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International Agreement Report

Analysis with TRACE Code of PKL-III Test F 1.2

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ABSTRACT

The goal of this report is to explain the main results obtained in the simulations performed with the consolidated code TRACE for the OCDE TEST PKL-III F 1.2. The transient was produced by a set of successive extractions of refrigerant performed through the bottom of the vessel of the PKL-III facility in Germany, after each extraction phase no extraction was performed during a certain time, this no-extraction time was long enough to reach a quasi-stationary state so the new natural circulation conditions could be experimentally observed. Therefore, the goal of this test is to see how the inventory of refrigerant in the primary circuit affects to the natural circulation conditions in the primary circuit and when the natural circulation stops. The experiment had two different parts during, the first one were performed a set of extraction of refrigerant followed by no extraction intervals, until a minimum inventory was reached, during this set of extractions and the quasi-stationary periods that followed to each extraction period, the power was maintained constant. The second step of the experiment consisted in a set of injections symmetrical to the extractions, which refilled again the primary system although the total number of refilling steps was smaller than the number of the extractions and, therefore, the initial conditions were not achieved. The total duration of the experiment was 90000 s. After each extraction step the relief valves of the secondary system were manipulated in order to maintain constant the pressure in the primary system, this was done manually by the operator. In the code simulation, we simulate with TRACE the first 40000 s of the experiment until the natural circulation was completely stopped and the system enters in reflux condenser conditions.

The TRACE code was able to predict correctly the natural circulation mass flow rate along time. We note that the natural circulation mass flow rate at the beginning of the transient is 1.21 kg/s that is correctly predicted by TRACE, then after several successive extractions steps this mass flow rate increases reaching a maximum value of 3 kg/s. This value is also correctly predicted by the TRACE code. When the inventory is too low the natural circulation start to diminish progressively with the successive extractions until it stop.

FOREWORD

Extensive knowledge and techniques have been produced and made available in the field of thermal-hydraulic responses during reactor transients and accidents, and major system computer codes have achieved a high degree of maturity through extensive qualification, assessment and validation processes. Best-estimate analysis methods are increasingly used in licensing, replacing the traditional conservative approaches. Such methods include an assessment of the uncertainty of their results that must be taken into account when the safety acceptance criteria for the licensing analysis are verified.

Traditional agreements between the Nuclear Regulatory Commission of the United States of America (USNRC) and the Consejo de Seguridad Nuclear of Spain (CSN) in the area of nuclear safety research have given access to CSN to the NRC-developed best estimate thermalhydraulic codes RELAP5, TRAC-P, TRAC-B, and currently TRACE. These complex tools, suitable state-of-the-art application of current two-phase flow fluid mechanics techniques to light water nuclear power plants, allow a realistic representation and simulation of thermalhydraulic phenomena at normal and incidental operation of NPP. Owe to the huge required resources, qualification of these codes have been performed through international cooperation programs. USNRC CAMP program (Code Applications and Maintenance Program) represents the international framework for verification and validation of NRC TH codes, allowing to:

- Share experience on code errors and inadequacies, cooperating in resolution of deficiencies and maintaining a single, internationally recognized code version.
- Share user experience on code scaling, applicability, and uncertainty studies.
- Share a well documented code assessment data base.
- Share experience on full scale power plant safety-related analyses performed with codes (analyses of operating reactors, advanced light water reactors, transients, risk-dominant sequences, and accident management and operator procedures-related studies).
- Maintain and improve user expertise and guidelines for code applications.

Since 1984, when the first LOFT agreement was settled down, CSN has been promoting coordinated joint efforts with Spanish organizations, such as UNESA (the association of Spanish electric energy industry) as well as universities and engineering companies, in the aim of assimilating, applying, improving and helping the international community in the validation of these TH simulation codes1, within different periods of the associated national programs (e.g., CAMP-España). As a result of these actions, there is currently in Spain a good collection of productive plant models as well as a good selection of national experts in the application of TH simulation tools, with adequate TH knowledge and suitable experience on their use.

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 continued 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/FAP2 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 2001 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 safety community during the coming decade.

CSN, as Spanish representative in CSNI, is involved in some of these research activities, helping

1 It's worth to note the emphasis made in the application to actual NPP incidents.

2 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).

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 enough investigated safety issues and phenomena (e.g., boron dilution, low power and shutdown conditions), or enlarging code validation and qualification data bases incorporating new information (e.g., multi-dimensional aspects, non-condensable gas effects). In particular, CSN is currently participating in the PKL and ROSA programmes.

The PKL is an important integral test facility operated by of AREVA-NP in Erlangen (Germany), and designed to investigate thermal-hydraulic response of a four-loop Siemens designed PWR. Experiments performed during the PKL/OECD program have been focused on the issues:

- Boron dilution events after small-break loss of coolant accidents.
- Loss of residual heat removal during mid-loop operation (both with closed and open reactor coolant system.

ROSA/LSTF of Japan Atomic Energy Research Institute (JAERI) is an integral test facility designed to simulate a 1100 MWe four-loop Westinghouse-type PWR, by two loops at full-height and 1/48 volumetric scaling to better simulate thermal-hydraulic responses in large-scale components. The ROSA/OECD project has investigated issues in thermal-hydraulics analyses relevant to water reactor safety, focusing on the verification of models and simulation methods for complex phenomena that can occur during reactor transients and accidents such as:

- Temperature stratification and coolant mixing during ECCS coolant injection
- Water hammer-like phenomena
- ATWS
- Natural circulation with super-heated steam
- Primary cooling through SG depressurization
- Pressure vessel upper-head and bottom break LOCA

This overall CSN involvement in different international TH programmes has outlined the scope of the new period of CAMP-España activities focused on:

- Analysis, simulation and investigation of specific safety aspects of PKL/OECD and ROSA/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 experiments and plant application with the last available versions of NRC TH codes (RELAP5 and TRACE). A CAMP in-kind contribution is aimed as end result of both types of studies.

Development of these activities, technically and financially supported by CSN, is being carried out by 5 different national research groups (Technical Universities of Madrid, Valencia and Cataluña). On the whole, CSN is seeking to assure and to maintain the capability of the national groups with experience in the thermal hydraulics analysis of accidents of the Spanish nuclear power plants.

Francisco Fernández Moreno, Commissioner

Consejo de Seguridad Nuclear (CSN)

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EXECUTIVE SUMMARY

This report presents the main results obtained with the NRC consolidated code TRACE for the simulation of the OCDE PKL-III test F 1.2 with a model of the PKL facility.

The transient was produced by a set of successive extractions of refrigerant performed through the bottom of the vessel of the PKL-III facility in Germany, after each extraction phase no extraction was performed during a certain time, this no-extraction time was long enough to reach a quasi-stationary state so the new natural circulation conditions could be experimentally observed. Therefore, the goal of this test is to see how the inventory of refrigerant in the primary circuit affects to the natural circulation conditions in the primary circuit and when the natural circulation stops. The experiment had two different parts, during the first one were performed a set of extraction of refrigerant followed by no extraction intervals, until a minimum inventory was reached, during this set of extractions and the quasi-stationary periods, that followed to each extraction period, the power was maintained constant. The second step of the experiment consisted in a set of injections symmetrical to the extractions, which refilled again the primary system, although the total number of refilling steps was smaller than the number of the extractions and, therefore, the initial conditions were not achieved. The total duration of the experiment was 90000 s. After each extraction step the relief valves of the secondary system were manipulated in order to maintain constant the pressure in the primary system, this was done manually by the operator. In the code simulation, we simulate with TRACE the first 40000 s of the experiment until the natural circulation was completely stopped and the system enters in reflux condenser conditions.

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ACKNOWLEGMENTS

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 AREVA NP. The CSN financed this work, and help to develop this report. Also we are indebted to the UPC and in particular to Francesc Raventos and Carmen Pretel that provides a model of the PKL-III facility for the TRACE code.

ABBREVIATIONS

CSN	Spanish Nuclear Regulatory Commission
CRGT	Control Rod Guide Tubes
ECCS	Emergency Core Cooling System
CVCS	Chemical and Volumetric Control System
HPIS	High Pressure Injection System
LOCA	Loss of coolant accident
LPIS	Low Pressure Injection System
OCDE	Organization for the Cooperation and Economic Development
PKL	Pimärkreislauf facility in Erlangen
PRZ	Pressurizer
PTS	Pressurized Thermal Shock
PWR	Pressurized Power Reactor
RCP	Recirculation Pump
RHRS	Residual Heat Removal System
SBLOCA	Small Break Loss of coolant accident
SG	Steam Generator
SRV	Safety and Relief Valve
UNESA	Spanish Electricity Producers Association
UPC	Universidad Politécnica de Catalunya
TRACE	TRAC/RELAP Advanced Computational Engine

1. INTRODUCTION

The present work is a contribution to the OCDE international collaborative research project PKL-III. The Spanish Nuclear Regulatory Commission coordinated the participation in this project, 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 analysis of the experiment PKL-III F 1.2 with the TRACE code was assigned to the “thermal-hydraulics and nuclear engineering group” of the Polytechnic University of Valencia. This test was performed in the PKL (Primärkreislauf) facility located in the research centre of AREVA FRAMATOME in Erlangen (Germany) which is operated by FRAMATOME ANP [1, 2].

The Test PKL III F 1.2 consisted in two stages, that we will call extraction and injection stages, respectively. The first one formed by a set of successive phases that consisted in a set of extractions of refrigerant fluid, performed through the lower part of the vessel, followed by a period without extraction after each individual extraction. The period without refrigerant draining after each extraction phase was long enough to attain a pseudo-stationary state. During this set of steps, the power was maintained constant through the entire transient and, at the same time, the operator of the facility changed manually the area of the secondary relief valve in order to maintain constant the pressure in the primary system along the transient.

The total duration of the two stages was 90000 s. In this report, we will analyse the first 40000 s of the transient that, correspond to the extraction stage. We will compare the experimental data with TRACE results for a set of characteristics thermal-hydraulic variables.

Because no experimental data of the area of the relief valve or stem position through the transient were recorded, the variation of this area was computed by trial and error, i.e. at each extraction step we selected the new area value that was able to maintain the pressure constant in the primary system during each quasi-stationary period. Because after each extraction step the fluid inventory in the system was smaller, then to maintain the pressure constant into the system we need to remove less heat from the primary. This was accomplished by raising the temperature in the secondary, to do this the facility operator adjust the valve stem position in order to increase the secondary pressure and in this way to reduce the primary secondary heat transfer.

One subject of special interest in this test was to study the influence of the primary refrigerant inventory on the natural circulation mass flow rate, when the refrigerant inventory is too small the system enters in reflux condenser conditions and the natural circulation stops.

The goal of test series 1 was to obtain the multidimensional temperature distribution in the cold legs and the vessel downcomer during the ECCS injection for verification of computer codes and models. In test 1.2 the break was located in the bottom of the hot leg B, in such a way that the break does not disturb the stratification in the cold leg.

The main goal of this work is to compare the experimental results with the predictions of the TRACE code and to analyze the set of phenomena that take place in the primary and secondary loops.

The work has been organized as follows; section 2 is devoted to study the facility model and the boundary conditions. In section 3 we study the transient sequence and we compare the TRACE results for the main physical magnitudes with the experimental data. Finally, section 4 contains the main conclusions of this study.

2. INITIAL AND BOUNDARY CONDITIONS

2.1 Description of the PKL facility

The experiment PKL III F 1.2 was performed in the PKL facility that reproduces, as displayed in figure 2.1, a four loops 1300 MWe PWR scaled with a factor of 1:145 in volume, and power. The PKL facility is scaled 1:1 in height. The facility contains all the components of the primary system denoted as (1) pressure vessel, (2) downcomer, (3) steam generators, (4) primary pumps, (5) pressurizer. As displayed in figure 2.1 the facility has four primary loops.

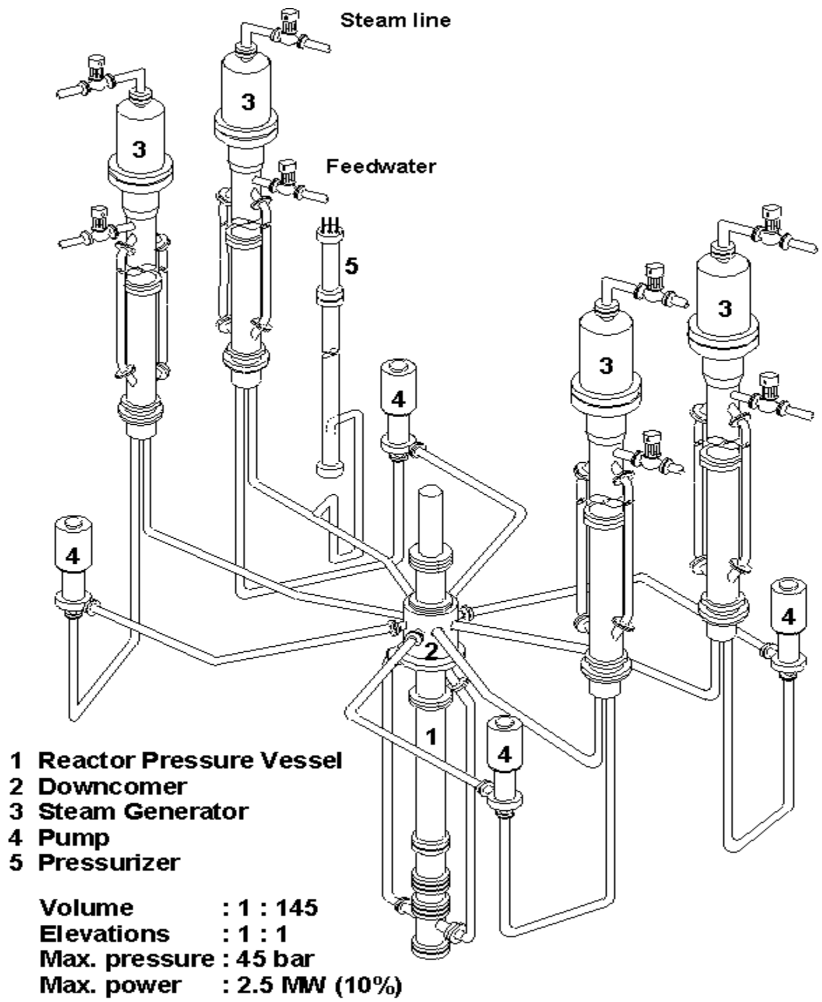

Figure 2.1 Primary system of the PKL-III facility.

The special characteristics of this facility are:

I) Four loops symmetrically arranged around the pressure vessel.
II) Identical lengths of the pipes connecting the same components in the four loops, and identical friction losses
III) The connexions of the hot and cold legs to the reactor vessel are located at the same height.
IV) The upper part of the reactor vessel downcomer modelled as a ring.
V) The modelling of a power plant with three loops is performed isolating one of the four loops.

The mass inventory in the primary circuit of the PKL-III facility at 100% of its capacity is 2500 kg, this amount of water is enough to fill the pressurizer up to a height of 1.3 meters with an average density in the primary circuit of 890 kg/m^3. The heat losses of the primary circuit at 250 ºC of temperature are 86 kW.

The actual design of the PKL III facility allows the simulation of accidental scenarios under symmetrical and non-symmetrical conditions, and the research on individual effects of multiple failures. The laboratory performed several modifications in the original PKL facility to adapt it to a Westinghouse PWR design.

The PKL facility is equipped, in the primary and secondary circuits, with all the important operational and safety systems of the original plant design displayed at figure 2.2. These safety systems are:

In the primary circuit:

- Four independent safety injection systems at high and low pressure, which are connected to the hot and cold legs:
    - Removal system of residual heat
    - 8 Accumulators
    - Pressure control system (pressurizer)
    - Volume control system

Secondary circuit:

- Main steam lines with all the characteristics of the original system (the condenser and the turbine are not simulated)
- Feed water system
- Emergency feed water system
- Depressurization system

2.2 <u>Fundamentals and goals of the injection experiments with borated water</u>

2.2.1 General information on the heat transfer and circulation regimens during a SBLOCA

During a SBLOCA transient the mass inventory in the primary system depends on the break size and the number of systems available for emergency cooling. Therefore, we will have different heat transfer mechanisms along time in the core, and in the steam generators, depending on the mass inventory and the enthalpy of the cooling water. If the primary system is practically full with sub-cooled cooling water, then the heat transfer regime to the secondary will be single-phase natural circulation. Then, it stars the production of steam in the reactor core channels when we reach saturation conditions in the primary. After some time, a two-phase natural circulation regime is established. If the primary system continues loosing cooling water through the break, then after a certain time, it is produced the phase separation in the upper part of the inverted U tubes (∩) . This fact causes the stop of the natural circulation and the system enters into the reflux condenser mode. This means that the steam produced in the core flows toward the steam generators, where it condenses. Then, the condensate flows toward the pressure vessel though the hot or cold legs, depending on the position where the steam has condensed inside the tubes. During this operational mode, the removal of the core decay heat to the secondary is assured unless while the level of the two-phase mixture covers the upper reactor core level. We must also consider the fact that the condensate from the steam generators is free of dissolved boron, and bags of low-borated water can accumulate in the seal pump of the cold leg.

If the pressure of the primary system continues decreasing with time, then because the amount of coolant discharged through the break is smaller than the amount of coolant injected through the emergency cooling systems (ECCS), then it is possible to re-establish again natural circulation conditions. While it continues the refilling of the primary system and before the re-establishment of the natural circulation, the condensate, with de-borated water contained in the pump seal, will be transported first in the opposite direction of the ordinary flow, i.e. toward the steam generator exit. Nevertheless, when the natural circulation is re-established, these slugs of condensate are transported in the ordinary direction of the flow, i.e. toward the reactor pressure vessel. The amount of low-borated water that enters into the reactor core will depend on the amount of condensate that is formed and stored during the reflux condenser phase and how this low borated slugs mixes with the borated water in the downcomer and the lower plenum.

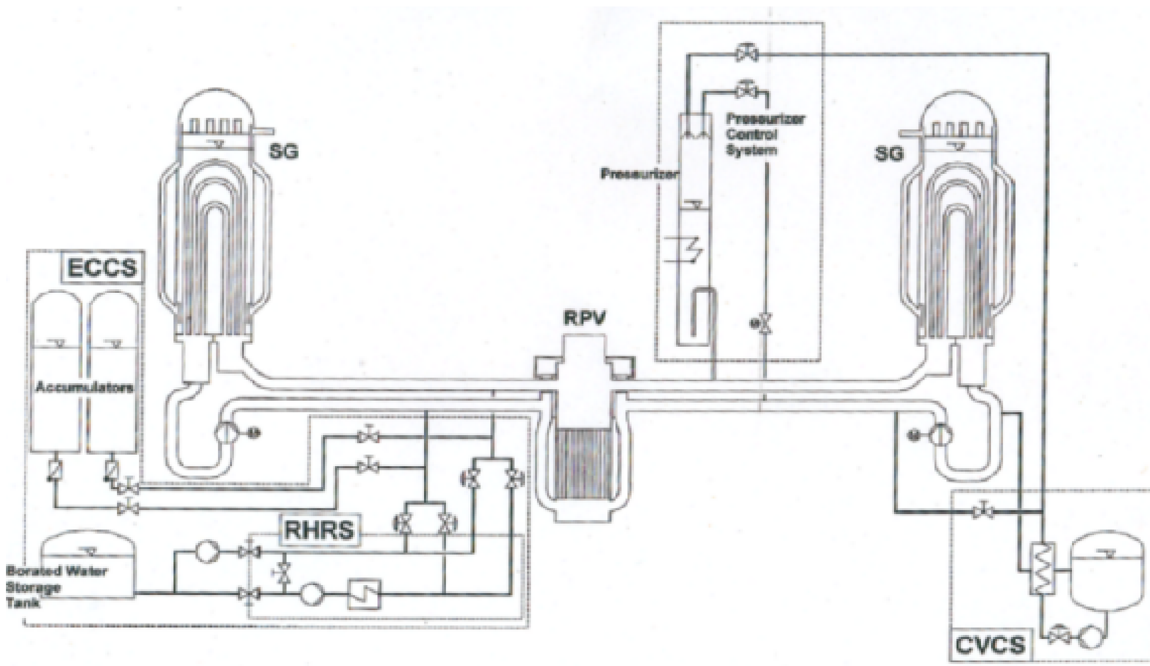

Figure 2.2 Configuration of the safety system of PKL facility.

2.2.2 Specific goals of the F1.2 experiment.

The experiments of the PKL III series have shown that one of the conditions to have an accumulation of non borated water in the pump seal is to have a small inventory of coolant in the primary system. In other words, it has been observed a continuous accumulation of non borated water in the pump seals only when the water level at the exit side of the steam generator drops below the tube sheet. For higher levels of water inside the steam generator tubes, it was not possible the accumulation of condensed non-borated water in the pump seal. In this last situation, it exits a discontinuous transport of borated water from the inlet to the outlet of some of the U tubes of the steam generator, and obviously, this has an influence on the boron concentration in the pump seal. The water inventory is, in this last case, too big to have reflux condenser conditions in all the tubes. This effect has been observed not only during the phase of inventory reduction in the primary system but also during the beginning of the refilling phase, when most of the U tubes of the steam generator were empty.

The consequence of these observed phenomena is that the size of any condensate slug is limited by the volumes of the pump seal and the pipe connecting the exit of the SG with the pump seal.

Therefore, we must exclude any additional accumulation of non borated condensate inside the SG tubes. The condensing process and the transport of coolant inside the SG tubes dominate the phenomena explained in this section, and also we must consider the heterogeneous behaviour of the different tubes of the SG. This means that not all the SG tubes behaves in the same manner, i.e. in some of the tubes we can have reflux condenser conditions while in others we can have transport of two-phase mixture.

One of the main goals of the experiment F 1.2 is to improve our understanding of the physical processes that we have mentioned above, and to analyze the parameters that have a relevant influence on the system behaviour. The F 1.2 experiment have been planned in order to perform a parametric study about the importance of the water inventory inside the steam generators on the accumulation of non borated water in the pump seal. This research was conducted as a validation tool for thermal-hydraulic codes.

Therefore, the main goals are to know the maximum size of the non borated slugs that are formed in the pump seals and the minimum boron concentration inside these slugs when the water levels are maintained above the sheet of the SG tubes.

2.3 Initial and boundary conditions for the experiment PKL III F 1.2, comparative analysis with TRACE model initial conditions

2.3.1 Initial conditions

The experiment PKL III F 1.2 did not have a conditioning phase as in earlier experiments. For the test phase, the experiment starts from the initial conditions displayed at tables 2.1 and 2.2. The primary circuit was filled with sub-cooled coolant at the beginning of the test stage, which flows through the loops and core in single-phase natural circulation regime. The boron concentration was homogeneous in all the primary circuit with a value of 2000 ppm. The pressure in the primary system was 12.0 bar, the fluid temperature at the core exit was 184 ºC and the primary mass inventory was 2500 kg. The secondary pressure in the SG at the beginning of the test stage was 5.9 bar with a collapsed level of water in the SG of 12 m.

Table 2.1 Primary initial conditions at t=0 for the experiment PKL III F 1.2. The primary system is full of sub-cooled water flowing in single phase natural circulation regime

Coolant inventory	2500 kg
Boron concentration	2000 ppm in all the primary loops
Heating power of the rods	600 kW (1.8%)
Pressure	12.0 bares
Fluid temperature at the core exit	184 ºC
Subcooling temperature at the core exit	4 K
Coolant temperature in the pressurizer	189 ºC
Water level in the pressurizer	1.3 m
Flow conditions	Single phase natural circulation in the four loops

Table 2.2 Initial conditions in the secondary of PKL III facility at the beginning of test F 1.2

Steam pressure in the 4 steam generators	5.9 bar
Steam temperature in the four steam generators	158 ºC
Water collapsed level in the four steam generators	12 m
Feed water temperature	115-120 ºC

The TRACE input-deck model for the PKL facility was provided to the authors of this study by the Polytechnic University of Catalunya (UPC), the nodalization of this model is displayed in figure 2.3. To obtain the initial conditions for the experiment PKL III F 1.2, we performed a conditioning phase with the TRACE code. Also we performed a set of modifications in the input-deck model in order to comply with the boundary conditions of the F 1.2 experiment. The initial conditions of the model provided by UPC were a pressure in the primary system of 41.5 bars, with single phase natural circulation and a liquid temperature of 500 K. The secondary pressure in the UPC model was 28.5 bars, and in this way the secondary acts as a heat sink. The power in the primary was set to 600 kW and the mass inventory in the primary was 2500 kg. To achieve the initial conditions required by the experiment F 1.2, we performed a depressurization in the secondary at a constant rate until we achieve the desired initial conditions of the experiment, this phase lasts 9600 s. At the end of this conditioning phase, we have practically the desired initial conditions as displayed in table 2.3. The figure 2.4 displays the initial conditions at the beginning of the experiment, and the degree of sub-cooling in the different parts of the primary circuit.

We observe that at the beginning of the experiment the pressurizer is practically empty of coolant fluid. The degree of sub-cooling at the beginning of the transient in the cold legs, in the downcomer and in the lower plenum is bigger than 20 K. The steam generators are full of coolant water up to a height of 12 meters that cover completely the U tubes.

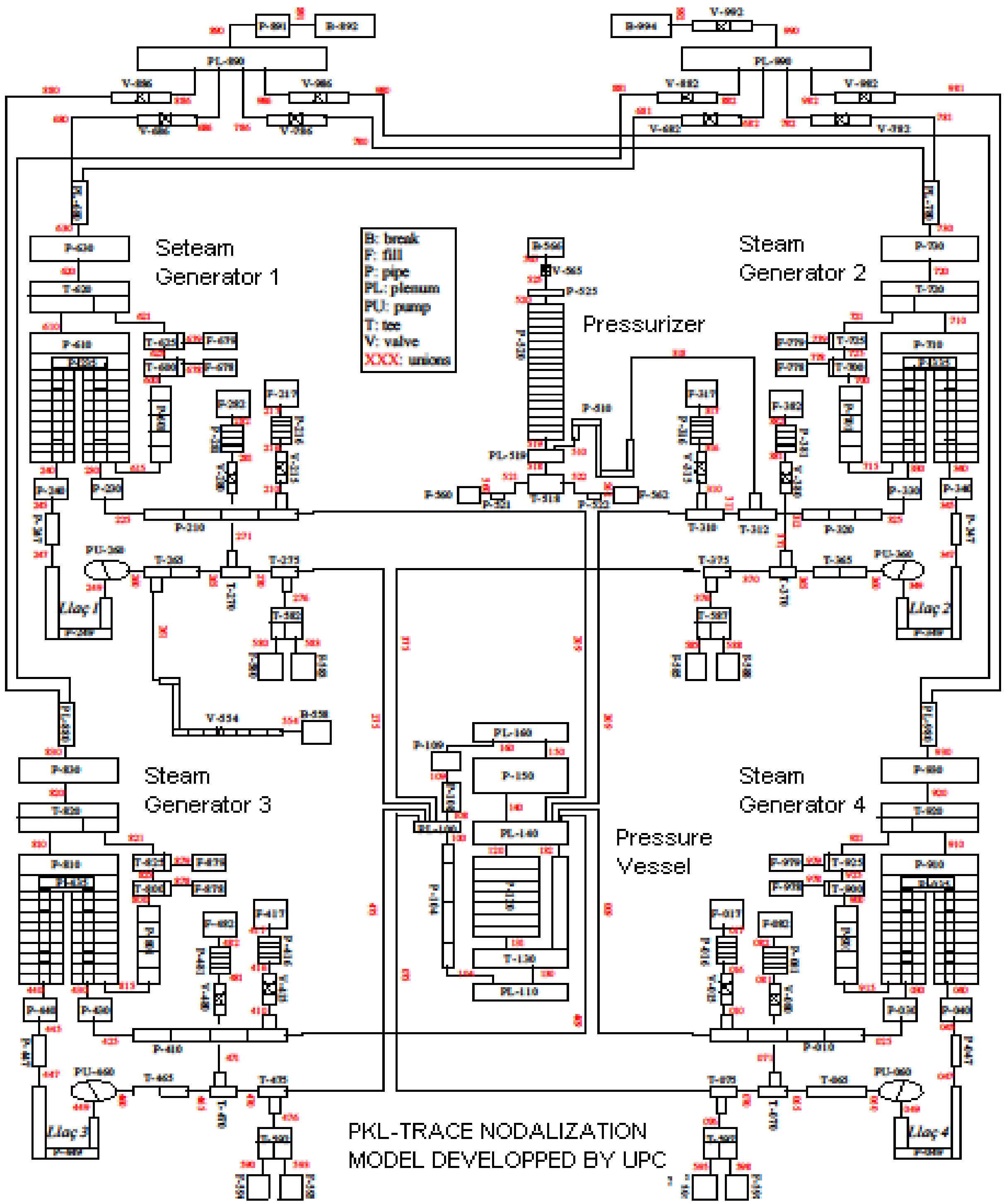

Figure 2.3 TRACE model developed by the Polytechnic University of Catalunya and that was used as starting point to model the PKL-III facility.

Table 2.3 Comparison of the initial conditions of the PKL III facility for test F 1.2, and the data computed with the TRACE model at the beginning of the transient

Physical Magnitudes	Initial Conditions for Test PKL III F 1.2	Initial conditions in TRACE
Coolant inventory	2540 kg	2500 kg
Power of the heating rods	600 kW	599.1 kW
Pressure in the core	12 bar	12.16 bar
Fluid temperature at the core exit	184ºC (457.15 K)	182ºC (455 K) Component 120 cell 7
Natural circulation mass flow rate	1.2 kg/s per loop	1.16 kg/s per loop
Secondary pressure	6 bar	6.2 bar Component 610-cell 9 Secondary-SG.
Secondary Temperature	158ºC (431.15 K)	157ºC (430.15 K) Component 610-cell 9 Secondary-SG
Pressure at the exit of the steam generator in the main steam line	5.9 bar	5.83 bar Component 612-cell 2

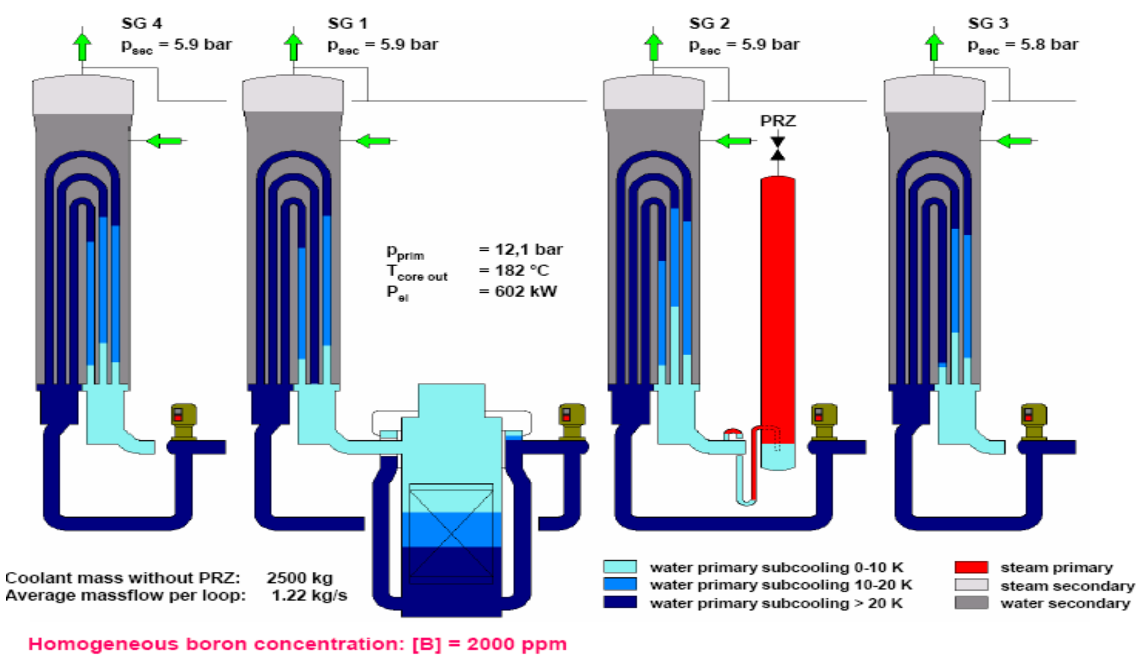

Figure 2.4 Coolant distribution at the beginning of the F 1.2 experiment. The blue colour shows the liquid distribution while the red colour shows the steam distribution.

2.3.2 Sequence of events and procedures during the PKL III F 1.2 experiment

The experiment F 1.2 started with single-phase natural circulation conditions in the four loops. During the transient, the secondary pressure was controlled by opening and closing manually the relief valves, with the goal to maintain the pressure in the primary circuit at the desired level. At the 1300 s of the beginning of the transient the main steam valve was partially closed, which produced an increase of the pressure in the secondary. This increase in the secondary pressure reduced the primary to secondary heat transference and the primary pressure started to increase. At time 3800 s from the beginning of the transient we attained saturation conditions at the core exit and we started to accumulate steam in the vessel head. After the first accumulation of steam in the upper head of the vessel, the operators closed at time 4650 s the pressurizer isolation valve located in the purge line. Then a set of coolant draining stages began, followed by quasi-stationary states (stages without draining). Table 2.4 displays the sequence of events during the draining phase of this experiment.

Other boundary conditions considered during the F 1.2 test are:

- The LPIS system was not available
- The HPIS system was not available
- The accumulators were not available
- The RHRS system was not available
- The recirculation pumps (RCP) were stopped
- The butterfly valves of the RCP, were closed to simulate the hydraulic resistance of the RCP pumps.
- The system CVCS was modified in order to use it to increase the coolant inventory. Injecting cold water with a 2000 ppm concentration of boron water into the lower plenum.

Table 2.4   Sequence of events in the F 1.2 experiment

Time (seconds)	Events	Inventory of coolant in the primary system (kg)
0	Starting of the test	2500
1300	Partial closing of the MSV and the secondary pressure starts to increase	2500
3800	The saturation temperature at the core exit is attained	2495
4650	Isolation of the pressurizer	2415
5100	Steady state	2415
5850	Start of draining	2415
6100	End of draining	2365
6890	Start of draining	2365
7350	End of draining	2240
9660	Start of draining	2240
10150	End of draining	2110
13150	Start of draining	2110
13850	End of draining	1990
19500	Start of training	1990
20300	End of draining	1860
22300	Start of draining	1860
23150	End of draining	1730
25300	Start of draining	1730
26150	End of draining	1605
28360	Start of draining	1605
29200	End of draining	1470
32620	Start of draining	1470
33450	End of draining	1310
37250	Start of draining	1310
38100	End of draining	1120
40410	Start of draining	1120
41200	End of draining	935
44150	End of the data file of the day 8, and beginning of the data file of day 9	935
45690	Start of draining	935
46850	End of draining	810
49880	Start of draining	810
51100	End of draining	685
53050	Start of the coolant injection test	685

3. POST TEST RESULTS WITH THE TRACE CODE OF THE EXPERIMENT PKL III F 1.2

3.1 Conditioning phase with the TRACE code

As we mentioned earlier in this experiment there is not conditioning phase, table 2.3 displays the results obtained with the TRACE code when we simulate the beginning of the experimental phase. In our case, as we mentioned earlier, we departure from a PKL model for TRACE provided by UPC, with initial and boundary conditions different from the conditions of the F 1.2 experiment. To attain the experimental conditions of the F 1.2 experiment, we modified these boundary conditions according to the test data provided by the experimentalists and then we performed a preconditioning phase that consisted in a cooling by reducing the secondary pressure at a constant rate. At the end of this preconditioning phase we attained the conditions displayed in table 2.3, that are very close to the initial conditions for the experiment F 1.2. It is remarkable the good agreement between TRACE results and the experimental data for the natural circulation mass flow rate at the beginning of the experimental phase. In this case the prediction of TRACE code was 1.16 kg/(s loop) while the experimental data was 1.2 kg/(s loop).

The small difference in the power displayed at table 2.3 was produced by the fact that in the UPC model there was a small source of 1 kW of heat in the vessel head. This negligible source heated the steam accumulated in the vessel head much above the saturation temperature and gives problems during the test execution. To solve this problem we reduce this heat source to a value of 0.01 kW.

3.2 Results with the TRACE code for the experiment F 1.2

We have performed the analysis with the TRACE code for the phase of successive coolant extractions through the lower part of the vessel until the natural circulation in the primary circuit is completely stopped performed during the experiment F 1.2. We have simulated a total time of transient of 37400 s, plus the 9600 s of the pre-conditioning phase. When the natural circulation stops, the system enters in reflux condenser conditions and the TRACE code uses a very small integration time step of 10^{-4} s, and because it is necessary to perform a manual adjustment of the relief valve stem position (valve area) in order to maintain the primary pressure at 12 bar, then the time necessary to perform this adjustment with this small time step becomes very long. For this reason we decided to simulate only the first phase of the transient until the natural circulation in the primary was stopped completely.

We will give the total time that include the 9600 s of preconditioning phase in TRACE code, and between brackets the experimental time. The transient starts with natural circulation conditions with a mass flow rate of 1.2 kg/(s loop). Then a set of extractions that lasts from 750 to 850 s are performed through the lower part of the reactor vessel. Following each extraction, we do not purge the vessel for a variable period that lasts from 2500 to 4500 s, during this time the system attains quasi-stationary conditions. The coolant draining performed during the first five extractions promotes an increase in the natural circulation mass flow rate of the primary, that rises from 1.2 to 3 kg/s per loop, this change is very well predicted by the TRACE code, although the rise starts earlier in time. This increment in the mass flow rate per loop is produced because we pass from single-phase natural circulation regime to two-phase natural circulation due to the reduction of the coolant inventory in the primary, and to the transference of heat from the rods to the coolant in the reactor core. This causes an increase of the natural circulation driving force produced by the difference of densities between the cold and hot legs. If the coolant extraction through the core lower part continues, then after the sixth extraction, at t=32600 s (23000 s), starts a progressive reduction of the mass flow rate circulating through the primary. This decrease in the circulating mass flow rate is produced by the fact that the successive inventory reductions increase the void

fraction not only in the hot leg but also in the cold leg. Therefore, the difference of density between the hot and cold legs decreases and this causes a reduction of the natural circulation driving force, until a point where the natural circulation is completely stopped. This happens at time 47000 s (37400 s), from that moment the time step in the TRACE code becomes very small, around 10^{-4} s.

The first magnitude that will be analyzed will be the pressure evolution with time. We observe at figure 3.1 that the primary pressure is kept more or less constant during this phase of the experiment, except when we perform an extraction. During each extraction we observe that the pressure diminishes to recover after a certain time. The pressure reduction is produced by the reduction of coolant inventory, and the recovery that follows is due to the transference of heat to less mass inventory (higher specific enthalpy), and the reduction of heat transference from the primary to the secondary through the SG due to the increase of the pressure in the secondary, which is produced by manually partial closing the relief valves.

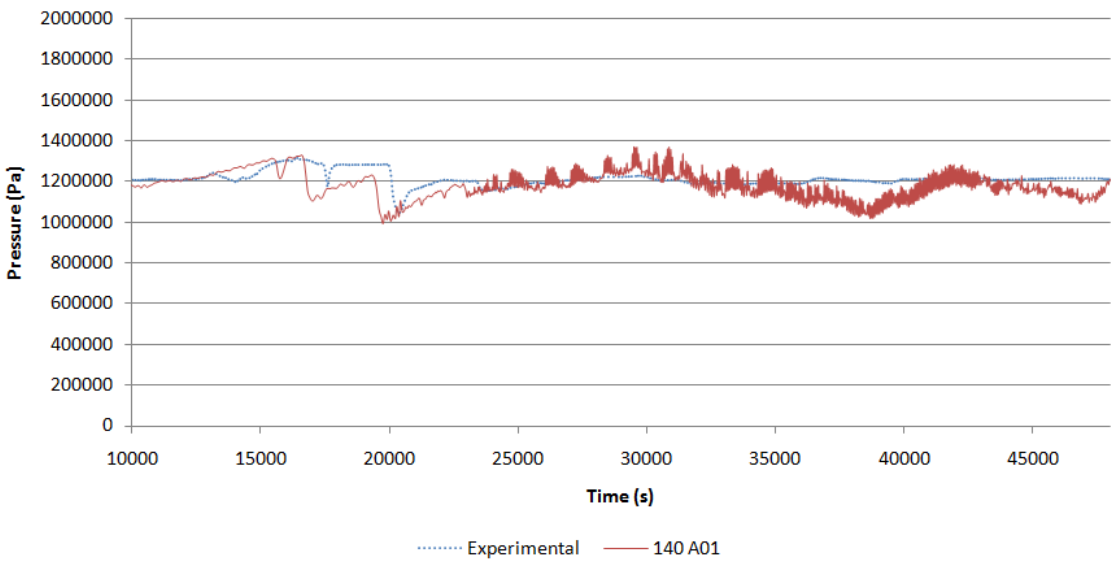

Figure 3.1 Pressure evolution at the core exit. The experimental results are displayed in blue, and the TRACE results in red.

When figure 3.1 is observed, we notice that approximately at time t=19260 s (9660 s), the pressure diminish faster than in previous extractions, after that the pressure recovers again. This fact is produced by a coolant draining that begins at that time 19260 s and ends at 19750 s (10150 s). The recovering of the primary pressure is due to the partial closing of the relief valve in the secondary in order to increase the pressure in the primary. The main difficulty in simulating this transient is to know how much is necessary to close the relief valve to raise the pressure in the primary to the previous level of 12 bar. When the mass inventory in the primary diminishes, these adjustments in the relief valve area are more difficult to be performed because the pressure reacts with bigger changes to smaller changes in the relief valve flow area.

The evolution of the steam and liquid temperatures in the hot leg along the transient are displayed at figures 3.2 and 3.3, we notice that these variables are well predicted by the TRACE code and that its evolution with time is similar to the pressure evolution.

The evolution of the secondary pressure is displayed in figure 3.4. We observe that the secondary pressure increases continuously from 5.9 bar to about 10 bar in about 15000 s, then the secondary pressure remains constant during the rest of the transient. As we explained earlier, the continuous closing of the relief valves performed during the draining steps produces this rise in the

secondary pressure. As we can see in figure 3.4, the secondary pressure is approximately predicted by the TRACE code.

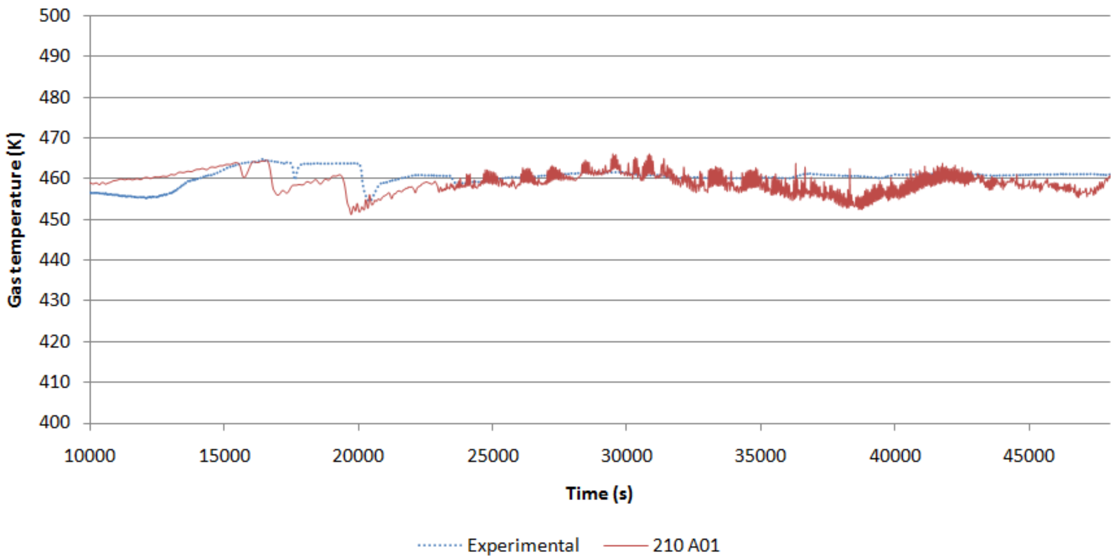

Figure 3.2 Evolution with time of the steam temperature in the hot leg of the second loop. The blue line denotes the experimental data while the red line denotes the TRACE simulation.

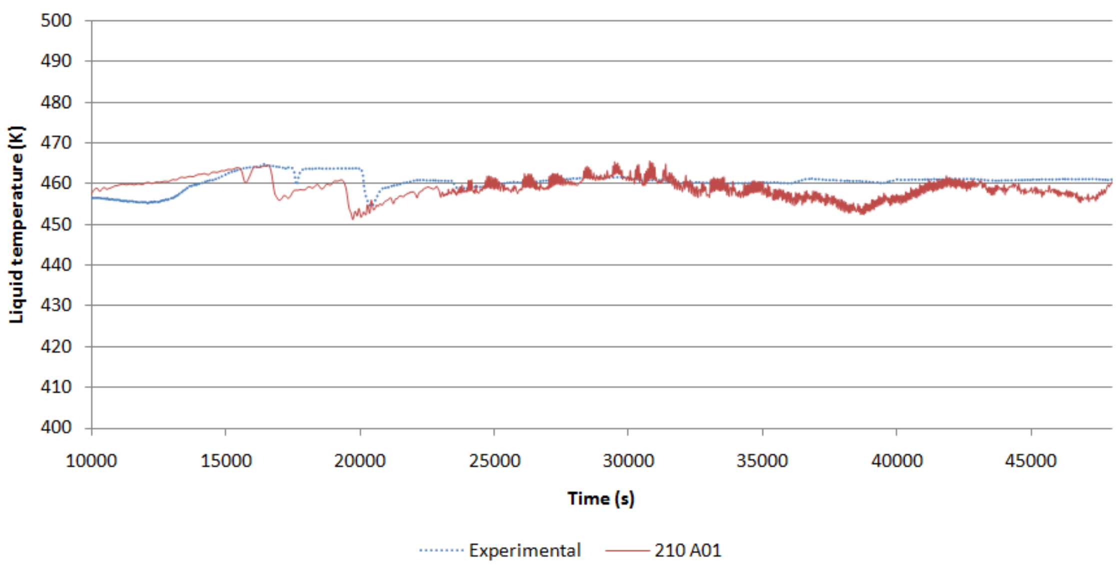

Figure 3.3 Evolution with time of the liquid temperature in the hot leg of loop 2. The blue line displays the experimental results.

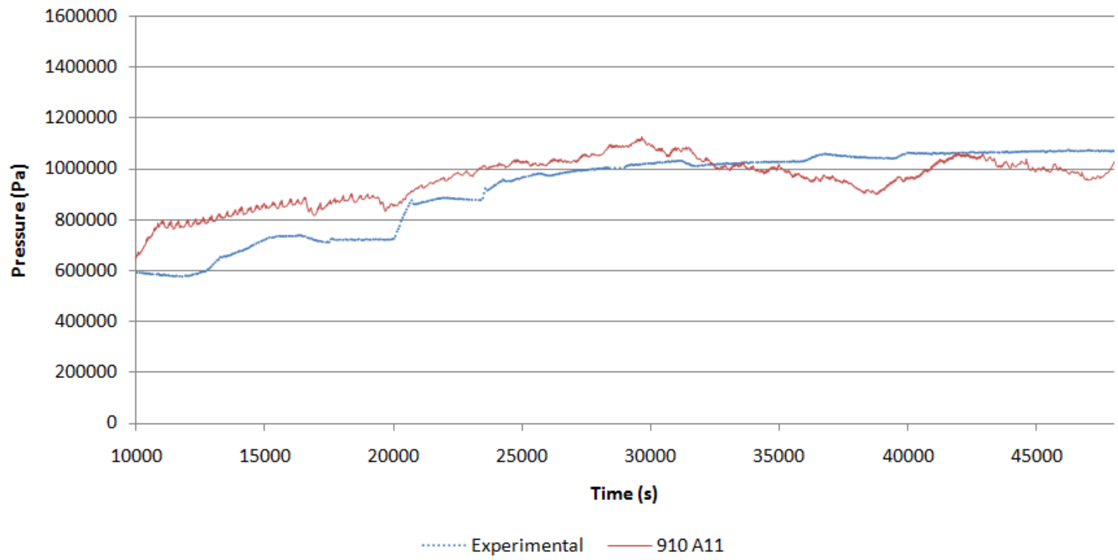

Figure 3.4 Pressure versus time at the exit of the secondary of the steam generator in the four loop.

Next, we are going to comment the evolution along the transient of the natural circulation mass flow rate in loops 1 and 3. In figure 3.5 we display the mass flow rate evolution in loop 1, and in figure 3.6 we display the mass flow rate evolution in loop 3. We observe that at the beginning of the transient the mass flow rate is 1.21 kg/(s loop) in both loops, that is very well predicted by the TRACE code, that gives practically the same value. From time 10000 s (400 s), to time 20000 s (10400 s) the experimental mass flow rate remains constant and at time 20000 s the mass flow rate rise suddenly from 1.2 to 2.3 kg/(s loop). The TRACE code gives a good prediction of the evolution of the mass flow rate during this time interval, the only difference is that at around 16000 s the mass flow rate rise from 1.26 to approximately 2.0 kg/(s loop), and then at t=20000 s rise again to 2.6 kg/(s loop). Therefore, the TRACE code predicts very well the increase in the natural circulation mass flow rate due to the increase of the void fraction in the core and in the hot leg. However, the mass flow rate starts to increase earlier in the TRACE code than in the experiment. Then, at time 23400 s (13850 s) the experimental mass flow rate rises again due to the fifth extraction and attains its maximum value of 3.1 kg/(s loop). This value is very well predicted by the TRACE code that gives the same value, i.e. 3.1 kg/(s loop), however the TRACE code displays bigger oscillations than the ones observed experimentally.

Then, at time 30000 s (20400 s), due to new extractions starts to diminish the natural circulation mass flow rate due to the appearance of some void fraction at the exit side of the U tubes of the steam generator. The progressive extractions of coolant increase more the void fraction in the cold leg. And at time 50000 s (40400 s), the void fraction predicted by the TRACE code in the pipe connecting the steam generator exit with the pump seal is 0.9, this means that the void fraction is very high also in the cold leg, and the driving force for the natural circulation becomes very low and the natural circulation flow stops. The TRACE code predicts that at time 50000 s there is not natural circulation flow in loop 3, this result match the experimental one as displayed in figure 3.6.

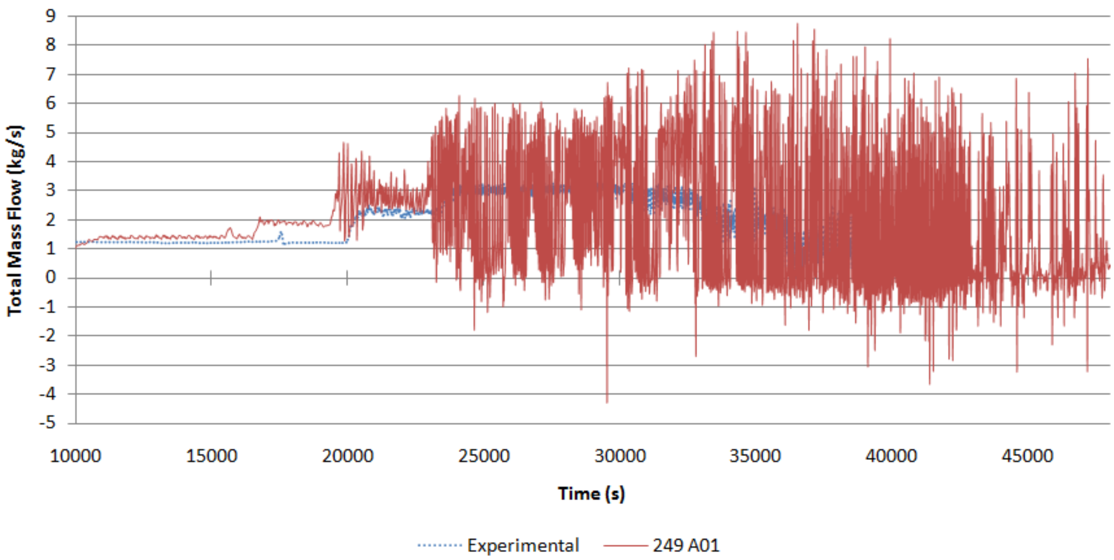

Figure 3.5 Mass flow rate in kg/s versus time in the recirculation pump seal (cell 1, component 249) of the first loop.

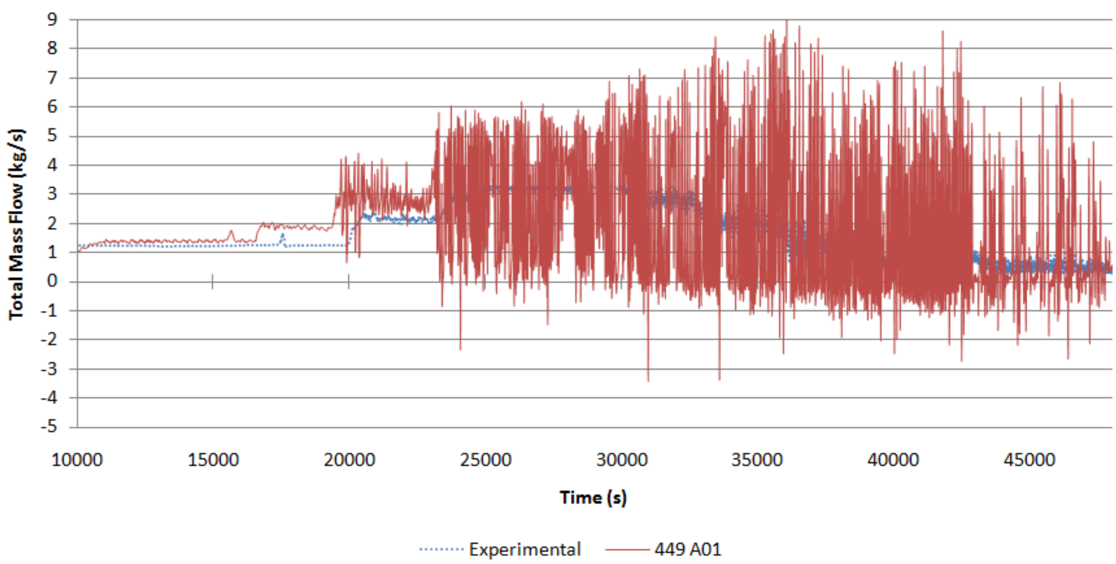

Figure 3.6 Mass flow rate in kg/s versus time in the recirculation pump seal (cell 1, component 449) of the third loop.

Another parameter to analyze is the boron concentration at the pump seal and at the exit of the steam generator. In this case, it is observed in figure 3.7 that the boron concentration remains constant for the first 43000 s (32400 s) and then diminishes for 300 s, to recover again to its initial value of 2000 ppm, this small change in the boron concentration is reproduced by the TRACE code. At the end of the natural circulation period, the steam generator enters in reflux condenser conditions and starts the accumulation of condensate in the pump seal.

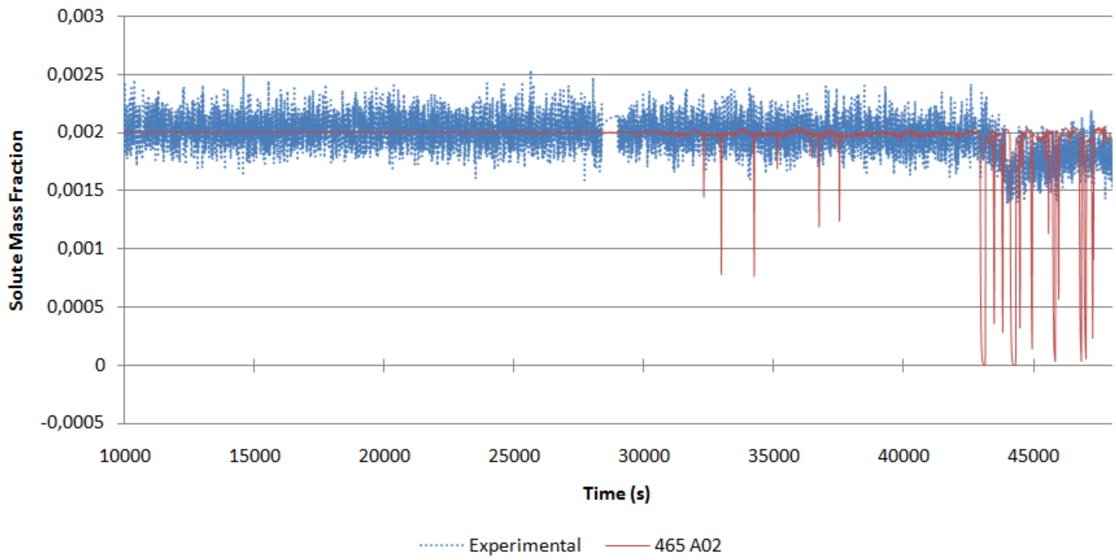

Figure 3.7 Boron concentration in mass fraction versus time in the pump seal of the loop number 3.

Next, we are going to perform a study of the void fraction evolution in the different components of the PKL III facility during the phase of successive extractions performed in the Test F 1.2. In the steam generator the void fraction start to rise in the upper part of the U tubes at time 18000 s (8400 s), but the first noticeable increase in the void fraction is produced at time 23000 s (13400 s), when the void fraction attains a value of 0.55, as it is displayed in figure 3.8. This increase in the void fraction is also produced at lower levels, but the void fraction attains logically smaller values as displayed in figure 3.9, where the void fraction at time 23000 s (13400 s) rise to 0.35. While, at the entrance of the U tubes (cell1) the void fraction is still lower at the same time and equal to 0.3, as displayed in figure 3.10. Therefore, a big part of the void fraction at the different levels of the SG is due to the steam produced in the core, only in the upper part of the U tubes the higher value of the void fraction is produced by a smaller collapsed water level produced by a smaller water inventory. The next important increase in the void fraction in the SG upper level is produced at time 33000 s (23400 s), when ends the sixth extraction, in this case it is produced a bigger increment in the void fraction that rises above 0.9. This new increase in the void fraction is produced by the fact that the collapsed liquid level has decreased as result of the successive extractions, what is noticed mainly in the upper part of the steam generator. However, in the hot leg the void fraction increases progressively, with the successive extractions as displayed in figure 3.11 and at time 33000 s (23400 s) is equal to 0.5 that agrees with the value at the entrance of the steam generator.

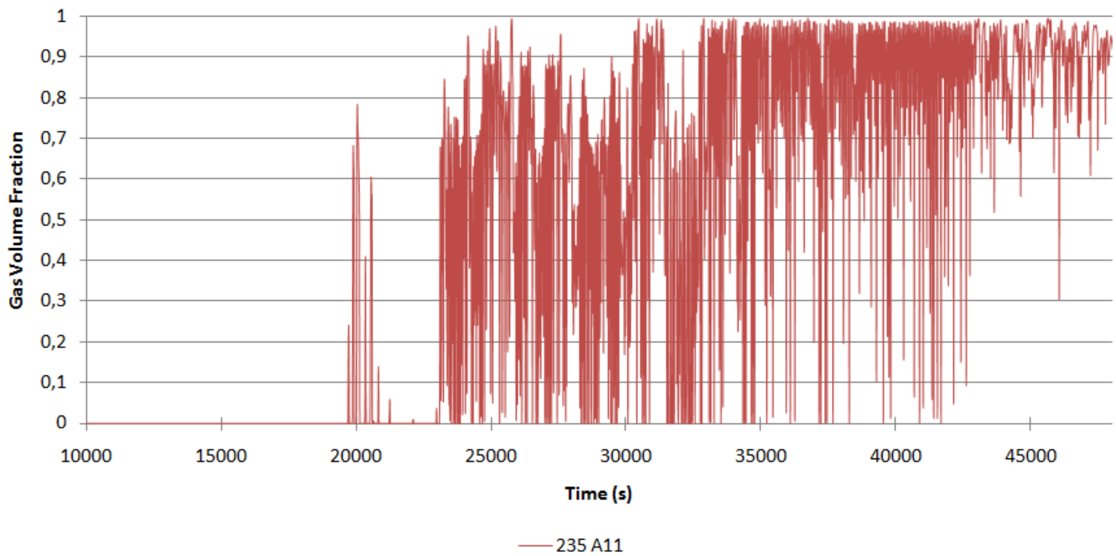

Figure 3.8 Void fraction versus time in cell 11 (Upper level) of the steam generator 1.

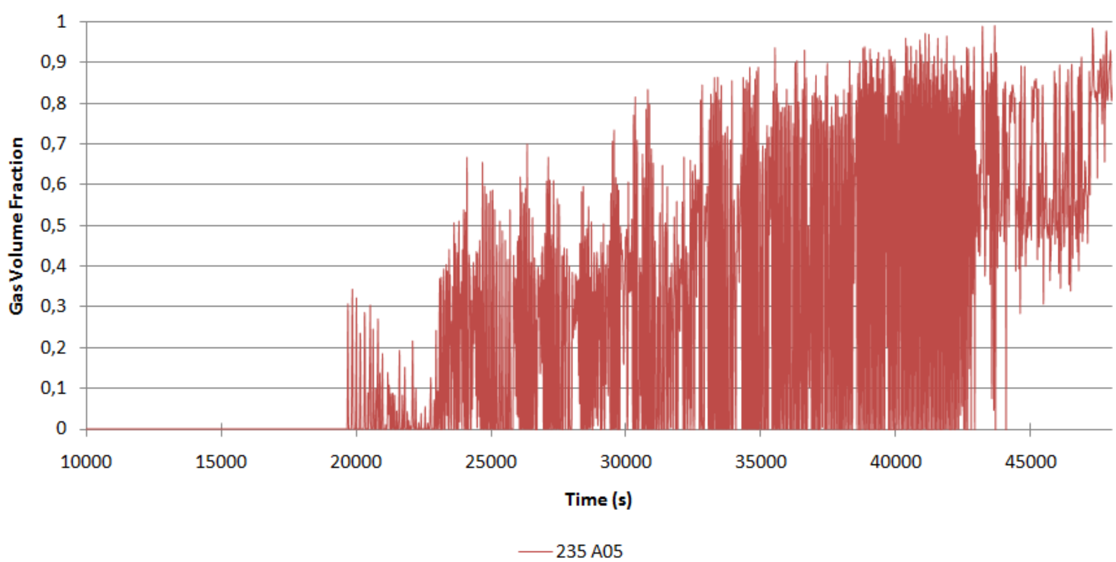

Figure 3.9 Void fraction versus time in cell 5 (intermediate level) of the steam generator 1.

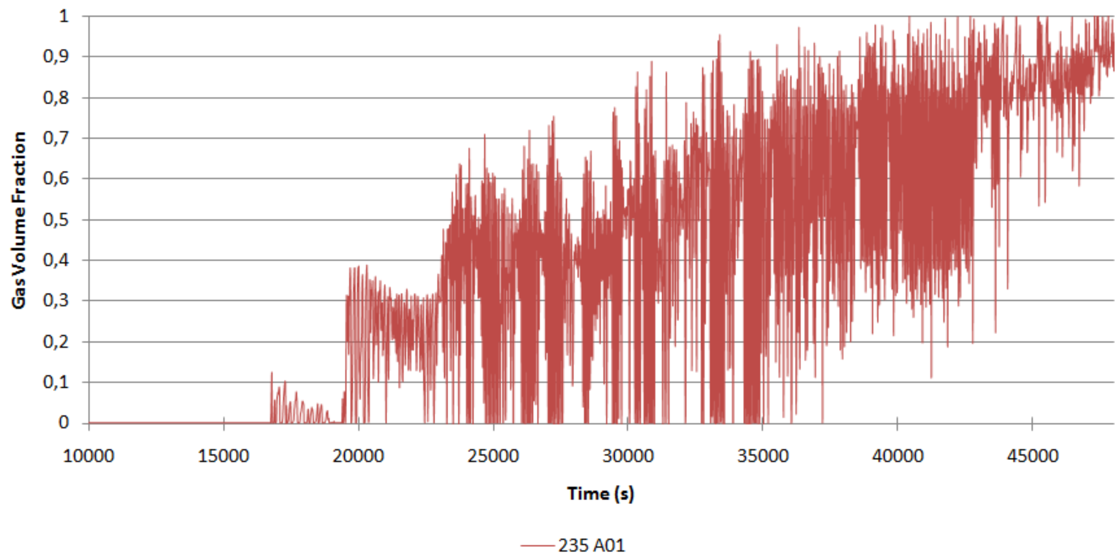

Figure 3.10 Void fraction versus time in the lower part of the SG primary in loop 1.

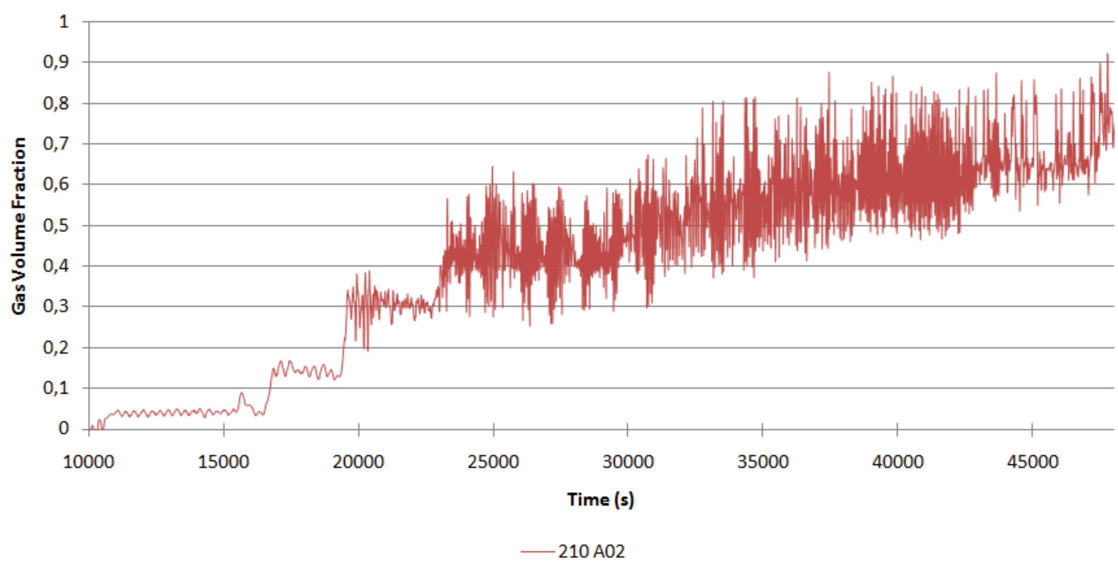

Figure 3.11 Void fraction versus time in the hot leg of loop 1 at component 210.

Concerning the time evolution of the void fraction in the cold leg, displayed in figure 3.12 for loop 1, we notice that in spite of the successive extractions performed trough the vessel lower part, the steam generator acts as a heat sink and it condenses the steam, and as a consequence the void fraction in the cold leg is negligible until time 40000 s (30400 s), only when the mass inventory is very small start to increase the void fraction in the cold leg. At the end of the natural circulation the void fraction in the cold leg rises to 0.9.

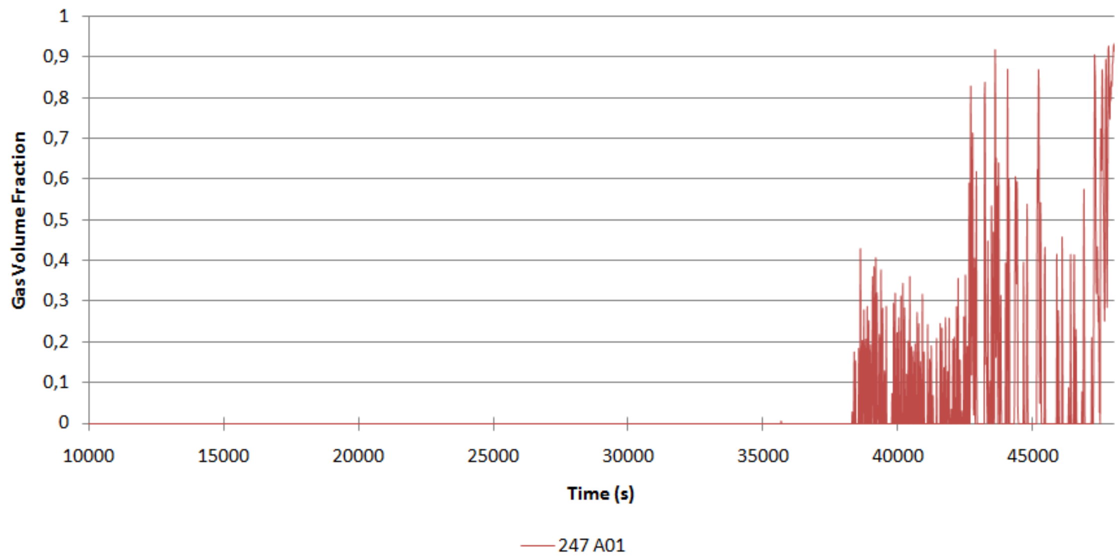

Figure 3.12 Void fraction versus time in the cold leg of loop 1 at component 247.

We also notice that when is finishing the natural circulation stage and we are entering into the reflux condenser mode, the condensate start to accumulate in the pump seal at the cold leg, and the void fraction start to diminish in the RCP seal (Component 249) as it is displayed in figure 3.13. The void fraction in the RCP seal becomes very small at time 47000 s as displayed in figure 3.13.

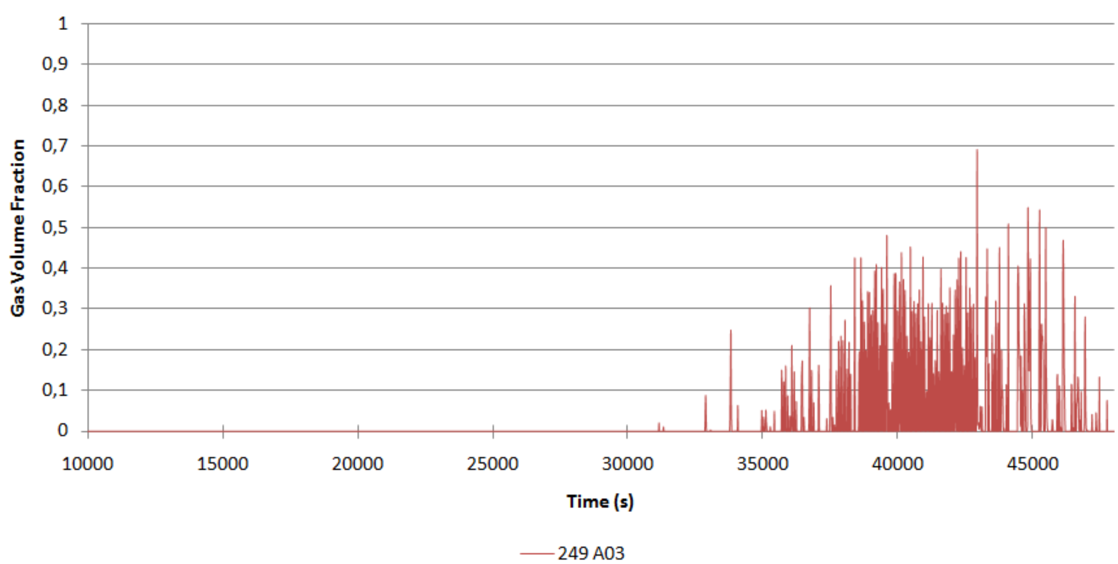

Figure 3.13 Void fraction versus time in the RCP seal, in the cold leg of loop 1.

Concerning the evolution with time of the level of condensed water in the steam generator 1, we notice in figure 3.14, that this level diminish continuously with the successive extractions. The collapsed level evolution in the steam generator is well predicted by the TRACE code, however the code calculations display bigger oscillations than the experimental results. The water level in the steam generator drops from 10.35 m at the beginning of the transient to 1 m at time 47000 s

(37400 s), while the water level predicted by the code at this time is slightly higher, as it is displayed in figure 3.14.

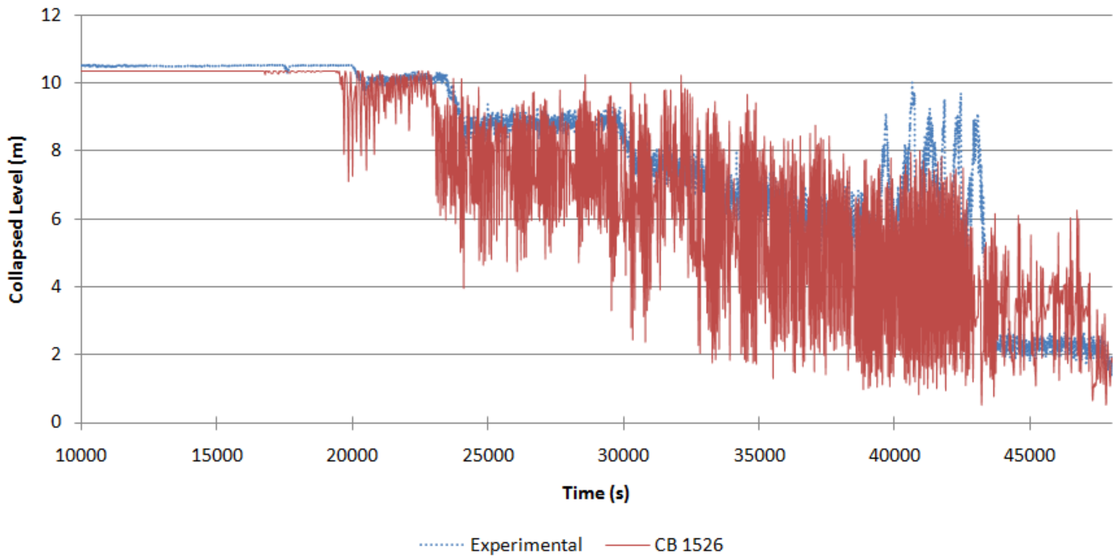

Figure 3.14 Collapsed level of water in the steam generator of loop 1, calculated by the control block 1526.

4. CONCLUSIONS

In this work we have performed a simulation with the TRACE code of the coolant extraction phase during the experiment PKL III F 1.2, until the natural circulation is completely stopped and the system pass from natural circulation regime to reflux condenser conditions. In general we have noticed a good prediction with the TRACE code of the pressure and natural circulation mass flow rate evolutions along this phase of test that last for 37000 s. The experiment consisted in a set of successive coolant extractions performed through the lower part of the reactor vessel, while the primary pressure was maintained constant at 12 bar by adjusting manually the stem position of the relief valve in the secondary. Previous to the test simulation we performed with TRACE a preconditioning phase to attain the initial conditions of the experiment. In table 2.3 we display the initial conditions for TRACE and the initial conditions for the experiment. The initial conditions for both cases in the main thermal-hydraulic variables are very close.

The main conclusions obtained during the analysis of this experiment performed with the TRACE code are:

1) We observe a progressive increase in the natural circulation mass flow rate during the set of extractions that finish at time 23250 s (13850 s). During this interval the natural circulation mass flow rate evolves from 1.2 kg/(s loop), at the beginning of the test, to a maximum of 3.1 kg/(s loop) at time 23000 s (14400 s), this maximum value is well predicted by the TRACE code. The increase of the mass flow rate produced by the successive extractions is due to an increase in the natural circulation driving force, produced by an increase in the void fraction in the hot leg and in the core, while the void fraction remains practically zero in the cold legs and in the cold side of the U tubes. This situation is maintained for a long time 8000 s until time 30000 s (20400 s). At this time start to appear small amounts of steam in the cold legs and in the cold side of the U tubes that reduce the natural circulation driving force.

2) At time 47000 s (37000 s) the mass flow rate is very small, this is produced by the reduction of the mass inventory in the primary circuit, that produces an increases of the void fraction that reach a value close to one in the upper part of the U tubes, that stops the natural circulation through the steam generator. In this situation only flows steam that condenses and we enter into the reflux condenser mode. This reduction in the mass flow rate is well predicted by the TRACE code as displayed in figures 3.5 and 3.6.

3) It is noticed a progressive pressure increase in the secondary, from 6 bar at the beginning of the transient to 10 bar, as displayed in figure 3.4. The reason of this is that when performing the successive extractions in the primary circuit, the operator must maintain constant the primary pressure at a value of 12 bars. To achieve this goal the operator close the steam relief valve in the secondary in order to rise the temperature in the secondary. This fact diminishes the heat transference from the primary to the secondary and as a consequence increases the pressure in the primary system. The TRACE simulation reproduces well this increase in the secondary pressure. Although the main problem is that is not available the flow area of the relief valves versus time, this was obtained by trial and error.

4) The reduction of the natural circulation mass flow rate is observed from time 34000 s (24400 s), and progresses with time. The causative mechanism of this reduction is the appearance of voids in the cold legs as it is displayed in figures 3.12 and 3.13. This increase in the void fraction provokes that the natural circulation driving force diminishes. The TRACE code reproduces pretty well this reduction in the natural circulation mass flow rate, and through the analysis of the void fraction in the hot and cold legs it is possible to understand the origin of the reduction in the mass flow rate.

5) The collapsed level of water in the steam generator is well predicted by the TRACE code, as displayed in figure 3.14. The level decreases with time with periods were the level is practically constant, which are produced by the quasi-stationary periods between successive coolant extractions. During the time interval from 39000 s (29400 s) to 43000 s (33400 s) the steam generator water collapsed level displays big oscillations. Two draining of coolant are performed during this time interval. These draining performed when the mass inventory is small could induce these bigger oscillations of the water level in the steam generator.

6) It is observed in figure 3.13 that when the natural circulation diminishes and we enter in reflux condenser conditions the void fraction in the pump seal decreases to practically 0. at time 50000 s (40400 s). This is produced because the primary system has entered into reflux condenser condition, the natural circulation has stopped, and the condensed water from the steam generator started to accumulate in the RCP seal.

In general we can say that TRACE predictions for this case are very good and the natural circulation mass flow rates are predicted with a great precision in comparison with previous codes

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10. SUPPLEMENTARY NOTES
A. Calvo, NRC Project Manager

11. ABSTRACT *(200 words or less)*
The goal of this report is to explain the main results obtained in the simulations performed with the consolidated code TRACE for the OCDE TEST PKL-III F 1.2. The transient was produced by a set of successive extractions of refrigerant performed through the bottom of the vessel of the PKL-III facility in Germany, after each extraction phase no extraction was performed during a certain time, this no-extraction time was long enough to reach a quasi-stationary state so the new natural circulation conditions could be experimentally observed. Therefore, the goal of this test is to see how the inventory of refrigerant in the primary circuit affects to the natural circulation conditions in the primary circuit and when the natural circulation stops. The experiment had two different parts during the first one were performed a set of extraction of refrigerant followed by no extraction intervals, until a minimum inventory was reached, during this set of extractions and the quasi-stationary periods that followed to each extraction period, the power was maintained constant. The second step of the experiment consisted in a set of injections symmetrical to the extractions, which refilled again the primary system although the total number of refilling steps was smaller than the number of the extractions and therefore the initial conditions were not achieved. The total duration of the experiment was 90000 s, after each extraction step the relief valves of the secondary system were manipulated in order to maintain constant the pressure in the primary system, this was done manually by the operator. In the code simulation, we simulate with TRACE the first 40000 s of the experiment until the natural circulation was completely stopped and the system enters in reflux condenser conditions.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*	13. AVAILABILITY STATEMENT
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