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Post-Test Thermal-Hydraulic Analysis of PKL Tests F1.1 and F1.2

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ABSTRACT

Two different post-test analyses have been performed by making use of the UPC's model of the PKL facility. The nodalization has been developed using the RELAP5mod3.3 code and two tests of the OECD/PKL project, namely Test F1.1 and F1.2, have been simulated. For both transients, the simulations correctly reproduce the finalization of natural circulation and the beginning of the reflux condensation conditions with the consequent formation of low borated water slugs in the loop seals due to the phenomenon of boron dilution.

Test F1.1 is a Small Break LOCA in the cold leg assuming the non-availability of the LPI system and the accumulators while Test F1.2 simulates a series of steady state situations for different primary inventories in order to study the phenomenon of boron dilution as a function of the mass inventory.

Different sensitivity analyses are also reported and the nodalization of the U-tubes bundle is discussed for both scenarios. The results cover the formation of slugs in the loop seals under reflux and condensation conditions and their movement through the loop when the U-tubes are refilled and natural circulation is re-established.

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 codes[1], 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/FAP[2] 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

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).

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 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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This report shows the development and the improvement of the UPC's model of the PKL test facility that has been developed using the RELAP5mod3.3 system code and used for the simulation of the two OECD/PKL project tests F1.1 and F1.2.. For both transients, the simulations correctly reproduce the natural circulation finalization and the beginning of the reflux condensation conditions with the consequent formation of low borated water slugs in the loop seals due to the phenomenon of boron dilution.

In Test F1.1 (Small Break LOCA in cold leg assuming non-availability of the LPI system and the accumulators), the results of a sensitivity calculation shows the influence of the nodalization of the head of the vessel bypass on parameters like downcomer levels and mass flow at the break. Based on the good results obtained, the report also displays graphically the formation of the slugs in the loop seals under reflux and condensation and their movement through the loop during the process of system refilling and start of natural circulation.

In Test F1.2 (simulating various steady state situations for different primary inventories in order to study the phenomenon of boron dilution), a sensitivity analysis on the U-tube nodalization is reported. The conclusion is that the simulation of U-tubes of different lengths is only relevant for transients in which, for a considerable period of time, the water level stabilizes around the middle of the U-tube bundle or experiences very slow variations such that natural circulation may take place exclusively within the shorter U-tubes. In contrast, this development can result in an important increase of computing time for the rest of transients with no improvements to the simulation.

ABBREVIATIONS

Acc	Accumulator
AFW	Auxiliary FeedWater
COMBO	COntinious Measurement of BOron concentration
CVCS	Chemical and Volume Control System
DC	DownComer
ECCS	Emergency Core Cooling Systems
EOP	Emergency Operational Procedure
HPSI	High Pressure Safety Injection
INTE	Institut de Tècniques Energμetiques (Institute of Energy Technologies)
LOCA	Loss Of Coolant Accident
LP	Lower Plenum
LPSI	Low Pressure Safety Injection
LS	Loop Seal
MS	Main Steam
NC	Natural Circulation
NPP	Nuclear Power Plant
OECD	Organization for Economic Cooperation and Development
PKL	Primärkreislauf (Primary System)
PRZ	Pressurizer
PS	Primary System
PWR	Pressurized Water Reactors
RC	Reflux-Condensation
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RELAP	Reactor Excursion Leak Analysis Program
RHR	Residual Heat Removal
RPV	Reactor Pressure Vessel
SBLOCA	Small Break LOCA
SESAR	Senior Group of Experts on Nuclear Safety Research
SETH	SESAR Thermal Hydraulics
SG	Steam Generator
SIP	Safety Injection Pump
SOT	Start Of Transient
UPC	Universitat Politècnica de Catalunya (Technical University of Catalonia)

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1 INTRODUCTION

Safety studies for low power and shut-down conditions of nuclear plants performed in several countries during the last decade directed the interest to accident sequences for which a local boron dilution in the reactor core by a plug of pure water or water of reduced boron concentration might occur. These investigations comprise events during shut-down conditions including event sequences with boron dilution. Also, for loss-of-coolant accidents with small leaks, sequences that involve boron dilution have been identified.

This report presents an analysis of two different PKL experiments. Test F1.1 which represents a small break loss of coolant accident with boron dilution and Test F1.2 which analyses the boron dilution rate as a function of the primary mass inventory.

1.1 Boron Dilution Events

Boric acid is used as a soluble neutron absorber in the primary coolant of pressurized water reactors. The main functions of boric acid are to compensate for fuel burn up and xenon poisoning with the required reactivity margin during normal operation, and to provide the necessary subcriticality of the core during refueling and maintenance. During normal reactor operation, the specified boron concentration is maintained by the volume control system. In case of a loss-of-coolant accident, borated water is injected by the emergency core cooling system (high-pressure safety injection pumps, accumulators, and low-pressure pumps).

Inadvertent boron dilution might occur in two different scenarios:

- Unintentional injection of unborated water from outside the primary cooling system by malfunctions of injecting systems.
- Separation of primary coolant into highly borated water and almost boron-free water by evaporation and condensation.

The first kind of events would progress slowly in normal reactor conditions. In other words, it can be detected and corrected easily. Transients of the second kind could result in event sequences that are more difficult to analyze and constitute a challenge to the analytical methods.

For the event sequences with boron dilution multiple failures of systems are assumed. In scenarios where the primary coolant inventory has been reduced, for example by a small break, and the reactor is shut down, the water evaporates in the core and condensates in the steam generators. Boron is mainly retained in the liquid phase so that the vapor phase and the condensate are almost boron-free. This condensated water totally unborated precipitates to the loop seals. If these conditions are maintained during a long period of time, the loop seals and the cold legs will be full of unborated water; meanwhile the core cooling inventory will be highly borated. These amounts of unborated water form plugs in the primary system. If a later time circulation in the cooling system is re-established either by natural circulation following refilling or by restarting of a main coolant pump, water of low boron concentration may be driven through downcomer and lower plenum into the core giving a reactor supercriticality.

The most important analysis referred to boron dilution events considers a small leak with multiple failures in the emergency core cooling system. Differences between tests are referred to leak size, leak location and the different characteristics and distribution of the emergency injection systems.

1.2 Definitions of Boron Dilution

Rapid boron dilution transients supposes a nonhomogeneous distribution of the boron in the primary system. There could be boron dilution in one part of the RCS although the mean boron concentration is maintained at its normal value. It is clear that for inherent boron dilution two different aspects have to be analyzed as there is normally coolant exiting the RCS (in the case of a SBLOCA) and, therefore the average boron concentration will also vary. It is necessary here to introduce two definitions that will be helpful throughout this paper in order to differentiate two different types of boron reduction involved in rapid boron dilution events:

Boron dilution The process where a local decrease in boron concentration in PS (primary system) occurs

De-boration The process where a net loss of boron from PS occurs that implies a decrease in average boron concentration

In the same way, the following definitions are accepted as well:

Boration The opposite of de-boration
Boron concentration recovery The opposite of boron dilution
De-boration rate The rate of de-boration
Dilution rate The rate of boron dilution

These definitions were first introduced by D'Auria [3] and are nowadays accepted in the international community.

1.3 PKL Test Facility

PKL is an experimental power facility plant designed to simulate pressurized water reactors (PWR) under accidental conditions. The plant, situated in Erlangen (Germany), has been the scenario of several experiments in the last 25 years. The PKL facility replicates the entire primary system and most of the secondary system (except for the turbine and condenser) of a 1300-MW PWR plant, with elevations scaled 1:1 and diameters reduced by a factor of 12. Therefore volumes and power have been reduced by a factor of 145. The number of rods in the core and the U-tubes in the steam generator has been divided by 145 too. The core has been modeled by 314 electrical heater rods. Unlike many experimental facilities with only two available loops (one for the break loop and one to simulate the other three loops) PKL simulates all four loops separately. This is very important in order to analyze asymmetrical transients, e.g. with injection in two out of four loops. A diagram of the PKL test facility is shown in Figure 1.

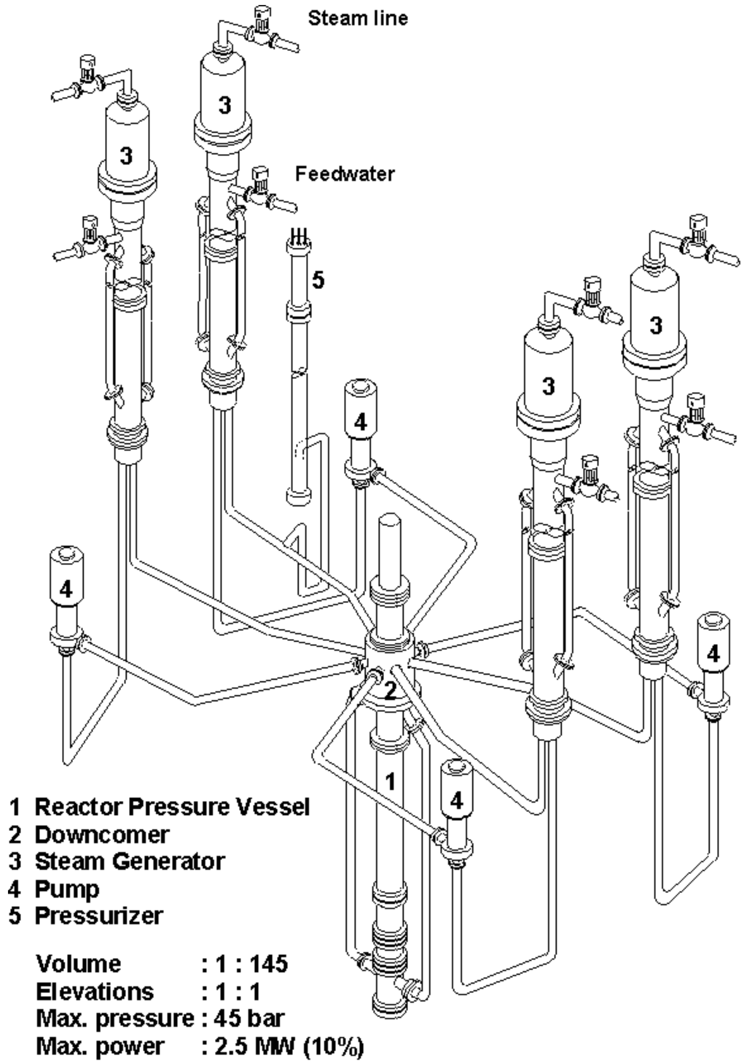

Figure 1.1 Diagram of the PKL test facility

The operating pressure of the PKL facility is limited to 45 bars on the primary side and to 56 bars on the secondary side. This allows simulation over a wide temperature range (522K to 322K) that is particularly applicable to the cooldown procedures investigated.

All emergency systems are represented and have a wide versatility referred to their functions and positions. There are 8 accumulators (one for each cold and hot leg). The pump injection system is available in all the hot and cold legs. Many break locations are available too.

PKL test facility has about 1500 measurement points that permit an exhaustive analysis of the tests. There are measurement devices for cladding, wall and fluid temperature, absolute and differential pressure, one and two phase mass flow, density and boron concentration.

Sixty of the measurement devices are identical to those that are used in a commercial plant to simulate what an operator would control in case of accident.

There are 4 measurement devices for the boron concentration; these are called the COMBO devices. They can be placed in any point of the facility, around pipes or even in big vessels (more than 150 mm). The COMBO devices measure the boron density from the outside so it is quite easy to change their location. The COMBO uses an irradiation method to calculate the proportion of boron in the coolant. A neutron source is placed in the outside of the pipe or the vessel. Some limitations arise when using the COMBO methodology. In order to get reliable data, the volume in which the boron is measured has to be totally filled with water. Moreover, results show high oscillations due to the error induced by the methodology.

It is important to mention that the break discharge experimental data have to be computed from other values. One can calculate the break mass flow by differentiating the level variation of the two separator vessels (where the discharged water goes) and subtracting the mass released through the separator relief line. Hence, the break mass flow is expected to be just an estimation of the experimental value as other effects like fluid density and vaporization might interact.

1.4 PKL II OECD (Organization for Economic Co-operation and Development) Project

OECD/SETH program included four tests performed in the PKL test facility; two of them were carried out in 2001 and the reminders during 2002. Three of these tests were designed to study boron dilution after a small break in the primary system. Before the OECD program started, a previous test of boron dilution was performed: Test E1.1, which served to define the configuration of the following tests handling the same phenomena. Table 1 shows the main characteristics of each of the SBLOCA with boron dilution tests.

OECD/PKL project comprises the F series of tests, which are a continuation of the SETH program. There are four groups of tests that cover the following issues:

- Boron dilution events after small break loss of coolant accident (first series F1, tests F1.1 and F1.2).
- Loss of residual heat removal during mid-loop operation with closed (series F2) and open (series F3) reactor coolant system.

In this paper a post test analysis of tests F1.1 and F1.2 is brought out covering the study of boron dilution events of the OECD/PKL project.

Test F1.1 is a clear continuation of the E series (SETH project) related with SBLOCA with boron dilution. The test is complementary to tests E1.1 and E2.2 with similar break location/size and same sequence of events. In this case the test is configured as to resemble a PWR Westinghouse design, e.g. steam generator cool down rate of about 50 K/h and ECC injection into all 4 cold legs. The main objective of the test is to gather the maximum size of low borated water in the loop seals and study the restart of natural circulation providing the minimum boron concentration at the reactor pressure vessel inlet. Three COMBO measurements were located along loop 4 improving the study of the mixing and the real shape of the boron diluted slug in this loop. This had not been done previously.

Test F1.2 was designed to analyze the rate of boron dilution depending on the mass inventory in the primary system. The test follows a series of steady states with different mass inventory and with a high SG level maintained in the U-Tubes thus showing at what U-tube levels and mass inventories the accumulation of condensate in the loop seals occurs. One of the main objectives of the test is to analyze the transport of borated water from the SG inlet to the SG outlet when the SG levels are maintained in the U-tubes. The test can be used as to see the performance of the code and model to simulate the dilution of the loop seals during the different steady states.

Table 1.1 Tests on boron dilution events performed at the PKL test facility in the recent years

	National Program 2000	OECD/SETH Program 2001-2002			OECD/NEA PKL I Program	
	E1.1	E2.1	E2.2	E2.3	F1.1	F1.2
Break size	40 cm^2	40 cm^2	32 cm^2	50 cm^2	21 cm^2	Adjusted according to the mass inventory plateaus
Break location	Hot leg in loop with PRZ	Hot leg in loop with PRZ	Cold leg 1	Hot leg 1	Cold leg 1	Lower plenum
HPSI	All 4 into cold legs	All 4 into hot legs	2 out of 4 SIPs, cold legs (1 in broken loop)	2 out of 4 SIPs, cold legs (1 in broken loop)	All 4 into cold legs	---
CVCS	---	---	---	---	---	LP injection for replenishment of the system
ACCs	---	---	---	All 4 into hot legs	---	---
LPSI	All 4 into cold legs					
SG secondary side	100K/h	100K/h	100K/h	100K/h	56K/h	---
Central topics of investigation	Symmetry, boron concentration	Symmetry, boron concentration	Maximum condensate accumulation	Hybrid state with condensate accumulation in two loops	Simulating a Westinghouse design	Boron dilution rate as function of primary side mass inventory

1.5 Code and Nodalization

The experience gained in the UPC-INTE group during the last years with the use of PWR models of real plants as well as of other experimental facilities has been very useful to develop a new nodalization for the PKL Test Facility. This nodalization was improved during the simulation of the different tests as various problems were faced at each transient. All improvements were included in the previous post test calculations so the final model was able to represent all tests at a similar accuracy. During this process, the information sent by Framatome ANP was always useful to improve this model. Some of the control systems and some coefficients were taken from the Framatome nodalization, which was available for all OECD/SETH participants.

Calculations were initially performed with RELAP5/MOD3.2gamma but all simulations were finally done with the newest version (RELAP5/MOD3.3) with an improved boron transport model implemented by the UPC-INTE group. New code improvements along with the possibility to modify the source code have encouraged the group to use this version. The step forward implied some modifications and some new expected discrepancies.

In order to test the effect of the U-tube bundle[3] nodalization, two different models were generated: one with a single pipe for the U-tubes and another one with five different pipes at 5 elevations. The differences and results between these two models will be explained in section 4.2. Figure 2 shows both nodalizations of the PKL test facility. The nodalization is especially detailed along the legs. As a guidance reference, the length of the volumes was chosen to be around 0.5 meters for a good performance of the models although the lengths vary from 0.1 to 1.0[4] .

[3] In the PKL test facility there are 7 U-tube bundles with different elevations

[4] meterSome volumes in the secondary system are larger

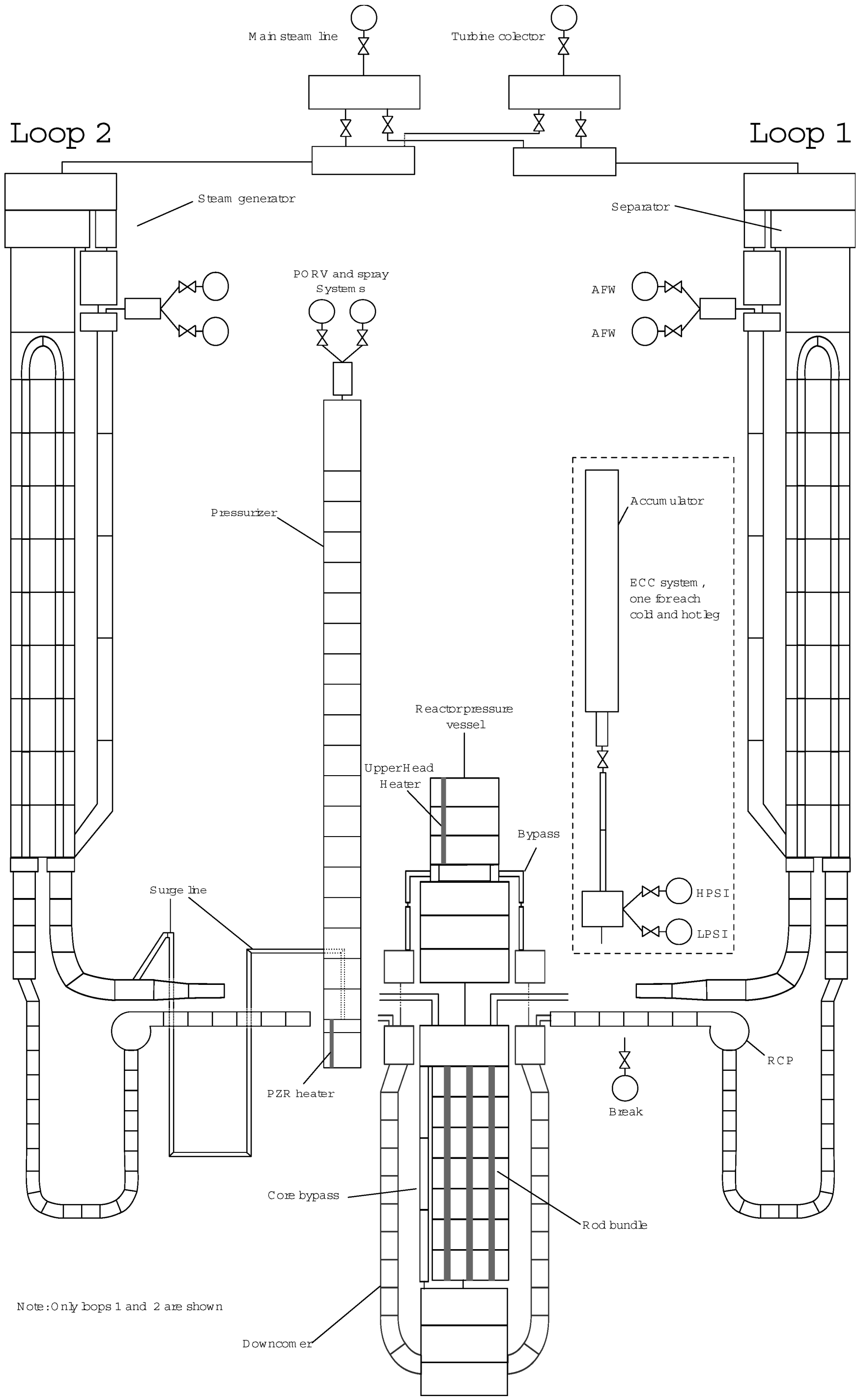

Figure 1.2 RELAP5 nodalization for the PKL test facility. Only loops 1 and 2 are shown.

The number of components used is:

- 438 volumes and 775 for the 5 U-tube nodalization
- 468 junctions and 817 for the 5 U-tube nodalization

- 331 heat structures 651 for the 5 U-tube nodalization
- 1356 mesh points in the heat structures 2636 for the 5 U-tube nodalization

All walls and superficies are modeled by heat structures to take into account any heat loss or exchange. The core fuel rods and other heaters (upper head and pressurizer) are modeled by means of heat structures.

Most auxiliary, safety and control systems are modeled by means of time dependent volumes and junctions. The turbine, main steam line and the pressurizer relief system (PORV) are all simulated using time dependent volumes and valves. The AFW system, the high and low pressure injection systems and the pressurizer spray system are modeled with time dependent volumes and junctions. Accumulators are nodalized with acc components and the accumulator discharge line is nodalized with the same length and elevation as in the facility.

The core region is nodalized by a single pipe with 7 axial volumes. A core bypass is modeled by a pipe of three axial volumes. The downcomer is modeled with two separate pipes since some recirculation phenomena were detected in some of the experiments. On the other hand, the downcomer of the SGs are simulated with a single pipe as the required detail in the secondary system is not as high. There are four bypasses from the upper plenum to the downcomer which are nodalized with two different lines to allow asymmetry phenomena. In these bypass the throat is located at the same elevation as in the real facility.

1.6 Notes about Boron Transport Models

Second order Godunov scheme was not working properly in RELAP5 MOD3.2gamma and MOD3.3 versions. Macian-Juan (ref. [11]) pointed out the incapability of first order upwind models (the RELAP5 default model) to simulate boron dilution transients. UPC-INTE group detected and fixed a mistake in one of the RELAP subroutines that was disabling the accurate model. This modification was reported and accepted by the RELAP group, the model will be available in new released versions. Moreover, a new model for the boron transport to reduce numerical diffusion and introduce physical diffusion was implemented and was thereby used for all calculations in this paper. The new model is extensively explained in reference [9].

2 TEST F1.1

Test F1.1 is a boron dilution transient with a small break in cold leg 1. The test is similar from its precedent series (E), although this one was meant to simulate a Westinghouse design. Therefore, the cooldown of the secondary system is slower and each HPSI pump injects symmetrically in all loops. For this test, unavailability of LPSI and accumulators is supposed. Besides, one of the HPSI pumps is also not operable.

Since the maximum operating pressure of the PKL test facility is 45 bars, it is not possible to simulate the entire transient of a normal PWR (normal operating pressure of 160 bars). Hence, in the test, the transient starts at a primary pressure of less than 45 bar and with initial conditions corresponding to those that would prevail in a real plant at this time. The initial conditions for Test F1.1 consist of a partially emptied primary system at a pressure of 39 bars.

2.1 Boundary Conditions

The hardware configuration of test F1.1 is described in references [10, 2]. Some important points are the following:

1. *Break assembly*. Small break (21 cm^2/145) in cold leg 1 between RCP and RPV.
2. *Accumulator and LPSI*. Unavailability of LPSI and accumulators.
3. *High pressure ECCs*. Primary feed by 1 out of 2 HPSI pumps, injection via header symmetrically into all 4 cold legs ([B] = 2200 ppm).
4. *Steam generators secondary side*. Cooldown of all 4 SGs at 56 K/h using all MS-RCVs (SGs connected via main steam header).

2.2 Conditioning Phase

The conditioning phase can be subdivided into 3 parts:

Phase 1 was initiated at t=-8730s by stopping the feedwater supply and closing the main steam lines of all 4 SG secondaries in order to increase the secondary pressure (fig. 3). Secondaries remained connected via the main steam header. Due to the increase of secondary temperature, the primary temperature rose and approached saturation at core outlet. Primary pressure increased.

Phase 2 was started by opening the break in cold leg 1 (at t=-7750 s). Primary pressure decreased to a value approx. 3 bar above the secondary pressure. The RPV level decreased to the coolant line and the PZR to the surge line, whereby the primary started to void. When secondary pressure had reached 38 bar, the main steam lines were opened again (t=-6610 s) and the secondary pressure was controlled as to keep the primary pressure at approx. 40 bar. The control implemented in the calculation is finer than the experimental one although, it did not affect the results and the final initial conditions were reached. RPV level stabilized around RCL as it was in the test facility. Phase 2 was finished at t=-5500 s by closing the break valve. By this time, natural circulation in all loops had stopped and reflux condenser conditions had been established. The SG inlet chambers were still filled by water/steam mixture and the residual primary coolant inventory was 1230 kg.

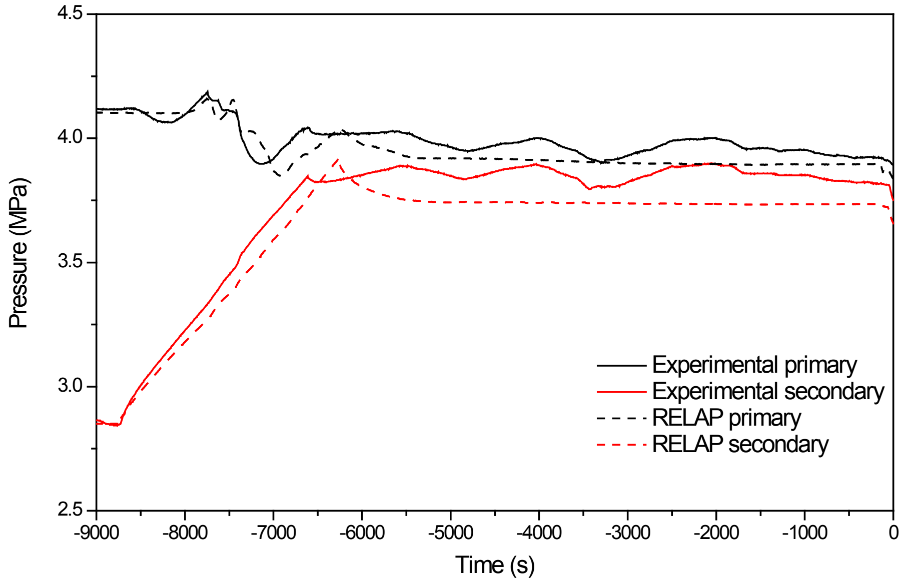

Figure 2.1 Primary and secondary pressures, conditioning phase of test F1.1

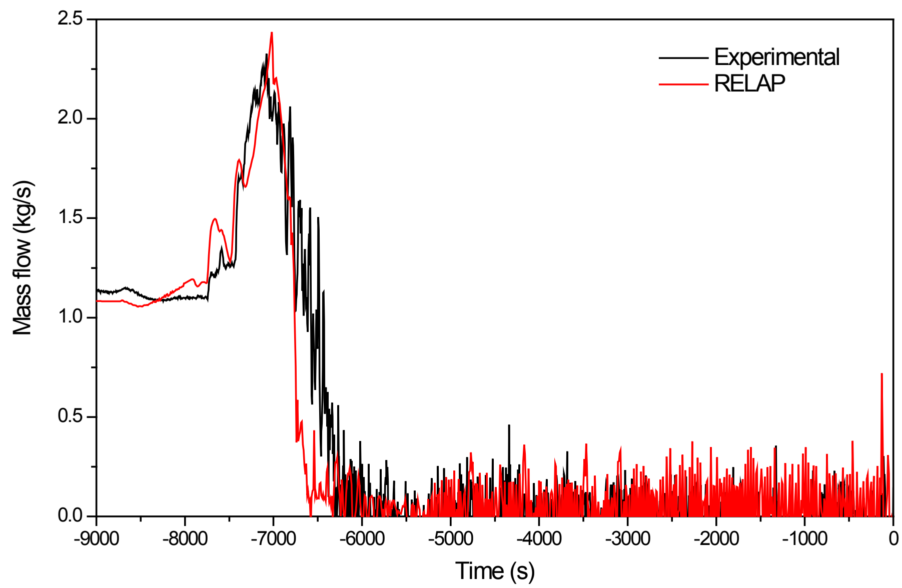

Figure 2.2 Mass flow in loop 4, conditioning phase

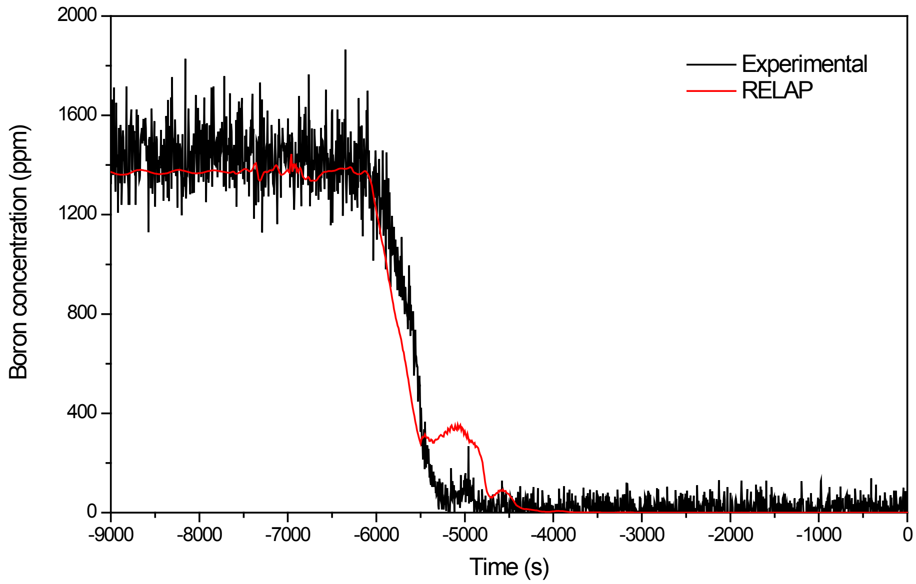

Figure 2.3 Boron concentration in the loop seal of loop 4, conditioning phase

These conditions were kept constant during phase 3. The break was closed during the whole phase and water evaporated in the core and condensated in the U-tubes. From t = -5500 s until test started, approx. 300 kg of condensate were accumulated in the loop seals.

The transition from conditioning phase to test was performed stepwise in order to avoid sudden changes in the differential pressure distribution at test start due to condensation caused by the ECC water injected. All test actions, but the break opening, were performed prior the start of the transient.

Figure 4 shows the loop 4 mass flow during the conditioning phase that increased when the break was opened. Figure 5 shows the boron concentration in loop seal 4 and how the boron concentration was reduced in both, the simulation and the test.

Finally, the test initial conditions were reached with a quite good agreement with the experimental ones. Table 2 presents a comparison between the initial conditions achieved and the actual ones.

2.3 Initial Conditions at Test Start

Initial conditions used for Test F1.1 consist of a partially emptied primary system at a pressure of 38.9 bars. Low borated water has been accumulating in all loop seals.

The initial conditions obtained in the post-test calculation (Table 2) of test F1.1 after the conditioning phase are in quite close agreement with the experimental values. The most significant discrepancy in the initial conditions is a difference of 70 kg in the initial inventory mass.

Table 2.1 Initial conditions of Test F1.1, experimental and calculated data

	Initial conditions at t=0s	
	Experimental Data	**RELAP**
Core power	485 kW	485 kW
Primary pressure	39.2 bar	38.9 bar
Temperature at core outlet	522 K	522 K
Subcooling at core outlet	0 K	0 K
Fluid temperature pressurizer	522 K	522 K
Pressurizer level	0.8 m	0.65 m
Boron concentration	<50 ppm in loop seals and downcomer Approx. 4000 ppm in the core	<50 ppm Approx. 4000 ppm
Main steam pressure in all 4 SGs	38.1 bar	37.4 bar
Main steam temperature	519 K	520 K
Collapsed level in all 4 SGs	12.2	12.2
Feedwater temperature	383-393 K	388 K

2.4 Test Phase

The test is started by:

- Starting the HPSI to inject into all 4 cold legs (t=-140 s, [B]= 2500 ppm)
- Start of the rod bundle power decrease (t=-60s)
- Start of cooldown of all SG-secondaries by 56 K/h (t=-50s)
- Opening of the break in cold leg 1 (t=0 s)

Until SOT, the primary coolant inventory has increased up to a value of 1280 kg as the break has remained closed while the HPSI have injected water during 140 seconds. The HPSI rates are controlled according to the correct pump characteristics.

During the first part of the test, the primary and secondary pressures decrease due to the secondary cooldown and the power decay. As the quantity of injected mass is larger than the discharged mass, the RPV level increases. At t = 5000 s the primary system is almost full again and natural circulation is established in all loops asymmetrically. Times for establishment of NC in all loops are shown in Table 3. Primary pressure rises and levels off. The PRZ level sharply increases.

Table 3 shows the chronology of the main events occurred in test F1.1, comparing the experimental values with the calculated ones.

Table 2.2 Chronology of the main events in Test F1.1

Event	Experimental data (s)	RELAP (s)
Starting the HPSI injection into all 4 cold legs	-140	-140
Start of the rod bundle power decrease	-60	-60
Start of 56K/h cooldown of all 4 SGs	-50	-50
Opening of the break in cold leg 1	0	0
Establishment of NC in loop 2	4651	5080
Establishment of NC in loop 4	4991	5080
Establishment of NC in loop 3	5556	4890
Establishment of NC in loop 1	6851	5020
End of transient	11911	11911

All actions taken in this test happen just before SOT. The HPSI starts to inject symmetrically into all 4 cold legs 140 seconds before SOT. Afterwards, the rod bundle power decrease starts according to a heat decay table. Fifty seconds before the test started the SGs initiate the cool down. At SOT, the break cross section is opened again. There are no further actions during the transient. Most of the difficulties found during the simulation occurred at the conditioning phase, once the initial coolant mass is correctly matched the rest of the transient presents acceptable results.

Figure 6 shows the primary and secondary pressures. The primary pressure has small discrepancies after the primary system is filled again (5000 seconds) although it stabilizes at similar values.

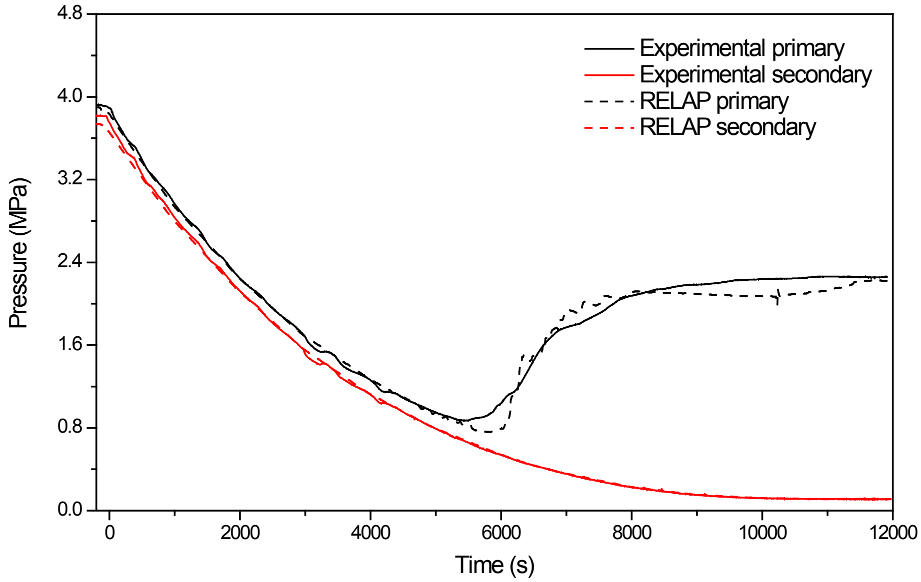

Figure 2.4 Primary and secondary pressures for test F1.1

Differences shown in the RPV level (Figure 7) are similar to the ones seen on previous post-test calculations [4]. For the pressurizer level (Figure 8) the results have a good agreement with the experimental data. There is a 500 seconds difference on the level increase, although the rise ratio is similar. Break mass flow is shown in Figure 9. As said in Section 1.3, the experimental break flow was indirectly calculated from other variables. The simulation flow appears to be all the time slightly greater. That is consistent with the RPV level differences. In the simulation there is stagnant vapor in the upper head, which causes that the final mass at NC establishment is lesser than the experimental.

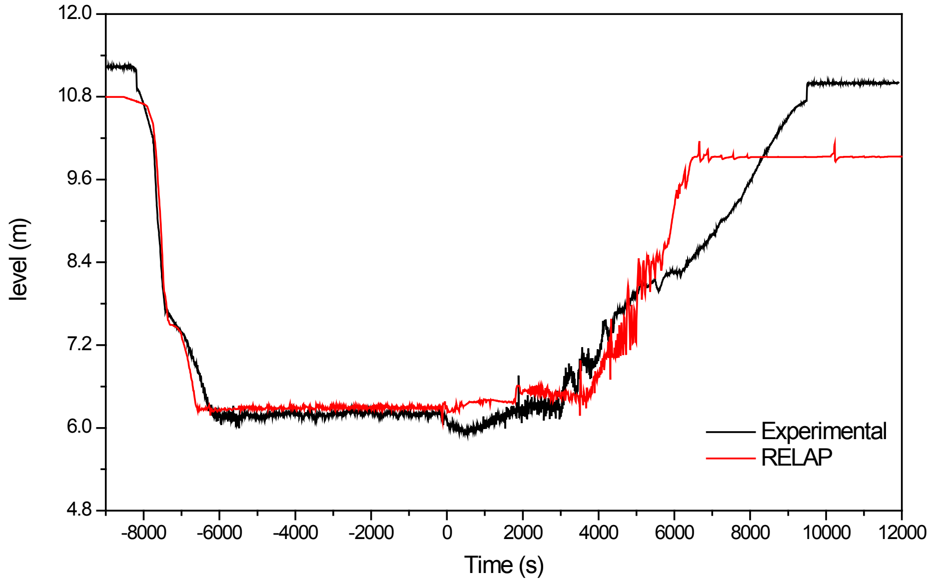

Figure 2.5 RPV level for test F1.1 during the conditioning and the test phases

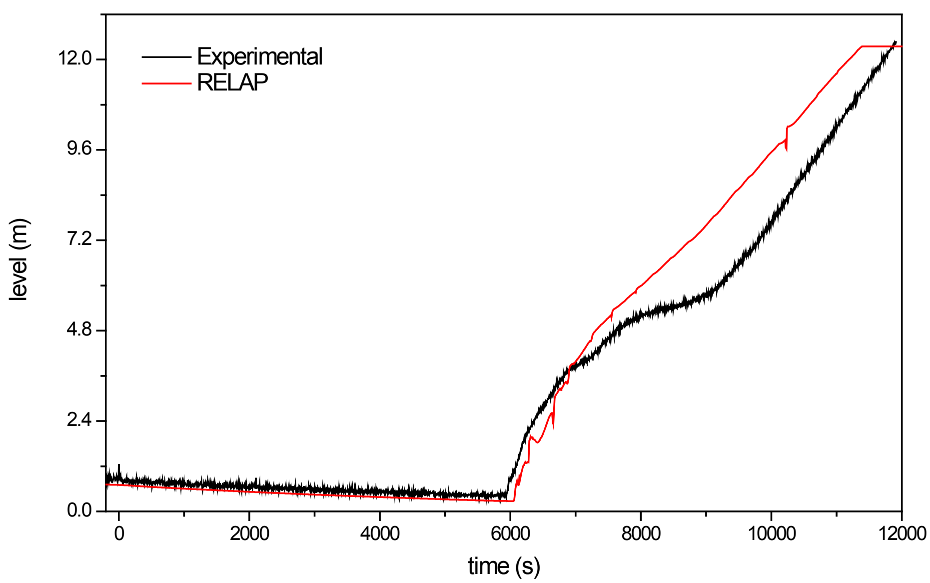

Figure 2.6 Pressurizer level for test F1.1

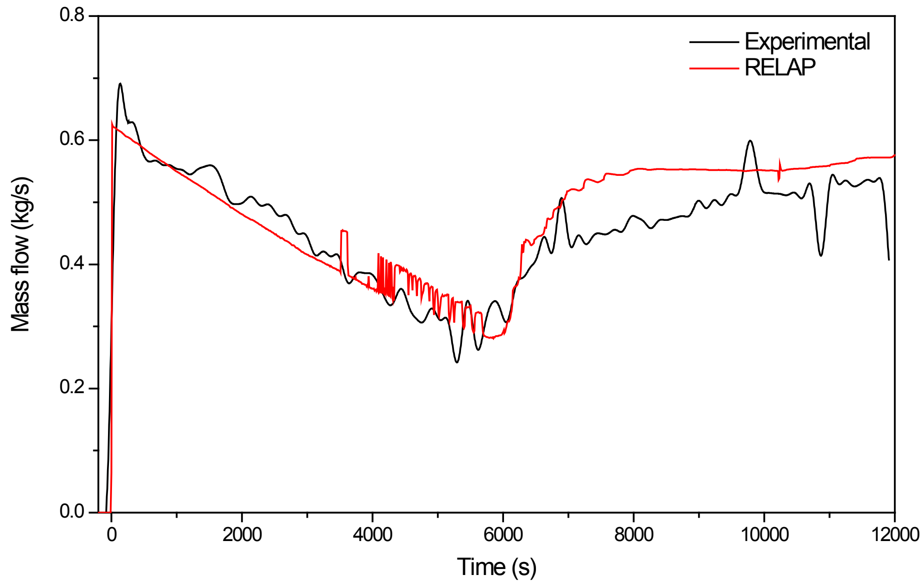

Figure 2.7 Break mass flow for test F1.1

Figure 10 show the mass flow in all loops. Discrepancies simulating loop 1 were found. These differences were also observed in loop 2 of test E2.2, even by different groups performing analytical studies of the experiment [13] and are still an open issue. Natural circulation is correctly matched for the rest of loops although even small discrepancies hinder the analyses of the boron concentration at the COMBOs for the slugs are moved at different times and speed.

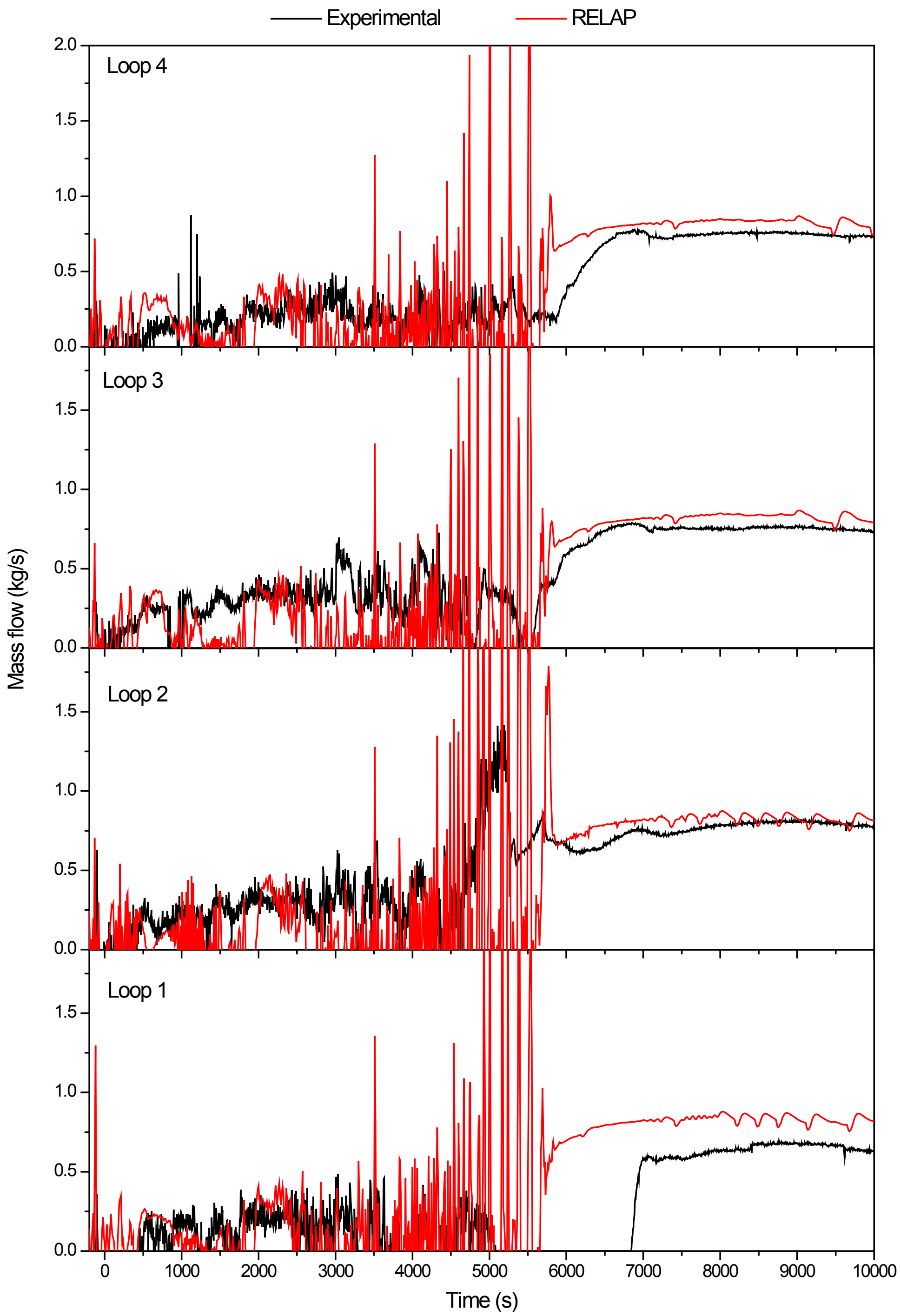

Figure 2.8 Mass flow in all loops for test F1.1

Boron concentration at the COMBOs is displayed in Figure11. The tracking of the boron concentration will be explained in the next section along with a complete analysis of the evolution of the boron diluted slugs.

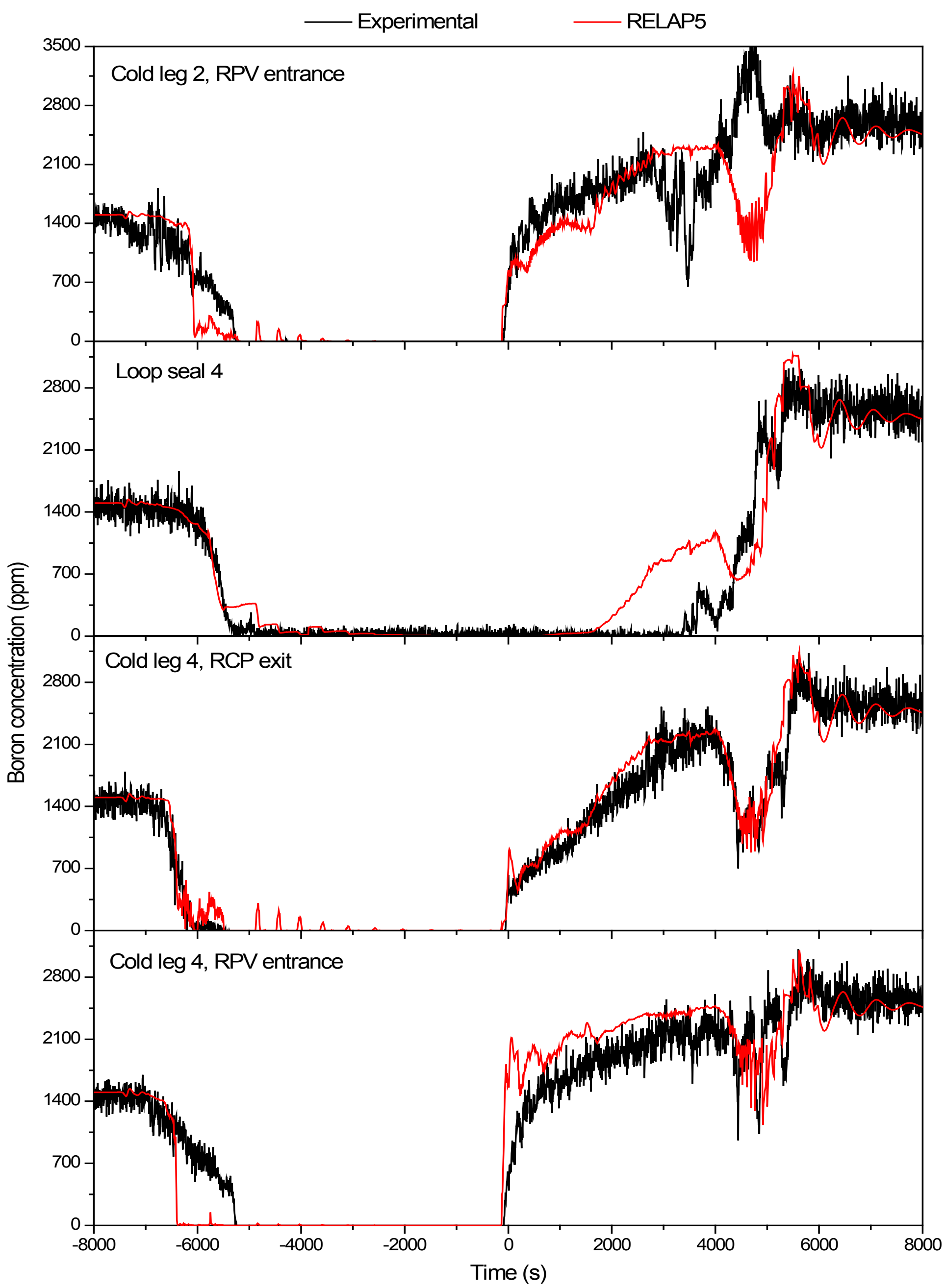

Figure 2.9 **Boron concentration at the COMBOs located in: cold leg 2, LS 4 and both sides of cold leg 4. Test F1.1**

2.5 Analysis of Results Concerning Boron Dilution

Figures 12 to 18 show the boron concentration evolution along loop 4 of post-test F1.1 to illustrate the formation process and the behavior of the slugs prior the re-start of NC. In all these plots, the color criterion is red for non borated water, blue for highly borated water and grey for steam (null liquid void fraction). The values range from 0 to 2500 ppm. There is a plot in each figure with the boron concentration evolution of the volume marked with a circle.

2.5.1 Formation of the Boron Diluted Slugs

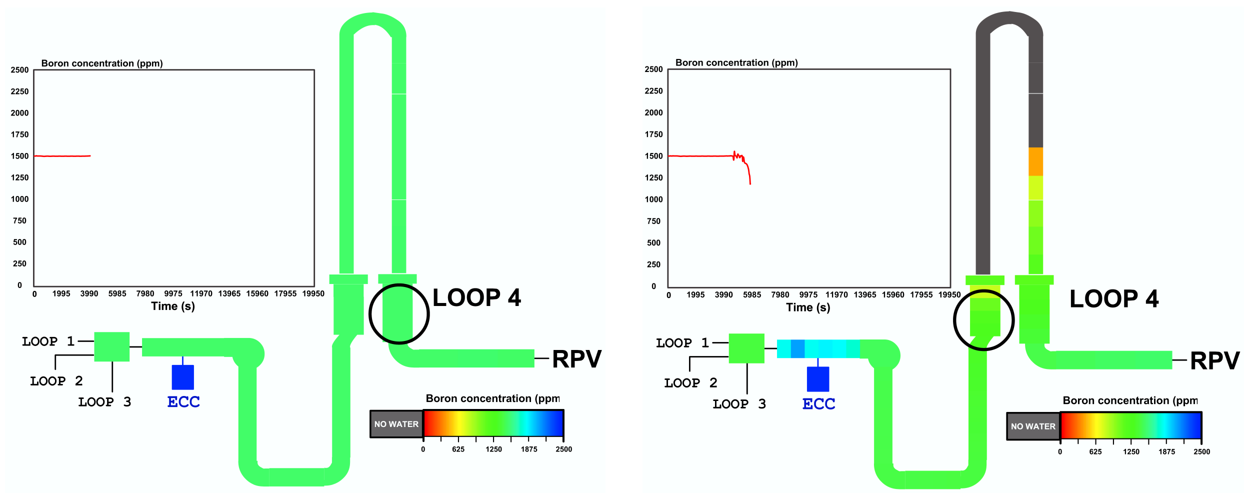

Figure 2.10 Post test calculation of test F1.1, evolution of boron concentration in loop 4. Left: start of transient. Right: reflux-condenser conditions established

After the break is opened the primary mass inventory decreases until the primary level stabilizes around mid loop. At this point, if the SG levels are high enough, reflux-condensation conditions are established (Figure 12). Water evaporates in the core and condenses in the U-tubes. This condensed water precipitates either to the loop seals or to the hot legs, forming boron diluted slugs (left picture of Figure 13). If reflux-condensation conditions are maintained for a long period of time the LSs can be totally filled up with pure water (right picture of Figure 13). The behavior of the hot leg slugs is different; condensed water flows back to the core where it mixes with highly borated water so only a small amount of condensate is gathered in this region.

On the other hand, water accumulated in the loop seals will be pushed to the downcomer for very long periods of reflux-condensation conditions. In that case, coolant in the downcomer will be highly diluted. Generally the size of the slug is limited by the volume of the LSs although small slugs can be formed in hot legs and downcomer.

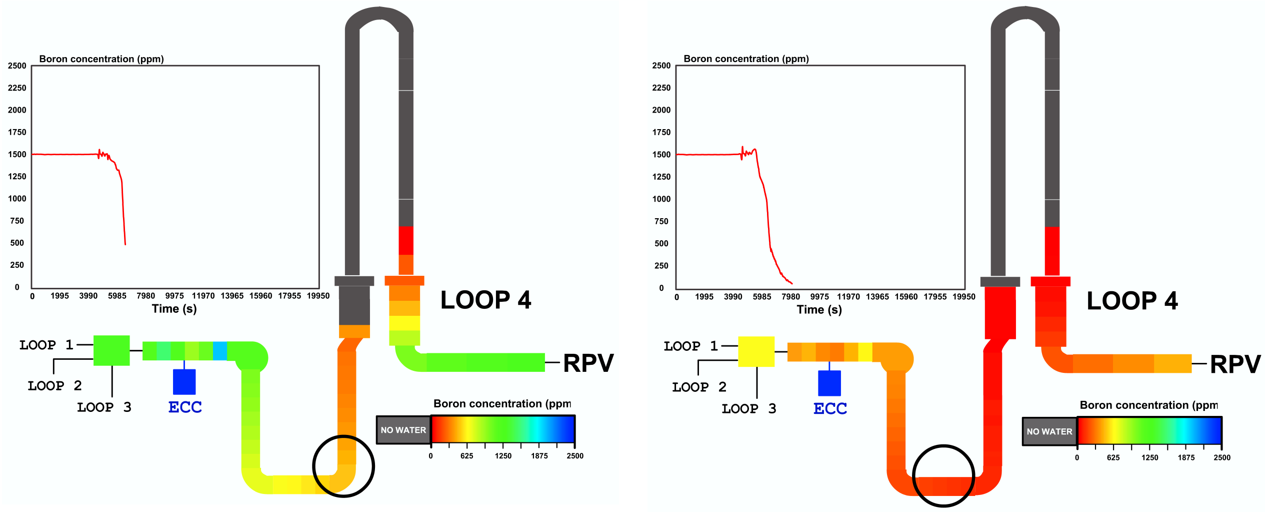

Figure 2.11 Post test calculation of test F1.1, evolution of boron concentration in loop 4. Left and right: Boron dilution in hot leg and LS

Right picture of Figure 13 shows full boron dilution in the LS and partial dilution in the hot legs. For this test the downcomer was also full of un-borated water[5]. It is worth mentioning that Figure 10 of the final report of test F1.1 (ref. [12]) illustrates very similar results.

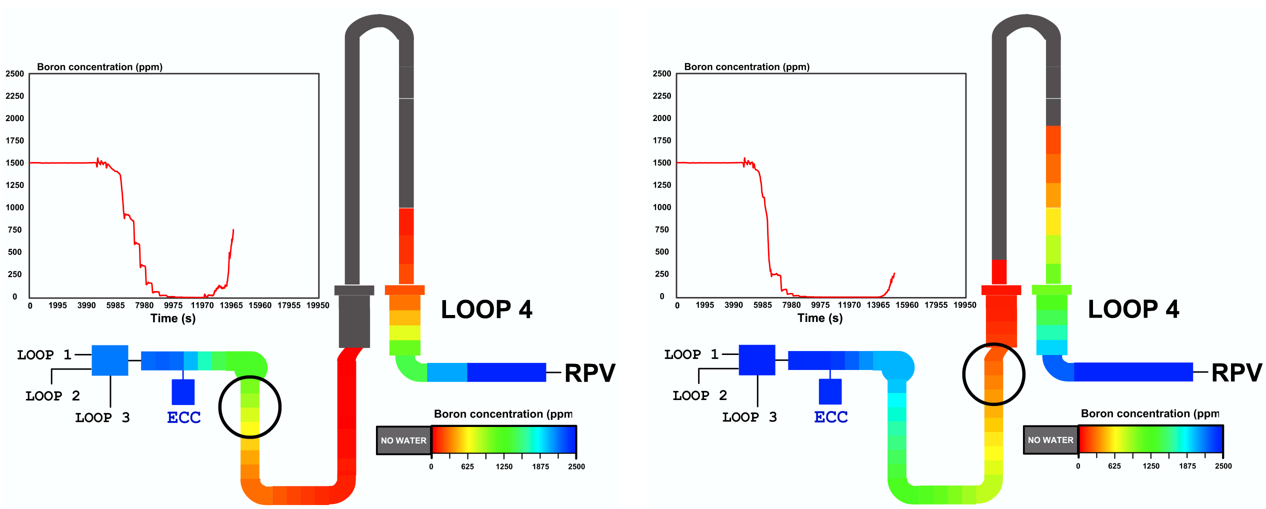

Figure 2.12 Post test calculation of test F1.1, evolution of boron concentration in loop 4. Left: ECC flows to LS. Right: upward displacement of the slug

2.5.2 Evolution of the Boron Diluted Slugs Prior NC Establishment

[5] During the conditioning phase of the test both the break and the ECC valves remain closed and the facility is kept under stationary reflux-condensation conditions for a long period of time to enhance the formation of condensate

The simulation of test F1.1 gave quite good results and permitted to follow up the movements of the slug during the filling up process. After the conditioning phase, with the start-up of the cold leg injection, reverse flow occurred only in the cold legs. High borated water from the ECC flowed down the LS and mixed with the slug which was not pushed upward to the U-tubes (Figure 14, left).

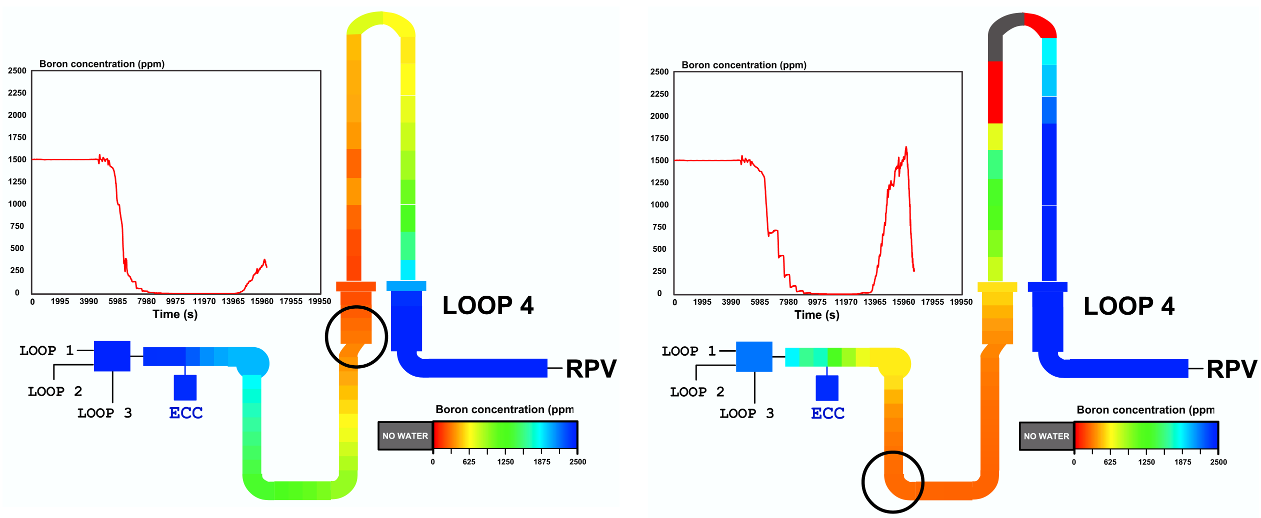

Figure 2.13 Post test calculation of test F1.1, evolution of boron concentration in loop 4. Left: upward displacement of the slug continues. Right: the slug is moved back to the LS.

As the filling up process advanced the slug was displaced upward to the SG outlet plenum and ECC water reached the horizontal region of the LS (figure 14, right). The slug remained there (Figure 15, left) only for 200 seconds. Some mass flow was detected even before the filling up process that pushed the slug back to the LS (Figure 15, right). The reason was that water could be transported from SG inlet to outlet side by entrainment. The same phenomenon occurred to a small extent in test E2.2 although in that case it only took place in the loops with no injection [12].

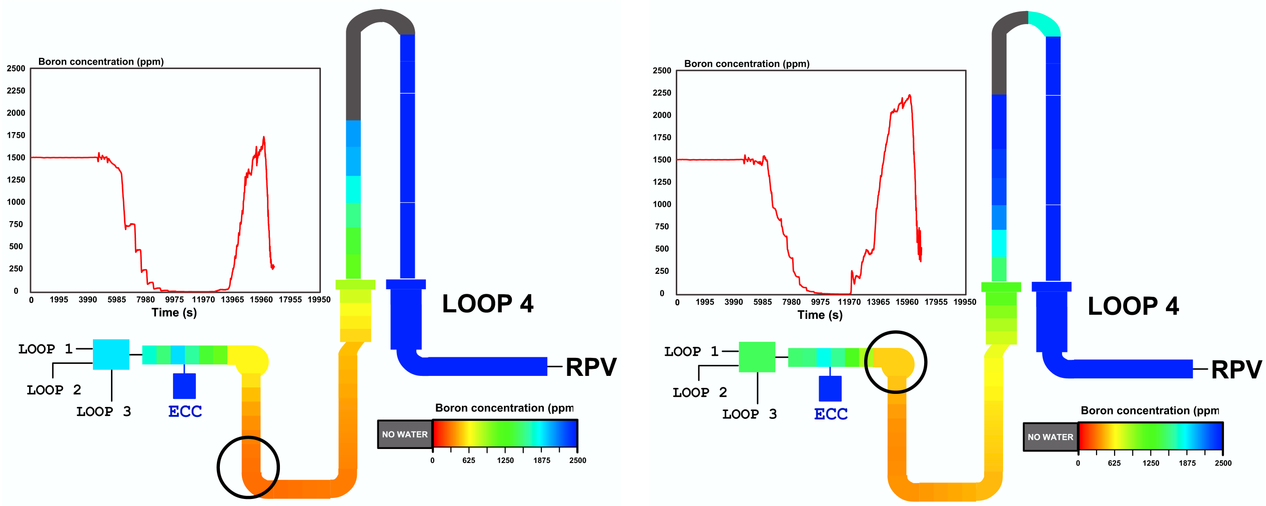

Figure 2.14 Post test calculation of test F1.1, evolution of boron concentration in loop 4. Left and right: intermittent forward and backward movements of the slug.

Afterwards, intermittent movements of the slug were seen in both the calculation and the experiment. The slug advanced to the injection point and came back to the LS at least three times increasing the mixing (Figures 16 and 17).

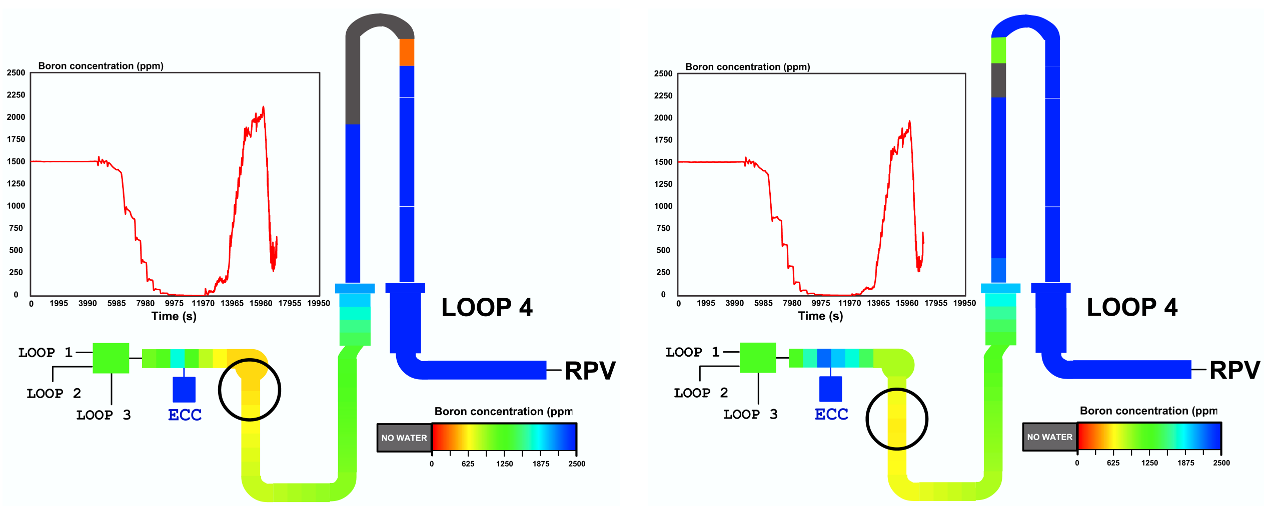

Figure 2.15 Post test calculation of test F1.1, evolution of boron concentration in loop 4. Left and right: intermittent forward and backward movements of the slug.

Before the establishment of NC, the slug was placed below the pump and the minimum boron concentration was around 600 ppm in the calculation (Figure 17, right), similar to the results obtained in the experiment (approx. 600 ppm; as shown in Figure 10 of reference [2]).

2.5.3 Establishment of Natural Circulation

It is clear that, it is difficult to represent large asymmetries between loops and usually some of the NC establishments are not matched with RELAP5. Still, in loop 4 of test F1.1 the agreement allowed a good analysis of the main phenomena. Intermittent mass flows were observed in the test facility and in the calculation. The slug moved forward and backward before crossing the cold leg.

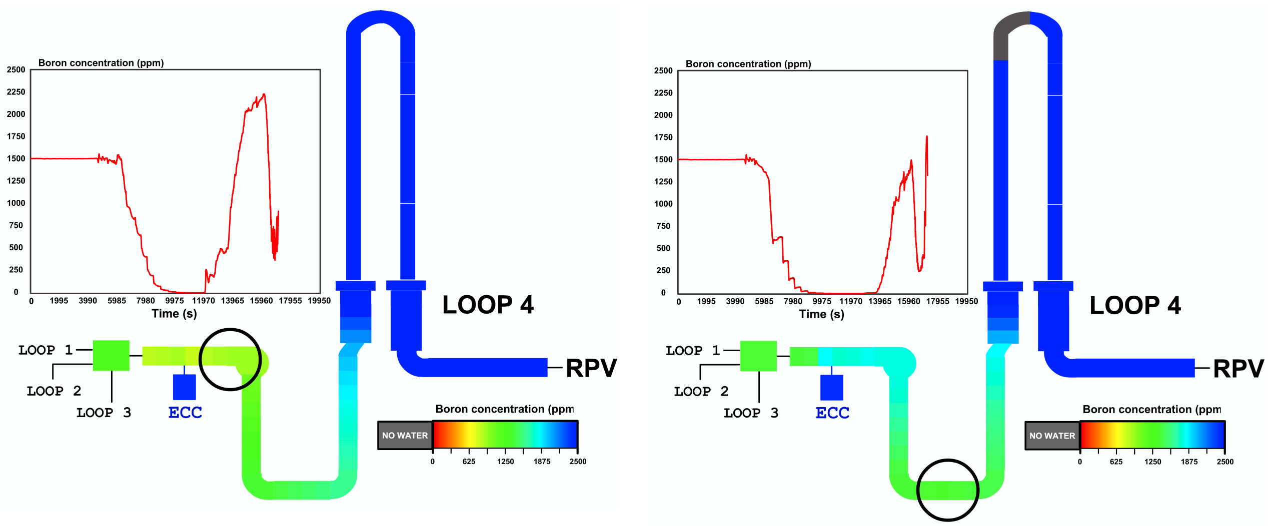

Figure 2.16 Post test calculation of test F1.1, evolution of boron concentration in loop 4. Left and right: establishment of natural circulation.

Figure 18 shows the continuation of the simulation of Test F1.1. As pointed out in the previous section, a slug of 600 ppm was placed below the RCP before natural circulation establishment (Figure 17, right). A last reverse movement of the slug was detected 10 seconds before the full natural circulation was established (Figure 18, left). The slug was cut in two due to the ECC water injection as shown in the right picture of Figure 18.

3 TEST F1.2

Test F1.2 is a parametric study for the investigation of inherent boron dilution due to reflux-condensation conditions as a function of the primary coolant inventory [1]. The test was composed by a sequence of steady states with intermediate transition phases consisting of the actual change of parameters and subsequent relaxation phases. The test was started with the primary system completely full of borated water and natural circulation in all loops. The mass inventory was first reduced stepwise and thereafter the CVCS was used also stepwise to replenish the primary system. The test was interesting as to investigate the dependence of the boron dilution with the mass inventory and the RPV level.

3.1 <u>Boundary Conditions</u>

- Test start with the primary system completely filled with water, 1-diameter natural circulation and homogeneous boron concentration
- Stepwise reduction and replenishment of the primary coolant inventory at constant primary pressure, drain and injection via lower plenum
- Additional steady states with varied pressure and core power
- Isolation of the pressurizer at the beginning of the transient as to eliminate its influence in the test.
- Main steam and feedwater mass flows were adjusted manually to constant values and corrected only from time to time.

3.2 <u>Initial Conditions at t=0s</u>

The initial conditions of the test and the calculation are shown in Table 4. The test was initiated at steady-state conditions. The test facility was completely filled with water at high homogeneous boron concentration and a constant core power. The secondary sides were kept in operation. There was subcooled natural circulation in all 4 loops. The primary and secondary pressures were 12 and 6 bar, respectively. There was no special conditioning phase.

The main difference is the distribution of the mass inventory. During the steady state calculation the primary coolant was redistributed, i.e. the pressurizer level increased while the RPV dropped. The same occurred in the first part of the experiment, even before that any action had been taken except for the secondary pressure increase. This disagreement did not affect the simulation since, when the pressurizer was isolated at 4650 seconds, the level of the PRZ and the mass inventory in the primary system (without the PZR) were the same in both the test and the RELAP5 simulation.

Table 3.1 Initial conditions of Test F1.2, experimental and calculated data

	Initial conditions at t=0s	
	Experimental Data	**RELAP**
Primary coolant inventory	2540 kg (40 kg in PZR)	2550 kg (130 kg in PZR)
Boron concentration	2000 ppm	2000 ppm
Core power	600 kW	600 kW
Primary pressure	12 bar	12 bar
Temperature at core outlet	457.3 K	458.1 K
Subcooling at core outlet	4 K	3 K
Fluid temperature pressurizer	462.3 K	462.1 K
Pressurizer level	1.3 m	3.1 m
Mass flow in all 4 loops	1.23 kg/s	1.12 kg/s
Main steam pressure in all 4 SGs	5.9 bar	5.9 bar
Main steam temperature	431 K	434 K
Collapsed level in all 4 SGs	12 m	12.15

3.3 Nodalization with 5 U-tubes

This test goes through different steady states with different natural circulation mass flows. During its simulation it was found out that during the last steady state period, just before the NC resumed, there was natural circulation only in some of the U-tubes and whereby boron dilution started only slightly. This behavior could not be simulated using a single U-tube and therefore, a nodalization with 5 U-tubes was used for this test. This nodalization was able to simulate this phenomenon and the end of natural circulation occurred at the same time as in the experiment. The comparison between the two nodalizations will be reported and discussed in Section 4.2.

3.4 Test Phase

Test F1.2 was started at steady state flow conditions with the initial conditions just described. Throughout the test, the secondary pressure was controlled by partly opening and closing the main steam relief valves in order to adjust the primary pressure to the desired values; these actions were performed manually and without any specific control system. The primary and secondary pressures are plotted in Figure 19 displaying a quite good agreement between the experiment and the calculation.

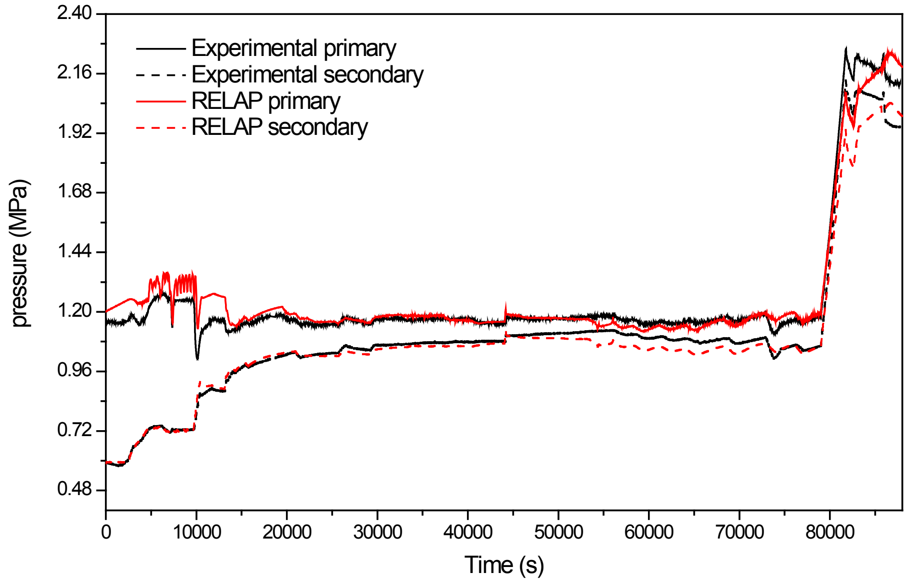

Figure 3.1 Primary and secondary pressures for Test F1.2

After a first accumulation of steam in the RPV upper head, the pressurizer was isolated by closing an isolation valve in the surge line (t=4650 s). Afterwards the PZR had no influence to the test. Figure 20 displays the pressurizer level evolution. Even though the initial level displays a large discrepancy the values are very similar when the PZR is isolated so the primary total mass is not affected. Variations after the isolation have no influence to the rest of the system and are therefore meaningless.

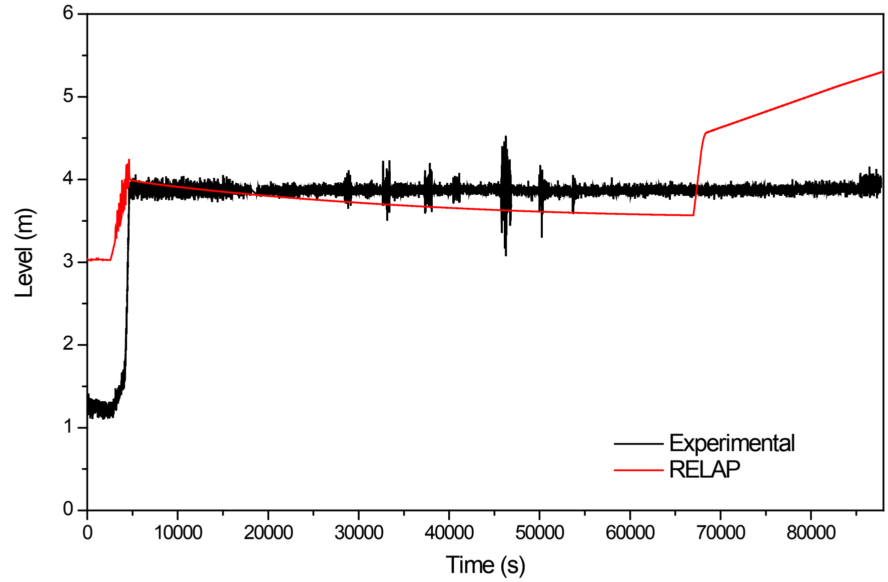

Figure 3.2 Pressurizer collapsed water level for Test F1.1

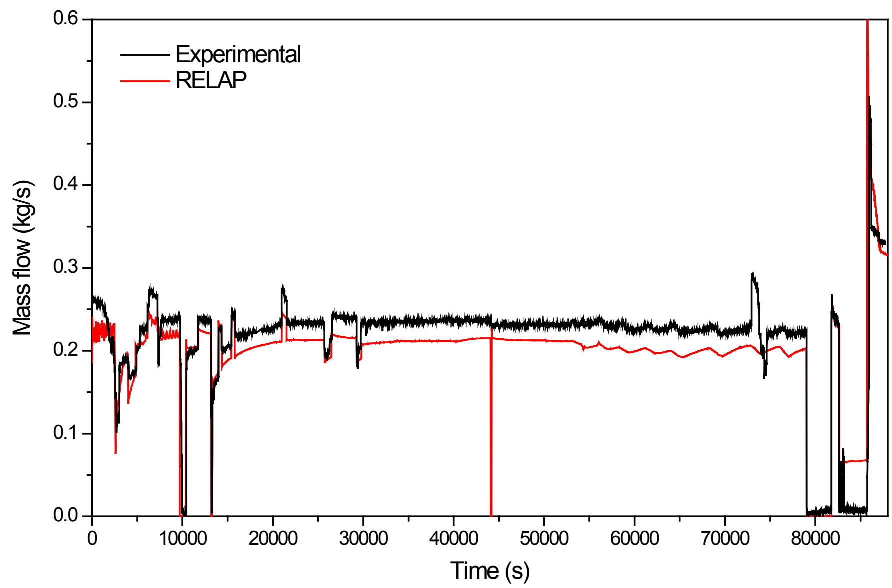

Figure 3.3 Total main steam flow for Test F1.2

There were no control systems for the feedwater and main steam valves. One of the main objectives of the test was to establish real steady states whereby control loops for feedwater injection, main steam pressure and secondary levels were removed in order to restrain their influence. The SG relief valve areas and the feedwater mass flows were manually modified from time to time. Figure 21 shows the total main steam flow. As the information about the modifications performed at each time on the main steam valves was not given, the section of these valves was modified from time to time so the secondary pressure had a similar evolution as in the experiment.

The mass inventory was reduced stepwise as shown in Figure 22 by temporarily openings of a drain line in the lower plenum. The calculation value does not take into account the pressurizer mass hereby the discrepancy at the beginning of the test. Once the pressurizer had been isolated, the mass inventory shows similar results. There was no specific section for the drain line, the actions were performed as to open the valve (with no determined section) until the new desired mass inventory value had been reached. Hence, in the calculation the areas of each opening were matched by a process of try and check until the mass was reduced to the correct value and with the same amount of time.

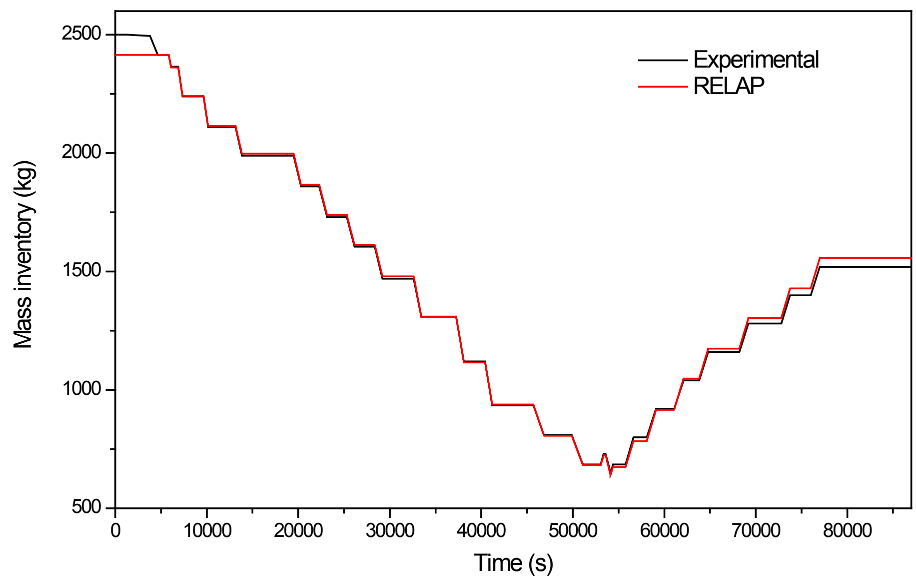

Figure 3.4 Primary mass inventory for Test F1.2

When the core was uncovered the primary mass inventory was increased again by injection of borated water in the lower plenum. Figure 24 shows the RPV level. The initial level is different since part of the RPV inventory had flown to the PZR before SOT in the calculation. After the isolation of the pressurizer the RPV levels equalize. Due to the reduction of the mass inventory, the mass flow of the loops increased (Figure 25) and became twice and thrice of the initial natural circulation. With high natural circulation the RPV level in the calculation was lower.

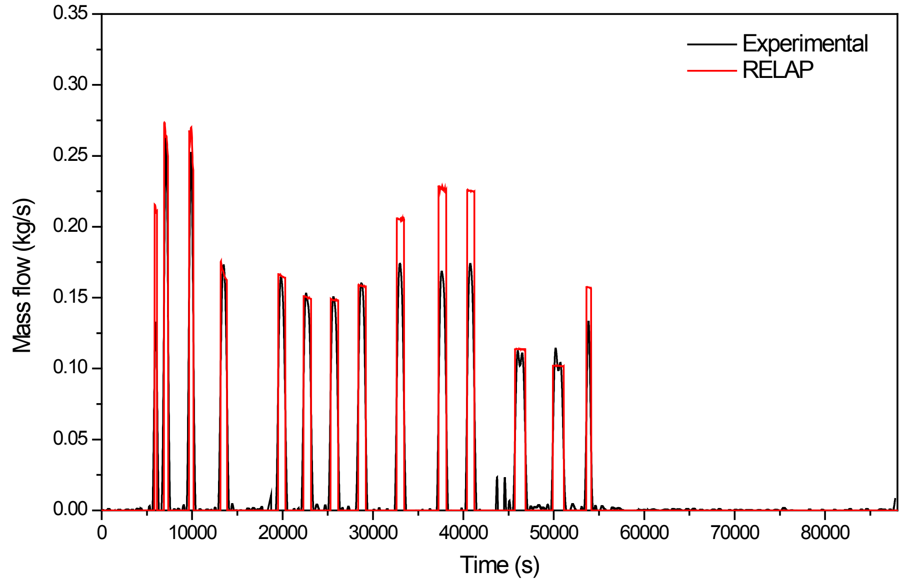

Figure 3.5 Break mass flow for Test F1.2

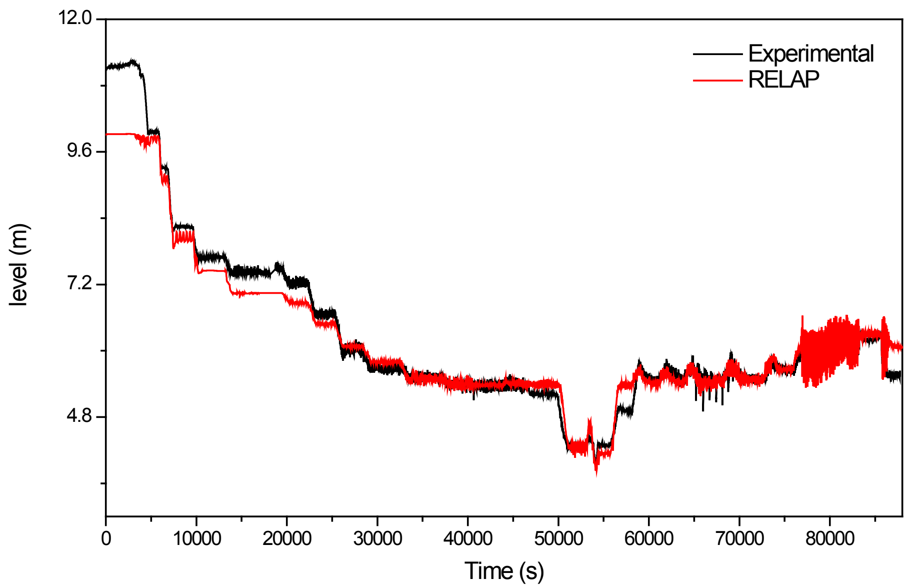

Figure 3.6 RPV collapsed water level for Test F1.2

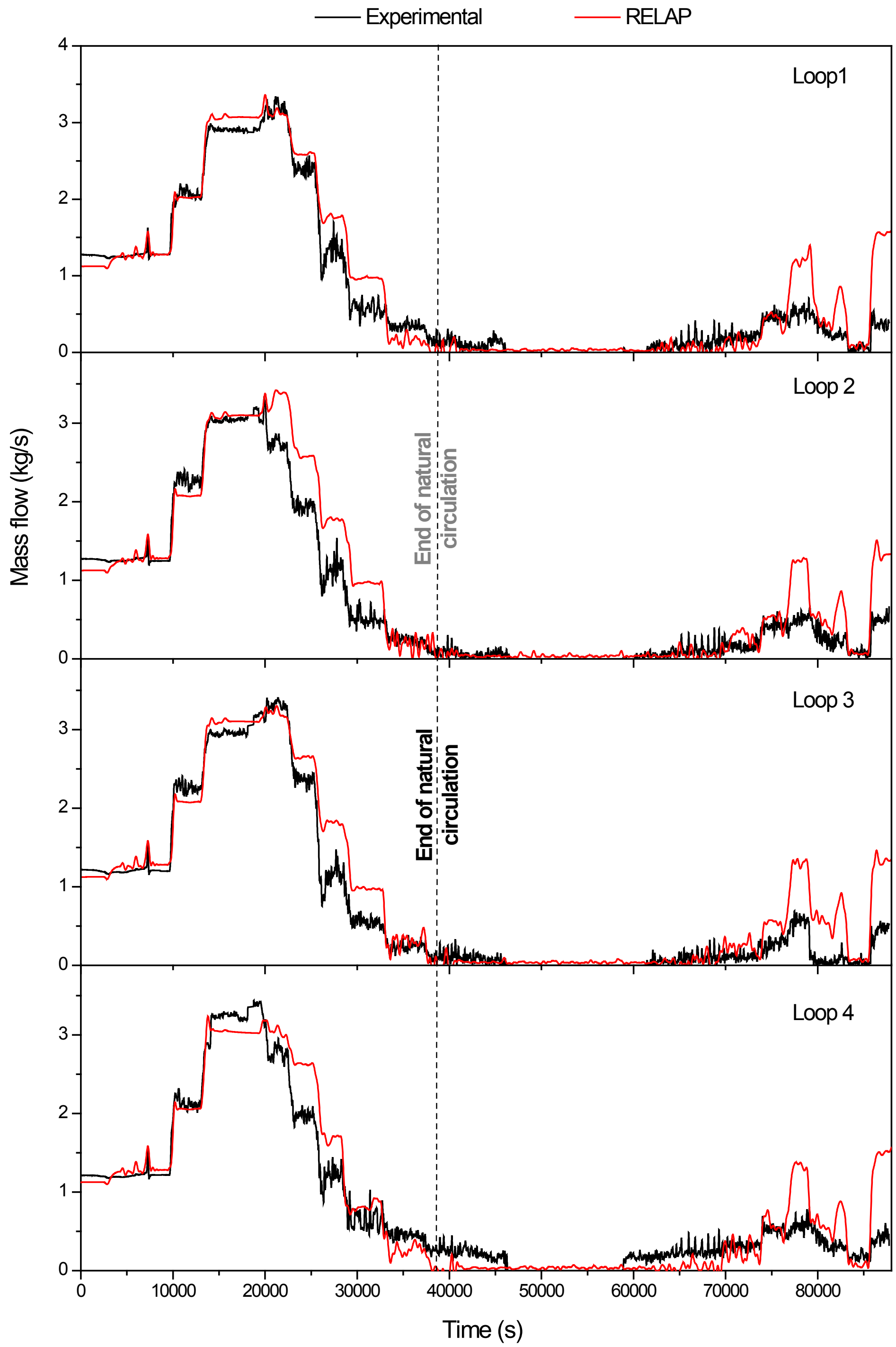

Figure 3.7 Mass flow of loops 1 to 4 for Test F1.2

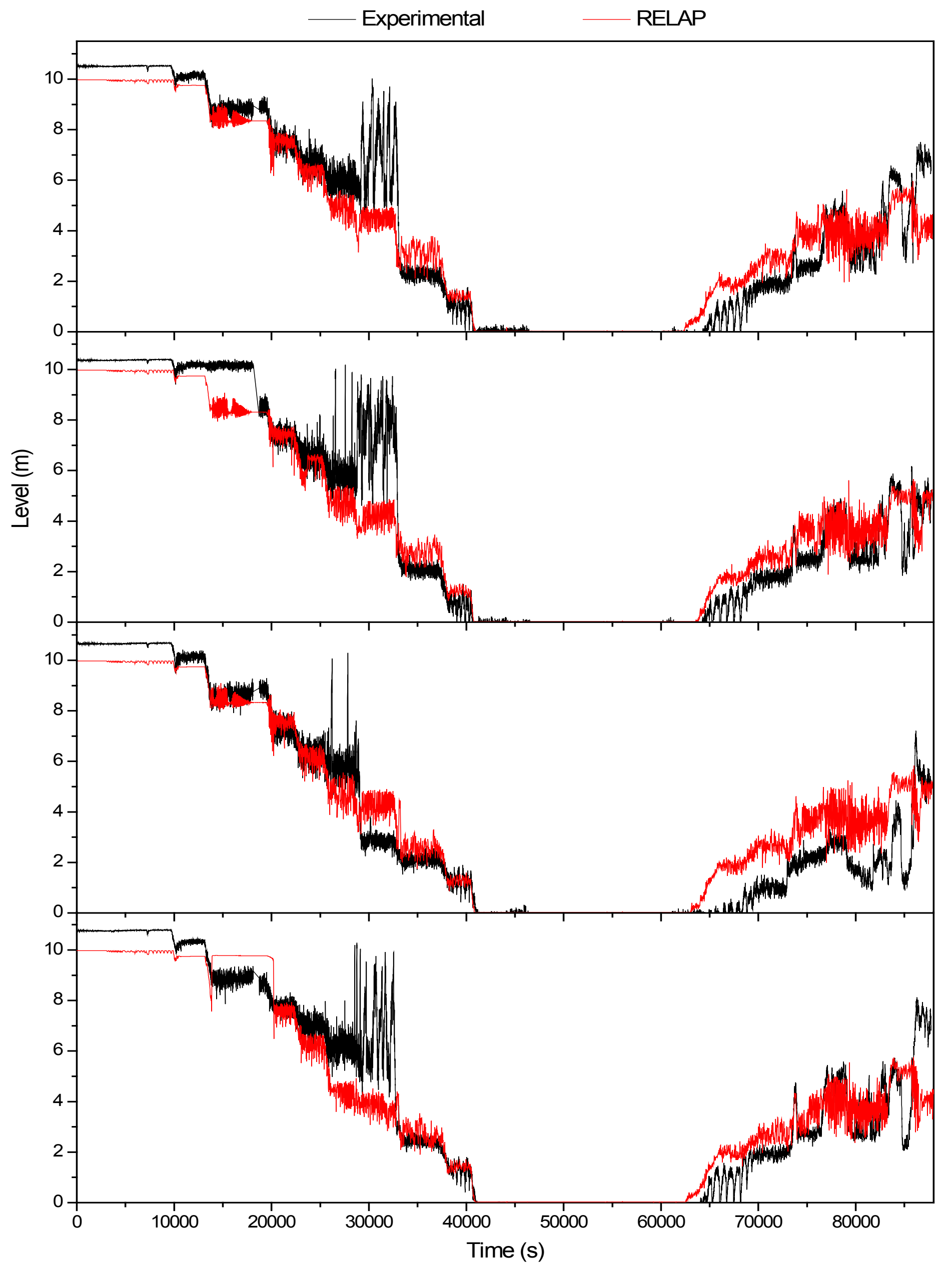

Figure 3.8 U-tube collapsed water levels of loops 1 to 4 for Test F1.2

The different mass flows reached in the steady states were basically achieved by the calculation. Results shown in Figure 25 were smoothed from the real values since the mass flows in some periods had large oscillations. Although there was no special reason, the test showed asymmetries between loops which were not represented by the nodalization. The last steady state before the end of natural circulation was only achieved when using 5 different elevations for the U-tubes. Natural circulation ended at similar times.

3.5 Analysis of Results Concerning Boron Dilution

Figure 27 shows the boron concentration in each loop seal. Boron dilution starts at similar time and the dilution rate is similar in both the test and the calculation. Reflux-condensation conditions were detected in both the test and the calculation even with low mass flow in the loops. There was a two phase natural circulation that slightly diluted the loop seals, at a very low rate. The circulation occurred only in some of the U-tubes and vapor flowed boron free in the rest of the U-tubes, thus boron dilution took place only partially. This could, certainly, not be simulated with only one U-tube. After NC was broken the dilution rate was similar in both the calculation and the test.

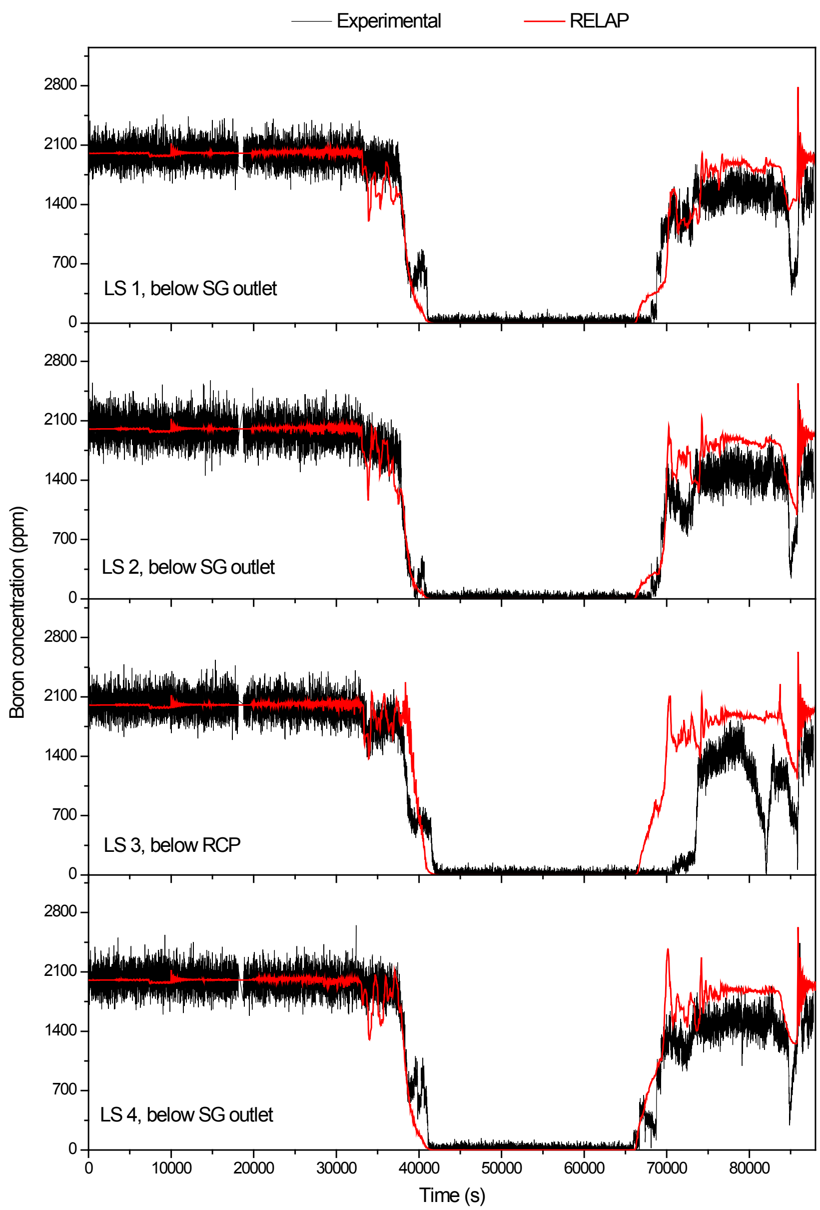

Figure 3.9 Boron concentration at each COMBO measurement for Test F1.2

4 SENSITIVITY STUDIES ON TESTS F1.1 AND F1.2

4.1 Upper Head Bypass Nodalization

One of the problems when simulating test F1.1 was the first uncovery of the break during the conditioning phase. In the first simulations the downcomer level decreased under the cold legs and the break was uncovered too early. Therefore the break mass flow had a sudden plunge (Figure28). The DC level (Figure 29) in the facility does not decrease under the cold legs and the break mass flow is still high during the second part of the conditioning phase. Hence, the coolant mass at the beginning of the transient was about 330 kg greater than expected. That mistake made the primary system fill up before the experimental data and so the primary pressure had an early increase (Figure 30). That discrepancy caused also an early establishment of natural circulation.

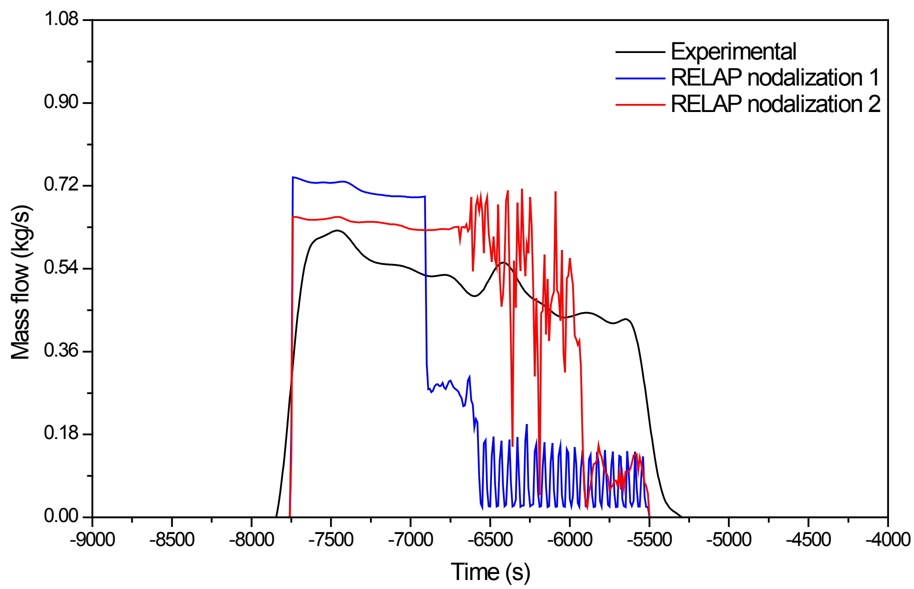

Figure 4.1 Break mass flow during conditioning phase of Test F1.1, upper head bypass sensitivity

In order to better simulate that behavior, a sensitivity study on the bypass nodalization was performed. Improving the detail in the bypass nodalization changed the downcomer level and, therefore, the total mass at the end of the conditioning phase. The four bypasses were previously modeled as two parallel volumes and a small junction at the upper part. Those volumes were subdivided into two so the small orifice was in its real position. All changes performed were done in order to better represent the real geometry so the final input deck is more realistic. The changes on this part of the nodalization improved the simulation as the downcomer level stabilized around the cold leg line (Figure 29) and the coolant mass at the end of the conditioning phase was almost matched. Initial coolant mass for the first nodalization was 1560 kg whereas the experimental mass was 1230 kg. After the bypass changes the final mass is 1163 kg. This ended up with a better simulation of the primary pressure during the transient (Figure 30).

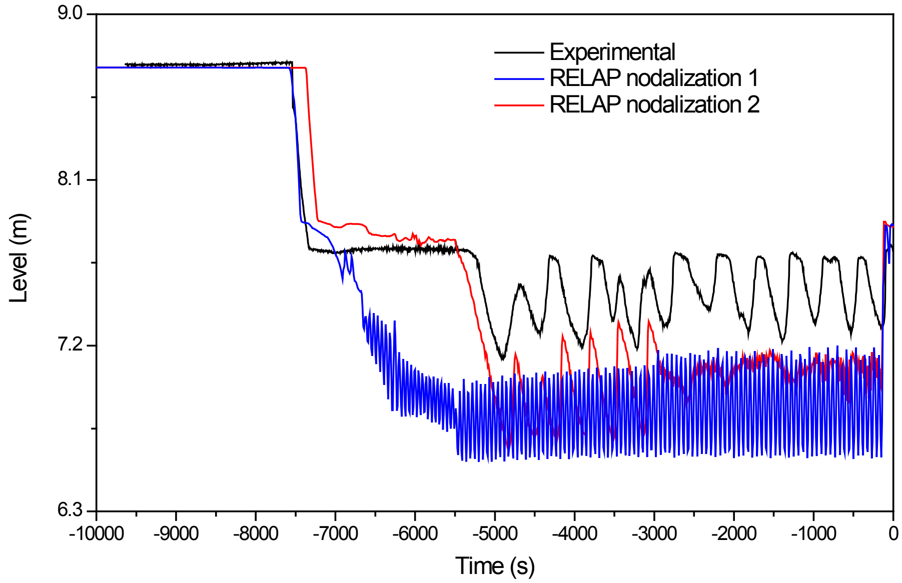

Figure 4.2 Downcomer Collapsed water level during the conditioning phase of Test F1.1, upper head bypass sensitivity

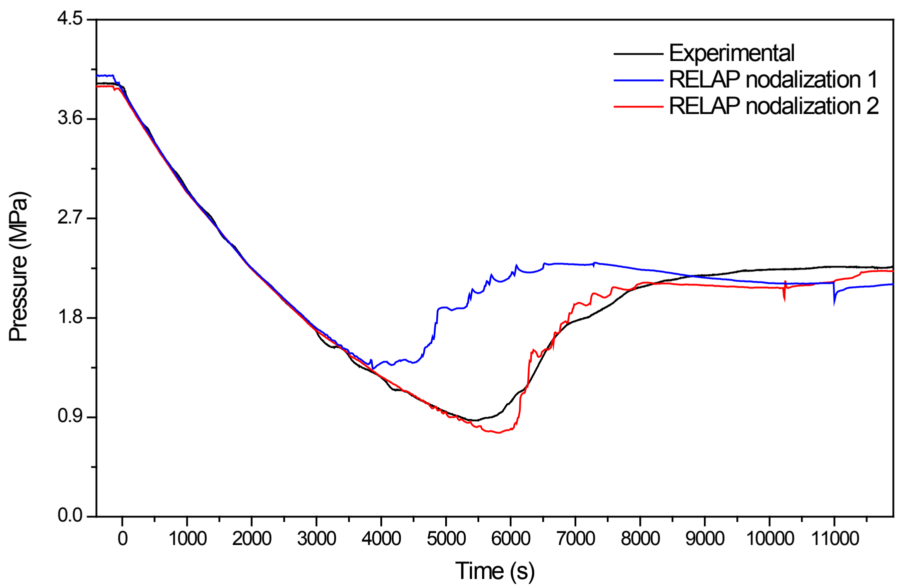

Figure 4.3 Primary pressure of Test F1.1, upper head bypass sensitivity

4.2 <u>Nodalizing 5 U-tubes</u>

During the OECD/SETH project, one of the most relevant discussions was whether the U-tube bundle should be nodalized using more than one pipe at different elevations to capture all phenomena involved in SBLOCA with boron dilution. The actual U-tube bundle has 7 different elevations, allowing a smooth transition from natural circulation to a static state. Thus, NC might be occurring in the lowest tubes of the facility while water in the highest tubes is not able to cross to the descending part. It is clearly not possible to simulate such behavior using a single U-tube pipe, however what is not so obvious is to what extension the use of several tubes improves results.

Most of the groups used 3 different pipes at different elevations. Other participants used a single pipe and a few nodalized the region with 5 pipes. Although most participants using more than one pipe stated that it was necessary to nodalize the U-tube in this way, other participants, e. g. the UPC-INTE, brought in results that had an agreement with the experimental data with the same degree of accuracy. Dr. J. Macek from the Nuclear Research Institute (Czech Republic) stated that ``the increase of number of SG U-tubes (from 1 to 5) had no significant effect on the results'' when simulating tests E2.1, E2.2 and E2.3 [14]. Similarly, a nodalization with 5 different U-tubes for each loop was used by the UPC-INTE team in order to assure that using a single tube was a suitable description of the U-tube bundle.

The 5-Utube nodalization was first generated for test E2.3 due to discrepancies found in the natural circulation of the loops [7]. It was thought that a nodalization with 5 U-tubes would help to hold NC in loops 1 and 3 at SOT. The results showed very little or no differences between the two nodalizations as shown in ref. [7]. This nodalization was hence rejected.

Figures 31 and 32 show results on test F1.1 with very small or inappreciable differences. The results were similar for the other SBLOCA with boron dilution tests (test E1.1, E2.2 and E2.3 [4]).

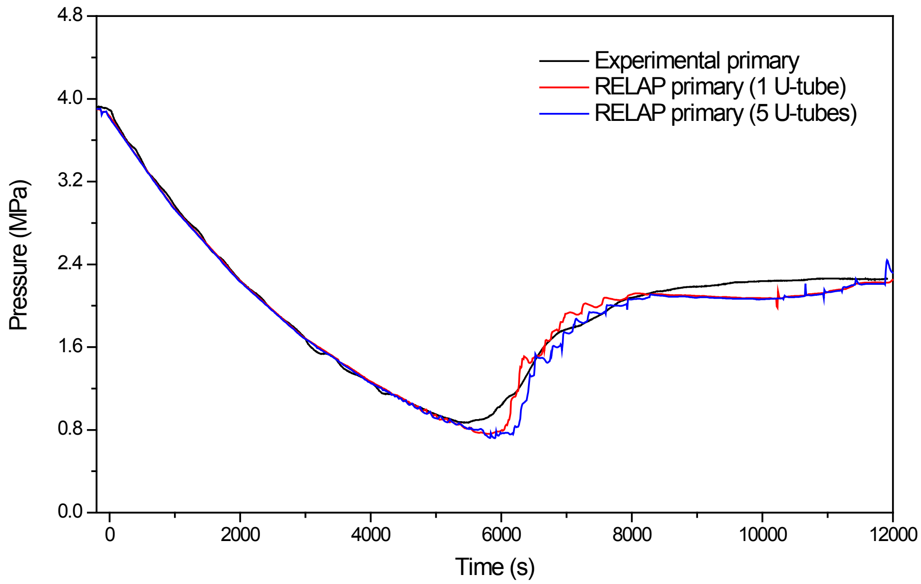

Figure 4.4 Primary pressure for Test F1.1 with 1 and 5 U-tube elevations

The reason is that when natural circulation starts, the level in the U-tubes rises sharply. Hence, there is not much difference between using 1 or 5 elevations. That behavior was already studied in ref. [13], where U-tube levels of all SETH participants where compared for test E2.2. Results showed that it takes about a hundred seconds for the U-tube level to rise or fall from the coolant line to the top of the U-tubes. The error induced by using a single pipe is of the order of 10 seconds[6]. As the transition is so fast, there is no intermediate state and the use of 5 elevations seems to be not necessary.

The simulation of test F1.2 was first performed with a single U-tube. The results obtained with the model had a good agreement with the experimental data although boron dilution started earlier according to the RELAP5 results. Analyzing the experimental data, it was seen that during the last steady state the test had very low mass flows while, on the other hand the UPC-INTE nodalization did not. As there was no liquid crossing to the descending part of the U-tubes (only vapor flowed) boron dilution started in the simulation. Moreover, even though some mass flow was detected, the loop seals were slightly diluted in the test during this last steady state, thus it was thought that NC occurred only in the lowest U-tubes while in the highest ones, boron free vapor was circulating. Bearing this in mind, the 5 U-tubes nodalization would be needed. The change of nodalization improved the results impressively. Natural circulation stopped just at the same time as in the experiment (Figure 33) and the last steady state with mass flow (by entrainment) only in the lowest U-tubes was simulated. Therefore full boron dilution started also as it did in the experiment (Figure 34).

[6] It takes 10 seconds for the liquid level to raise from the top of the lowest U-tube to the highest

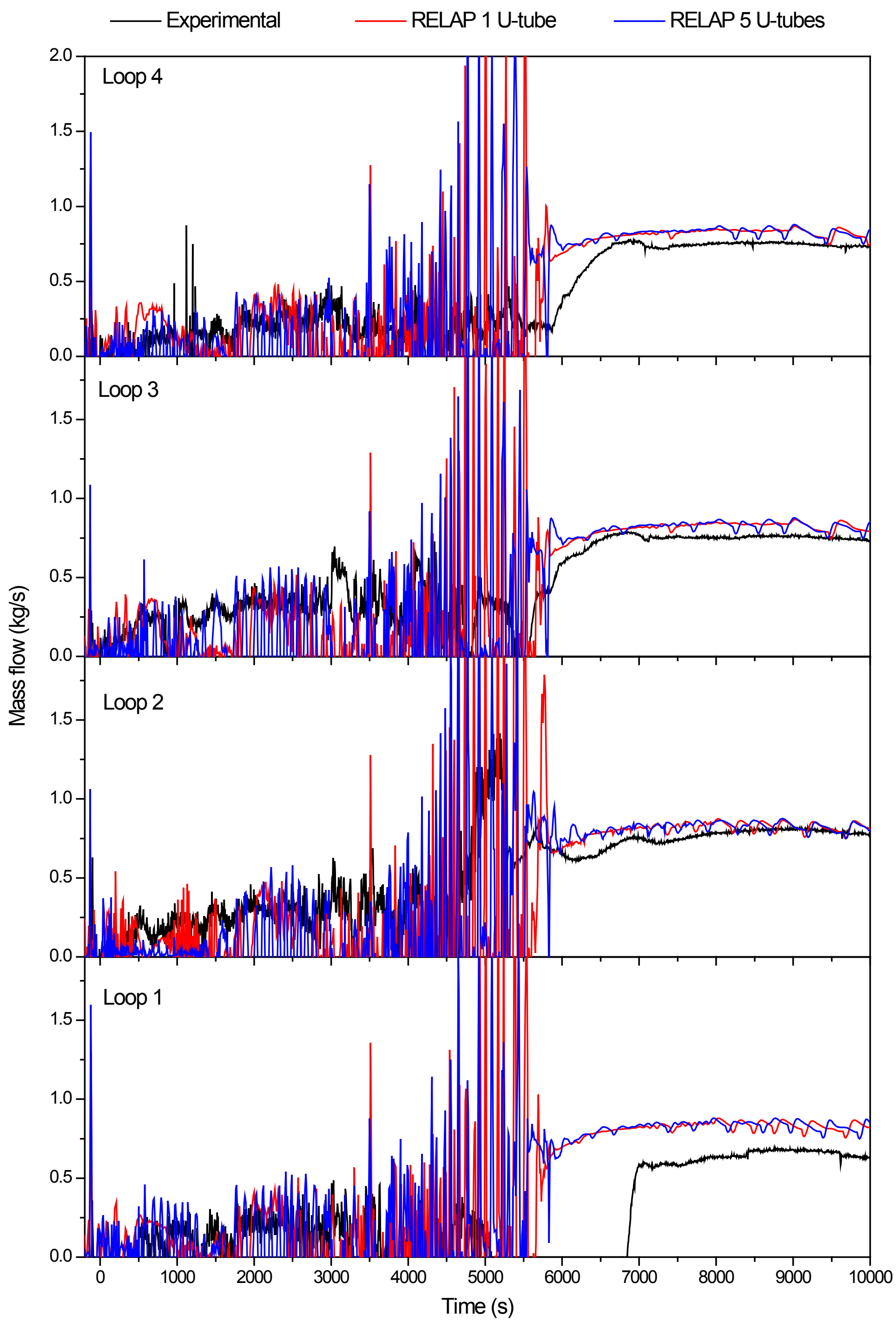

Figure 4.5 Mass flow at loop 4 for test F1.1 with 1 and 5 U-tube elevations

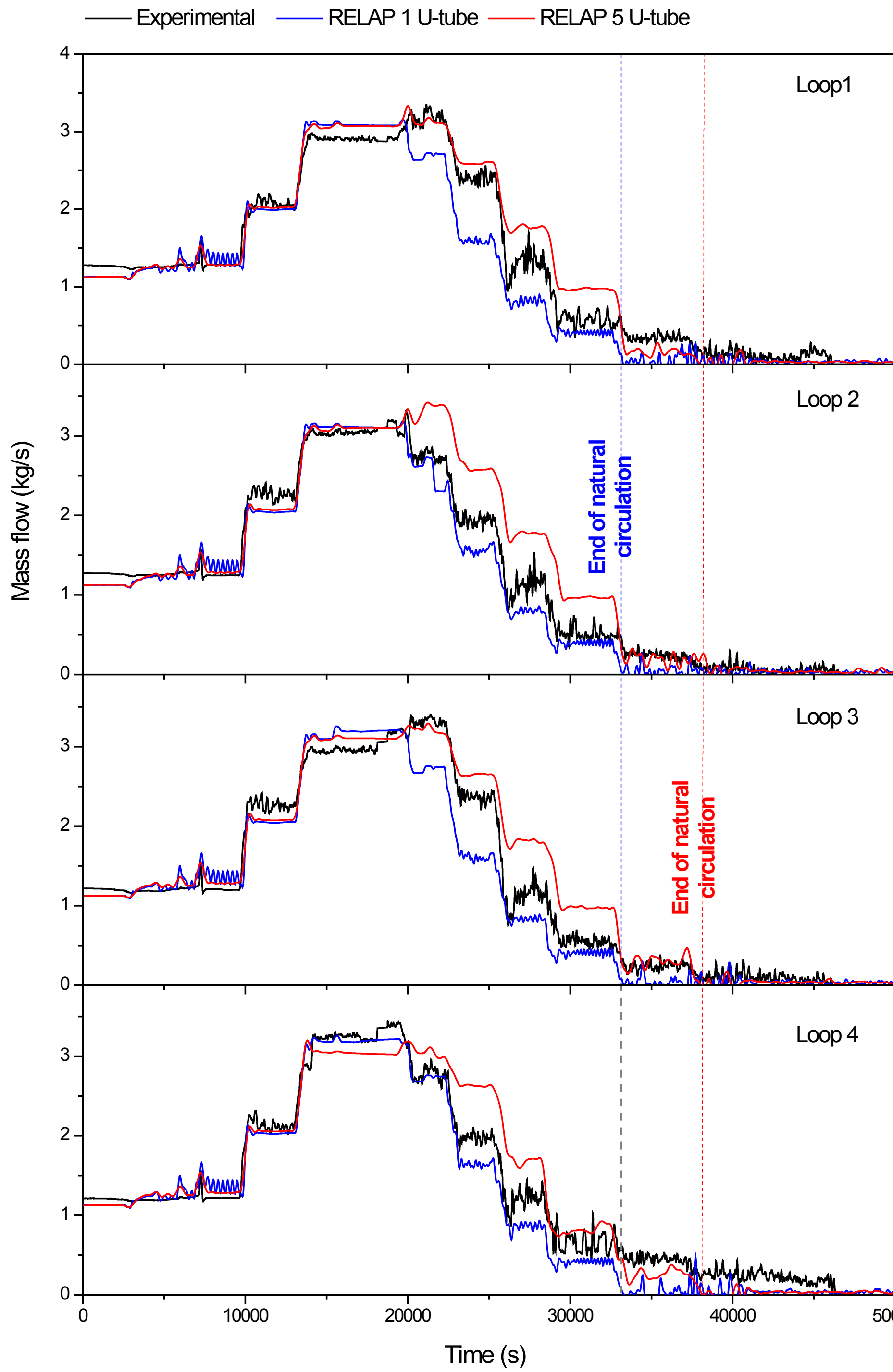

Figure 4.6 Loop mass flows for Test F1.2 with 1 and 5 U-tubes

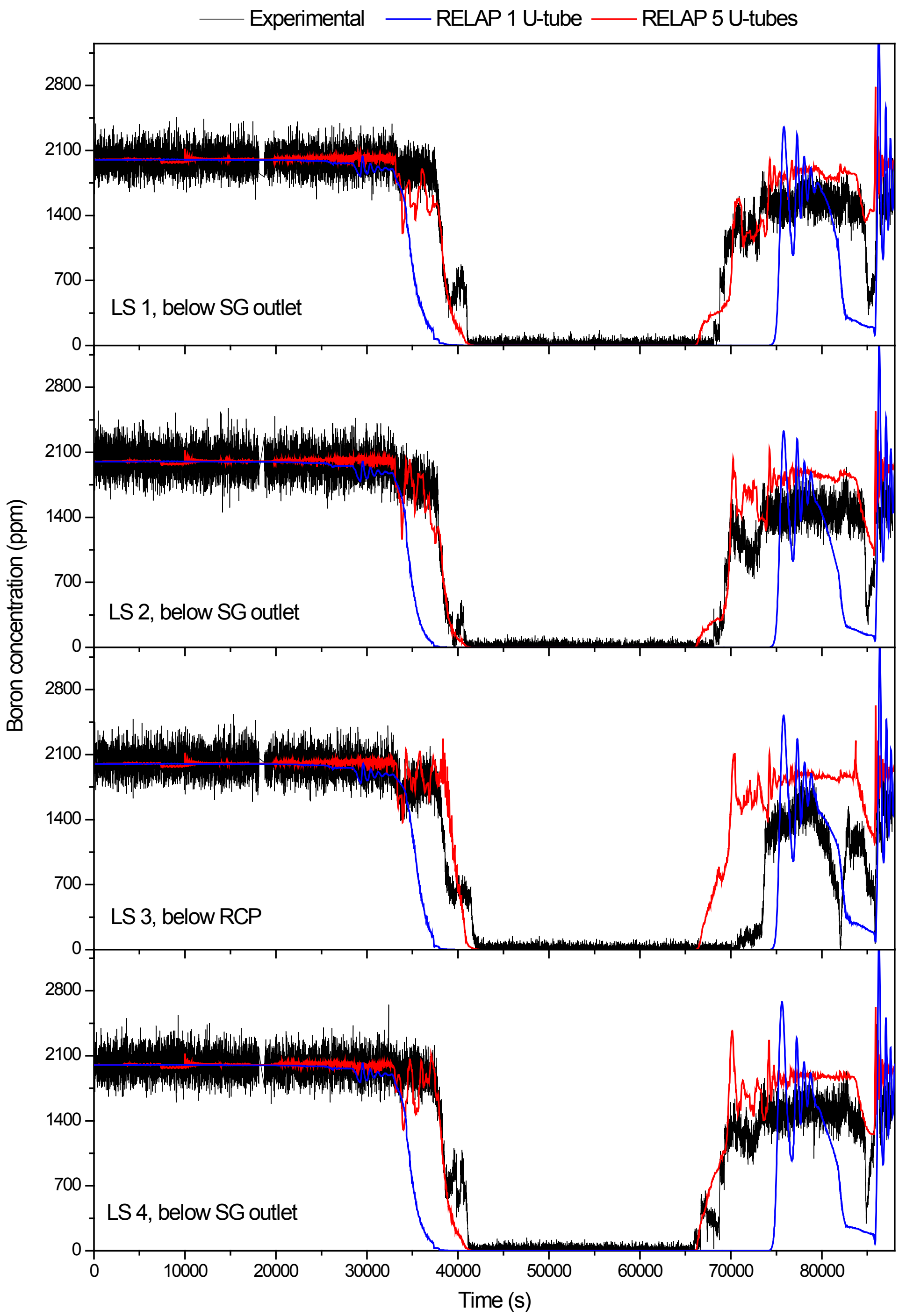

Figure 4.7 Boron concentration in all LSs for Test F1.2 with 1 and 5 U-tubes

The 5 U-tubes nodalization was necessary for test F1.2 because, unlike in the other tests where NC was stopped or initiated abruptly, in this case the reduction of the mass inventory was performed steadily.

After these results, all tests were performed again with 5 U-tubes to see the influence on the results. The new nodalization barely modified the results, the differences were either negligible or could not be observed at all. Both nodalizations were able to represent tests E1.1 [6], E2.2 [5], E2.3 [7] and F1.1 [8]; however, test F1.2 had to be nodalized with 5 U-tubes to obtain better results [4].

Another issue arose at that point. It is important to consider that the number of volumes was increased from 438 to 775; therefore the time step was dramatically pumped up. Table 5 shows the CPU times of all tests when using one or the other nodalization. The computer time was doubled or tripled when using the 5 U-tubes nodalization. Therefore, it is suitable to keep both nodalizations and decide when it is necessary to use one or the other. For instance, it is very convenient to use the simplest nodalization in order to perform sensitivity studies.

Table 4.1 CPU times using 1 and 5 U-tubes. Calculations performed on a PC, Pentium 4 at 3.4GHz and 512 RAM

	Test Time (s)	CPU time (s), 1 U-tube	CPU time (s), 5 U-tubes
Test E1.1	15000	3530	8470
Test E2.2	16700	3892	32714
Test E2.3	19145	4707	14325
Test F1.1	20000	3825	10920
Test F1.2	88000	19070	51250

5 CONCLUSIONS

A model of the PKL Test Facility has been set up and it has proved to be a suitable tool to simulate the behavior of this facility.

Simulation of test F1.1 was in close agreement with the experimental data. A modification of the nodalization of the upper head bypass was done improving the results of the test.

The post-test calculation of test F1.2 produced satisfactory results. The different steady states were accomplished along with their correspondent natural circulation mass flows. The reduction of the boron concentration occurred at similar times and with matching rates. The model proved to be able to simulate the boron dilution phenomena when the reflux-condensation conditions were established and can be, therefore, used to study this phenomenon in commercial power plants.

The issue of the U-tube bundle nodalization turned out to be a key point. The interpretation of the experimental data pointed out that during the last steady state before the end of NC, liquid water would flow through the lowest U-tubes and vapor in the highest ones. This behavior can certainly not be simulated with a single U-tube. Therefore, the nodalization with 5 different U-tubes was used for this test.

Two different sensibility studies were performed in order to improve the response of the nodalization in both tests:

- **U-tube bundle.** To properly simulate the U-tube test bundle was one of the main issues within the OECD/SETH and OECD/PKL projects. The onset of natural circulation is supposed to be greatly affected by how the U-tubes are nodalized since, geometrically, the U-tubes have different elevations and therefore natural circulation might be established in some of them while circulation in other U-tubes remain still. Simulations carried out for various tests where the U-tube bundle was simulated with 5 pipes revealed different conclusions. In most cases, i.e. e. in SBLOCA with boron dilution the results were barely affected. The computer time was increased as much as 200%, thus in these cases the use of more than one U-tube is optional. On the other hand, in test F1.2 the use of 5 different elevations improved the results and circulation in some of the U-tubes was simulated successfully. Hence, in some cases, when the U-tube level might stabilize amidst the top of the U-tubes, an accurate nodalization is needed.
- **Upper head bypass nodalization** It is well known that the upper head bypass nodalization highly affects the behavior of the model and specially the downcomer level. A sensitivity study was focused on the nodalization of this part of the facility. The changes performed were designed to represent more accurately the geometry yielding improved results. In the middle of the four bypass of PKL there is a throat. The calculations revealed the importance of both the elevation position of the throat and the distance from the downcomer and upper head. Detailed nodalization of this area is hereby required. The changes highly affected results of test F1.1.

The formation of boron diluted slugs was correctly simulated in both PKL tests. Reflux-condensation conditions were reached in all tests with a very similar behavior toward the ones observed in the tests. Dilution occurred at both sides of the U-tubes and small boron diluted slugs were placed in the hot legs as well. These slugs were formed in both the calculations and the experiments although their size was larger in the UPC-INTE simulation. It can be concluded that the UPC-INTE nodalization was able to reproduce the necessary conditions and with such conditions the boron dilution in the loop seals occurred with the same rates as in the experiments.

6 RUN STATISTICS

The calculations have been performed using the NRC RELAP5 3.3 code, running on a PC Pentium 4 3.6MHz. The operating system was Windows 2000. The base case calculation for tests F1.1, F1.2 (one U-tube) and F1.2 (5 U-tubes) took 1.8, 5.3 and 14.2 hours respectively of CPU time. Figures 35 and 36 display the CPU time for these three calculations. The time step remained quite constant and was only substantially increased when the core level was at its minimum.

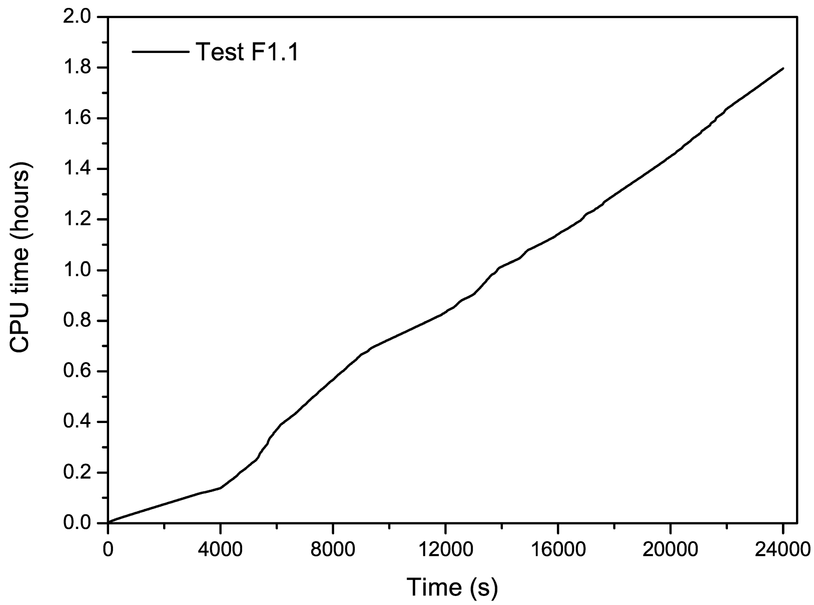

Figure 6.1 CPU time usage for Test F1.1

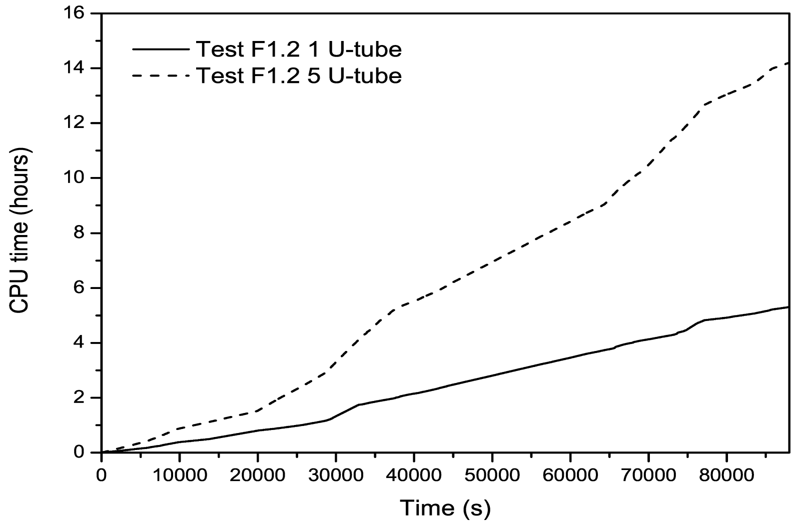

Figure 6.2 CPU time usage for Test F1.2 using 1 and 5 pipes to simulate the U-tube bundle

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Two different post-test analyses have been performed by making use of the UPC's model of the PKL facility. The nodalization has been developed using the RELAP5mod3.3 code and two tests of the OECD/PKL project, namely Test F1.1 and F1.2, have been simulated. For both transients, the simulations correctly reproduce the finalization of natural circulation and the beginning of the reflux condensation conditions with the consequent formation of low borated water slugs in the loop seals due to the phenomenon of boron dilution.

Test F1.1 is a Small Break LOCA in the cold leg assuming the non-availability of the LPI system and the accumulators while Test F1.2 simulates a series of steady state situations for different primary inventories in order to study the phenomenon of boron dilution as a function of the mass inventory.

Different sensitivity analyses are also reported and the nodalization of the U-tubes bundle is discussed for both scenarios. The results cover the formation of slugs in the loop seals under reflux and condensation conditions and their movement through the loop when the U-tubes are refilled and natural circulation is re-established.

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