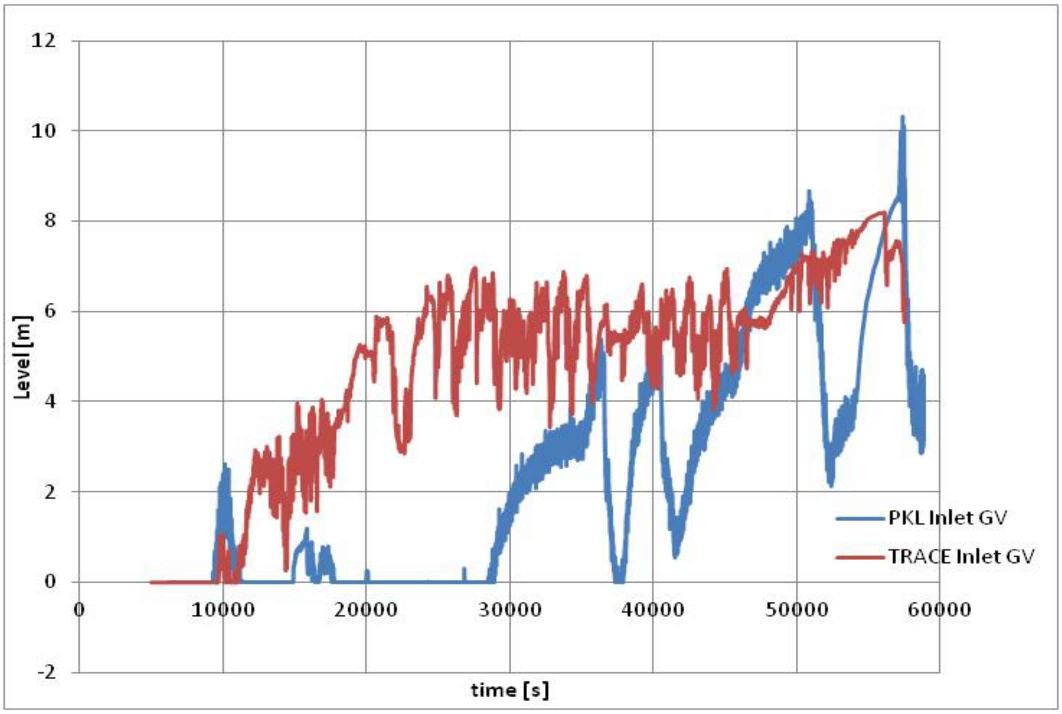

Figure 3-6 Test G1.1, Steam Generator Level of PKL Facility (MST 71) vs. TRACE Simulation

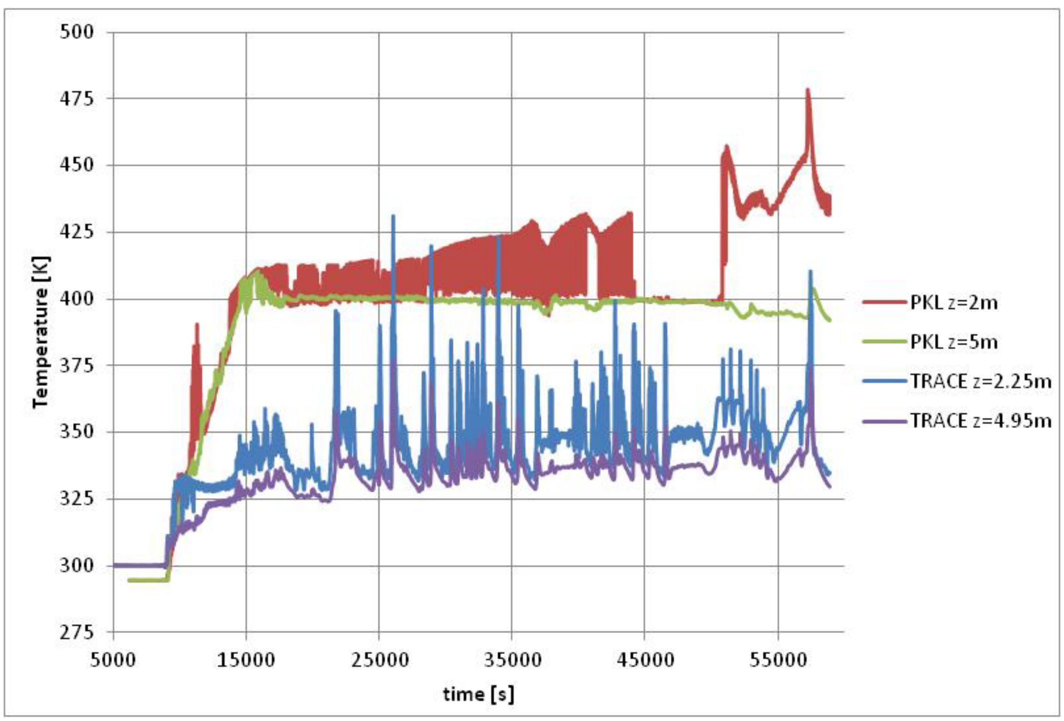

Figure 3-7 Test G1.1, Steam Generator Temperature of PKL Facility (MST 745 & 753) vs. TRACE Simulation (Pipe 235, cells 3 & 6)

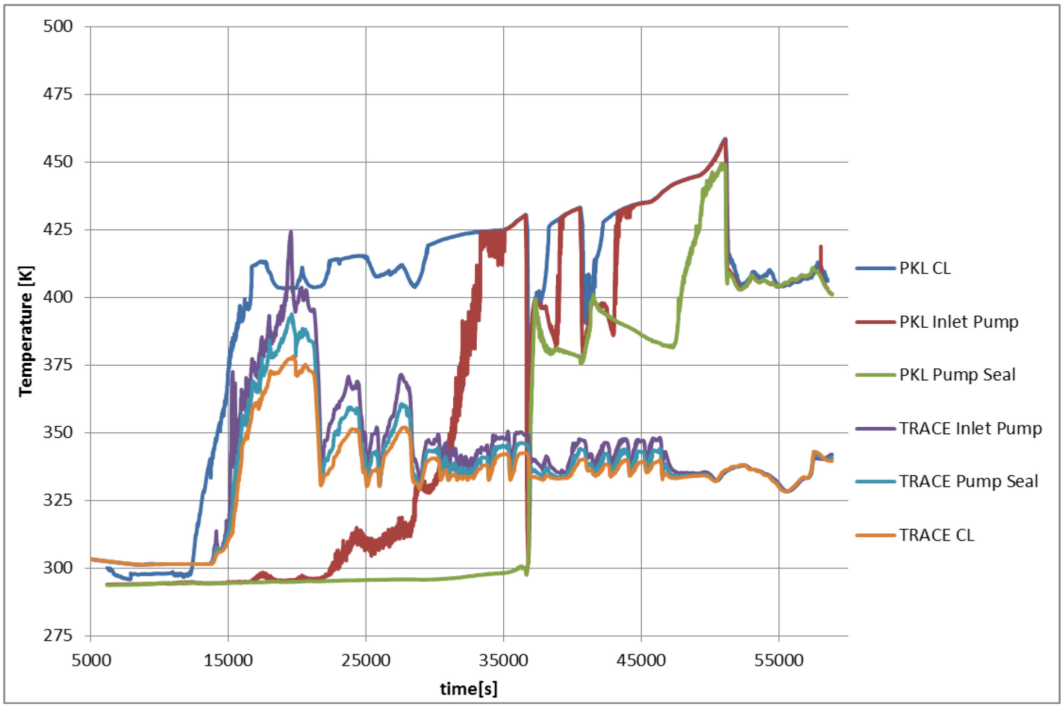

Figure 3-8 Test G1.1, Cold Leg Temperature of PKL Facility (MST 1373, 1207 & 1161) vs. TRACE Simulation (Pipe 249)

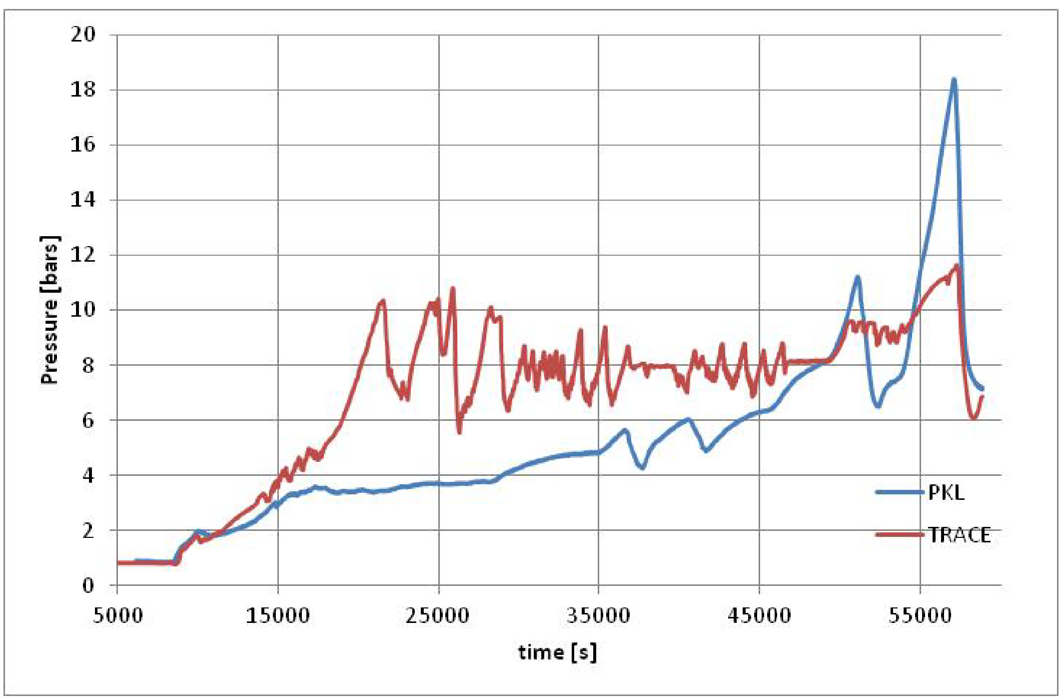

Figure 3-9 G1.1, Upper Plenum Pressure of PKL Facility (MST 243) vs. TRACE Simulation (Plenum 160)

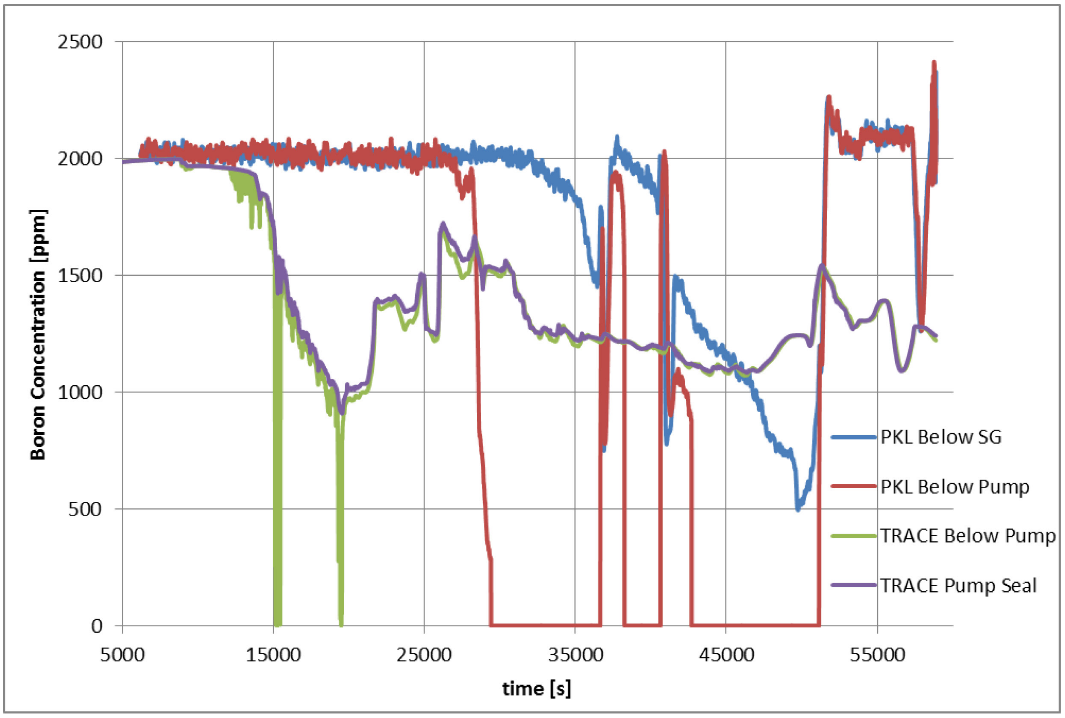

Figure 3-10 G1.1, Boron Concentration in the PKL Facility (MST 1557 & 1556) vs.TRACE Simulation (Pipe 249, cells 3 & 2)

3.2 G1.1a Test Phase Results

The comparison of the main characteristics curves between experimental PKL facility and TRACE simulation results to G1.1a are presented in the next paragraphs. First presented graphic is the comparison of experimental versus TRACE simulation core level measures. Next figures presented are the comparative temperature curves in the most significant components, such are the core, downcomer, lower plenum, hot line, steam generator and cold leg. Finally, the pressure curve in the upper plenum is presented.

Figure 3-11 shows the comparison between experimental PKL facility data and TRACE calculations of the water level in the vessel. The calculations performed by TRACE provide a quite good correlation of the water level into the vessel, although, in some periods of the transient the level calculated differs from the experimental data. For instance, the initial decrease in the collapsed water level, caused by the core heat-up after the shut-down of the RHRS, is produced later in the simulation and reaches a lower level than the one produced in the experimental measures.

The core experimental versus simulated core temperature is presented in Figure 3-12. Both temperatures evolve in a similar way until the second 7000-8000 approximately, with an abrupt initial increase caused by the shut-down of the RHRS. From that moment on the increase in the experimental measured temperature is bigger than the TRACE simulation one. At about 25000 seconds the measured temperature falls down abruptly, recovers until approximately 30000 seconds when decreases abruptly once more time, those peaks have no explanation because not injection nor extractions are carried out in the facility. Meanwhile the TRACE simulation has a smaller temperature increase than the one in the experimental facility followed by a completely flat period, from 15000 to 35000 seconds, where the first injection is realized. That coolant inventory injection, at lower temperature than the one of the core, produces a decrease in temperature, so much pronounced as nearer to the injection point, the downcomer bottom. That decrease in temperature also appears in the measured temperatures.

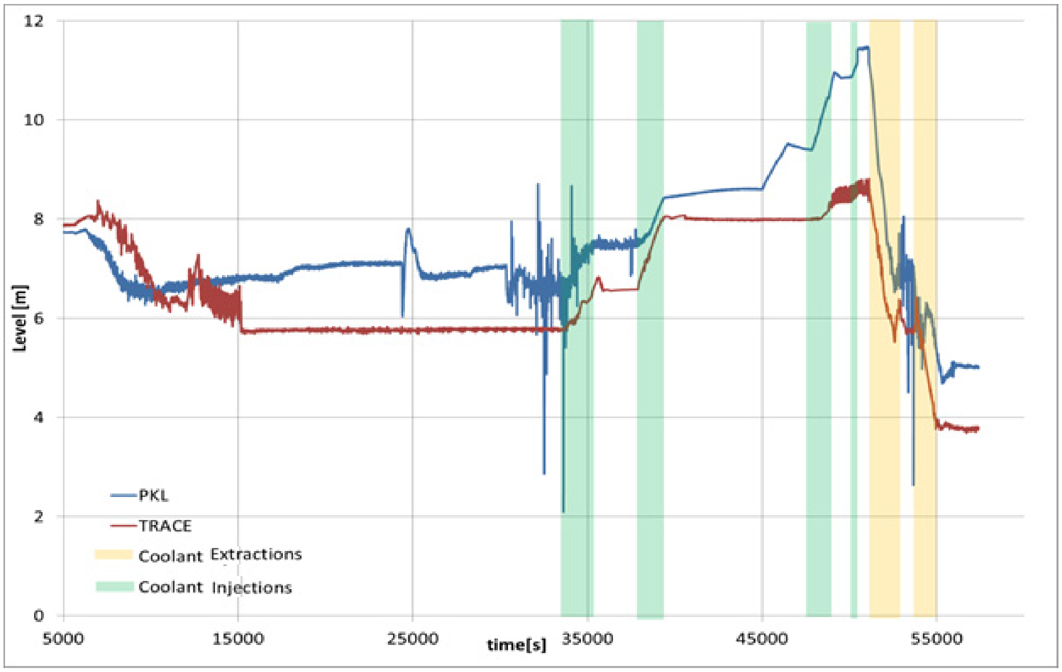

Figure 3-11 Test G1.1a, Vessel Level of PKL Facility (MST 45) vs. TRACE Simulation

Figure 3-13 presents the experimental lower plenum temperature versus the TRACE simulation results. Both lower plenum temperatures increases caused by the shut-down of the RHRS. The obtained temperature with the TRACE simulation increases gradually and after approximately 15000 seconds stabilizes until approximately 35000 seconds where decreases sharply caused by the coolant injection, ending with the temperature recovery produced by the coolant drain at the end of the test run. Whereas the experimental values increases sharply at the beginning and continues with the increase but less pronounced, until 25000 seconds when a sudden decrease appears, followed by a sharp recovery and another sudden fall down and the subsequent recovery once more time a decrease appears, but this time does not recovers because the first injection is realized. The temperature remains almost constant and finally recovers produced by the coolant drain at the end of the test run. The TRACE simulation temperature decreasing produced by the coolant injections are quite bigger than the produced into the experimental measures.

The comparison among the different downcomer temperatures are presented in Figure 3-14. All four TRACE simulation temperatures evolve in a similar way, initial abrupt increase caused by the shut-down of the RHRS, with a subsequent stabilization, from 15000 to 35000 seconds. After that stabilization a temperature decrease is produced by the coolant injection and finally a recovery, caused by the final drainage event is produced. Whereas the experimental values of the three measure points of the downcomer present a delayed temperature peak among 15000-30000 seconds, this peak is more pronounced and less delayed in the top measure than in the middle one and the lowest and more delayed is produced in the bottom measure. At 35000 seconds approximately appears the temperature decrease produced by the coolant injection followed by the final recovery caused by the drainage events.

As far as hot leg temperatures concerns, Figure 3-15, say that evolve in a very similar way than the core temperature, see Figure 3-12. The hot leg temperature figure presents the same characteristics that the core temperature one, for instance, a big increase in the experimental measured temperature, bigger than the TRACE's simulation, the two experimental peaks that are present in all measures, the flat temperature evolution from 15000 to 35000 seconds in the TRACE simulation, and so on.

Figure 3-16 presents the steam generator inlet level measurements. Both run present an increase produced by the head up of the core, caused by the shut-down of the RHRS. The TRACE simulation level values stop its increase at approximately 15000 seconds, where stabilizes until 35000 seconds, when the first coolant injection is made. Whereas the experimental level measures keep increasing until 25000 seconds approximately, where the abrupt fall down appears, as in the other measured, followed by the subsequent recovery and another fall down. In both cases there are a level increase caused by the coolant injections that began at approximately 35000 seconds. Both cases end with a sharp decrease caused by the two coolant drain events.

Values of the steam generator temperature are presented in Figure 3-17. A sudden initial temperature rise in both cases takes place, much more marked in the experimental measures, at 15000 seconds experimental data stabilizes at 400 K whereas TRACE results stabilizes at 350 K approximately. This increase is followed by a flat profile almost until end of test in both cases. Except a sharp increase at 2 meters of the SG bottom, 50-75 degrees from 30000 to 52000 seconds approximately, which takes place in the experimental data. While TRACE evolves similarly, being 10 degrees higher the temperature upper part of the SG throughout the transient.

The cold leg temperatures are presented in Figure 3-18. TRACE simulation presents an almost flat profile, only a small temperature increase appears at the beginning of the test run, approximately until 15000 seconds, after that moment stabilizes at about 330 K and remains constant. Whereas the experimental measures present a sudden increase which start at about 12000-14000 seconds, reaching its maximum at about 20000-23000 seconds. This maximum is followed by a fall down, with the minimum at approximately 25000 seconds, with a posterior recovery, the maximum at 28000-30000 seconds followed by a sudden fall down. From that moment on, the temperature remains constant at about 410 K and the test run ends with a small decrease in temperature.

Figure 3-19 represent the upper plenum pressure evolution to both cases, TRACE simulation and experimental measures. The TRACE simulation pressure starts with an increase caused by the shut-down of the RHRS, the pressure evolves from the atmospheric pressure approximately to 5 bars, at 13000 seconds stabilizes and remains constant until 35000 seconds, where the coolant injection produces the pressure rise to 8 bars. It remains almost constant until approximately 50000 seconds when the drainage events cause the fall down to 3 bars approximately. Whereas the experimental measures present a pressure evolution quite different, the initial increase is much more pronounced, reaching 25 bars. The two peaks, present in all measures, are also present, these peaks appear at 25000 and 30000 seconds respectively, reaching 25 and 23 bars as maximum values and 8 as minimum in both cases. The test continues with a pressure increase at about 35000 seconds caused by the coolant injection events, the reached pressure is about 40 bars. The test run ends with an abrupt decrease in pressure, caused by the drainage (only 560 kg of CI), reaching a value of approximately 3 and 6 bars to the TRACE and PKL respectively.

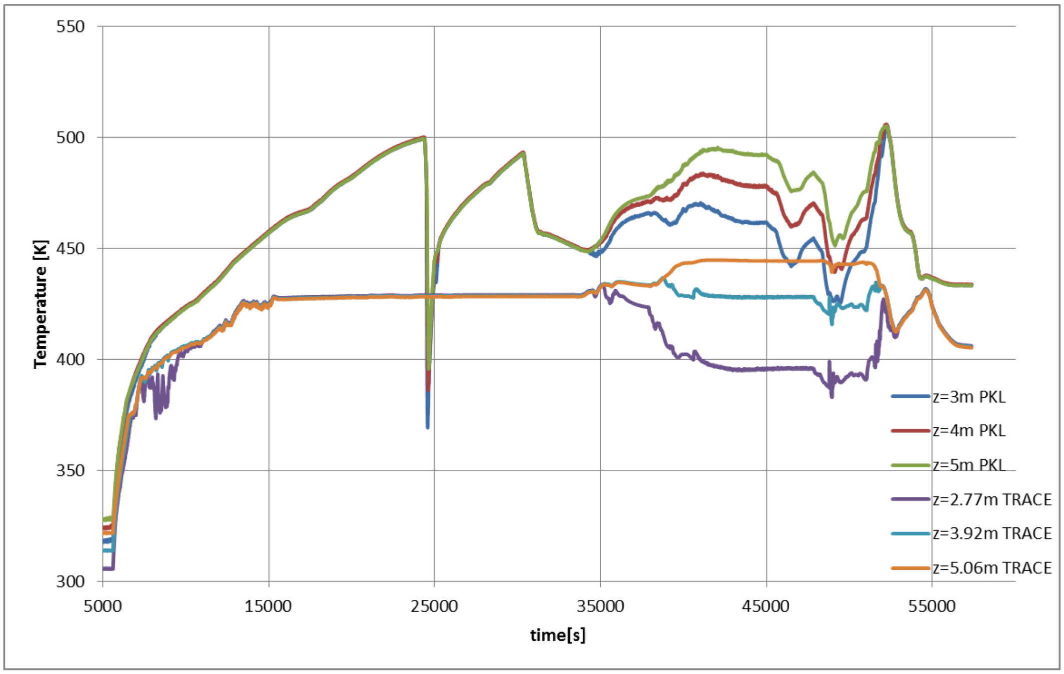

Figure 3-12 Test G1.1a, Core Temperature of PKL Facility (MST 612, 574 & 575 Respectively) vs. TRACE Simulation (Pipe 120, cells 2, 4 & 6 Respectively)

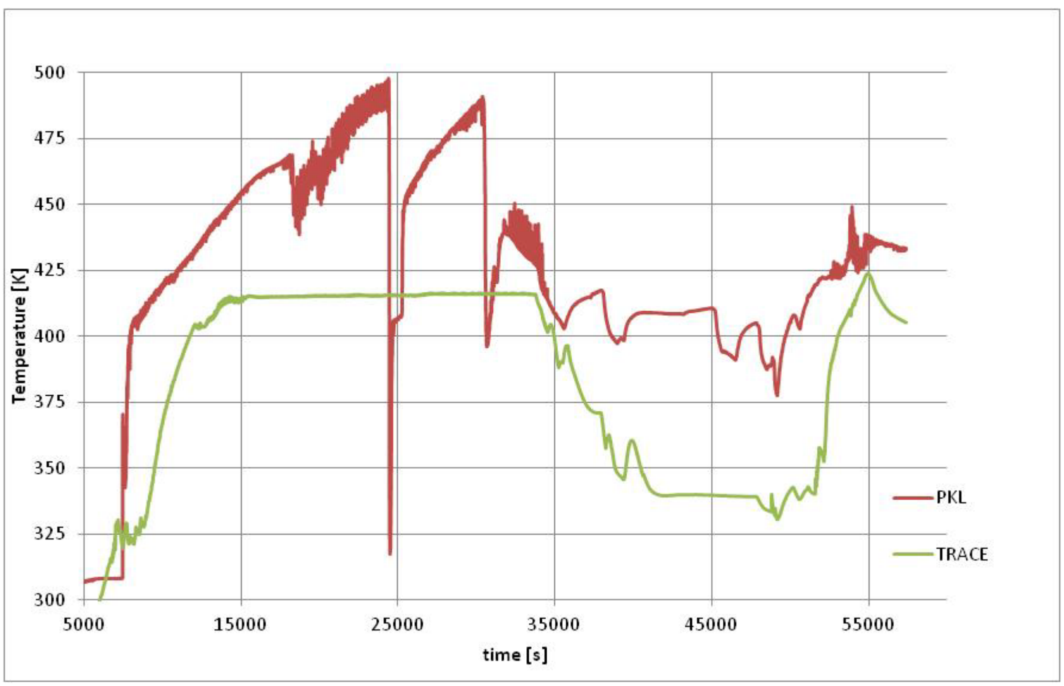

Figure 3-13 Test G1.1a, Lower Plenum Temperature of PKL Facility (MST 636) vs. TRACE Simulation (Plenum 110)

Figure 3-20 shows the evolution of the experimentally measured curves in the PKL facility compared with simulations using the TRACE code. Last one has a boron concentration almost constant along the entire experiment, taking a slight fall from the initial value of 2000 ppm to about 1500 ppm after the second 40000. While for the experimental values, as happened in the test G1.1, the experimental measurements made below the pump and below the SG evolve differently. The first of them has an earliest and more pronounced fall, although in both cases evolve in a similar way, taking a strong recovery of the boron concentration, reaching a value of 3000 ppm. Followed by a sharply falling down, after this the boron concentration recovers once again and remains almost constant for 20000 seconds (between 30000-50000 seconds). Finishing with a fall until 1500 ppm which is the value in which the test ends.

Concerning the comments on the test results, start by saying that, only up to 7000-8000 seconds approximately the main experimental measurements and the obtained into the simulation are similar. This region is the abrupt initial increase of temperatures and pressure caused by the shut-down of the RHRS. From this point on, there is an increasing difference between TRACE simulation results and experimental values. The aforementioned difference is growing over the time due to the fact that the simulation reaches a steady state, stabilization of the main parameters. Meanwhile, the experimental values continue growing, although the trend is cut shortly before the second 25000, at this point there is a strong fall in the main experimental parameters, without apparent explanation, but almost immediately the previous trend is recovered. This trend continues until about 35000 seconds, which effected the first injection of coolant. From this point there are certain analogies in both trends, but differing in their values, with higher increases or decreases in the experimental variables that on the TRACE simulation results. In conclusion say that the experimental curves and the TRACE simulations are very different, namely, the code cannot simulate with 1-D components the experimental results in which natural circulation processes take place.

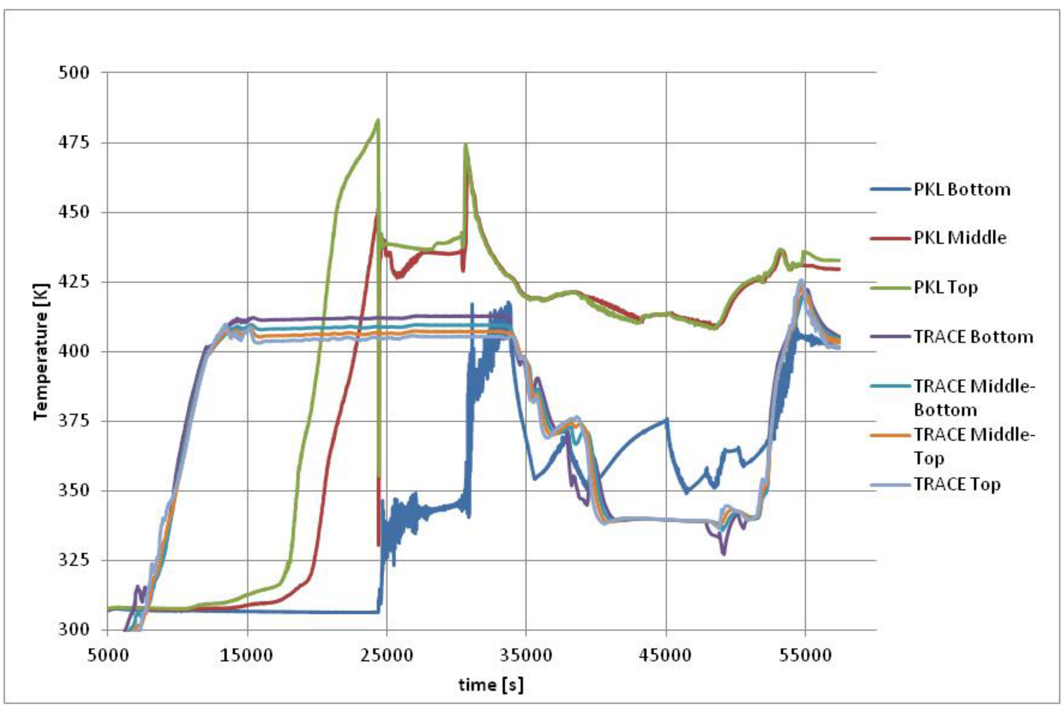

Figure 3-14 Test G1.1a, Downcomer Temperature of PKL Facility (MST 1153, 1155 & 1157 Respectively) vs. TRACE Simulation (Pipe 104, Cells 4 to 1 Respectively)

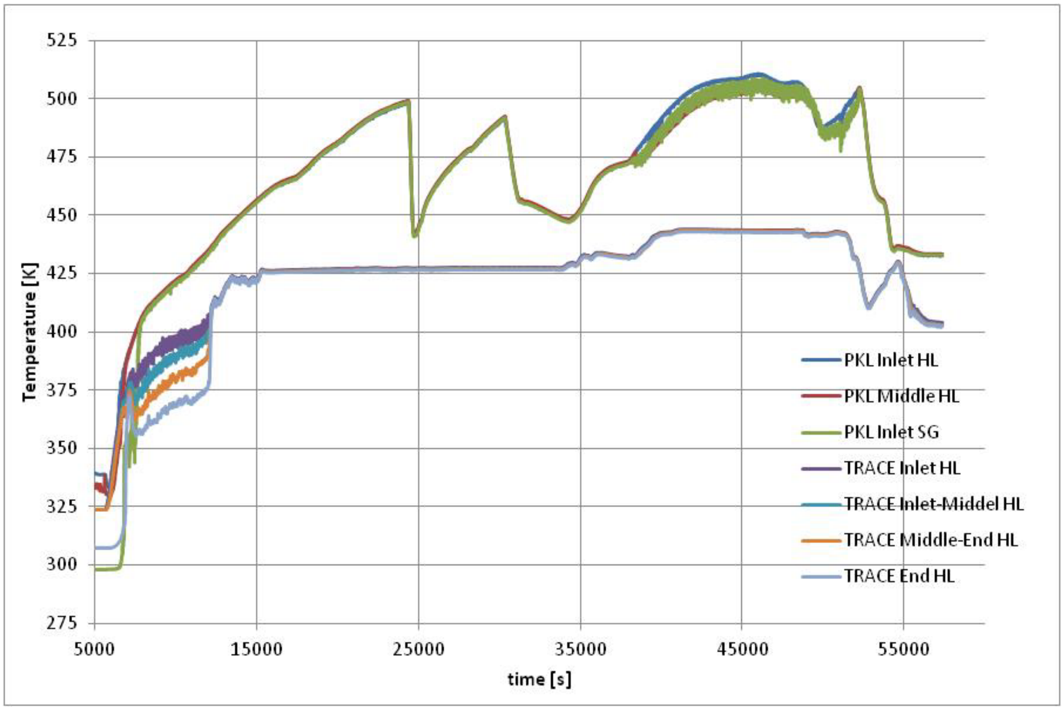

Figure 3-15 Test G1.1a, Hot Leg Temperature of PKL Facility vs. TRACE Simulation (Pipe 210 Inlet GV)

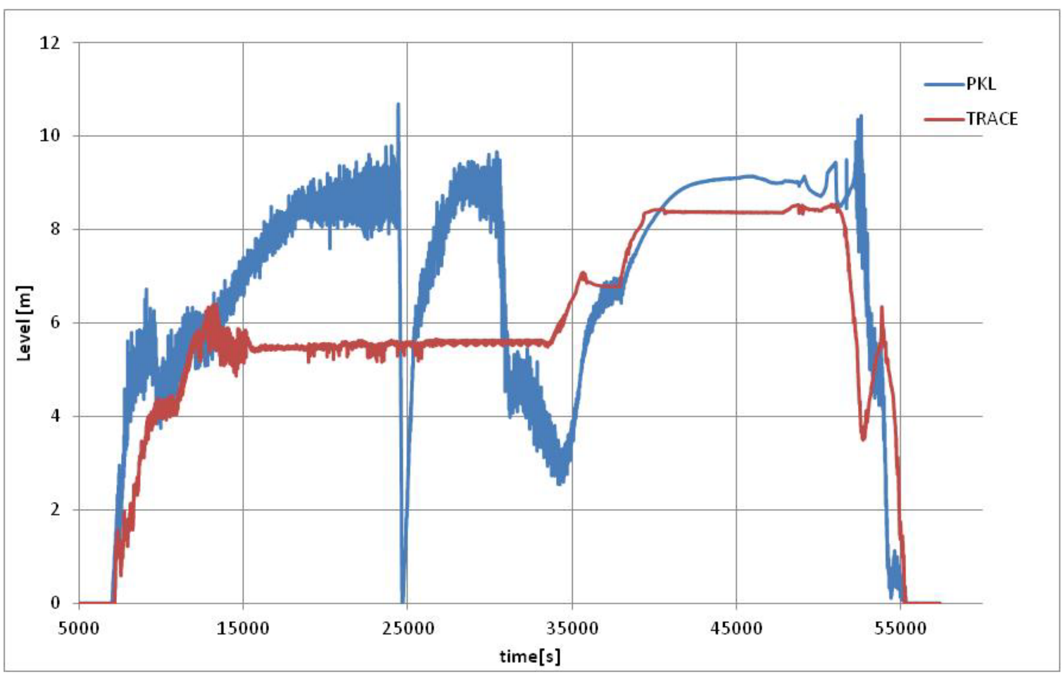

Figure 3-16 Test G1.1a, Steam Generator Level of PKL Facility (MST 71) vs. TRACE Simulation

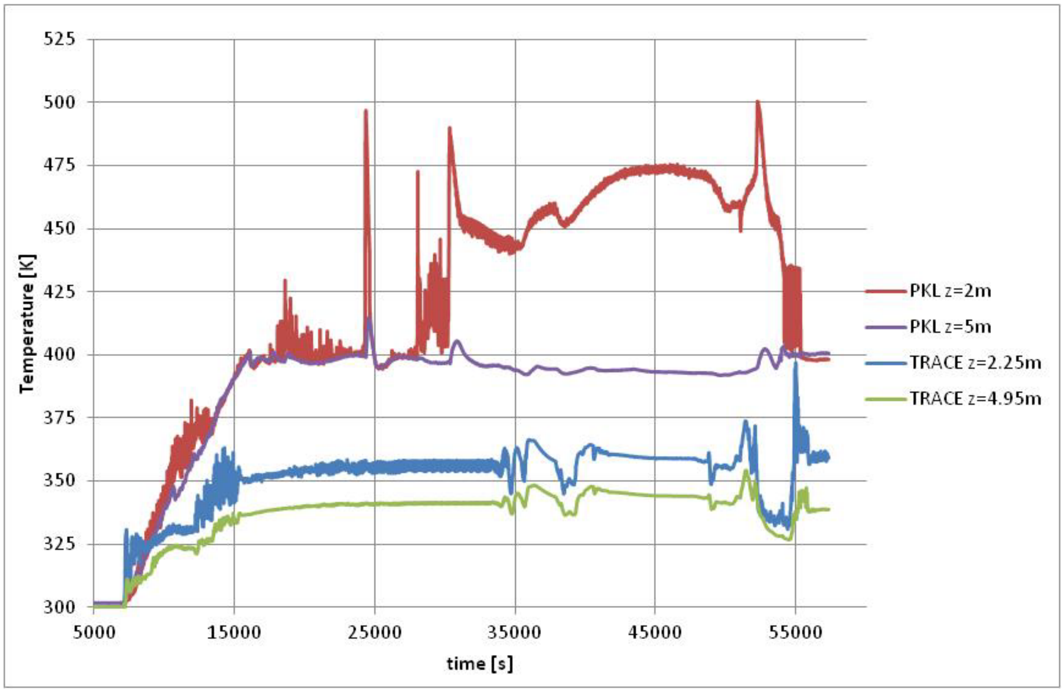

Figure 3-17 Test G1.1a, Steam Generator Temperature of PKL Facility (MST 745 & 753) vs. TRACE Simulation (Pipe 235, Cells 3 & 6)

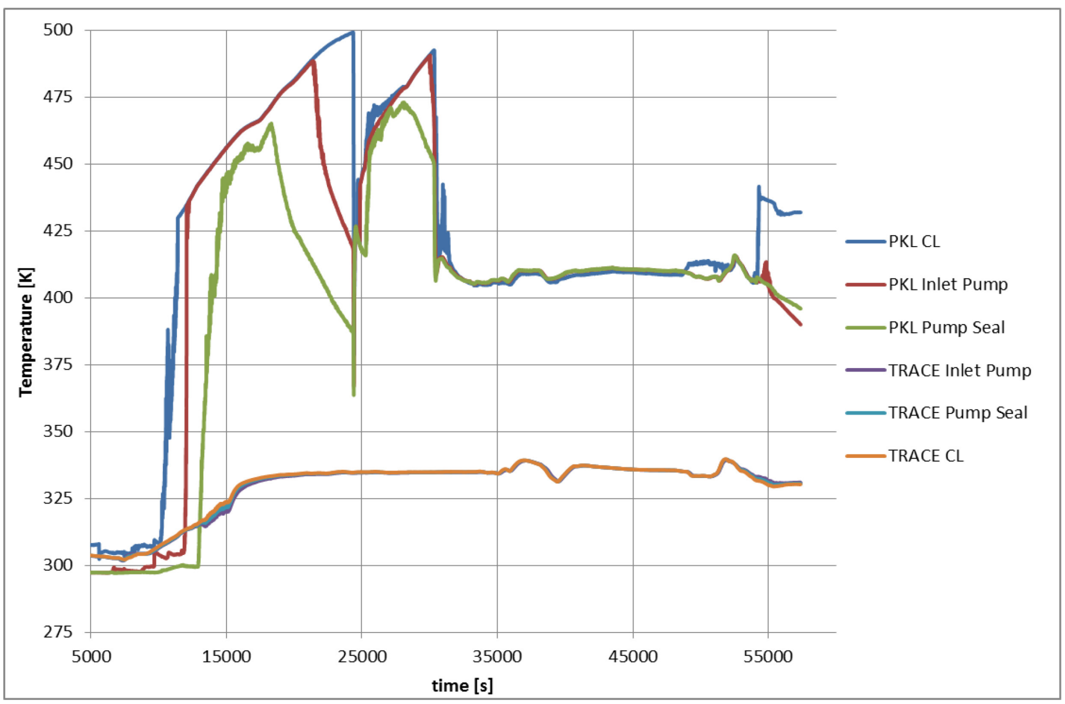

Figure 3-18 Test G1.1a, Cold Leg Temperature of PKL Facility (MST 1373, 1207 & 1161) vs. TRACE Simulation (Pipe 249)

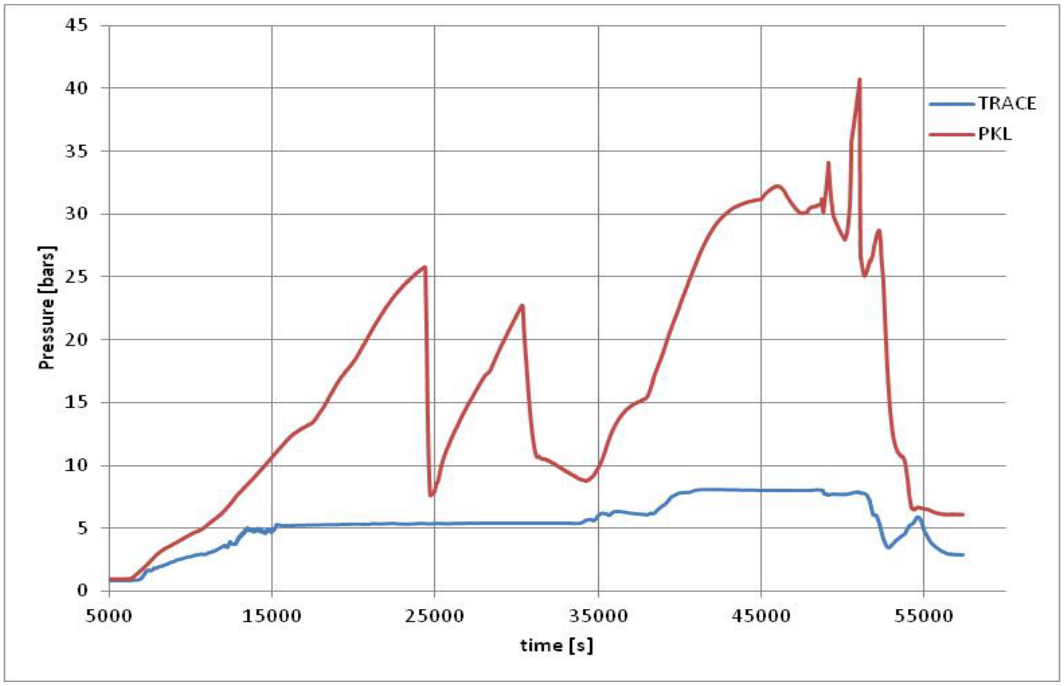

Figure 3-19 G1.1a, Upper Plenum Pressure of PKL Facility (MST 243) vs. TRACE Simulation (Plenum 160)

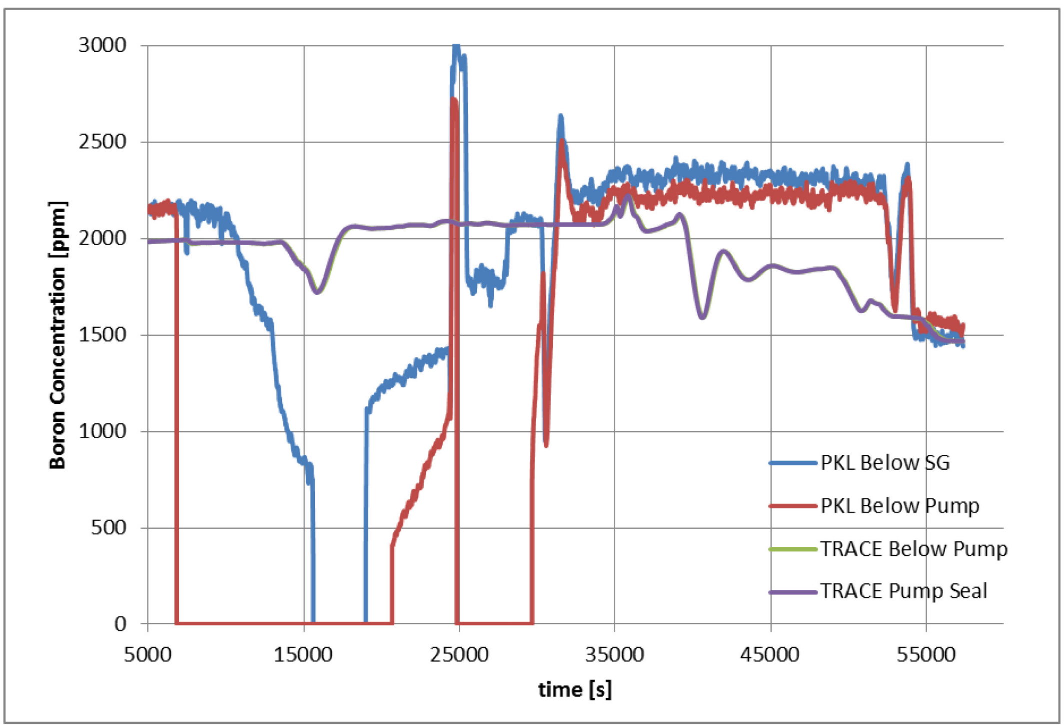

Figure 3-20 G1.1a, Boron Concentration in the PKL Facility (MST 1557 & 1556) vs.TRACE Simulation (Pipe 249, Cells 3 & 2)

4 CONCLUSIONS

The PKL III test facility simulates a typical 1300 MWe pressurized water reactor of Siemens / KWU design. In G1.1 and G1.1a tests run, the primary coolant inventory was at 3/4-loop level and thus, the heat transfer mechanism in the steam generator in presence of nitrogen, steam and water as a function of the primary coolant inventory in single loop operation has been investigated.

In this document, a post-test analysis of PKL III G1.1 and G1.1a tests run using TRACE code, Version 5.0p2, has been presented. The comparison of measured values in the PKL III facility and calculated results by a TRACE model is discussed.

In these experiments a PKL III facility model created with TRACE code has been used to reproduce the whole tests run performance. Initial steady-state conditions were achieved by maintaining every variable of the model at the intended initial value, for as long as seven thousand nine hundred seconds to G1.1 test and five thousand six hundred to G1.1a test, in order to assure that every relevant variable stabilized at a value close to the intended, experimental ones. After these pre-test periods (7900 and 5600 seconds to G1.1 and G1.1a tests respectively) the tests start and run for about fifty thousand seconds approximately.

First important aspect to report on is the use of several by-passes in the core and adjacent components to “reproduce” the mixing processes that 1-D core components of the TRACE model are unable to simulate. This artifice arises from inconvenience that the code is not intended to take into account mixture processes under natural circulation, i.e., TRACE code has not implemented turbulence models. The bad reproducibility is caused fundamentally by the predominance of natural circulation processes, phenomena which are not possible to be accurately reproduced with 1-dimensional components. But what is more, not even with 3-dimensional components probably (vessel components in the core region and/or pressurizer) would be able to reproduce the experimental measurements, unless fine mesh and turbulence models would be introduced, which are out of the code aims. Consequently, the current document displays the transients simulation results using only 1-D components, information which is valuable because explores the TRACE V5.0patch2 code behaviour beyond its design limits.

An important aspect to emphasize in G1.1a test is the fact that a steady state is reached in the TRACE simulation (from approximately 15000 to 35000 seconds, when the first coolant injection is done). Whereas that point is not reached in the PKL test facility and, what is more, two sudden falls down followed by sudden recovers are present, these experimental events have not theoretical explanation. With regard to the G1.1 test, let us say that the TRACE calculations provide a quite good correlation, particularly into the core, although, in some periods of the transient the TRACE calculations differ from the experimental data. The best results are obtained to the core level, it has a good tracking between experimental and simulation results, especially in G1.1 test. Good results to the core temperature are also obtained to the G1.1 test.

As a result of the previously exposed comments, let us say that the simulation have been completely fulfilled, but the comparison of experimental measures to the TRACE code simulation results show that there are many differences among them along the different phases of the transient. The main reason arises from the fact that natural circulation processes are the dominant mechanisms during all the transient, and specifically by their increase in predominance as the difference in temperature among different levels of the liquid phase in the core region accentuates, maximum difference which is reached at the end of the core head up. Then, from this moment on, these natural circulation processes are even more dominant, as TRACE code cannot reproduce them appropriately, the simulations results differs from the experimental data. Unsuitability which is especially evident when using 1-D components in the core region. Then, in order to be able to capture the evolution of these processes the code should have had implemented turbulence models and a finest component meshing. Consequently, not even with a 3-D vessel in the core region the code would probably be able to capture these phenomena, as TRACE was not intended originally to capture this turbulence phenomenon. Added to this predominance of the long-term natural circulation processes, boron dilution and diffusion processes are also present, which lead to important differences between the experimental data and the simulation results, caused by turbulence phenomena. Consequently, the current document notes the difficulties that TRACE code has in simulating these long-term experiments in which forced circulation has no longer importance, these huge difficulties are common to all the different thermal-hydraulic codes. In addition, so extremely long transients, with almost sixty thousand seconds, and which evolve under natural circulation and diffusion processes are beyond the initial objectives of TRACE code design. But, despite the very high difficulty of these transient simulations, at the same time, the simulations are useful to find and explore the calculation limits of the different TRACE code versions. In particular, this document mainly explores the capacity of TRACE V5.0 patch 2 to reproduce natural circulation processes in two long-term transients, displaying the code behaviour beyond its design limits.

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April 2022