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International Agreement Report

Analysis with TRACE Code of ROSA Test 1.1: ECCS Water Injection Under Natural Circulation Condition

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ABSTRACT

The goal of this report is to explain the main results obtained in the simulation performed with the consolidated thermal-hydraulic code TRACE of the OECD/NEA natural circulation test ROSA 1.1, conducted at the Large Scale Test Facility (LSTF) in Japan. To attain the initial conditions the power was reduced from 7.11 MW to 1.44 MW, followed by a shutdown of the primary coolant pump with the 100% of water inventory in the primary. After some time the test initial conditions are attained and steady-state natural circulation conditions are established in the primary loop. The test can be divided in three different stages, each one characterized by attaining natural circulation conditions under different two-phase states in the primary coolant circuit, achieved reducing the primary inventory to 80, 70 & 50% of its original value, discharging the primary coolant water via auto bleed line located near the bottom of the RPV. The main goal of this report is to analyze the ability of TRACE code to precisely simulate the stratification and natural circulation conditions of both single and two-phase flows inside the primary circuit. During the experiment, the secondary side conditions were obtained by manually controlling the steam and feed-water flow rates in order to maintain the secondary pressure at 6.7 MPa, while in the simulation the secondary conditions were automatically controlled. At the beginning of the conditioning phase the severe power reduction and the shutdown of the coolant pump produces a mass flow rate reduction which is almost perfectly matched by the simulation with the TRACE code, with only a slightly higher mass flow rate than in the experiment. Meanwhile, the pressure remains practically constant in the experiment while it drops during the simulation with TRACE to recover after some time. After the first extraction (20% of main inventory) two-phase flow natural circulation conditions are attained in the primary loop. It is worth to note that TRACE properly models the pressure and temperature evolution with time in the primary system when the secondary pressure is kept constant at 6 MPa. The predictions of the natural circulation mass flow rates are good after the first extraction but after the second extraction are below the experimental values.

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 a number of experimental facilities and programmes of potential interest for present or future international collaboration within the safety community during the coming decade.

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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).

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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EXECUTIVE SUMMARY

This report presents the main results obtained with the NRC consolidated code TRACE for the simulation of the OCDE natural circulation test ROSA 1.1 that was carried out at LSTF.

The LSTF facility represents a PWR reactor reduced to 1/48 scale in volume and power. The facility has two primary loops, A and B, with one steam generator per loop, one recirculation pump per loop and a pressurizer located in loop A. The emergency core cooling system (ECCS) is formed by the accumulator tanks and the high pressure injection system (HPIS). The amount of water injected by the ECCS system depends on pressure. Both systems, i.e. the HPIS and the accumulators, actuate when the primary pressure drops below specific set point values. In test ROSA 1.1 there are three main discharges, amounting for 20%, 10% and 20% of the water inventory, which are not followed by HPIS water injection. In any other instance, water injected by the HPIS is subsequently discharged from the system, keeping the water inventory constant. Conditions in the secondary are manually controlled in the experiment in order to maintain the pressure and the water level constant, while in the code an automatic controller has been used.

The objective of this assessment is to compare code predictions with experimental data obtained during the ROSA 1.1 test in order to establish TRACE's capability to predict complex transients with multidimensional natural two-phase flow convection, and, if possible, to improve the available LSTF TRACE model.

A reference steady state situation was first obtained with the TRACE code using the same initial boundary condition measured in the LSTF facility for this experiment. During this phase the power is reduced from an initial value of 7.11 MW to 1.44 MW (80% reduction) which is equivalent to a scaled value of 2% of the reactor power at nominal conditions, followed by a shutdown of the primary coolant pumps. Then there is a waiting period of 1.200 s until the system attains the single flow natural circulation conditions. Then the ECCS system injects water into the loop A, followed by a release of the injected mass through the bleed line, located at the bottom of the RPV, then there is a waiting period of 10 minutes followed by a new injection period now into loop B, and a new extraction of the injected mass through the bleed line. This sequence of operations (waiting time plus injection into loops A or B and release of the injected water) is repeated two more times. Finally at the end of this sequence the pressurizer is isolated from the rest of the system.

Then the primary coolant inventory is reduced in three time steps by 20%, 10% and 20% respectively of the initial inventory. Each inventory reduction period is followed by a ten minutes waiting period followed by injection into cold legs A/B at a rate of 0.3 kg/s during 80 seconds. Then a new 10 minutes period without coolant extraction is run in order to attain quasi-stationary conditions in the system. After, each quasi-stationary period there is a small injection that lasts 80 s into loops A/B followed by an extraction period through the bleed line that releases the previously injected mass except at the beginning of the next extraction period.

The first reduction of the mass inventory to 80% of the initial one, starts at time 4032 s and finishes at time 6037 s. During the first 400 seconds of the extraction period an increase of the natural circulation mass flow rate is observed in the experiment, being predicted with some delay by the TRACE simulation. Then the TRACE code in cold leg A predicts at the beginning of the extraction an increase in the mass flow rate but then the simulation results show big oscillations, as well as an average mass flow rate that is smaller than the experimental one.

After the second release of water from 80% to 70% at time 9229 s there is a reduction in the natural circulation mass flow rate from 10 kg/s to 5 kg/s. The TRACE code predicts also a reduction from 7 kg/s to 3 kg/s but displays bigger oscillation in the mass flow rate circulating through the cold legs. The third inventory discharge that finishes at time 15.166 s provokes a reduction of the coolant inventory to 50% of the initial one and also the natural circulation mass flow rate diminishes from 5 kg/s to practically zero, in the simulation with TRACE this last reduction is also observed but the natural circulation mass flow rate stops earlier in time.

One of the main goals of the present experiment is to analyze the capability of TRACE code to predict natural circulation under two phase flow conditions. In this test the thermal stratification which appears produced by the injection of cold water by the ECCS system in the cold legs is also important. However to analyze the thermal stratification with 1D TRACE components is not possible. Only with a 3D modelling of the full primary circuit is possible to analyze this issue, and this is only possible with CFD codes.

In order to evaluate the capability of the TRACE code to model this scenario experimental data and simulation results have been compared for the following magnitudes: pressure in the RPV upper plenum and steam generators, temperatures in both cold leg's seals, liquid level in the secondary of both steam generators and mass flow rates in cold legs A and B.

At the start of the test, pressure in the primary system (measured in the RPV upper plenum) decreases slightly before the pressurizer, and heat released by the core acts restoring pressure to its initial value. This is not correctly simulated by the TRACE code, where the pressure drop is larger than the experimental one and takes more time to recover. During the first main discharge, pressure in the system suffers an intense decrease, which is mostly matched by the TRACE model. After the first main discharge, pressure in the primary system suffers only slight variations, which are not exactly matched by the model, although it gives values not far away from the experimental ones. Pressure in the primary side of the steam generators follows a similar evolution to the evolution of the pressure in the RPV, while in the secondary side pressure is kept between 59 and 66 bars, and does not present a drastic decrease after the first main discharge. The TRACE code predicts this behaviour pretty well oscillating between 64 and 65 bars.

Temperature in the cold leg seals also experiment a decrease after reactor power output decreases at the start of the test, being this variation larger and longer in the simulations predictions than in the experimental data. After stabilizing again, temperatures grow and later decrease between each of the main discharges, with small variations about 5 K, with temperatures being between 546 K and 551 K. However after the third main discharge, which finishes at time 15166 s the experimental temperature in the cold leg displays temperature oscillations of about 75 K. In contrast, TRACE results becomes constant at 551 K between the first and second main discharges, then decreases steadily from 551 K to 545 K between the second and third main discharges and, after the aforementioned third discharge, increases to remain stable at a value higher than the experimental one, not matching the oscillations of the experimental data. However both experimental data and TRACE results are close in a band ranging from 545 K to 551 K, except at the end of the transient.

Experimental data on the liquid level in the secondary side of the steam generators starts at a level of 9.5 m that is maintained oscillating between 9 and 10.2 m. The TRACE simulation predicts a value that is maintained practically constant at 10 m during the full transient.

Mass flow rates measured in both cold leg A and B show similar patterns: After the original reactor power output decreases, the mass flow rate also decreases to become almost constant around a value of approximately 6 kg/s per loop. After the first discharge, the natural circulation mass flow rate increases to a value of approximately 10 kg/s per loop, remaining again constant until the next main discharge, in which it drops to a constant value of 5 kg/s. After the third and last main discharge, experimental mass flow rates shows a decrease in both loops to almost zero kg/s. TRACE results matches experimental data until the first main discharge. After this, mass flow rate in cold leg A presents a markedly oscillatory behaviour, with an average value of about

7.5 kg/s, which is lower that the experimental one. Model data are worse in cold leg B, with flow rates becoming almost zero after the first main discharge.

ACKNOWLEGMENTS

The thermal-hydraulic and nuclear engineering group of the UPV is indebted to the management board of the ROSA project and to the people of the Thermal-Hydraulics Safety Research Group of JAEA. The CSN financed this work, and helped to develop this report. Also we are indebted to Cesar Queral that provided a model of the LSTF facility for the TRACE code and many interesting suggestions for the improvement of the model.

ABBREVIATIONS

CSN	Spanish Nuclear Regulatory Commission
CRGT	Control Rod Guide Tubes
ECCS	Emergency Core Cooling System
HPIS	High Pressure Injection System
LOCA	Loss of coolant accident
LSTF	Large Scale Test Facility
OCDE	Organization for the Cooperation and Economic Development
PH	High-Pressure Injection Pump
PJ	Charging Pump
PTS	Pressurized Thermal Shock
PV	Pressure Vessel
PWR	Pressurized Power Reactor
ROSA	Rig of Safety Assessment
RPV	Reactor Pressure Vessel
SG	Steam Generator
TH	Thermal-Hydraulics
UNESA	Spanish Electricity Producers Association
TRACE	TRAC/RELAP Advanced Computational Engine

1. INTRODUCTION

The present work was performed as a contribution to the OCDE international collaborative research project ROSA. A consortium formed by the CSN and several Spanish Technical Universities developed the Spanish participation in the project that was coordinated by the CSN and a steering committee.

The analysis of the experiment ROSA 1.1 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 nuclear safety research centre of the Japan Atomic Energy Agency in the large scale test facility (LSTF) on October 26 and 27, 2006 [1,2].

The goal of the 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, and to check the ability of the present generation of TH codes to model complex phenomena where stratification 3D effects are of relevance for the safety of the plants.

The ROSA TEST 1.1 consists of several stages. At the start of the transient, core power was decreased to 20% of nominal power (from 7.11 to 1.44 MW), followed within 20 seconds by the stop of the primary coolant pump. Conditions in the system are then maintained until variables stabilize, resulting in a single-phase natural circulation stage. Thereafter, the pressurizer is isolated and the primary water inventory is reduced three times to 80, 70 and 50% of its original value, keeping secondary side conditions constant by manually maintaining pressure and liquid level in the SGs secondary sides. This is done in order to attain three different two-phase natural circulation states in the primary loop. Discharges are produced at a valve located at the end of an auto bleed line connected to the RPV near its bottom. The high pressure injection system (HPIS) is activated automatically with a delay of 12 seconds when the pressure falls below 12.27 MPa. The accumulator injection is activated when the pressure falls below 4.51 MPa. Cold water injected into the cold legs by the ECCS system mixes partially with the hot primary coolant flow and flows into the downcomer of the pressure vessel. As injected water is colder than the one already present in the coolant system, it does not mix completely with the fluid of the cold leg and accumulates in the bottom of the pipe, forming a cold layer which moves towards the downcomer, while the upper part contains coolant fluid at higher temperature and some steam above the interface. This steam partially condenses on the lower boundary layer interface and on the sides of the injected jet, and the local pressure variations triggered can cause unstable flow oscillations that in turn promote coolant mixing. Such multidimensional and non-equilibrium flow phenomena are of concern for pressurized thermal shock (PTS) [3,4].

Aside from the three main aforementioned coolant extractions, there are several ECCS water injections which are subsequently mirrored by a mass release via the auto bleed line in order to maintain the actual secondary system inventory constant.

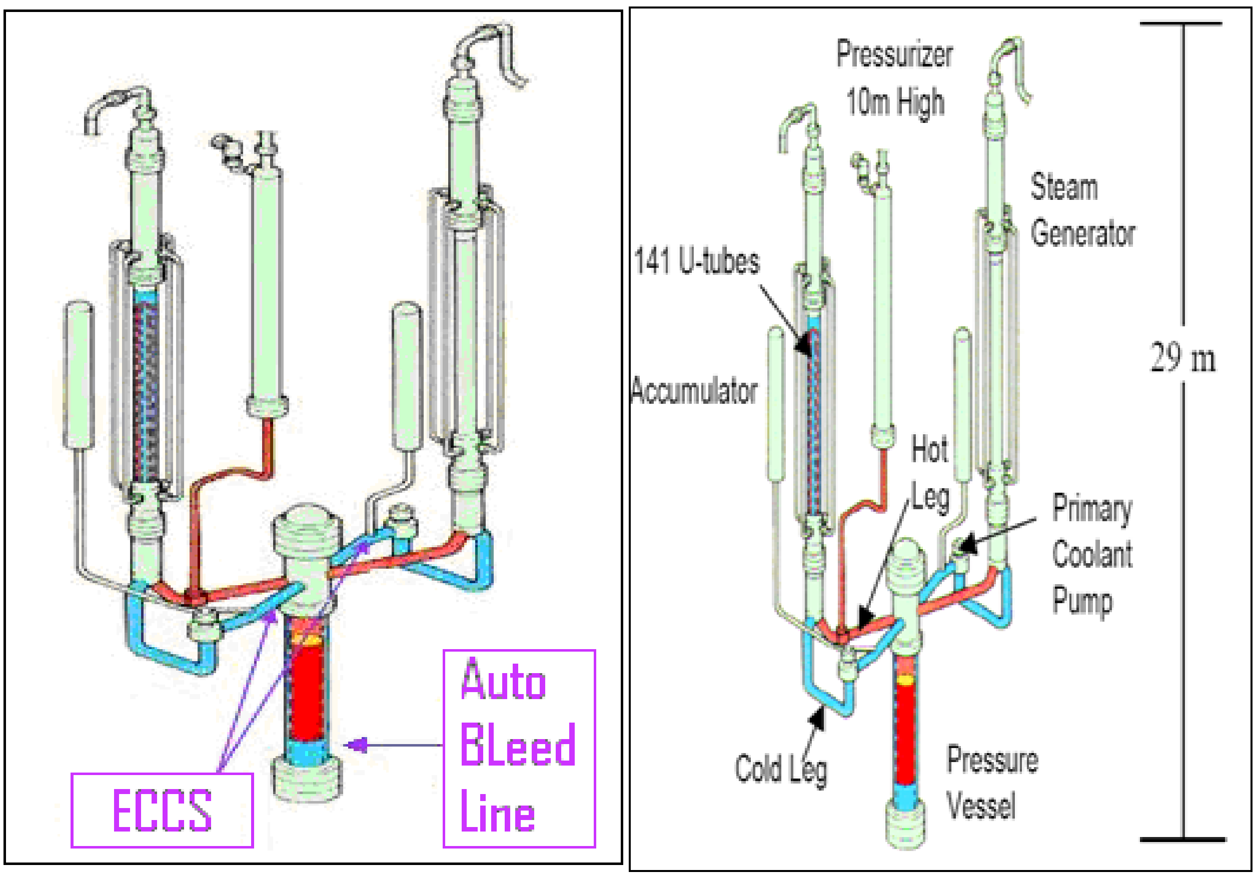
The goal of this work is to compare the experimental results with the predictions of the TRACE code simulation and to analyze the set of phenomena that take place at the primary and secondary loops. Special emphasis is devoted to the analysis between the code results and the experimental data.

This work has been divided into four sections: section 1 is an introduction to the ROSA test series 1; section 2 described the LSFT facility, the initial and boundary conditions of test 1.1 and the study of the transient sequence; section 3 deals with the comparison of TRACE simulation results for the main physical magnitudes versus the experimental data; finally the conclusions are presented in section 4.

2. INITIAL AND BOUNDARY CONDITIONS

2.1 Description of the LSTF facility

The LSTF facility as displayed in figure 2.1 simulates a Westinghouse-type four-loop PWR on full-height and scaled by a factor of 1/48 in volume and power. The flow areas are scaled with a factor of 1/48 in the vessel, and 1/24 in the steam generator. As displayed in figure 2.1 the facility has two primary loops denoted by A, and B, respectively, which are of similar length and diameter but have different shape and location of the ECCS injection nozzles. The hot and cold legs, with an inner diameter of 207 mm, have been dimensioned to conserve the volumetric scaling 2/48, and the ratio of the length to the square root of the diameter, i.e. $L/\sqrt{D}$, in order to properly simulate the flow regime transitions in the horizontal legs which is one of the goals of this test.



(a) (b)

Figure 2.1 Large Scale Test Facility (LSTF) used to perform the ROSA test 1.1. Figure (a) displays the points of injection of the emergency core cooling system and the location of the break/auto bleed line in the RPV. Figure (b) shows the different components of the facility.

The LSTF represents the reference PWR bypasses by including eight upper-head spray nozzles (inner-diameter of 3.4 mm each) and the hot leg nozzle leakage. The spray nozzles allow bypass flow that amounts to 0.3% of the total core flow rate during the initial steady-state, while bypass area of the hot-leg nozzle is set to allow 0.2% bypass flow for each loop.

Control rod guide tubes (CRGT) represent the flow paths between the upper-head and the upper plenum. Eight CRGTs are attached to the upper core plate and pass through the upper core support plate to simulate the CRGT in the reference PWR.

The accumulator tanks have an initial gas volume of 0.46 m^3 for both loops. The initial water level and volume above the standpipe are 1.58 m^3 and 1.12 m^3 respectively for both loops. The volume of the accumulator injection lines with and without pressurizer are 0.2 and 0.14 m^3 respectively.

2.2 Stationary initial conditions for ROSA 1.1 test and results of TRACE code

Third column of table 2.1 displays the stationary initial conditions for Test 1.1 specified by the final data report, while second and fourth columns show the experimental measured conditions in loops A and B and the results of the TRACE code simulation respectively. These initial conditions were the operating ones prior to the beginning of data recording.

Table 2.1 Comparison of stationary initial conditions measured in the ROSA experiment against data calculated using the TRACE code model

Items	Experimental A/B	Specified	Simulation (TRACE)
Pressure Vessel			
Core Power (MW)	7.11	10.0	7.11
Upper Plenum Pressure	15.26		15.4
Primary loop			
Hot leg fluid temperature (K)	581.3/580.8	598.0	583
Cold leg fluid temperature (K)	555.3/555.0	562.0	553
Mass flow rate (kg/s/loop)	24.83/24.45	24.3	23.8
Pump rotation speed (rps)	13.8/13.6	13.3	13.8
Pressurizer (PZR)			
Pressurizer pressure (MPa)	15.36	15.5	15.3
Liquid level (m)	7.68	7.2	5
Steam Generator (SG)			
Secondary side pressure (bar)	6.41/6.39	6.5	6.2
Secondary side liquid level (m)	9.11/9.11	9.1	10.5
Steam mass flow rate (kg/s)	1.77/1.73	2.74	1.8
Main Feed-water flow rate (kg/s)	1.87/1.65	2.74	1.8
Main Feed-Water Temperature (K)	483.9/483.0	495.2	495

2.3 Test conditions and set points

After initial conditions have been fully established, core power is reduced from a measured value of 7.11 MW to 1.44 MW, which corresponds to 20% of the measured power output and 2% of the scaled nominal power, respectively. Primary coolant pumps are shutdown and thereafter steady-state single-phase natural circulation conditions are established in the primary loops, at a pressure of 15.5 MPa. The pressure and water level in the secondary side were kept manually constant at 6.4 MPa and 9 meters during the experiment, a point which could not be reproduced adequately in the simulation due to lack of information. Instead of a manual control, the model incorporates an automatic control which turns on when secondary pressure goes outside the 6.0/6.4 MPa interval. During this phase of the experiment, ECCS water is injected alternatively in the cold leg A and B of the system using the charging pumps (PJ), as injections cannot be performed simultaneously in both cold-legs due to a limitation of the pump head. Each of these injections is followed between 80 and 100 seconds later by a discharge through the bleed line of the same amount of water introduced in the system by the last injection, thus maintaining the primary coolant water inventory constant.

After letting the system attain quasi-stationary conditions, a second stage is started by isolating the pressurizer from the rest of the primary loop, and then consecutively reducing the primary inventory to 80, 70 and 50% of its initial value, in order to force a two-phase flow regime in the primary loop with three different condition sets. Each one of these discharges is not coupled with a previous injection, and is always followed by a time period in which conditions in the system are left intact in order to let them to reach a quasi-stationary state. During this stage, ECCS water is injected using the high pressure injection pumps (PH), which means that they can operate in both cold leg A and B at the same time as displayed in tables 2.2 and 2.3. Throughout the experiment, injection mass flow rates are of only two types: 0.3 kg/s (which corresponds to the actual injection mass flow rate of power plants) and 1 kg/s (which is almost the maximum flow rate attainable at 15.5 MPa for the LSTF), aside from an additional 1.8 kg/s injection performed in cold-leg B at 70% and 50% water inventory levels, with these additional injections being the only ones not followed by a discharge. The duration of each injection is approximately 80 seconds, and the temperature of the ECCS water around 300 K.

The sequence of events of this test, as described in the final data report, is shown in table 2.3. In this work, only the data presented in the OECD/NEA final data report regarding ROSA project 1-1 was taken into account to simulate the experiment using the TRACE code.

Table 2.2 Sequence of events

Time (s)	Event
-1901	Data record start
-1535	Core power decreased from 7.11 to 1.44 MW
-1519	Primary coolant pump stopped
18 - 100	0.225 kg/s injection into cold leg A
275 – 314	Discharge
1128 – 1211	0.203 kg/s injection into cold leg B
1315 - 1349	Discharge
2097 - 2184	0.98 kg/s injection into cold leg A
2267 – 2421	Discharge
3192 – 3275	0.851 kg/s injection into cold leg B
3442 – 3600	Discharge
3822	Pressurizer isolation
4032 – 6107	Discharge: primary inventory 100% -> 80%
6929 – 7004	0.253 kg/s injection into cold leg A
6926 - 7004	0.265 kg/s injection into cold leg B
7155 – 7281	Discharge
8237– 8318	0.997 kg/s injection into cold leg A
8232 - 8319	0.87 kg/s injection into cold leg B
8466 – 9229	Discharge: primary inventory 80% -> 70%
10835 – 10917	0.253 kg/s injection into cold leg A
10828 – 10918	0.279 kg/s injection into cold leg B
11007 – 11135	Discharge
12114 – 12193	1.0 kg/s injection into cold leg A
1212 – 12196	0.889 kg/s injection into cold leg B
12328 – 12547	Discharge
13703 – 13776	1.576 kg/s injection into cold leg B
13926 – 15166	Discharge: primary inventory 70% -> 50%
15834 – 15909	0.254 kg/s injection into cold leg A
15825 - 15913	0.269 kg/s injection into cold leg B
16499 – 16571	Discharge
17339 – 17414	1.0 kg/s injection into cold leg A
17335 – 17417	0.901 kg/s injection into cold leg B
17855 - 18085	Discharge
18876 – 19252	1.565 kg/s injection into cold leg B
19764	Core power off
20408	Data record end

Table 2.3 Report events versus experimental measures from the LSTF

Event Number	Report Event	Experimental Event	Experimental Duration (s)
1	Core power reduced from 10 to 1.426 MW	Core power reduced from 7.11 to 1.44 MW	NA
2	Primary coolant pump stopped	Primary coolant pump stopped	NA
3	0.3 kg/s injection into cold-leg A	0.225 kg/s injection into cold-leg A	82
4	Mass release through PV auto bleed line	Mass release through PV auto bleed line	39
5	0.3 kg/s injection into cold-leg B	0.203 kg/s injection into cold-leg B	83
6	Mass release through PV auto bleed line	Mass release through PV auto bleed line	34
7	1 kg/s injection into cold-leg A	0.98 kg/s injection into cold-leg A	87
8	Mass release through PV auto bleed line	Mass release through PV auto bleed line	154
9	1 kg/s injection into cold-leg B	0.851 kg/s injection into cold-leg B	83
10	20% of inventory release through PV auto bleed line	20% of inventory release through PV auto bleed line	2075
11	0.3/0.3 kg/s injection through PJ/PH into cold-leg A/B	0.253/0.265 kg/s injection through PJ/PH into cold-leg A/B	75/72
12	Mass release through PV auto bleed line	Mass release through PV auto bleed line	126
13	1.0 kg/s injection through PJ/PH into cold-leg A/B	0.997/0.87 kg/s injection through PJ/PH into cold-leg A/B	81/87
14	10% of inventory release through PV auto bleed line	10% of inventory release through PV auto bleed line	763
15	0.3/0.3 kg/s injection through PJ/PH into cold-leg A/B	0.253/0.279 kg/s injection through PJ/PH into cold-leg A/B	82/90
16	Mass release through PV auto bleed line	Mass release through PV auto bleed line	128
17	1.0 kg/s injection through PJ/PH into cold-leg A/B	1.0/0.889 kg/s injection through PJ/PH into cold-leg A/B	79/76
18	Mass release through PV auto bleed line	Mass release through PV auto bleed line	219
19	1.8 kg/s injection through PJ into cold-leg B	1.576 kg/s injection through PJ into cold-leg B	73
20	20% of inventory release through PV auto bleed line	20% of inventory release through PV auto bleed line	1240
21	0.3/0.3 kg/s injection through PJ/PH into cold-leg A/B	0.254/0.269 kg/s injection through PJ/PH into cold-leg A/B	75/88
22	Mass release through PV auto bleed line	Mass release through PV auto bleed line	72
23	1.0 kg/s injection through PJ/PH into cold-leg A/B	1.0/0.901 kg/s injection through PJ/PH into cold-leg A/B	75/82
24	Mass release through PV auto bleed line	Mass release through PV auto bleed line	130
25	1.8 kg/s injection through PJ into cold-leg B	1.565 kg/s injection through PJ into cold-leg B	76

2.4 Divergence in bleed-line discharges between simulation and experimental results

In figure 2.2 it can be clearly seen that there are divergences between model results (provided in the final data report) and the experimental data (contained in the experimental files): although any single discharge in the experiment is mirrored by the simulation, with start and end set at the same time, there are clear differences in the actual mass flow rate of each discharge. Also, it can be seen that the experimental data gives values for the discharge mass flow rate that are different from zero between discharges, which could be accounted as noise or even systematic error, as the non-zero value tends to be almost constant (near 0.024 kg/s). The systematic error assumption seems also to be in line with the actual discharge data, as almost every discharge (with the sole exception of the fifth one) is bigger in the experiment than in the model, so a systematic error would take both results closer. Disregarding this error, the experimental water discharge mass surpasses that of the model by 197 kg, which accounts for around 6% of the total, experimental discharged water mass. Taking the 0.023 permanent discharge flow rate into account from the start of the experiment at -1901 seconds, adding it to the modelled discharge will result in the modelled discharge being 498 kg higher than the experimental one, which will account for roughly 14% of the experimentally discharged water mass. In the end, it was decided not to take into account the noise/systematic error, in order to get modelled the total water mass discharge closer to the one in the experiment. Even so, it can be seen in table 2.4 that this 6% difference between the experimental and model data is not evenly distributed among every discharge, with the three main discharges (those which start at 4032, 8466 and 13926 seconds, accounting for 20, 10 and 20% of the original primary coolant water inventory, respectively) being farthest away from the intended values in absolute numbers.

Table 2.4 Auto bleed line discharges

Time [s]	Duration [s]	Flow rate [kg/s]	Total mass (Experiment) [kg]	Total mass (Simulation) [kg]	Difference (Simulation-Experiment) [kg]	Accumulated difference [kg]
275-314	39	0.473	22.347	18.447	-3.9	-3.9
1315-1349	34	0.496	18.87	16.864	-2.006	-5.906
2267-2421	154	0.55	92.423	85.162	-7.261	-13.167
3442-3600	158	0.447	94.2	70.179	-24.021	-37.188
4032-6107	2075	0.519	960.365	1076.925	116.56	79.372
7155-7281	126	0.315	54.3	39.69	-14.61	64.762
8466-9229	763	0.70684	662.51	536.2	-126.31	-61.548
11007-11135	128	0.3568	52.0945	45.568	-6.5265	-68.0745
12328-12547	219	0.6694	170.721	146.73	-23.991	-92.0655
13926-15166	1240	0.869877	1118.255	1068.36	-49.895	-141.9605
16499-16571	72	0.548	54.82	42.744	-12.076	-154.0365
17855-18085	230	0.647	192.601	148.81	-43.791	-197.8275

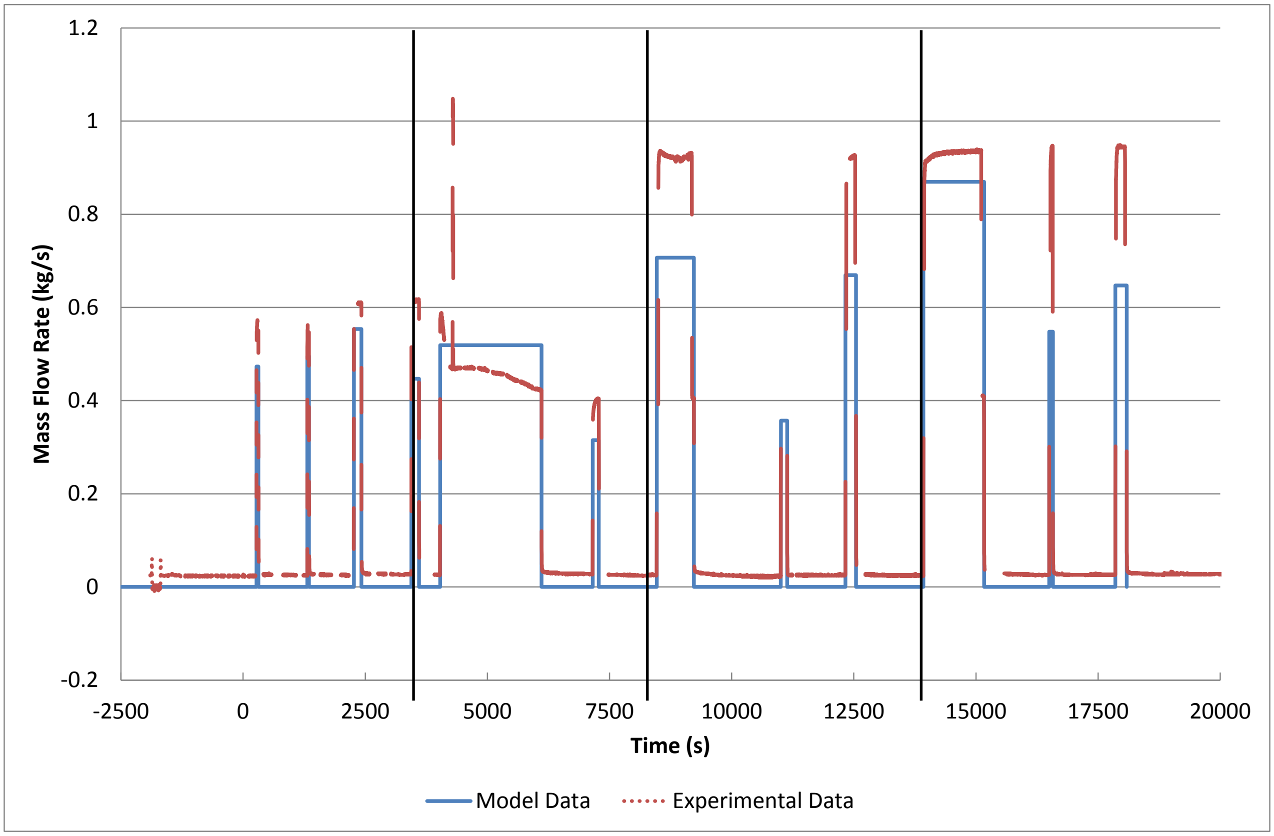


Figure 2.2 Comparison of discharged mass flow rate between experimental and simulation data.

2.5 Divergence in ECCS injections between simulation and experimental results

As ECCS injections were different in cold leg A and B, it was deemed necessary to analyze the ECCS injections in each cold leg separately. Figure 2.3 shows water injections into cold leg A, while figure 2.4 shows water injections into cold leg B.

In figure 2.3 it can be seen that every programmed injection into cold leg A appears also in the model. The experimental data again presents an injection flow rate different from zero between programmed injections, which could be due to data noise or a systematic error, as it fluctuates around a value of 0,.061 kg/s. The figure also shows that there are five flow rate peaks (corresponding to the second, fourth, ninth and twelfth injections) which do not correspond to programmed injections, being attributed to data acquisition errors. Also, most injections have a top value greater in the experiment than in the simulation, which could be accounted for an inertial effect. At the end, even if the noise/systematic error is not taken into account, the experimental mass injected in cold leg A exceeds the model injected mass by 70 kg, which accounts for roughly 17% of the simulated total mass.

Table 2.5 Cold leg A injections

Time [s]	Duration [s]	Flow rate [kg/s]	Total mass (Experiment) [kg]	Total mass (Simulation) [kg]	Difference (Simulation-Experiment) [kg]	Accumulated difference [kg]
18-100	82	0.225	20.25	19.575	-0.675	-0.675
2097-2184	87	0.98	91.63	85.26	-6.37	-7.045
6929-7004	75	0.253	27.61	21.75	-5.86	-12.905
8237-8318	81	0.997	92.606	79.76	-12.846	-25.751
10835-10917	82	0.253	26.035	22.77	-3.265	-29.016
12114-12193	79	1	93.5	79	-14.5	-43.516
15834-15909	75	0.254	23.749	19.05	-4.699	-48.215
17339-17414	75	1	97	75	-22	-70.215

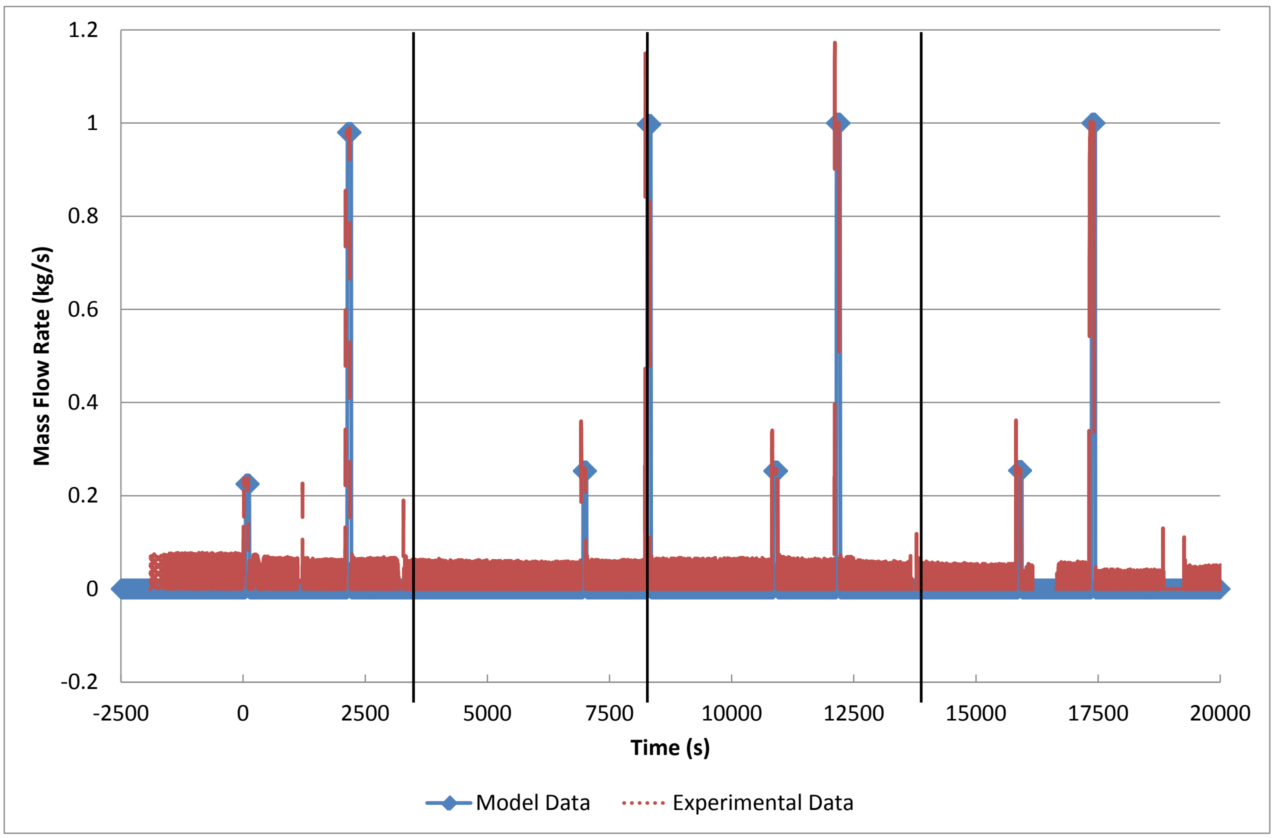


Figure 2.3 Comparison between experimental and simulation data of injected mass flow rates into cold leg A.

In figure 2.4 it can be seen that every programmed injection into cold leg B appears also in the model. The experimental data again present an injection flow rate different from zero between programmed injections, which could be due to data noise or a systematic error, with an almost constant value of 0.08 kg/s. Unlike the data regarding cold leg A, in cold leg B there are no unplanned flow rate peaks, and generally injections are almost identical in experimental data and simulation results (with the 7^{th} and 10^{th} injections presenting the greater deviations). Even so, the experimental total mass injected into cold leg B exceeds the model injected mass by 120 kg, which accounts for 11% of the simulation total mass.

Table 2.6 Cold leg B injections

Time [s]	Duration [s]	Flow rate [kg/s]	Total mass (Experiment) [kg]	Total mass (Simulation) [kg]	Difference (Simulation-Experiment) [kg]	Accumulated difference [kg]
1128-1211	83	0.203	16.6	16.6	0	0
3192-3275	83	0.851	72.675	70.55	-2.125	-2.125
6926-7004	78	0.265	21.38	20.67	-0.71	-2.835
8232-8318	86	0.87	79.17	75.69	-3.48	-6.315
10828-10918	90	0.279	24.823	23.157	-1.666	-7.981
12120-12193	73	0.889	76.985	67.64	-9.345	-17.326
13703-13776	73	1.576	154.9895	115.048	-39.9415	-57.2675
15825-15913	88	0.269	25.824	24.21	-1.614	-58.8815
17335-17417	82	0.901	88.2	76.5	-11.7	-70.5815
18876-19252	376	1.565	650.52	600.6	-49.92	-120.5015

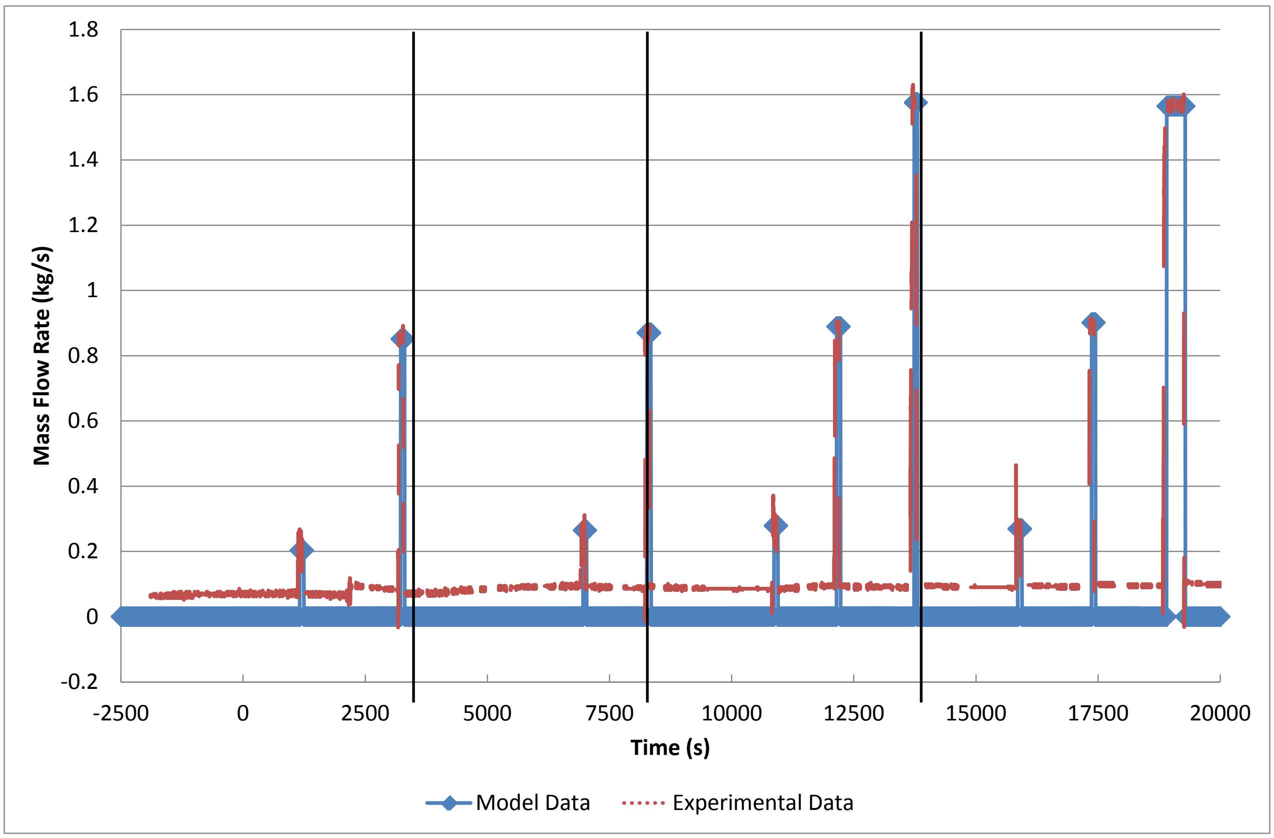


Figure 2.4 Comparison between experimental and simulation data of injected mass flow rates into cold leg B.

In the end, although there is a divergence between experimental and simulation data, the differences between both injections and discharges seem to compensate partially each other: The model injects less water into the system, but it does so in almost the same proportion for both injections and discharges.

3. TEST RESULTS AND COMPARISON WITH TRACE

3.1 Overview of test results and comparison with TRACE

This section is devoted to review the main experimental results and to discuss the results obtained with the TRACE code. Steady-state conditions were attained prior to the start of the experiment. Table 3.1 shows these initial conditions as they were originally intended to be, as registered during the experiment and the ones calculated by the TRACE model. Concerning to the experimental data obtained, the most important events are the core power decrease, the primary coolant pump stop, the pressurizer isolation and the three main discharges. According to this, the experiment can be divided into the following phases:

Table 3.1 Experiment phases

PHASE	Starting event / time	Ending event / time
1	Core power decrease / -1539	Pressurizer isolation / 3822
2	Pressurizer isolation / 3822	Discharge 80 -> 70% inventory / 8466
3	Discharge 80 -> 70% inventory / 8466	Discharge 70 -> 50% inventory / 13926
4	Discharge 70 -> 50% inventory / 13926	End of test / 20408

3.1.1 Phase 1 analysis (-1539 s – 3822 s)

Phase 1 of the experiment starts at -1539 seconds with a core power output reduction from 7.11 to 1.44 MW. The conditions at the start of this phase are those previously listed in table 2.1. The power reduction is followed in 20 seconds by the shutdown of the primary coolant pump, thus prompting the establishment of natural circulation in the primary side. It's followed by 4 injections (two in leg A, two in leg B) and their respective discharges. The phase ends at 3822 seconds with the isolation of the pressurizer in cold leg A.

At the beginning of this phase, pressure in the upper plenum of the RPV (displayed at figure 3.1) decreases in the experiment from 15.45 to 15 MPa, recovering original conditions shortly afterwards (around 156 seconds). In the other hand, the simulated pressure gets a more remarkable decrease, going down to 12.7 MPa, and then needing 3436 seconds to match experimentally measured conditions. This difference could be explained by the use of an automatic controller for the secondary side flow rate. Pressure in the secondary side of the steam generators A and B (shown respectively in figure 3.2 and figure 3.3) behave in a similar way: in both cases, the experimental pressure decreases from 6.3 to 5.9 MPa, returning in around 1200 seconds to the original value, while the pressure in the model drops to a lower value (3.75 MPa) and takes more time to recover the intended experimentally determined conditions (around 2000 seconds in both cases).

Temperature in the seal sections of both cold legs A and B (shown in figures 3.4 and 3.5) evolves in a way similar to the cold leg pressures: experimental temperature in cold leg A goes down from 555 to 549 K, after the power decrease to recover the initial condition value in 1100 seconds. After 440 seconds, temperature decreases again, and begins to oscillate between 547 and 551 K. The simulation results show a more pronounced decrease, arriving to 524 K, then increases to 541 K at t = 550 seconds. From that point onwards the model temperature oscillates around 551 K close to the experimental value.

Experimental temperature in cold leg B decreases from 555 to 550 K, to recover the initial condition value in around 1000 seconds. After 520 seconds, temperature decreases again, and begins to oscillate between 549 and 551 K, in a way similar to that of cold leg A. The simulation results again display a more pronounced decrease at the beginning of the transient after the shutdown arriving to 523 K, then the temperature increases to 550 K at t = 550 seconds close to the experimental values. The temperature obtained with TRACE oscillates around 551 K, as in cold leg A, and close to the experimental value.

Experimental values of the water level in the secondary of the steam generator of cold leg A (figure 3.6) change constantly during this phase, dropping from 9.36 meters at -1129 seconds to roughly 7.2 meters at 402 seconds, only to rise again to 9.5 meters at 1482 seconds, oscillating from that point onwards in response to the operator actions, varying from 9 to 10 meters. On the other hand the liquid level in steam generator A computed by the TRACE code don't change until second -1091, in which it drops from 10.4 to 10 meters, a value around which the water level will slightly oscillate for the remainder of the test.

In the case of water level in cold leg B in the secondary of the steam generator (figure 3.7), experimental values are almost identical to those measured in cold leg A. On the other hand, TRACE results for liquid level in steam generator B don't change until second -1232, in which it increases from 10.4 to 11.7 meters at -888 seconds, to immediately start decreasing again to 10 meters at 514 seconds, a value at which the water level slightly oscillates for the remainder of the test.

In this phase, the mass flow rates on both legs seem to be adequately predicted by TRACE. The mass flow rate in cold leg A (figure 3.8) decreases from its initial value immediately after the reactor power reduction, reaching an experimental value of roughly 6.2 kg/s while TRACE model yields a value of around 7.37 kg/s, to decrease to a value around 6.7 kg/s short after the power decrement. Mass flow rate in cold leg B (figure 3.9) follows a similar pattern, with experimental and computed mass flow rates in this phase stabilizing around 6.2 and 6.7 kg/s respectively, therefore TRACE results for the natural circulation mass flow rates are close to experimental ones in loop B and slightly higher in loop A. So TRACE model predicts adequately the single phase natural circulations mass flow rates during this initial phase.

3.1.2 Phase 2 analysis (3822 s – 8466 s)

Phase 2 of the experiment starts at t=3822 seconds with the pressurizer's isolation, and finished at time 8466 s with the beginning of the second main discharge. At time 4032 s starts the first main discharge of 20% of the main water inventory, which finishes at time 6107 s. This phase also comprises 4 minor injections in loops A/B and one single discharge through the bleed line as shown in tables 2.4, 2.5 and 2.6.

Once the pressurizer becomes isolated, it is no longer able to regulate the pressure in the primary coolant circuit and when the first main discharge starts the pressure registered in the upper plenum begin to decrease. When the extraction finishes at time 6107 s the pressure stabilizes at a lower level of 7.0 MPa. TRACE code predicts pretty well the decrement of the pressure while the extraction is taking place with the same slope at the beginning of the extraction and with a slightly different slope between 4500 s and 5500 s, to finish at the same pressure than the experiment short after the end of the bleeding period (figure 3.1).

The pressure at the secondary of the SG presents, as displayed in figures 3.2 and 3.3, the same behavior in both loops, displaying a pressure decrement during the first extraction period. The experimental pressure diminishes during this phase from 6.7 MPa at the beginning to 6.2 MPa at the end. The pressure decrement during this extraction phase is governed by the manual actions taken by the operator to compensate for the pressure diminishment caused by the coolant extraction in the primary that produces less heat transference from the primary to the secondary coolant in the SG. However, TRACE results oscillates between 6 MPa and 6.4 MPa as result of the action of the automatic controller implemented in the TRACE model that maintains the pressure at an average value of 6.2 MPa.

Temperature in the seal section of loop A starts at 556 K at the beginning of this phase, then drops to 550 K, at 8415 seconds with small variations, maintaining this value until the end of the phase II (figure 3.4). On the other hand, TRACE results during this phase display small oscillations around 551 K, maintaining practically this value until the end of this phase.

Temperature in the seal section of loop B follows a similar pattern as that on loop A, although with slightly smaller temperatures (555 and 550 K at start and end of the phase). TRACE results for loop B behave in a similar way as that for seal section A, although it more clearly reproduces experimental temperature's rises and drops, matching experimental data for most of the phase (figure 3.5).

The experimental values of the water level in the secondary of the steam generator A remain almost constant for the entire phase, with an average value of about 9.7 meters while TRACE simulation gives during this phase a constant value of 10 meters (figure 3.6). Water level in the secondary of the steam generator B starts this phase decreasing from 10.2 meters to 9 meters, then rises again to a value of 10 meters, to again fall. TRACE results displayed at figure 3.7 show small oscillations around an average value of 10 meters.

Finally the experimental mass flow rate in cold leg A during this phase increases from a practically constant value of 5.9 kg/s to 11 kg/s at t= 5880 seconds, maintaining this value until the end of the phase. The mass flow rate predicted by the TRACE code, increases at the beginning of this phase from 7.37 kg/s to 14 kg/s and then begins to oscillate around an average value of 7.5 kg/s, maintaining this average value until the end of the phase, see figure 3.8. The experimental results in cold leg B are pretty similar to those observed in cold leg A, see figure 3.9. However, TRACE predictions show an increase of the mass flow rate from 6.7 kg/s at the beginning of the phase to 14.7 kg/s at time 4600 s, then the mass flow rate begin to oscillate with an average value of 9 kg/s and finally falls to 0.2 kg/s at the end of the extraction (t=6107 s). Two phase flow natural circulation conditions are established during this phase.

3.1.3 Phase 3 analysis (8466 s – 13926 s)

Phase 3 of the experiment starts at 8466 seconds with the start of the second main discharge that lasts for 763 s (reducing primary coolant water inventory from 80 to 70%). This phase finishes at 13926 seconds with the start of the last main discharge (reduction of the coolant water inventory from 70 to 50%). During this phase, two cold leg A+B injections and one cold leg single-B injection take place.

Experimental data on pressure in the upper plenum of the RPV shows that pressure starts at a value of around 6.8 MPa and decreases slightly to 6.7 MPa during the main discharge of this phase, then it remains practically constant with small variations between 6.7 MPa and 6.9 MPa during the rest of this phase (figure 3.1). TRACE results for pressure show average values close to the experimental ones, decreasing slightly from 6.9 MPa to 6.8 MPa.

Pressure in the secondary of both steam generators depends on the manual actions taken by the operator during this period and behaves experimentally in an almost identical way in both SG. The pressure starts with a value of 6 MPa at the beginning of this phase, and then increases for 1800 seconds up to 6.5 MPa. This value is maintained until t=10588 seconds, when pressure begins to decrease again to 6 MPa at the end of the phase. The predicted values by the TRACE code as displayed in figures 3.2 and 3.3, show that the pressure is maintained between 6 MPa and 6.4 MPa during this phase with an average value of 6.2 MPa, close to the average experimental result.

Experimental liquid temperature in the seal section of cold leg A starts decreasing at the beginning of this phase, to stabilize at a value of 549 K at t = 8550 s, then increases up to 555 K at 10500 seconds, with the increase becoming markedly stronger after the end of the main discharge, see figure 3.4. Temperature maintains constant for a while until t = 11005, when it decreases again to a temperature of 549 K. Experimental temperature in the seal section of cold leg B, see figure 3.5, evolves in the same way as temperature in cold leg A. TRACE results predicts a decrease in the liquid temperature from 551 K at the beginning of the second extraction to 547 K at the end of this phase, this reduction in temperature is mainly a consequence of the extraction through the bleeding line. Also it is worth nothing that the injection through the cold leg

A/B is cold water and the extractions through the bleeding line is coolant with more enthalpy, because the water injected by the ECCS partially mixes with hotter coolant in the cold leg and in the downcomer.

Experimental values of the water level in the secondary of SG A start this phase decreasing to a level of 9.2 meters at t = 9395 seconds (figure 3.6). It then increases to a level of 9, 8 meters at 10450 seconds, to again decrease in two steps to a level of 9 meters at t = 12800 seconds, from which it will steadily increase for the remainder of the experiment. Experimental values of water level in steam generator B follow a similar evolution during this phase, see figure 3.7. TRACE results show the same behavior in both cold legs, showing an almost constant value of 10 meters as result of the control system implemented to control the secondary pressure and the secondary collapsed level.

Experimental mass flow rate in cold leg A presents an oscillating behavior around a constant value of 10.2 kg/s until t = 8700 seconds as displayed in figure 3.8, at this time and as consequence of the second extraction it decreases to stabilize around 5 kg/s, oscillating around that value until the end of the phase. This reduction in the natural circulation mass flow rate is a consequence of the reduction of the natural circulation driving force between the cold and hot legs. In cold leg B experimental data follows a similar evolution pattern as that of cold leg A, see figure 3.9. TRACE results also display a reduction of the mass flow rate during the second extraction. But the reduction of the mass flow rate is stronger than that observed experimentally; the natural circulation mass flow rate drops to 2.5 kg/s. It can be observed in the simulation results that steam accumulates in the upper part of the U-tubes of the SG and this reduces the natural circulation mass flow rate. TRACE results in loop B also predict a reduction in the mass flow rate to an average value 0.2 kg/s, as it did in the previous phase, and continues this way for the rest of the phase.

3.1.4 Phase 4 analysis (13926 s – 20408 s)

Phase 4 of the experiment starts at 13926 seconds with the beginning of the last main discharge (reducing primary coolant water inventory from 70 to 50% of its original value), and finishes at 20408 seconds with the end of the experiment. During this phase, in addition the are two simultaneous cold leg A+B injections and one single-injection in cold leg B, with only the A+B injections being mirrored by proportional discharges through the bleed line.

Experimental data on pressure in the upper plenum of the RPV starts at a value of around 6.5 MPa, which is maintained, with a small increase, practically constant until 18600 s, as displayed in figure 3.1. From that point onwards, pressure decreases until the end of the experiment, with this decrease becoming stronger after the power gets shutdown. TRACE results oscillate around an average value of 6.5 MPa for almost all the duration of the phase, only showing an evident decreasing tendency after power is off. It can be concluded that experimental and predicted values match during this phase.

Experimental pressure in the secondary of both steam generators follows a similar pattern as pressure in the upper plenum, starting at a minimum initial value of 5.9 MPa, and then this value increases slowly until 18615 seconds with a maximum pressure of 6.2 MPa, followed by a two-step decrease until the end of the experiment, with the first step being seemingly related to the last injection into cold leg B, and the second step being related to reactor shutdown. TRACE results predictions are around a center value (6.20 MPa) not very far from the experimental values, only decreasing at t = 19600 seconds, seemingly due to the reactor shutdown (see figures 3.2 and 3.3).

Experimental temperature in the seal section of cold leg A (figure 3.4) starts at a value of 549.4 K, then, after a slight increase, decreases to a value of 545.5 K at t = 15653 seconds, which is roughly 200 seconds after the last main injection finishes. Subsequently temperature suffers an increase, reaching a value of 552 K at 16113 seconds, and from then on it decreases to 543 K at

16700 seconds. This temperature will be maintained for 500 seconds. After this, experimental temperature shows oscillations as displayed in figure 3.4. The maximum and minimum values of these oscillations are 550, 525 and 553 K in just 55 seconds, which seem related with the last simultaneous cold injections into cold legs A/B, then the temperature returns to 543 K. Temperature then remains almost constant until t = 18650, when it increases to 550 K, to decrease until the end of the experiment as consequence of the last cold injection and the power shut off. Experimental temperatures in cold leg B follow a similar pattern until the beginning of the last cold water injection which produces a reduction in the temperature, see figure 3.5. TRACE results show the same behavior in both cold legs, starting at 545 K at the beginning of the phase and decreasing to 544.8 K at 14397 seconds close to the experimental value. Then the predicted temperature rises to 552.7 K, a value around which it will oscillate until t = 18836 s, and that is about between 5 and 7 K above the experimental value. The only major change of temperature occurs when reactor is shutdown at t = 19700 s, and the temperature drops to a value of 550.93 K. In general the predicted temperatures in the loop seals during last step of phase 4 are between 5 and 7 K above the experimental values. This effect could be partially explained by the increase of the SG level during the last part of the transient, due to the manual operator actions. This rise of the water level in both SG, mainly in SG B, increase the primary to secondary heat transfer, reducing the experimental temperature in the primary. So TRACE predicted temperatures practically match the experimental ones except during the last part of phase 4 when a difference of 5 K appears.

Experimental values of water level in steam generator A (figure 3.6) start this phase at an almost constant value of 9.14 meters, then increase for the remainder of the test, with this increase becoming more pronounced after t = 18700 seconds, when reactor is shutdown, finishing the experiment at a value of 10.41 meters. Experimental liquid level in steam generator B (figure 3.7) follows the same pattern as the one in SG A, although with slightly higher values (it starts at 9.5 meters and ends at 11.2 meters). TRACE results for both steam generators show a value which oscillates around 10 meters close to the average experimental value during this phase except at the end.

Experimental mass flow rate in cold leg A starts this phase decreasing to a value of practically zero mass flow rate that sometimes becomes slightly negative (-0.332 kg/s), after which it presents three small increases (which seemingly correspond to the minor injections which take place during this phase) followed by a short constant period, to again drop to zero mass flow rate, a value which will be maintained until the end of the test, see figure 3.8. The experimental average mass flow rate reported during this period is located between 0.5 kg/s and 1.3 kg/s per loop. TRACE results for the mass flow rate started this phase oscillating around an average value of 1.2 kg/s, and slightly oscillate during this phase until reaching an almost stable value of around 0.2 kg/s.

Experimental mass flow rate in cold leg B also decreases during the last extraction to a value of 1.15 kg/s at t = 14391 seconds, see figure 3.9. Then, remains almost constant, displaying one main increase in the mass flow rate that starts at time 18.800 seconds which is related to the last injection. TRACE results display an oscillating behavior during this phase with an average mass flow rate of 0.2 kg/s. TRACE code also predicts a small increase in the mass flow rate during the last extraction period. Mass flow rates predicted by TRACE in cold leg B are below the experimental ones.

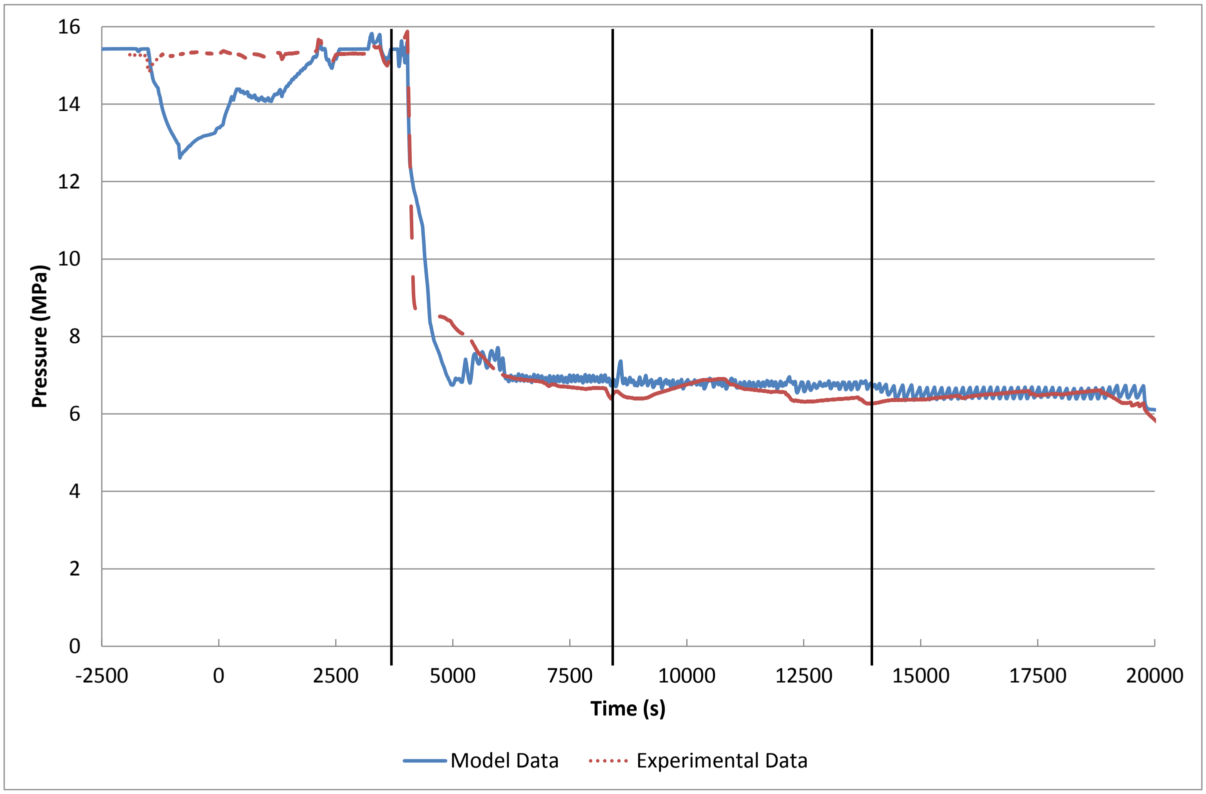


Figure 3.1 Pressure evolution in the upper plenum of the RPV versus time.

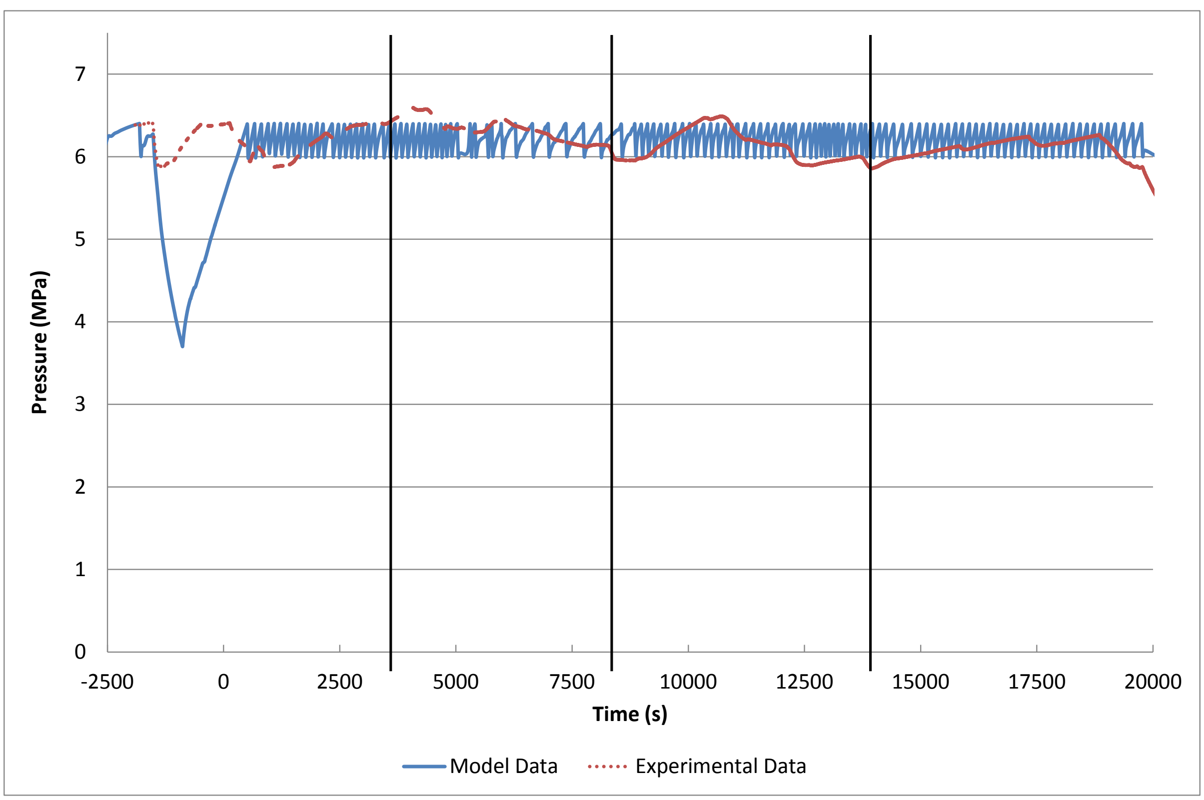


Figure 3.2 Evolution of pressure versus time at the secondary of the SG in loop A.

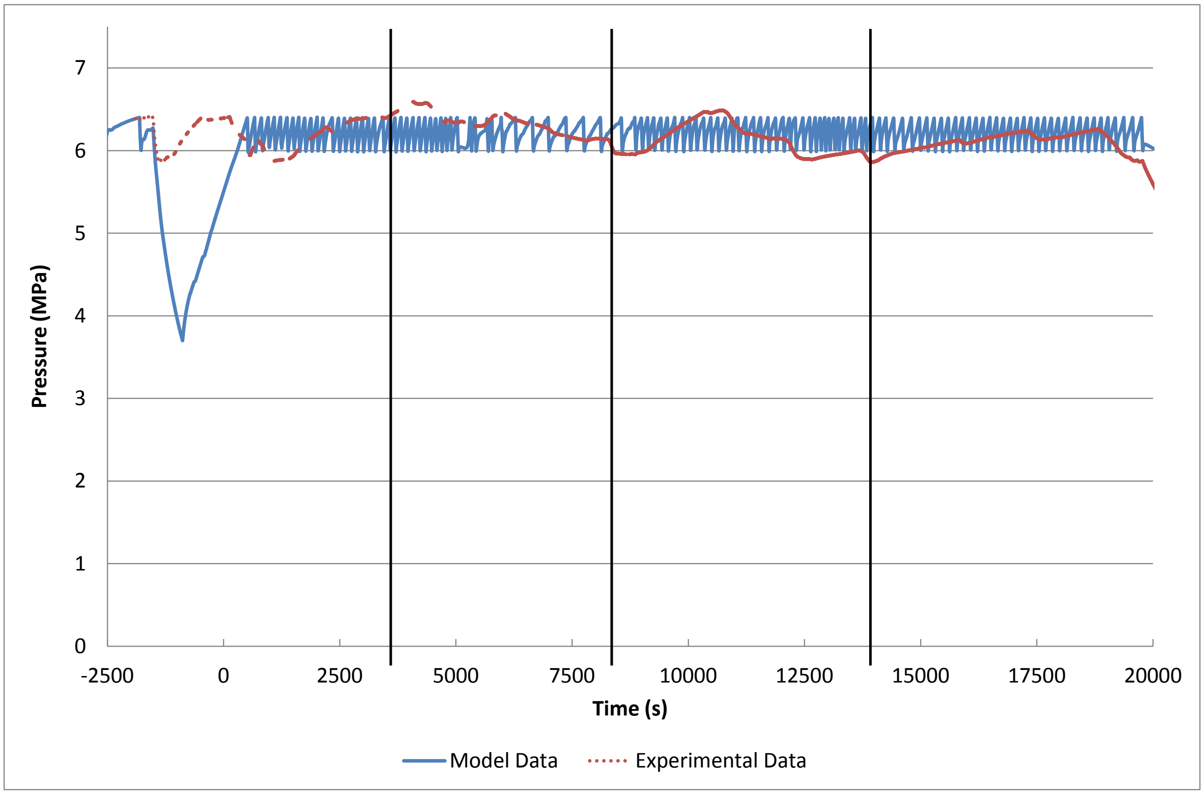


Figure 3.3 Evolution of pressure versus time at the secondary of the SG in loop B.

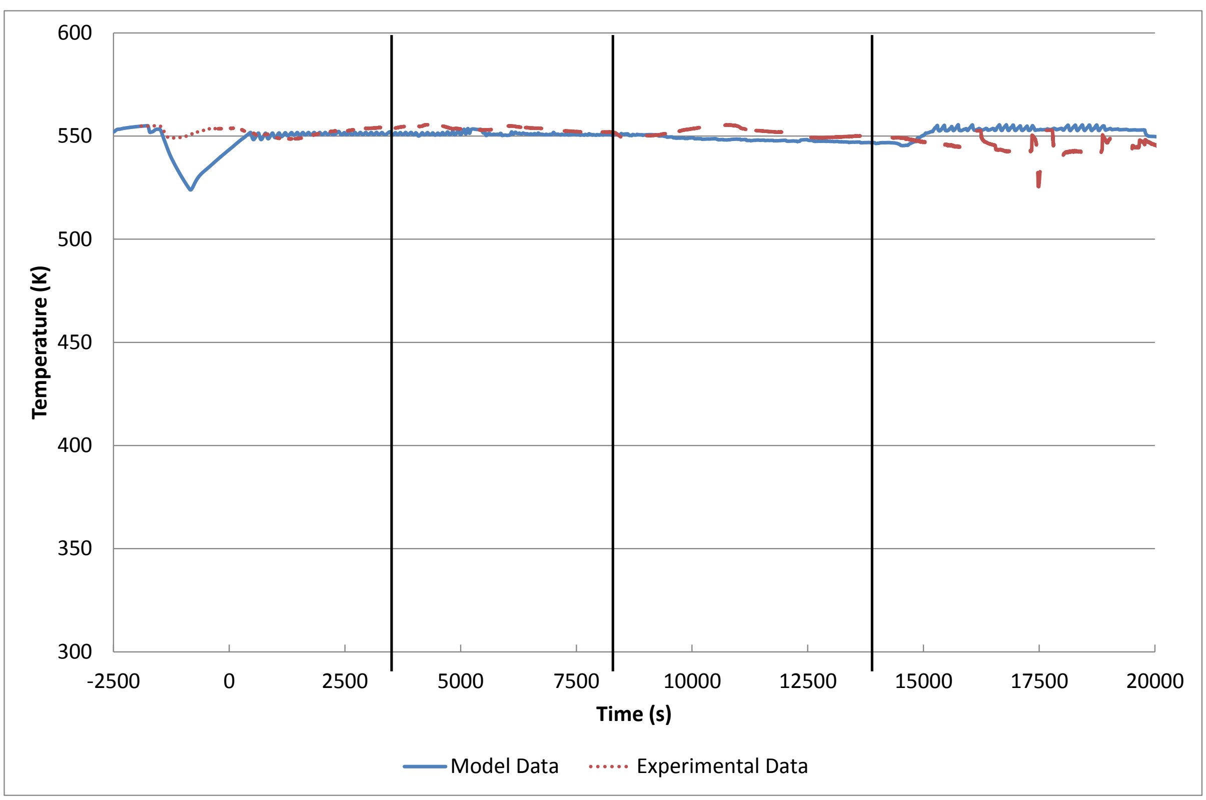


Figure 3.4 Evolution of the temperature at the seal of cold leg A.

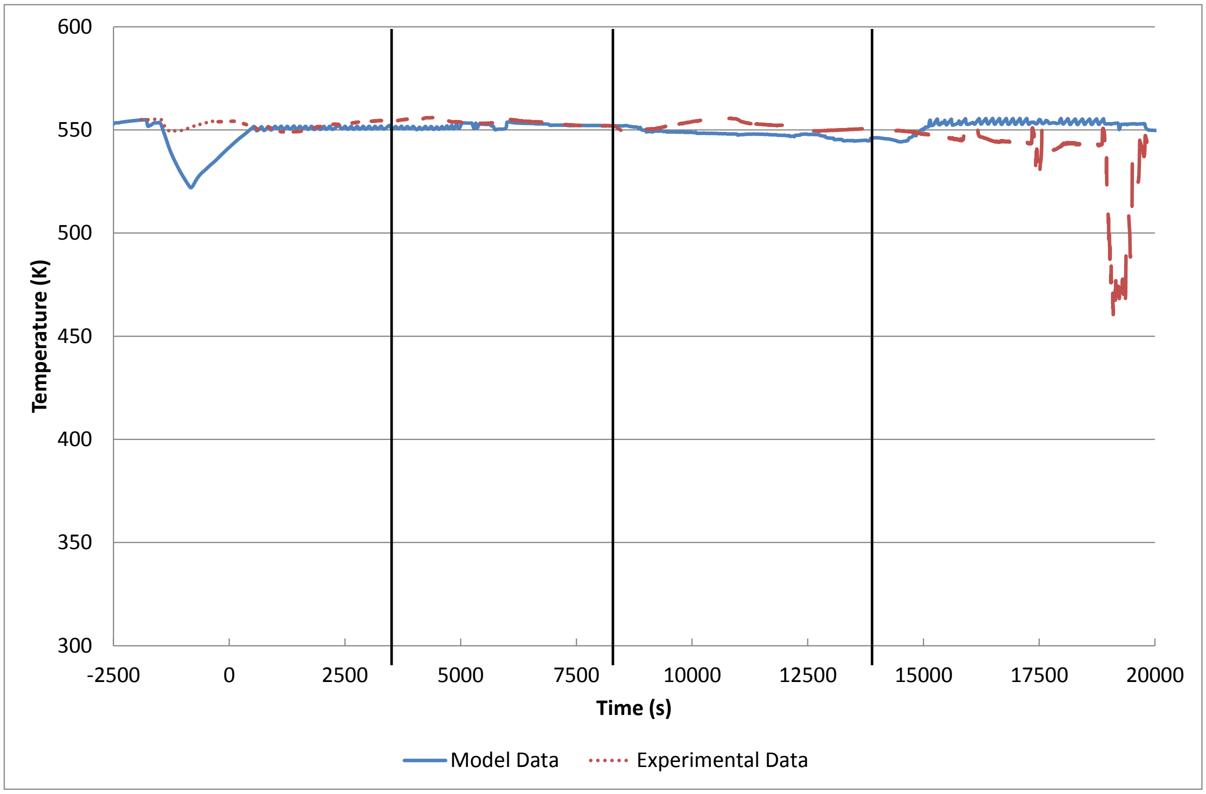


Figure 3.5 Evolution of the temperature at the seal of cold leg B.

Figure 3.6 Evolution of the liquid level at the secondary of the SG A.

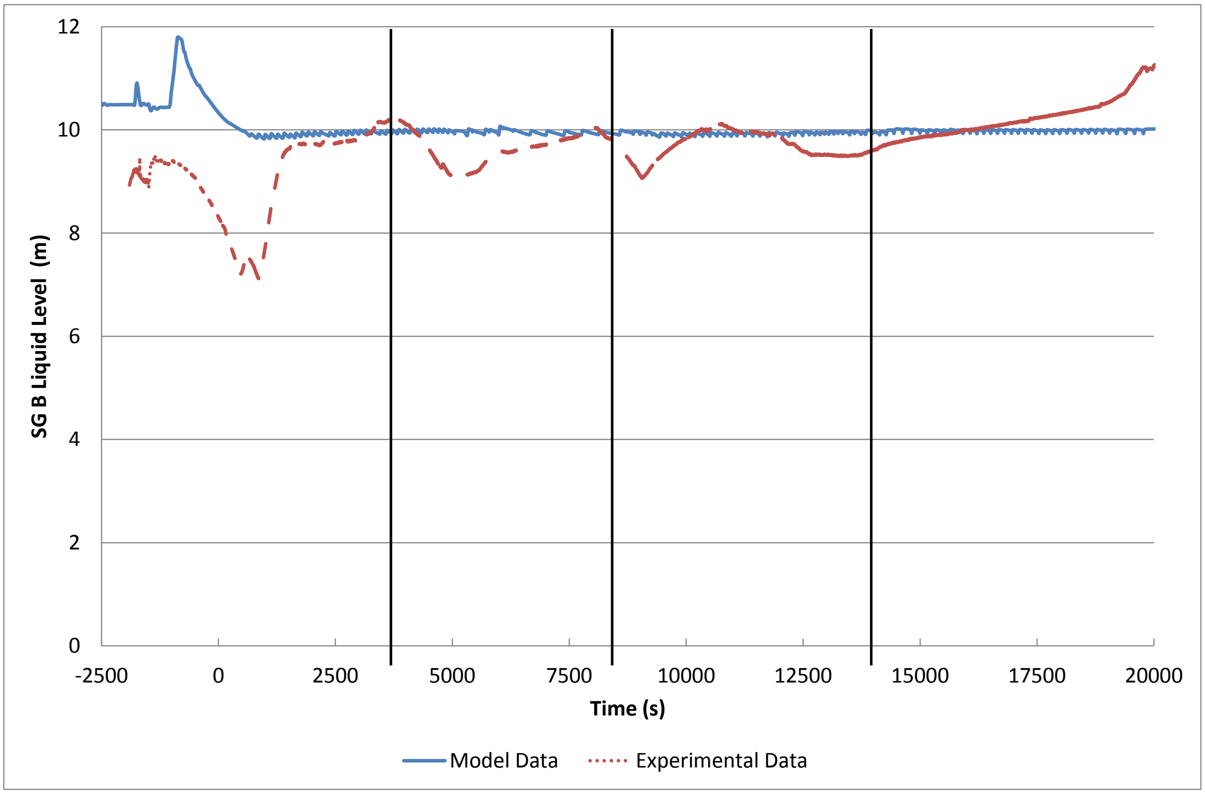


Figure 3.7 Evolution of the liquid level at the secondary of the SG B.

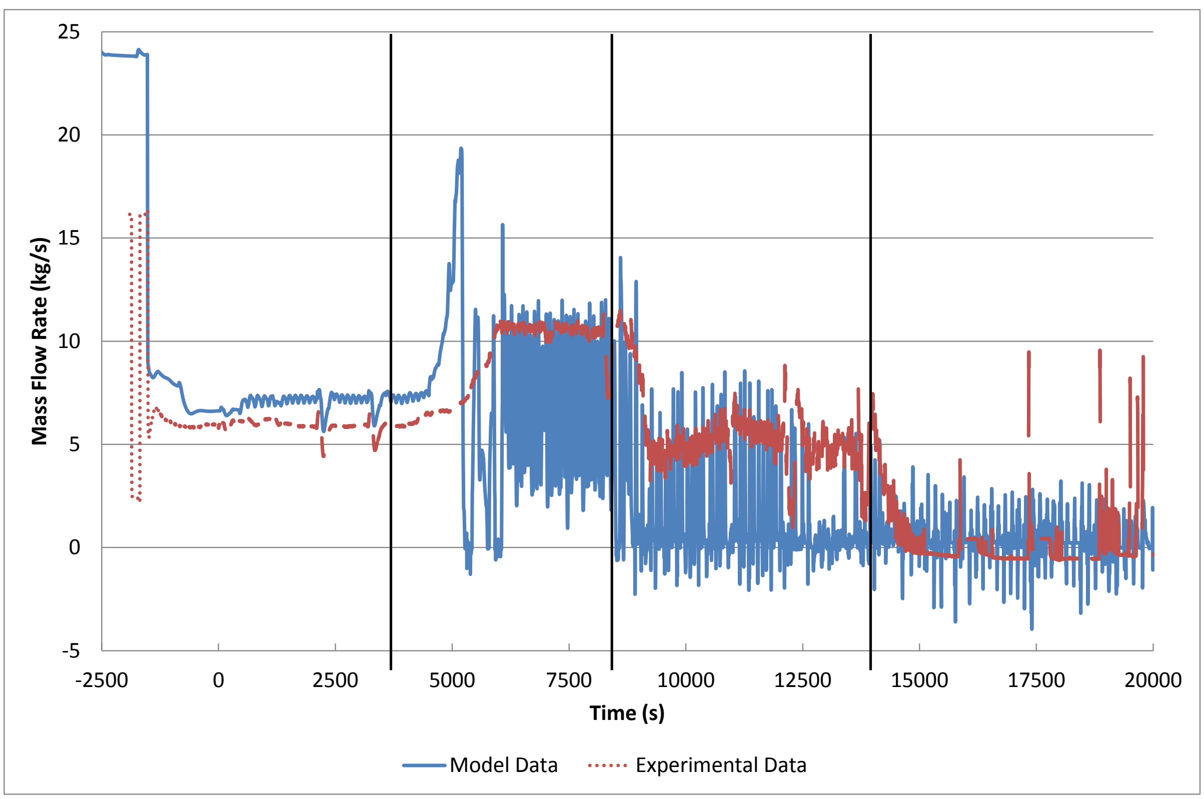


Figure 3.8 Evolution with time of the mass flow rate in cold leg A.

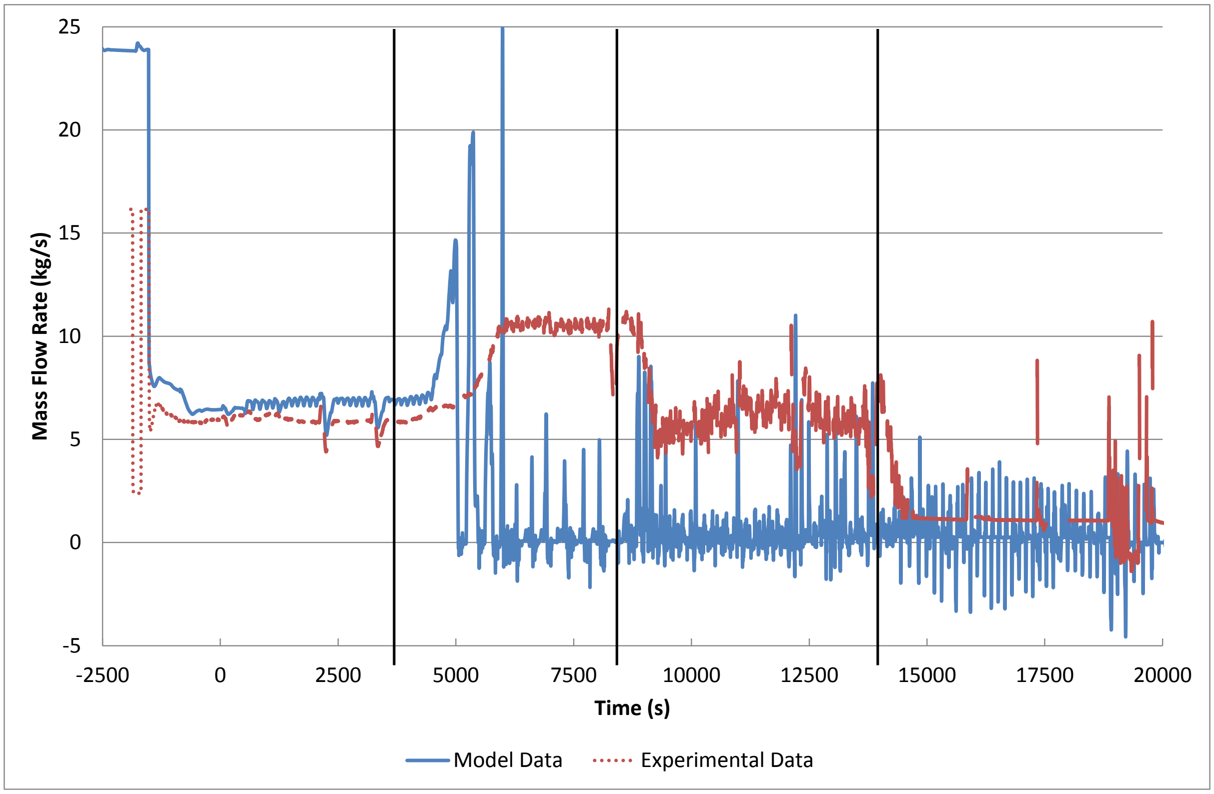


Figure 3.9 Evolution with time of the mass flow rate in cold leg B.

4. CONCLUSIONS

In this report ROSA test 1.1 has been analyzed using a model of the LSFT created for the TRACE code. Initial steady-state conditions were achieved by maintaining every variable of the model at the intended initial value for as long as seven thousand seconds in order to assure that every relevant variable stabilized at a value close to the shown in the final data report. This is not reflected in the data shown in this report, as it is irrelevant for its purpose.

At the beginning of the test, core power is decreased and primary coolant pump stopped, forcing one-phase natural circulation in the primary system. After 5200 seconds, the pressurizer is isolated from the rest of the secondary system and the first main discharge (accounting for 20% of the original primary water inventory) takes place, forcing two-phase natural circulation into the primary side of the system. 2400 seconds after the end of this first main discharge, a second main discharge accounting for 10% of the original primary water inventory takes place, the effect of this discharge is to reduce the natural circulation mass flow rate flowing through the primary system. Finally 5000 seconds later, the third and last main discharge (again accounting for 20% of the original primary water inventory) takes place; after this last extraction is performed, natural circulation mass flow rate reduces to very small values in loop A, and to 1.2 kg/s in loop B.

At the start of the test, and after the drop of power and the shutdown of the coolant pumps, pressure in the primary system (measured in the RPV upper plenum) decreases slightly before the pressurizer and the operator actions in the secondary, closing the steam valves and restoring pressure to its initial value. This is not correctly predicted by the TRACE simulation, where the pressure drop is larger and takes more time to recover to its initial value. This difference is caused by the different methods used to control the pressure in the secondary that is by the operator actions in the experiment, and implemented by means of an automatic-control system in the TRACE code. During the first main discharge, pressure in the system suffers an intense decrease, which is mostly matched by the TRACE simulations. After the first main discharge, pressure in the primary system suffers only slight variations, which are not exactly matched by the TRACE results, although it offers values not far away from the experimental ones. Pressure in the secondary side of the steam generators follows a similar evolution pattern during the transient maintaining an average pressure of 6.2 MPa, although it does not present a drastic decrease after the first main discharge, due to the operator actions, maintaining an almost constant value for the entire test. However, TRACE predictions for the pressure in the secondary of the steam generators displays a larger decrease immediately after the power reduction due to the type of control implemented that gives good results for the rest of the transient but is not able to restore immediately the pressure to the initial value when the heat transferred to the secondary side drops suddenly after the power reduction.

Temperature in the cold leg seals diminish after reactor power output decreases at the start of the test, being this decrement larger and longer in the TRACE simulation than in the experimental data. After stabilizing again, temperatures grow and later decrease between each one of the main discharges, to display some oscillations after the third main discharge. After the first discharge and during the second phase of the transient the temperature is maintained at an average value of 552.5 K, while TRACE results give a practically constant value of 551 K, close to the experimental one. During the third phase of the transient the experimental data shows an increase of the liquid temperature and then the temperature start to decrease continuously until the end of this phase. TRACE results show that the temperature diminishes during this phase with a constant slope approaching the experimental value at the end of the phase. During the fourth phase and after the last extraction the TRACE simulation displays an increase of the temperature in the seal of the cold leg at a value around 554 K in both legs maintaining this value practically constant during the rest of the test. However, the experimental value displays temperature oscillations caused by small injections and discharges that affect to the temperatures in the seal due to the small collapsed water level in the system.

Experimental data on liquid level in the secondary side of the steam generators starts at 9.5 meters which is lower than the one simulated by the TRACE code. Then both experimental and TRACE results decrease but while TRACE results decrease to a 10 m level, experimental data show a bigger decrement to then recover to a level of 9.6 m. Then, in the experiment the operator action maintains the level oscillating around an average value of 9.55 m in loop A, while the Level calculated by TRACE is maintained practically constant at 10 m. Water level in loop B follows a similar pattern to that of loop A, but experimental and calculated values are closer, experimental average water level is around 9.7 m while TRACE results are closer to 9.9 m.

Mass flow rates measured in both cold leg A and B show similar patterns: After the original reactor power output decrease, and the shutdown of the pumps, mass flow rate decreases to become almost constant around a value of approximately 6 kg/s, this stage is well predicted by the TRACE code. After the first discharge, the mass flow rate increases to a value of approximately 10 kg/s, remaining again constant until the next main discharge, in which it drops to a constant value of 5 kg/s. After the third and last main discharge, experimental flow rate shows a decrease to almost zero kg/s. TRACE results match the experimental data until the first main discharge. After this, the mass-flow-rate in cold leg A present a markedly oscillatory behaviour, with average values lower than the experimental ones. TRACE results are even worse in cold leg B, with small mass flow rates after the first main discharge.

In sight of the current results, it can be concluded that TRACE code can satisfactorily reproduce temperature and pressure changes under two-phase natural circulation conditions over long time periods. At the beginning of the test and before the first extraction, TRACE properly simulates the single-phase natural circulation mass flow rate. Also, TRACE predicts the increase in the natural circulation mass flow rate that takes place when the extraction begins but when the first extraction finishes TRACE predictions are below the experimental values for the mass flow rate. In general after the second and third extractions TRACE simulation are lower than the experimental value for the mass flow rate.

Finally, it seems that TRACE code simulations show consistent results for pressure, temperature, liquid level and also mass flow rate in single flow natural circulation conditions. But these results are not so good regarding mass flow rate calculations under two phase flow natural circulation conditions. Further analysis and reviewing of the ROSA facility model for TRACE are necessary to know the reason of this last discrepancy.

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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 simulation performed with the consolidated thermal-hydraulic code TRACE of the OECD/NEA natural circulation test ROSA 1.1, conducted at the Large Scale Test Facility (LSTF) in Japan. To attain the initial conditions the power was reduced from 7.11 MW to 1.44 MW, followed by a shutdown of the primary coolant pump with the 100% of water inventory in the primary. After some time the test initial conditions are attained and steady-state natural circulation conditions are established in the primary loop. The test can be divided in three different stages, each one characterized by attaining natural circulation conditions under different two-phase states in the primary coolant circuit, achieved reducing the primary inventory to 80, 70 & 50% of its original value, discharging the primary coolant water via auto bleed line located near the bottom of the RPV. The main goal of this report is to analyze the ability of TRACE code to precisely simulate the stratification and natural circulation conditions of both single and two-phase flows inside the primary circuit. During the experiment, the secondary side conditions were obtained by manually controlling the steam and feed-water flow rates in order to maintain the secondary pressure at 6.7 MPa, while in the simulation the secondary conditions were automatically controlled. At the beginning of the conditioning phase the severe power reduction and the shutdown of the coolant pump produces a mass flow rate reduction which is almost perfectly matched by the simulation with the TRACE code, with only a slightly higher mass flow rate than in the experiment.

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