OECD / SETH

Final Report of the PKL Experimental Program within the OECD/SETH Project

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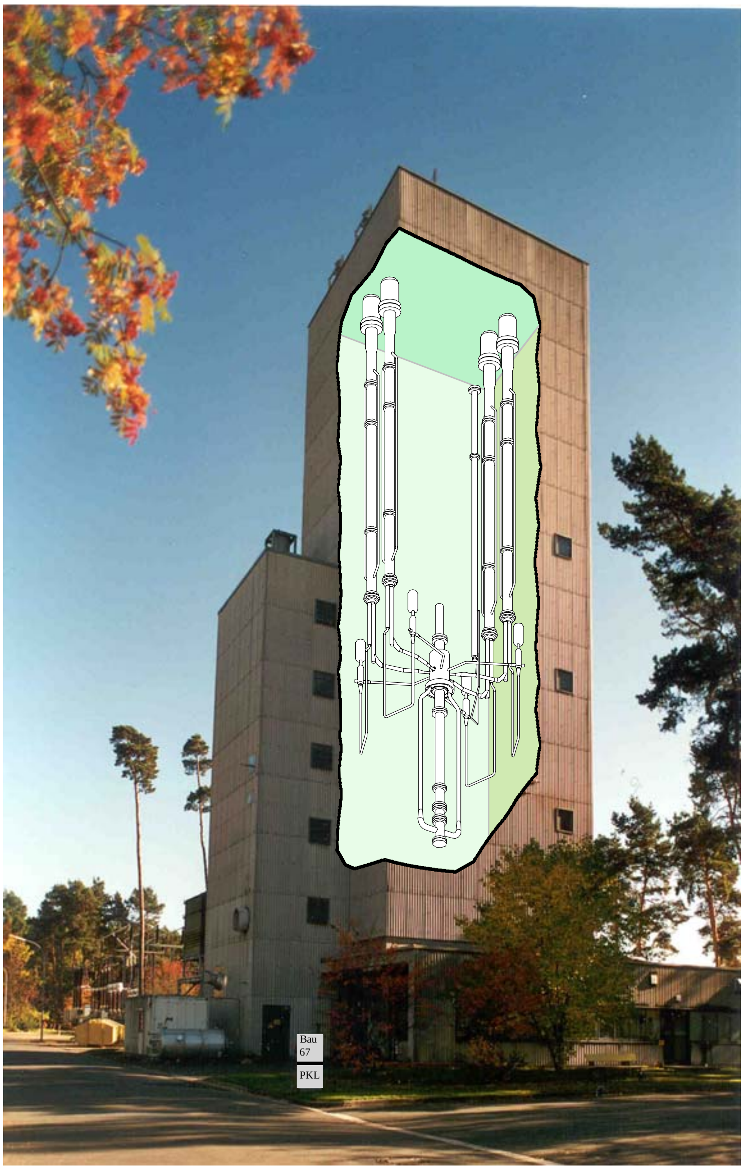

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Summary

This report documents the PKL experimental program within the OECD/SETH project. Within this test series, four PWR integral tests were carried out in the PKL III test facility[1]. This test rig replicates a 1300 MW pressurized water reactor (PWR) of KWU-design with elevations scaled 1:1. The scaling factor for volume and power is 1:145. The accident scenarios investigated were inherent boron dilution during small break loss of coolant accident (SB-LOCA) and loss of the residual heat removal system (RHRS) during ¾-loop operation for a shutdown plant. All five tests were conducted utilizing boric acid and instrumentation for the detection of the boron concentration. The report explains the background of the integral tests, gives a brief description of the objectives and results of the individual tests, discusses the possibilities of interpretation and application of the data gained and puts the project in perspective to other work.

[1] One additional test from a preceding national test program is also included because of its similar subject.

Distribution see page 3

Table of contents see page 6-7

List of revisions

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OECD / SETH Program

Since April 2001 the PKL project has been in progress – together with the PANDA project (conducted at the Paul Scherrer Institute, Switzerland) – in the course of the collaborative program SETH, which was initiated by the OECD with the following international participants:

Association Vinçotte Nuclear (AVN) jointly with Tractebel S.A., Belgium

Nuclear Research Institute (NRI) of the Czech Republic

Valtion Teknillinen Tutkimuskeskus (VTT) and Säteilyturvakeskus (STUK), Finland

Commissariat à l' Énergie Atomique (CEA), Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France

VGB PowerTech e.V., Framatome ANP GmbH, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany

Atomic Energy Research Institute (KFKI), Hungary

Agenzia Nationale per la Protezione dell'Ambiente (ANPA), Ente per le Nuove Tecnologie l'Energia e l'Ambiente (ENEA), Italy

Nuclear Power Engineering Corporation (NUPEC), Japan

Korea Atomic Energy Research Institute (KAERI), Korea

Consejo de Seguridad Nuclear (CSN), Spain

Statens Kärnkraftinspektion (SKI), Sweden

Paul Scherrer Institute (PSI), Switzerland

Turkish Atomic Energy Authority (TAEK), Turkey

Health and Safety Executive (HSE), United Kingdom

United States Nuclear Regulatory Commission (US NRC), USA

Electricité de France (EDF)

PKL Experiments within SETH (Test Series PKLIII E)

With the support of the partners participating in the SETH project, the PKL experimental program has been performed by Framatome ANP as operating agent with the following personnel being involved:

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Mechanical engineering and performance of the tests	H. Kremin R. Güneysu H. Limprecht P. Reghenzani M. Schumm
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Evaluation and documentation	Dr. T. Mull B. Schoen
Analytical pre test calculations	R. Wegner

The responsibility for the content of this report lies with the authors.

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In particular the authors gratefully acknowledge the substantial and comprehensive input of Mr. Andrea Bucalossi from the Association Vinçotte, Nuclear (AVN), Belgium on the subject of data interpretation and application which has been integrated in (chapter 5 of) this report.

Table of Contents

1 Introduction

1.1 Background and Purpose of the OECD/SETH Project

In 1997, the Committee on the Safety of Nuclear Installations (CSNI) of the OECD's Nuclear Energy Agency (NEA) set up an international working group whose aim was to identify how existing expertise in the field of reactor safety and an appropriate experimental infrastructure could be sustained in the future. One of the main tasks of this Senior Group of Experts on Nuclear Safety Research Facilities and Programmes (SESAR/FAP) was to identify those test facilities and research programs which were threatened by closure in the next years and to select facilities and programs which, if they were able to continue through involvement in OECD projects, would be of particular benefit to the member countries /22/. In selecting these experimental facilities, the group not only based their decisions on the technical capabilities provided by a specific facility but also assessed the competence of the team working there, including the way in which use was made of test results for analytical applications; e.g. for code validation.

As early as 1998, SESAR/FAP presented CSNI with a first set of results which not only comprised general and strategic recommendations but also proposed actions for immediate or near-term implementation. The safeguarding of integral test facilities for studying thermal-hydraulic issues was one of the actions assigned top priority, provided test programs with unquestionable scientific interest be proposed. At its annual meeting in December 1999, CSNI issued the recommendation that an international collaborative project be set up in the field of thermal hydraulics to implement the recommendation made to this effect by SESAR/FAP. Based on programs and time and cost schedules proposed by the various companies operating the test facilities, a proposal for a project called SETH (SESAR Thermal-Hydraulics) was elaborated in consultation with the NEA Secretariat and was submitted to the member countries in mid-2000. This proposal was based on experiments to be conducted in the PANDA and PKL test facilities.

A large scale test series with the scope on mixing and stratification of steam, air and further gases as well as heat transport and removal in these gases – i.e.: phenomena that are likely to occur in a containment atmosphere under accident and severe accident conditions – was suggested to be carried out in the PANDA facility at the Paul Scherrer Institute in Switzerland. This test series basically may be considered as a support of code development.

Boron dilution under reflux-condenser conditions remaining an insufficiently well-known phenomenon during SB-LOCA as well as loss of the RHRS at shutdown, an experimental program aiming at getting better understanding of these issues was defined for Framatome's PKL test facility in Erlangen, Germany, and proposed to the OECD-NEA members.

As is customary with OECD projects, half of the funds necessary for financing the project are to be provided by the host country in which the tests are performed. The other half is to be provided by those OECD/NEA member countries participating in the project. In view of the fact that funds for reactor safety research are scarce in all member countries and that these countries are already participating in a number of other OECD projects, the realization of the SETH project should be seen as quite an achievement.

The SETH project, which started in April 2001, altogether makes a vitally important contribution to safeguarding technical competence within the international research community in the field of thermal hydraulics.

1.2 PKL III Test Facility

The large-scale test facility PKL (Figs. 4, 5, /1 - 5/) is a scaled-down model of a pressurized water reactor of KWU design of the 1300 MW class. Reference plant is the Philippsburg 2 nuclear power plant. The PKL test facility models the entire primary side and essential parts of the secondary side (without turbine and condenser) of the reference plant. All elevations are scaled 1:1. Volumes, power and mass flows are modeled by the scaling factor 1:145.

As for other test facilities of this size, the scaling concept aims to simulate the thermal hydraulic system behavior of the full-scale power plant. The following features serve to meet this requirement:

- Full-scale hydrostatic head
- Power, volume, and cross-sectional area scaling factor of 1:145
- Full-scale frictional pressure loss for single-phase flow
- Simulation of all four loops with identical piping lengths
- Core and steam generators are simulated as a "section" from the actual systems, in other words, full-scale rod and U-tube dimensions, spacers, heat storage capacity are used; the numbers of rods and tubes are scaled down.
- In cases of conflicting requirements, simulation of the phenomena was given preference over consistent simulation of the geometry, e.g., in order to account for important phenome-

na in the hot legs such as flow separation and countercurrent flow limitation, the geometry of the hot legs is based on conservation of the Froude number and was finally designed on the basis of experiments at the full scale UPTF.

- The RPV downcomer is modeled as an annulus in the upper region and continues as two stand pipes connected to the lower plenum. This configuration permits symmetrical connection of the 4 cold legs to the RPV, preserves the frictional pressure losses and does not unacceptably distort the volume/surface ratio.

PKL is worldwide the only test facility with 4 identical reactor coolant loops arranged symmetrically around the reactor pressure vessel. This configuration permits accidents to be investigated under realistic conditions, including those accidents characterized by non-symmetrical boundary conditions between the loops. Modeling of a 3-loop plant is possible by simply isolating one loop. Each loop is equipped with an active reactor coolant pump with speed controllers to enable any pump characteristics to be reproduced. Under natural circulation conditions (i.e. reactor coolant pumps not in operation) the flow resistance of blocked pumps is simulated.

The reactor core is modeled by a bundle of 314 electrically heated rods with a maximum core power of 2.5 MW which is equivalent to 10% of nominal rating. Each of the 4 steam generators is equipped with 30 U-tubes of original size and material. Allowance has been made for the differing elevations (1.5 m) between the tubes with the smallest and largest bending radius.

As the functions of all major primary and secondary operational and safety systems are also replicated in the test facility, integral system behavior as well as the interaction between individual systems can be investigated under a wide variety of different accident conditions and the effectiveness of either automatically or manually initiated actions can be examined.

With its total of around 1300 measuring points, the PKL facility is extensively instrumented, something which permits detailed analysis and interpretation of the phenomena observed in the tests. Besides conventional measurements for temperature, pressure and mass flow rates, also special measurement techniques for the determination of the boron concentration (see chapter 1.4) were used for the experiments described in this report.

The maximum operating pressure of the PKL test facility is 45 bar on the primary side and 56 bar on the secondary side. Due to this pressure limitation, it is not possible to simulate the high-pressure portion of accident sequences (such as small-break LOCAs) starting from a PWR's actual operating pressure (155-160 bar) under original conditions. Hence, the PKL tests "start" at a primary system pressure of 45 bar and with initial conditions corresponding to those that would prevail in a real plant at this time (i.e. when the primary system pressure is at this level). These initial conditions are obtained from analyses conducted using system codes (such as RELAP 5) for a real PWR geometry and corresponding boundary conditions and are realized within a so called conditioning phase. The remainder of the accident sequence, where the most relevant phenomena are expected to occur (e. g. for the small break LOCA tests described here: refilling, onset of natural circulation and transport of low-boron water in the direction of the RPV) is then simulated in the tests using real PWR pressures. Accidents scenarios which would occur in the PWR under shutdown conditions (e.g. loss of residual heat removal system during mid-loop operation) are simulated in the PKL test facility under original pressure conditions.

The PKL test facility was designed, built and commissioned by Siemens/KWU (now Framatome ANP) in the seventies. At that time reactor safety research was centered above all on the theoretical and experimental analysis of large-break loss of coolant accidents (LB-LOCA), focusing on verifying the effectiveness of the emergency core cooling system (ECCS) required for controlling these accidents. In line with this original objective and considering topical issues[2], Siemens/KWU carried out the first PKL tests in the years from 1977 to 1986 in the course of the projects PKL I and PKL II which were sponsored by the German Federal Ministry for Education, Science, Research and Technology (BMBF).

The PKL III project, which was started subsequently, had the main goal of investigating experimentally the thermal-hydraulic processes on the primary and the secondary side of a PWR during various accident scenarios with and without loss of coolant. Within the scope of this project Siemens/KWU conducted tests concerning the investigations of transients from 1986 to 1999 with financial support of both the German Utilities operating PWRs[3] and the BMBF and the BMWi (German Federal Ministry for Economics and Technology). One focus of these activities was on the effectiveness of beyond design basis accident management measures being initiated manually by the operators. These measures for accident mitigation were theoretically analyzed within the German Risk Study, phase B /6/.

The PKL tests performed to date have altogether contributed to a better understanding of the sometimes highly complex thermal-hydraulic processes involved in various accident scenarios and to a better assessment of the countermeasures implemented for accident control. In addition, they have supplied valuable information regarding safety margins available in the plants. Another important benefit of the PKL tests is that they provide an extensive database for use in the further devel-

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2 The accident at TMI-2 (USA, 1979) made scenarios with small breaks and multiple failures the subject of many investigations, e.g. PKL test series I C and I D.

3 In 1995 the project was joined by the nuclear power plants Gösgen (Switzerland) and Trillo (Spain).

opment and validation of thermal-hydraulic computer codes, so-called system codes. These codes employed in designing and licensing nuclear power plants have to be validated beforehand.

1.3 Inherent Boron Dilution

1.3.1 Small Break Loss of Coolant Accidents

Since the early 90s interest has increasingly been focused in reactor safety research on the topic of boron dilution. The importance of boron dilution scenarios lies in the possibility of unborated or boron-depleted water entering the core, thus increasing core reactivity and potentially leading to core criticality or even power excursions in the most severe cases /7/. The assessment of various accident scenarios which might give rise to boron dilution shows that, in particular, SB-LOCAs should be investigated in this respect. Such events combined with limited availability of the ECCS can lead to a temporary reduction of the coolant inventory, resulting in reflux-condenser (RC) conditions[4] and hence in inherent boron dilution /8/ (see Figs. 1, 2). When the reactor cooling system (RCS) is refilled later on during the course of the accident, low borated masses of water may be transported into the core with the restart of natural circulation (NC).

Inherent boron dilution after SB-LOCA is the main topic of 4 out of 5 tests carried out within the test series PKL III E, which was started in the year 2000. The tests were conducted utilizing boric acid and boron measuring instrumentation technique. They provide an important contribution for the evaluation of boron dilution events and represent a valuable data source for the validation of computer codes used for the analytical handling of this subject.

The 4 tests on inherent boron dilution during SB-LOCA were as follows:

- E1.1 (break in hot leg, HPSI into all 4 cold legs /9/)
- E2.1 (break in hot leg, HPSI into all 4 hot legs /10/)

[4] The term "reflux-condenser" characterizes the following conditions in the RCS of a PWR: The coolant inventory is depleted (e.g. due to a loss-of-coolant accident) so that the primary is partly voided and the coolant circulation is interrupted. The heat transfer from the core to the SGs is accomplished by steam formation in the core and steam condensation in the SG tubes. The steam carries with itself only a very small fraction of the boric acid present in the primary coolant (leading to an increasing boron concentration in the core). The condensate formed in the SGs (which is nearly unborated) partly flows back from the SGs to the RPV through the hot legs but partly also drains down into the loop seals and gradually displaces the borated coolant which had filled the loop seals before. Thereby reflux-condenser conditions give rise to inherent boron dilution, i.e. seperation of the (originally homogeneously borated) primary coolant into fractions with high boron concentration (in the core) and low boron concentration (e.g. in the loop seals).

- E2.2 (break in cold leg, HPSI into 2 cold legs /11/)
- E2.3 (break in hot leg, HPSI into 2 hot legs /12/).

1.3.2 Loss of RHRS during ¾-loop Operation

Besides post-SB-LOCA boron dilution, an accident scenario for the shutdown state was also investigated in PKL III E. In recent years, increasing attention has been devoted to such incidents as various probabilistic safety assessments have shown that the contribution of these accidents to core damage frequencies is much larger than originally anticipated based on engineering judgement. In addition, accidents under shutdown conditions can also lead to situations similar to reflux-condenser and thus in principle to local boron dilution (Fig. 3). Therefore, the corresponding PKL test

- E3.1 (loss of RHRS in shutdown plant /13/)

was also conducted utilizing boric acid and boron concentration measuring technique.

1.4 Application of Boric Acid and Measurement of Boron Concentrations

The primary coolant of the PKL test facility was not charged with boric acid before a number of tests had proven that boric acid does neither damage to the integrity of the test facility materials and functionality nor to the instruments.

For detection of the boron concentration, special measuring technique was backfitted. The COMBO (Continuous Measurement of Boron Concentration) devices for continuously measuring the boron concentration are operating according to the principle of neutron absorption. In test E1.1, only one COMBO was available, in the other tests, four COMBO devices were used. The COMBO system was originally developed by Siemens (now Framatome ANP) for use in real PWRs. The measuring principle is based on the absorption of neutrons by the isotope boron-10, which varies according to the boron content of the coolant. The COMBO system, which basically consists of a neutron source (positioned on one side of the reactor coolant line (RCL)) and two counter tubes (installed close together on the opposite side of the RCL), can be mounted on the outer wall of the RCL so that it has no effect on the fluid being measured (see sketch in Fig. 7). As a result of using this neutron transmission method, the measurements are averaging over the entire flow cross section in the pipe.

Apart from the COMBO systems, the test facility was also retrofitted with sampling points for taking grab samples at several locations in the primary system, such as in the loop seals, in the steam generator (SG) inlet and outlet plena, in the RPV downcomer and in the region of the core. The instrument locations for the boron concentration measurements are shown in Fig. 6.

2 Objectives of the PKL III E Test Series

2.1 General Objectives of the Tests on Inherent Boron Dilution Following SB-LOCA

Inherent boron dilution /7, 8, 14/ can take place if an SB-LOCA[5] occurs in the primary cooling system of a PWR and gives temporarily rise to reflux-condenser conditions. If the blowdown rate at high pressure is higher than the injection rate of the SIPs, the primary coolant inventory will be decreased. If the depletion of the coolant inventory is extensive, even the SGs may be voided and natural circulation interrupted. As a result, energy would temporarily be transported from the primary to the secondary side under reflux-condenser conditions. Only small amounts of boron are transferred to the vapor phase. Therefore, the condensate produced in the SGs is nearly free of boron. This condensate may accumulate locally in the reactor coolant system, especially in the loop seals. At low pressure the leakage rate is lower than the injection rate of the ECCS leading to a refill of the primary circuit. When natural circulation starts, the low-boron water inventories could be transported towards the RPV. The main question is, will the boron concentration at the core inlet fall below acceptable levels?

Possible recriticality depends mainly on the following aspects:

- Size of the "condensate slugs" formed
- Mixing processes in the SGs and in the loops
- Intensity of the natural circulation restart transient (mass flow)
- Time difference between the startup of natural circulation in the different loops
- Mixing with more highly borated water in the annular gap of the RPV downcomer (DC) and in the lower plenum.

The first four items mentioned are issues investigated in the PKL test facility. Full scale or at least larger scale test facilities are more suitable for the reactor-like simulation of mixing processes in the downcomer of the RPV and the lower plenum /14/.

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[5] Breaks in the reactor coolant system are called "small" if they are so large that the blowdown rate cannot be compensated by the chemical and volume control system but so small that the SGs are necessary for heat removal.

The above mentioned aspects are dominated by boundary conditions such as break size, break location, injection rates, injection locations and cooldown rate.

PKL tests concerning post-SB-LOCA inherent boron dilution can be configured conservatively by "optimization" if their boundary conditions in such a way, that they are in favor of (temporarily) even lower boron concentrations at the RPV inlet than can be expected for the corresponding PWR cases. This optimization can follow two different approaches:

- Symmetric boundary conditions in all 4 loops:
  For these tests the boundary conditions are chosen in such a way that a simultaneous startup of natural circulation and a simultaneous arrival of the low borated slugs at the RPV are favored (E1.1, E2.1). These tests are more conservative than any reactor case, as far as for total symmetric boundary conditions, i.e. ECC injection by 4 SIPs into all 4 loops, there will not be a significant energy transfer to the SGs in the reference PWR, as the energy binding due to warm up of the ECC water simply does not leave enough energy for the formation of steam and significant amounts of condensate. In the tests, this is overcome by formation of condensate slugs before the test and/or by artificially small ECC injection rates.

- Large size of single condensate slugs in individual loops and poor mixing conditions:
  For these tests the boundary conditions are chosen in such a way that the influence of mixing processes is small (E2.3) and/or the mass of condensate produced is extremely large (E2.2). The facts that a PKL test enters the PWR accident transient at a pressure of 40 bar and that the test initial conditions have to be prepared in a conditioning phase (i.e.: the original slug formation is not dominated by a certain cooldown procedure as it is in a PWR) offer the possibility to arbitrarily adjust the amount of condensate present at the start of the test. It is therefore possible to run tests with larger condensate accumulations than imaginable in a PWR (and even to carry out sensitivity studies on the impact of the slug size).

For the first category of tests all four loops of the RCS are fed symmetrically with ECC water. For tests of the second category – at least at high pressure – not all loops are fed and the size of the break is chosen so that a maximum amount of condensate may be expected.

Tab. 1 summarizes all tests concerning inherent boron dilution after SB-LOCA within the test series PKL III E.

2.2 Specific Objectives of the Individual Tests on Post-SB-LOCA Boron Dilution

2.2.1 Objectives of the Tests E1.1 and E2.1

The tests E1.1 and E2.1 were fundamental tests in the 1st category of the framework described above. The purpose of the tests was not to simulate specific PWR transients but to contribute to an answer to fundamental questions regarding inherent boron dilution. The tests were intended to investigate the startup of natural circulation after a break in a hot leg under maximum symmetrical conditions for cold leg (E1.1) and hot leg injection of ECC water (E2.1). The aim of these tests was to answer the following questions:

- Can simultaneous restart of natural circulation in two or more loops be ruled out after mere cold-leg injection (E1.1) or mere hot-leg injection (E2.1) of ECC water?
- What are the minimum boron concentrations at the RPV inlet on symmetrical injection of ECC water into the RCS for the chosen break configurations?

In this respect, the boundary conditions of the tests were chosen conservatively:

- Maximum symmetry in the loops (uniform injection into all four loops and concentration of asymmetries – break and pressurizer – in one loop).
- Large amounts of condensate[6].

The symmetry between the loops favors the simultaneous restart of natural circulation and hence the concurrent arrival of the low-boron slugs of water at the RPV inlet from the individual loops. This and the large amounts of condensate initially present in all the loops can be regarded as a conservative assumption with respect to defining boundary conditions for further studies aiming at better evaluating recriticality risks.

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6 During a realistic accident scenario the duration of the reflux-condenser phase is not long – even with (symmetrical) injection into all four loops (by all four SIPs) – and therefore no (large) accumulations of condensate are formed.

2.2.2 Objectives of Test E2.2

Test E2.2 with a small break in cold leg 1 and only 2 out of 4 SIPs injecting into cold legs 1 and 2 falls under the 2nd category of the above classification, i.e.: its conditions are conservative in terms of the size of the condensate masses accumulating.

Analyses over the entire range of small break sizes[7] show that the largest condensate masses accumulating in the event of a cold-side break are to be expected if ECC water is also injected by the SIPs on the cold side and if the break is precisely big enough on the one hand to cause a long reflux-condenser phase but on the other that the filling level of the water/steam mixture present on the primary side does not drop below the top edge of the (hot-side) RCL at any time during the RC phase. As a result of the high filling level, the computations and estimates predict that zones with under-borated water will form not only in the loop seals, but also in the hot legs and SG inlet domes. Test E2.2 modeled precisely this scenario. In addition, about 800 kg of condensate was formed during the conditioning phase before start of the test (SOT). This is significantly more than the 240 kg that correspond to the mass of condensate predicted by RELAP computations to be formed in the PWR (namely 145 x 240 kg $\approx$ 35 tons) before 40 bar is reached. The test is thus conservative in terms of the amount of condensate accumulating in the event of a cold-side SB-LOCA. The points of pivotal interest in this test are the following:

- Size of the condensate slugs forming
- Mixing effects in the SGs and in the RCL
- Intensity of the natural circulation transporting under-borated coolant into the RPV
- Minimum boron concentration at the RPV inlet after the onset of natural circulation
- Time lag with which any under-borated coolant slugs from the individual loops reach the RPV.

2.2.3 Objectives of Test E2.3

Test E2.3 was designed to investigate a scenario involving a hot-side break with comparatively unfavorable conditions for mixing of the accumulated condensate with highly borated water, and

[7] These computations were also performed with various break positions but still subject to the condition that only 2 out of 4 SIPs are available und that 1 SIP is feeding into the ruptured loop.

with accumulation of large condensate masses in individual loops. Test E2.3 falls under the 2nd category of the above classification.

The break was postulated in hot leg 1. Only 2 out of 4 SIPs were postulated to be available and injecting into hot legs 1 and 3. Another conservative assumption was that NC is not yet interrupted in the two loops with HPSI at a pressure of 40 bar (departure point of the PKL-test). It was presumed that (at 40 bar) the SGs in the two loops without HPSI transferred energy to the secondary side under RC conditions while NC was going on in the two loops with hot-leg HPSI.

This scenario is conservative in two respects:

- If the flow of ECC water injected into the hot legs is (as assumed) reversed toward the SGs with natural circulation, the secondary-side temperature of these SGs will exceed the primary temperature during 100 K/h cooldown. Heat will be transferred from the secondary to the primary side. This will allow even more condensate to accumulate in the loops without SIP injection and with reflux-condenser conditions.

- If natural circulation resumes in these loops, too, once the refilling process has been completed and if the condensate masses are transported to the RPV, the conditions for mixing of the accumulated condensate with highly borated coolant in the RPV downcomer and in the lower plenum will be unfavorable (simultaneous flow through all loops at similar flow rates and absence of plumes of ECC water penetrating the core and reaching the lower plenum).

The main points to be investigated were as follows:

- General system behavior under the postulated conditions

- Flow conditions on resumption of natural circulation in the loops without HPSI (mass flow of reactivated natural circulation and flow rate in the loops with HPSI at the same time)

- Time lag between NC startup in the two loops without HPSI and time lag between the arrival of the boron-depleted slugs from these two loops at the RPV

- Size of the accumulated condensate slugs

- Time history and minimum boron concentration at the RPV inlet from start of NC.

2.3 Objectives of the Test on Loss of the RHRS during ¾-loop Operation

The purpose of this test was to investigate the system response following loss of residual heat removal in ¾-loop operation with the RCS still closed. In this plant condition the PWR has already been cooled down for refueling. The operating manual states that German PWRs in this condition should have at least one SG on standby ready to remove decay heat in case the RHRS fails. Loss of residual heat removal in ¾-loop operation can produce reflux-condenser-like conditions. Analyses using the ATHLET computer program have shown that this can cause an entrainment of reactor coolant from the inlet to the outlet side of the active SG with deboration of individual sections of the reactor coolant system as a possible consequence.

The objective of test E3.1 was to investigate what type of heat removal mechanism becomes established in the presence of nitrogen in the reactor coolant system following failure of the residual heat removal system and with subsequent heat removal via one operational SG, and whether the resultant energy and material transport processes produce an unacceptable decrease in the boron concentration due to inherent boron dilution.

The test was designed to answer the following important questions:

- Heat transfer from the core to the secondary side of the SGs
  - Nature of the evolving heat removal mechanism
  - Temperature and pressure increases on the primary side before steady-state conditions are established
- Development of the local boron distribution in the reactor coolant system
  - Accumulation of largely unborated condensate
  - Displacement of water with low boron content into the RPV before or after the accumulator injections.

3 PKL III E Test Matrix and Test Conditions

3.1 Test Matrix

Within the project PKL III E, 4 tests were carried out addressing inherent boron dilution during SB-LOCA (E1.1, E2.1, E2.2 and E2.3) and 1 test with the scope on loss of the RHRS during 3/4-loop operation (E3.1). The complete test matrix of the PKL III E series is shown in Tab. 1. Tab. 2 compares the 4 SB-LOCA tests.

3.2 Test Facility Configuration

The primary and the secondary sides were completely in operation in all 5 tests. For the SB-LOCA tests, all four SG secondaries were connected via main steam header and cooled down by 100 K/h. The interfacing systems were in operation as listed in Tab. 1 (only the most important ones).

3.3 Test Initial Conditions

SB-LOCA Tests:

The decay heat simulated at the start of the tests corresponds to the level in the PWR present approx. half an hour after reactor trip. Also the pressures on the primary and secondary sides at the start of the tests corresponded to those reached after secondary-side cooldown at 100 K/h for half an hour. The primary coolant inventory was reduced according to pre-test calculations and as schematically shown in Fig. 1. During conditioning phases before test start, condensate accumulations had been generated under reflux-condenser conditions corresponding to the postulated (accident) scenarios.

At test start, energy was still transferred to the secondaries under reflux-condenser conditions. Tab. 3 lists further details of the test initial conditions. They are also illustrated in Figs. 8, 12, 15 and 18. Tab. 4 compares the test conditions before the onset of natural circulation.

3/4-loop Test:

Test E3.1 was based on the following accident scenario: The PWR has already been shut down (p = 1 bar, T = 60 °C), e.g. in preparation for refueling and the reactor coolant inventory has been reduced to the level for ¾-loop operation. The space above the water inventory is filled with nitrogen that was injected into the reactor coolant system as the level was being reduced. The reactor coolant system is still closed and decay heat is initially still being removed through the residual heat removal system. With the reactor coolant system in this condition, complete failure of the residual heat removal system is now postulated. This point in time corresponds to test start, see Fig. 20.

Loss of the heat sink causes core temperatures to rise with resultant void formation once saturation conditions have been reached; void formation is in turn associated with an increase in primary-side pressure. The operating manual states that German PWRs should have at least one SG on standby ready to remove decay heat in case the residual heat removal system fails.

For the purpose of the present test it was postulated that two SGs are filled with water on their secondary sides (level = 12 m with air above) at onset of accident conditions (loss of residual heat removal). The other two SGs were completely filled with air. All four SGs were initially depressurized and isolated on their main steam sides. It was also postulated that one of the two water-filled SGs (SG 1) was maintained at a constant pressure of 2 bar and a constant level of 12 m by the main steam pressure and feedwater control system following a rise in secondary-side pressure as heat is absorbed from the RCS. The other water-filled SG (SG 2) and SGs 3 and 4 likewise were kept isolated on their main steam (MS) and feedwater sides for the entire duration of the incident.

4 Results of the PKL III E Test Series

4.1 Results of the Tests on Post SB-LOCA Boron Dilution

4.1.1 Results of Test E1.1

The results of test E1.1 (see Figs. 8 - 11) are as follows:

- In the final phase of refill, a limited displacement of coolant with flow through the loops occurred in all four loops within approx. 100 s balancing the weights of the hot-side (core, upper plenum and SG inlet side) and cold-side water columns (SG outlet side and RPV downcomer). The mass flow rates involved were relatively low (< 1 kg/s per loop) with different heights of the maxima in all four loops. In all SGs, only the shorter U-tubes took part in this process.
- In the further course of the test, natural circulation differed between the loops although there were similarities between loops 1 and 2 and loops 3 and 4. In the loops 1 and 2, there was no noteworthy mass flow before the SIPs were shut down (assuming the borated water storage tanks to be empty) and a short phase without coolant injection commenced.
- The condensate transported from the loops to the RPV reached the RPV at different points in time. In the loops 1 and 2, a part of the condensate remained in the SGs, as not all U-tubes were involved in circulation.
- Due to effective energy binding by warm up of the ECC water injected, the natural circulation mass flow rates remained relatively low throughout the course of the test.
- The boron concentration measured continuously in cold leg 1 at the RPV inlet did not drop by more than 10 % with respect to its mean value of 2200 ppm throughout the time after natural circulation restart. Taking into account the condensate slug present in loop seal 1 at SOT ([B] < 50 ppm), there was only a slight decrease of the boron concentration. This can be understood as the result of the following, mixing-relevant phenomena:
    - First mixing occurred during refill, when the condensate slugs were displaced from the loop seals up into the SGs and partly mixed with the more highly borated water following the slugs.
    - Natural circulation started at different times in the different U-tubes of a SG.

- Only a part of the U-tubes participated in natural circulation.
- Some U-tubes exhibited oscillatory flow (alternating forward / backward flow) before they took part in natural circulation. This behavior gave rise to mixing of water from inside the U-tubes with water from the SG inlet and outlet channels.
- In the cold legs, there was complete mixing of the circulating water with the well borated ECC water injected there. As the natural circulation mass flow rates remained relatively low, the boron concentration was increased significantly at the injection points.

In the course of an SB-LOCA involving temporary heat transfer under reflux-condenser conditions and refilling of the RCS by symmetrical injection of ECC water into all 4 cold legs, the conditions are unfavorable for a simultaneous startup of natural circulation in all 4 loops as long as ECC water is being injected, even if the boundary conditions are at maximum symmetry. Injection of cold ECC water by 4 SIPs will consume the largest part of the energy to be removed so that - in terms of energy - there is no need for natural circulation to transfer a lot of power to the SGs and therefore the natural circulation mass flow rates - if any - will be low.

Due to different mixing effects, first of all the mixing of condensate slugs traveling slowly through the cold legs with the ECC water injected there, there was only a minimum decrease of the boron concentration measured at the RPV inlet at the time of the slug transit. The minimum measured boron concentration was only 200 - 250 ppm below that of the injected ECC water.

4.1.2 Results of Test E2.1

The results of test E2.1 (see Figs. 12 - 14) are as follows:

- During the phase of refill by the SIPs the borated ECC water (boron concentration 2200 ppm) injected into the hot legs flowed directly into the upper plenum and the core and was partly mixed with highly borated water present there. This displaced water from the core and lower plenum into the downcomer. As a result, the displaced highly borated water mixed during refilling in the downcomer with the water at a low boron concentration (< 50 ppm) present there since the start of the test.

  In the further course of the test this borated water flowed into the loop seals and mixed there with the nearly unborated coolant already present. Thus the outlet sides of the SGs were refilled with borated water. Since the inlet sides of the SGs were refilled with borated ECC water from the SIPs injecting into the hot legs after refill no areas filled with unborated water remained in the RCS (at this point in time the lowest boron concentrations of 100 – 200 ppm were present on the outlet side of the SG tubes).

- Despite maximum symmetry between the loops no natural circulation started when the primary circuit was filled, with the SIPs continuing to inject into the hot legs, but a non-uniform, mainly reverse flow pattern developed.

  Consequently the low-boron water from refilling which remained in the SG tubes was displaced from most of the tubes and the greater part replaced by water from the loop seals. The boron concentration of this water continued to increase. The water displaced from the SG tubes mixes with more highly borated coolant in the inlet and outlet channels of the SGs depending on its flow direction.

- Due to the increase in temperature in the core region after shutdown of the SIPs in the phase without coolant injection prior to the activation of the LPSI, natural circulation started first in the affected (break) loop and then, 110 s later, nearly simultaneously with the other three loops. The mass flow rate in natural circulation differed between the loops but there were similarities between loops 1 and 2 and loops 3 and 4.

- Immediately after the onset of natural circulation the boron concentration measured in loops 1 and 2 at the RPV inlet decreased slightly for a short time. This was due to the high natural circulation mass flow rate in these loops with flow being restored even in those SG tubes which had not taken part in the above mentioned slow reverse flow. This displaced the less borated water still remaining in the tubing. However, the boron concentration did not fall below 1700 ppm (starting from 2050 ppm). In loops 3 and 4 no reduction of the boron concentration was observed. This in total only slight reduction of the boron concentration – despite loop seals being filled with water nearly free of boron (< 50 ppm) at the start of the test – can be explained by the interaction of the following processes contributing to mixing:

  - As early as during refilling, reverse flow caused mixing of the initially nearly unborated water (< 50 ppm) in the downcomer and the loop seals with highly borated water from the core and injected by the SIPs into the hot legs. As a result no areas of the RCS were filled with unborated water after refilling.
  - With the RCS nearly refilled, flow was re-established in the SGs. Thereby the low-boron water was displaced from most of the SG tubes and replaced by highly borated water.

- With the exception of the stalled SG tubes after the RCS had been refilled and the SIPs continuing to inject into the hot legs, the boron concentration in the RCS increased to above 2000 ppm.
- Natural circulation started in all loops following heating up of the fluid in the core region after shutdown of the SIPs. After high mass flow rates (loops 1 and 2) were reached, natural circulation started in SG tubes which had previously been stalled. The low-boron water displaced was transported to the RPV and mixed with highly borated water in the process (> 2000 ppm). Consequently only a slight decrease of the boron concentration was observed at the RPV inlet.

During a small-break loss-of-coolant-accident involving temporary heat transfer under reflux-condenser conditions, refilling of the RCS by symmetrical injection of ECC water into the hot legs and the occurrence of a phase without coolant injection, it cannot be excluded that natural circulation could start in several loops nearly simultaneously. The test showed that a marked reduction of the boron concentration at the RPV inlet is not to be expected. The minimum measured boron concentration was only 350 ppm below that of the injected ECC water.

4.1.3 Results of Test E2.2

The results of test E2.2 (see Figs. 15 - 17) are as follows:

- Natural circulation commenced at different times in the different loops.
- The condensate slugs with the lowest boron concentration at the RPV inlet were formed in loops 3 and 4, which were not fed with ECC water.
- Natural circulation first set in in the two unfed loops 3 and 4. In loop 4, circulation commenced in the final phase of refill, about 160 s earlier than in loop 3. The condensate slugs from the two loops thus reached the RPV at considerably different times.
- The steam flowing from the core to the SGs caused limited mixing of the water masses from core, upper plenum, hot legs and SG inlet channels. As a result, the boron concentration in the SG inlet channels at the onset of natural circulation was significantly higher than expected. Although the concentration could be reduced to 400 - 500 ppm in the conditioning phase and was still below 800 ppm at the start of the test (SOT), in the refill phase it rose to at least [B] = 1100 - 1400 ppm even before onset of circulation.

- The size of the condensate slugs formed on the cold side is limited by water being transported from the SG inlet to the SG outlet side (i.e. coolant circulation) as soon as the filling level in the SG outlet channel reaches the tubesheet, even if only temporarily. As a result of this effect, which was frequently observed also in all the work preparatory to this test, higher levels in the SG outlet channels than those established at SOT do not involve larger condensate accumulations but increasing boron concentrations in the loop seals.

- At the onset of natural circulation in the unfed loops, the minimum boron concentration at the RPV inlet was 350 ± 100 ppm. More specifically, the boron concentration sank below 1000 ppm for about 60 s in each loop and below 500 ppm for only about 30 s. These drops took place at mass flow rates of between 0.5 and 1.5 kg/s. A total of 37 kg of coolant at [B] ≤ 500 ppm and 88 kg at [B] ≤ 1000 ppm was transported to the RPV.

- The total size of the condensate slugs formed was significantly smaller than predicted by estimates performed on the basis of thermohydraulic analyses (RELAP etc.).

- At the onset of natural circulation, the condensate slugs from the unfed loops were found not in the SGs but in the loop seals (important for further mixing).

- At the onset of natural circulation in the loops supplied with ECC water, there was no significant drop in the boron concentration at the RPV inlet.

4.1.4 Results of Test E2.3

The results of test E2.3 (see Figs. 18, 19) are as follows:

- Condensate accumulation in the loops without HPSI was limited to the relatively small volume of the loop seals up to the bottom of the reactor coolant line (RCL). The relevant condensate accumulations were correspondingly small (35 - 40 kg per loop with [B] = 50 - 400 ppm).

- After start of the test (SOT), the levels in the previously drained SGs rose quickly with natural circulation becoming established even before the SG U-tube bundles had been completely refilled with water (indicative of the instability of the initial condition).

- Natural circulation, in which the boron-depleted coolant was transported to the RPV, became established with moderate mass flow rates (≤ 0.5 and approx. 0.7 kg/s) and with a time lag between the two loops.

- At the same time, mass flow rates in the loops with ECC injection were more than twice as high (> 2 kg/s).
- The two boron-depleted slugs of water reached the RPV with a time lag between each other.

The rapid refilling process and resultant onset of slow flow conditions in the loops without HPSI just a short time after SOT suggests that a break of equivalent cross section in the PWR would not have produced such an extensive drainage of the RCS as set for the test initial conditions. Such an outcome would have required a larger break in the PWR. It is also known from a preliminary test that a break cross section of 75 cm^2 already causes such extensive loss of coolant that natural circulation breaks down even in the loops with HPSI. This suggests that the postulated scenario could occur in the PWR - if at all - then only over a very small range of the break size spectrum.

4.1.5 Conclusive Findings for Inherent Boron Dilution after SB-LOCA

Some conclusive findings can be extracted from the ensemble of the specific test results compiled above. They are as follows:

- The size of a single condensate slug is limited by the volume of the loop seal plus a part of the volume of a SG outlet channel.
- Effective mixing processes may occur in the SGs during and after refill.
- At the end of SG fillup, there is the tendency for a forward mass flow peak, if steam is still present in the core[8]. This peak turns out to be the higher, the more steam is present (compare PKL III E test results to /15/)
- When NC restarts, pronounced condensate slugs arrive at the RPV only from those loops which have not been supplied with ECC water.
- NC startup does not occur simultaneously in the U-tubes of one and the same SG.
- NC prefers the loops without ECC injection.
- Even if maximum symmetry was presumed, NC did not start simultaneously and at the same time in all loops of the test facility.

[8] not observed in test E2.1 without steam in the core at this time

- For intensive hot leg ECC injection, stable forward natural circulation does not occur before HPSI shutdown. Instead, slow reverse will establish in the loops.

- The minimum boron concentration observed at the RPV inlet was 350 ± 100 ppm

As a comprising finding, it may be stated, that the results of the PKL III E tests have pointed out the borders of the SB-LOCA boron-dilution problem. Conditions for slug generation, slug size, minimum boron concentration and the NC startup behavior were found to be more favorable than the worst case assumptions, which had to be taken into account for the treatment of this problem before the PKL III E tests had been carried out.

4.2 Results of Test E3.1 on Loss of the RHRS

The results of Test E3.1 (see Figs. 21, 22) are as follows:

- Loss of the residual heat removal system at the start of the test caused the core temperatures to rise leading to void formation in the core after approx. 12 min. This led to raised pressure in the reactor coolant system resulting in compression of the nitrogen volumes.

  Reflux-condenser conditions became established in SGs 1 and 2 (the secondaries of which were filled with water) with condensation of steam on the SG inlet side in the lower areas of the U-tubes. The steam produced in the core and consequently the condensate accumulating in the lower areas of the SG U-tubes and also in the upper area of the SG inlet channels was almost boron-free. With secondary pressure in SG 1 constantly controlled at 2 bar and with primary-side pressure continuing to rise in the first instance, this SG became the main heat sink. The following heat removal conditions became established during this heating phase with the reactor coolant system pressure still rising: The steam generated in the core flowed mainly into SG 1 where it condensed on the inlet side in the lower U-tube areas. Above this the U-tubes contained a stable column of cold water at secondary-side temperature. The remaining U-tube area was filled with nitrogen also at secondary-side temperature.

- A continuous increase in the volume of steam entering SG 1 from the core was observed in comparison with that entering SG 2 (increase in RCS pressure with secondary system pressure in SG 1 constant at 2 bar). The swell level in the U-tubes of SG 1 continued to rise as a result of this and eventually reached the top of individual U-tubes. This caused the reactor coolant to spill over from the inlet to the outlet side, displacing the nitrogen contained in these U-tubes into the outlet channel. The almost boron-free condensate that had formed in the U-tubes and in the upper area of the SG inlet chamber was then transported to the SG outlet side and onward through the loop seal in the direction of the reactor pressure vessel (RPV) inlet.

- Heat transfer conditions stabilized at an RCS pressure of around 5 bar. Intermittent circulation then became established in the few U-tubes without N_2. With the plant in this quasi-steady-state condition the boron concentration in the loop seal and in the cold leg of loop 1 as well as in the RPV downcomer decreased slowly but continuously. There was a simultaneous increase in the reactor coolant boron concentration in the core area.

- The cold-leg accumulator injections raised RCS pressure slightly in each case (by around 1 bar in total during the test) and allowed slow continuous natural circulation to become established in Loop 1. As a result of this, reactor coolant with an initially low boron concentration entered the core from the RPV downcomer. Reactor coolant boron concentrations in the whole of loop 1 and in the RPV then leveled out at around 2400 ppm. Forward flow conditions through the N_2-free U-tubes were maintained and even increased. The hot-leg ACC injection caused a slight, transient reduction in RCS pressure due to steam condensation in the hot leg and upper plenum.

The test can therefore be stated to have produced two important findings. Under the selected boundary conditions, controlling secondary-side pressure in one SG at 2 bar limited the increase in RCS pressure following loss of the residual heat removal system to around 5 bar. A quasi-steady-state condition became established although there was a continuous reduction in the boron concentration in the reactor coolant on the cold side of the loop with the active SG. If the ACC injection is very delayed while the plant is in this condition, i.e. as in the test approx. 9 hours after loss of the RHRS, the boron concentration on the cold side including the RPV downcomer will be reduced. An ACC injection then has the effect of transporting water with a low boron concentration, particularly from the RPV downcomer, to the core. An early accumulator injection is therefore preferable to a delayed one because a significant reduction in the boron concentration on the cold side of the loop with active SG is avoided in this case.

5 Data Interpretation and Application

5.1 General Considerations

Boron dilution is a fundamental safety issue for PWRs since boron concentration is directly linked with core reactivity. The PKL integral test facility is well suited to experimentally investigate the natural circulation behavior and boron dilution events following SB-LOCAs and the heat transfer mechanisms occurring during shut-down conditions (also in combination with boron dilution) because of its design features (see chap. 1.2). The use of boric acid and suitable measurement devices for the detection of the boron concentration in the primary system additionally contributes to an improved understanding of the complex thermal hydraulic processes relative to the investigated scenarios. The PKL tests were basically focused on the system behavior but, to a certain extent, important findings relative to individual components (e.g. SG-U-tubes) were also gained.

So far the PKL experiments provide an important contribution for the identification and possible resolution of boron dilution safety issues of PWRs and a unique database for the validation of thermal hydraulic system codes. The PKL test results may also serve as boundary conditions for further experimental and analytical investigations (e.g. CFD codes) on mixing in the RPV downcomer.

The experimental results discussed in this report generally have to be compared and assessed with corresponding analyses using thermal hydraulic system codes and, for some local phenomena, with separate effect tests or corresponding analytical investigations. Only the interaction between experiments and codes finally leads to qualified results for PWRs.

5.2 Extrapolation of Test Results to PWR Plants

It can be assumed that certain relevant phenomena observed in the PKL tests would also occur in real PWRs under corresponding boundary conditions so that the general processes regarding the restart of natural circulation, the formation, the displacement, the dilution and the dynamics of the deborated water slug during refill and natural circulation can be extrapolated with caution (i.e. in qualitative terms) to power plants. Due to its realistic scale of the steam generators as a whole and especially of the steam generator tubes (including, for example, their differing heights) the processes observed in these regions can be also quantitatively applied to real power plant configurations. Hence, heterogeneous behavior in the steam generator U-tubes can likewise be assumed for an actual PWR plant under similar boundary conditions.

As usual for scaled test facilities some specific test results such as:

- Absolute minimum boron concentration at the reactor pressure vessel inlet
- Exact amplitudes and sequence of natural circulation after refill
- Rate of local boron dilution after loss of the residual heat removal system

cannot be directly/quantitatively extrapolated to existing nuclear power plants. The principle way to transfer those results to the real PWR in quantitative terms is the use of thermal-hydraulic system codes after having enabled them to describe properly the corresponding phenomena in the PKL tests. However, up to now, it still seems to be a challenge for all the system codes to correctly reproduce such sensitive mechanisms as the restart of natural circulation and the very complex mixing processes in the SG U-tubes and with respect to this, the post-test calculations performed to date do not sufficiently meet the experimental results (see chapter 5.4). Experiences gained up to now demonstrate that on the basis of adequate scaling considerations the use of PKL test results including certain conservatisms is currently the most practicable and suitable way to estimate the system behavior of PWRs under boron dilution aspects. In order to determine the boron concentration at the core inlet, additional calculations (CFD) or separate effect tests on the mixing in the RPV downcomer and upper plenum (which cannot be realistically simulated in PKL) are required. The boundary conditions for those investigations concerning the situation at the RPV-inlet (boron concentration and mass flow rates in the individual loops) can be obtained from PKL test results.

In general, when extrapolating PKL results, it must be considered that the results are relative to the PKL facility, which differs geometrically in some aspects with classical PWR installations. Furthermore the obtained results depend strongly on boundary conditions such as ECC characteristics and secondary side cool-down rate that vary between different plant types.

Before interpretation and application of the PKL test results and data, the following aspects should therefore be considered.

5.2.1 SB-LOCA Tests

Formation of the deborated slug

Due to the pressure limitations of the PKL test facility, the slugs for the SB-LOCA tests could not be formed under exactly the same conditions as in the PWR transient (i.e.: during a depressurization transient starting at 155 - 160 bar). Instead, a large part of the slug generation had to be accomplished in a conditioning phase at a constant pressure of about 40 bar.

The volume of the deborated slug has been maximized for the tests E2.1 and E2.2 and is not linked with the preceding depressurization transient. The slug conservatively fills entirely the loop seal.

Behavior of the deborated slug during refill

From the start of the test onwards, the PKL tests simulate the PWR transients at their original pressure. As in the real PWR, during the refilling phase the deborated slug is displaced backwards from the loop seal to the SG outlet and downcoming U-tubes by the refilling water. The slug stays in this location until natural circulation displaces it towards the vessel inlet. The deborated slug size may evolve during the turbulent primary side refill and restart of natural circulation. The mixing coefficients cannot be easily evaluated during these phases.

Startup of natural circulation

Natural circulation does not restart simultaneously in the individual loops, no matter whether the test conditions are chosen either as to optimize the symmetry between the loops or as to optimize the initial size of an individual slug. The simultaneous natural circulation startup in the loops is countered by a reduction of the vessel driving head once natural circulation starts in one of the loop since cold water transits in the core.

Behavior of the deborated slug during startup of natural circulation

Once natural circulation starts (in a particular loop) the deborated slug will displace toward the loop seal, then through the pump and finally transiting in the cold leg towards the location of the safety injection nozzle. If the safety injection is active the deborated slug will partially mix while transiting and heading towards the vessel inlet (the mixing efficiency will depend on the velocity ratio of the slug to the injection and on the injection geometry). Due to density differences a part of the hot deborated slug will tend to rise in the downcomer annulus (buoyancy) remaining trapped in the upper part of the downcomer. The remaining part will be mixed with the ECC-water in the downcomer and head towards the lower plenum. The COMBO concentration measurements at the RPV inlet are of course unable to detect this subsequent partitioning.

5.2.2 Mid-Loop Test

Formation of the deborated slug

The formation of the slug of deborated water has been directly simulated in the mid-loop test. The slug has been created during a reflux-condenser mode in the active SG. Initially the non-condensables present in the circuit are compressed in the hot side and top of the U-tubes confining the reflux condensation in the cold side of the U-tubes. In this situation a deborated slug cannot be formed on the outlet side, because there are columns of subcooled condensate present above the condensation zone in the U-tubes at the SG inlet side "plugging" the entire SG. At a certain pressure a U-tube unplugging phenomenon occurs. The shorter U-tubes are unplugged and the non-condensables are displaced initially into the SG outlet box and from there backwards into the other longer U-tubes. The short unplugged U-tubes now account for most of the heat transfer. Subsequently condensate constantly forms in the both the hot and the cold side of the short unplugged U-tubes. A (probably large) part of the condensate formed in the hot side at the inlet side is transported with the 2Φ-flow through the unplugged short U-tubes to the cold side. A deborated slug is slowly but continuously growing in the loop seal.

Evolution of the deborated slug during refill

The mass flow in the loop with the recovered SG strongly depends on the filling level of the RCS. For the test, it was assumed that the filling level was advertently increased by ACC injections. After the addition of a small amount of ECC water, the mass flow in the loop stepped up considerably and the deborated slug was transported into the RPV. (Generally speaking plant procedures tend to keep the primary inventory at mid-loop even when loss of the RHRS occurs. Therefore the refilling phase of the experiment is performed just to investigate the evolution of the deborated slug if refilling would occur.)

5.3 Impact on Code Development and Validation

The OECD-SETH PKL tests provide a valuable database for the validation/development of thermal hydraulic system codes with respect to

- Formation of a deborated slug
- Transport of coolant through U-tube SGs, when outlet channel is filled with water
  - Limitation of the slug size
  - Impact on natural circulation startup behavior
- Boron slug transport
- Mixing of differently borated masses of water in different sections of the reactor coolant system
- Heat transfer between primary and secondary for natural circulation taking into account a redirection of the hot leg ECC injection to the SGs (CCFL)
- Natural Circulation startup behavior after SB-LOCA
  - Symmetry and asymmetry between loops (break location, pressurizer connection, ECC injection location)
  - Different behavior of U-tubes with different lengths
  - Dependence on system behavior
- System behavior after loss of the residual heat removal system during mid-loop operation with the primary circuit closed.
- Plugging of the U-tubes and unplugging of single U-tubes for reflux-condenser conditions with non-condensables present in the primary

The PKL tests also provide boundary conditions for CFD-calculations on mixing in the RPV downcomer.

5.4 Performed Thermal-Hydraulic Code Analyses

The OECD SETH project participants have performed various simulations of the OECD-SETH PKL experiments using their own codes. The codes that were mainly used were: RELAP, ATHLET and CATHARE. The codes qualitatively predicted the thermal hydraulic phenomena but so far not quantitatively. The calculation results were presented during the PRG meetings and at a specific workshop held in Barcelona, Spain in September 2003. The following section summarizes the main findings of the workshop.

5.4.1 SB-LOCA Tests

Most of the participants had problems with obtaining the startup time and correct sequence of natural circulation compromising the remaining part of the transient (boron slug transport/dilution and temperature evolutions). Other problems were relative to the thermal stratification in the upper head (bad modeling) and the correct splitting of the safety injection flow (to the vessel and to the loop).

Some calculations investigated the effect of a return to criticality due to the deborated slug but these results are not readily usable for power plants.

CFD calculations illustrated two unidentified phenomena: a possible non mixing between the low cold safety injection flow and the slow hot deborated slug transiting in the cold leg and a buoyancy effect in the vessel inlet where the non-mixed hot incoming deborated slug would tend to rise and fill the top part of the downcomer while the cold SI water would tend to circulate downwards. These two non-mixing effects are clearly not visible when using a 1D model (system codes) of the cold leg and of the downcomer inlet zone.

5.4.2 Mid-Loop Tests

The experimental phenomenology (loop deborication, condensate overspill in short U-tube, U-tube heterogeneous behaviour and transport) was qualitatively predicted only when using a code model having 3 lumped U-tubes per SG rather than the classical 1 lumped U-tube approach. Further investigations are needed to determine the best lumped U-tube configuration (number and weight) for a better quantitative prediction for this kind of transients.

5.5 Boundary Conditions for Further Experimental and Analytical Investigations

There are further needs for experimental investigations in the domain of boron dilution.

5.5.1 Post SB-LOCA Boron Dilution

For the SB-LOCA series it is necessary to continue the investigations and determine the influence of primary power, secondary cooldown rates and ECC injection flowrates on

- General system behavior with respect to inherent boron dilution
- Natural circulation behavior
- Minimum boron concentration at the RPV inlet.

Systematic investigations (separate effect tests) on the transfer of borated water from the SG inlet to the outlet side must be performed in order to determine the influence of the water inventory in the SG tubes, the primary pressure and the cooldown rates.

It is necessary to instrument as fully as possible the area between the safety injection and the downcomer in order to trace the hot deborated slug and to verify it's mixing with the cold ECC water. Thermocouples must be placed as densely as possible without disrupting the hydrodynamic flow in the cold leg between the vessel inlet and the safety injection point. 3D system codes or CFD codes will be needed to try and reproduce the phenomena (since 1D modeling imposes perfect mixing between ECC water and deborated slug).

5.5.2 Loss of the RHRS during ¾-loop Operation

During ¾-loop state the plants may have different configurations of primary inventory, pressurizer temperature, SG availability, manhole/vent opening status, presence of nozzle dams, decay power. For the case of loss of the RHRS, different measures are foreseen in different plants. It is therefore necessary to determine the effects of the parameters listed and the interaction of the countermeasures with the deborication trends of the system.

For a closed primary system, it might turn out to be useful, for example, to have more than one SG available when possible (i.e. when nozzle dams are not installed and the SG is not on maintenance). This strategy will cause spreading of the loop seal deborication to various loop seals and diminishing of the primary pressurization.

The upper head bypass section may also be an interesting parameter since it varies from plant to plant and will influence the redirection of steam produced in the core.

5.6 Possibilities for Procedure Modifications

As the PKL tests have not been satisfactorily reproduced by the system codes it is impossible to suggest power plant procedure modifications as these codes would be necessarily used to test these modifications.

Moreover the ECCS is a central design and safety feature and accident management is arranged around this feature one should avoid to give general advice for changes based on one single issue.

5.6.1 Inherent Boron Dilution during SB-LOCA

Regarding SB-LOCA it is useful to remember that in a loop without safety injection, a slug of rather low borated water will be displaced into the downcomer after NC startup. From then on we cannot predict its dynamics. If the slug travels in a loop where safety injection is present we can feel confident that it will tend to mix with the borated ECC water. CFD calculations speculate only a partial mixing. The only recommendation at this stage can be relative to minimizing the condenser times in order to diminish as far as possible the volume of the deborated slug and for the sequence of safety injection pump stopping after refill has occurred. This sequence depends on subcooling level of the primary system. It might be foreseeable to add an action that checks whether natural circulation has started or not in a particular loop before stopping that particular injection pump.

5.6.2 Loss of the RHRS during ¾-loop Operation

Regarding mid-loop operation the current PWR plant procedures instruct the operator to try to keep the level at mid loop after a loss of residual heat removal occurs. The E3.1 test confirms the safety problematics of loop seal deborication and of core concentration and adds them to the standard core uncovery issue when the system is closed and loss of the RHRS occurs. The primary pressurization seen in the experiment also may imply possible failure of nozzle dams and instrumentation seals when present creating potential LOCAs.

Test E3.1 yields a distinct hint towards an early accumulator injection possibly mitigating the boron dilution problem. Recommendations cannot be given, however, before further studies are performed (common sense suggests to recover as fast as possible the RHRS to avoid boron concentration and pressurization issues).

5.7 Relation to Other Work and Projects

An overview over the experimental work performed in Europe (and Russia) on the subject of boron dilution up to 1999 is provided by the final report of the EUBORA Concerted Action on Boron Dilution Experiments /16/. The individual projects were BORABORA in France, the test series at the Vattenfall test facility in Sweden, ROCOM in Germany, a test series carried out at the UPTF, also in Germany, and experiments performed at the EDO Gidropress mixing test facility in Russia. In the USA, an experimental program addressing OECD CSNI ISP 43 was run at the UMCP 2x4 integral test facility at the University of Maryland and finished in 2000 /17/.

Tab. 5 lists the projects mentioned and gives a brief comparison.

Most of the work performed before PKL III E did not address the post SB-LOCA scenario but was focused on the issue of mixing of a clear water slug (possibly formed after SG tube rupture or by inadvertent injection of boron free water from outside into the RCS) transported to the RPV by the onset of forced recirculation after pump start (high mass flow rates, so called "rapid dilution"). The central test objective was mixing of a given slug with ambient coolant. The slug size was postulated or obtained as the result of calculations. For slug transport, typical RCP startup mass flow ramps were applied. This work has little evidence for the NC startup case.

Only a few experiments featured low mass flow rates typical for natural circulation. The most prominent among those are the tests in the UPTF /14/, /18/. Besides, first experiments with low mass flow rates were as well carried out in the ROCOM test facility /19/.

The test facilities were/are set up corresponding to the test objectives. Most of the test facilities used model only a part of the RCS. An exception is made by the UMCP 2x4 integral test facility.

Boric acid was not applied in any of the experiments mentioned. Differently borated water was simulated by temperature differences or addition of a dissolvable tracer (salt). The measurands were temperature and conductivity, respectively. The UMCP 2x4 tests were accompanied by tests in the B-MOV facility (also University of Maryland), where a dissolvable fluorescent (dye) and laser induced fluorescence (LIF) were used to make mixing measurements scanning the entire gap of an annular PWR downcomer /20/.

PKL III E with its SB-LOCA tests is the only experimental project that covers the combination of slug formation, evolution, transport, mixing and PWR-system behavior. Besides it features the application of original boric acid and the test results can be used as a database for mixing of differently borated masses of water in a complex geometry similar to a PWR.

Loss of the RHRS during mid-loop or ¾-loop operation was investigated in several system- and integral tests (as in the test facilities LSTF, BETHSY and others). To the authors' knowledge, however, there were only few tests with the primary system closed (e.g. in the LSTF: /21/) and there was not a single experimental investigation with the scope on inherent boron dilution after loss of the RHRS.

6 Conclusions

This final report documents the results of the test series PKL III E. The PKL III test facility replicates a 1300 MW pressurized water reactor (PWR) of KWU-design with elevations scaled 1:1. The scaling factor for volume and power is 1:145. Within the PKL III E test series, five PWR integral tests were carried out from Dec. 2000 to Feb. 2003. All five tests were conducted utilizing boric acid and instrumentation for the detection of the boron concentration.

Within PKL III E, four tests were addressing the inherent boron dilution issue after SB-LOCA. The individual accident scenarios modeled were as follows:

- Test E1.1: break (40 cm^2/145) in hot leg, HPSI into all 4 cold legs
- Test E2.1: break (40 cm^2/145) in hot leg, HPSI into all 4 hot legs
- Test E2.2: break (32 cm^2/145) in cold leg, HPSI into 2 cold legs
- Test E2.3: break (50 cm^2/145) in hot leg, HPSI into 2 hot legs.

These four tests had in common a 100 K/h cooldown of the SG secondaries.

In the course of an SB-LOCA in a PWR, the filling level of the RCS passes through a number of different phases, depending on the number of SIPs running and the blowdown rate. At high pressure, the blowdown rate may be larger than the injection rate of the SIPs; by contrast, at low pressure the blowdown rate can be smaller. Accordingly, the level in the reactor coolant system can decrease temporarily to the point that the decay heat is transferred to the secondary side under reflux-condenser conditions. The steam formed in the core and thus also the condensate forming on the primary side contain much less boron than the reactor coolant before the onset of the accident.

The condensate forming in the SGs can accumulate in the loop seals of the RCS, for example. When natural circulation sets in as the RCS is refilled, low borated masses of water may be transported to the RPV and the core, respectively. This might result in recriticality.

Among others, important results of these four tests are as follows:

- The size of a single condensate slug is limited by the volume of the loop seal plus a part of the volume of a SG outlet channel.

- When NC restarts, pronounced condensate slugs arrive at the RPV only from those loops which have not been supplied with ECC water (for ECC injection rates corresponding to German design PWRs).
- NC prefers the loops without ECC injection.

Besides post-SB-LOCA boron dilution, loss of the RHRS was also investigated in PKL III E. The scenario of test E3.1 was a PWR under shutdown conditions. The levels were reduced to ¾-loop. The primary volume above this level was filled with N_2. The RCS was closed. As required by German PWR operating manuals, a SG was kept on standby ready to remove the decay heat in case of RHRS failure. Under these conditions, loss of the RHRS was assumed and the SG ready for operation was activated and used as a heat sink.

It was found, that

- The primary pressure build-up as well as the primary heat transport mechanism to be established depend sensitively on the distribution and exact amount of the primary coolant inventory
- Inherent boron dilution is an issue that has also to be considered under these conditions.

The PKL III E test series

- provides a first experimental database for thermal hydraulic system codes to be enforced to cover the inherent boron dilution issue.
- provides insight into and understanding of complex thermal hydraulic processes relevant
  - for the startup of natural circulation in PWRs after SB-LOCA, voiding and refill of the primary
  - and for reestablishment of a heat sink after loss of RHRS in a shutdown plant during ¾-loop operation.

7 Outlook

The PKL III E tests on inherent boron dilution after SB-LOCA have provided a number of valuable findings. Among other results, these tests have revealed the basic impact of the ECC injection onto formation and stability of condensate slugs as well as the importance of the fillup process for NC startup. These results were gained by assuming certain boundary conditions concerning the plant cooldown procedure, the ECC injection rates and others. In order to complete the experimental investigations and to address some still open questions mainly on the effect of different plant configurations, it seems recommendable to perform further integral tests with the boundary conditions adapted to plant configurations differing from those which have already been investigated. Such tests could represent a reasonable complement of the database gained so far and significantly help to improve the predictability of TH codes to describe SB-LOCA with respect to boron dilution in PWRs worldwide.

More than this, the PKL III E tests have shown, that in an early phase of the fillup process (when most of the SG U-tubes are still largely voided) there may already be a transport of coolant from the SG inlet to the outlet side with impact onto the boron concentration of the condensate accumulations in the loop seals. None of the TH codes applied to the PKL III E test series was able to describe this transport phenomenon so far. Therefore the authors of this report see the need for systematic investigations into this transport phenomenon in order to be able to train TH codes to predict it reliably. Taking this process into account will in many cases mean to be able to eliminate too large conservative margins in current NPP procedures imposed by TH codes so far for inherent boron dilution after SB-LOCA.

Considering the loss of the RHRS for a shutdown plant at ¾-loop operation with the RCS still closed (or already closed again), test E3.1 and the preparatory work for this test have shown that the inherent boron dilution phenomenon has also to be taken into account under these conditions. The experimental work revealed a significant interaction between heat removal and boron dilution, depending on different parameters such as residual amount of primary coolant, temperature of the pressurizer, number of SGs acting as heat sinks and time of ACC injection or other measures. The complex of interactions and mechanisms could not yet be understood completely on the basis of this single test. Taking into account the increasing awareness of the importance of these accidents for the total core damage frequency (CDF) in many PWRs, it is recommended to invest further efforts on this topic. It is necessary to investigate systematically the influences of the different parameters identified to be relevant. This work is needed in order to enable TH codes to make the right predictions and, on this basis, to develop procedures which are suited for the treatment of such accidents in NPPs.

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9 Nomenclature

Abbreviations

ACC	Accumulator
AM	Accident management
ATHLET	Analyse der Thermohydraulik von Leckstörfällen und Transienten (computer code)
B	Boron ([B]: boron concentration)
BMBF	Federal Ministry for Education, Science, Research and Technology
BMWi	Federal Ministry for Economy and Technology
CDF	Core damage frequency
CL	Cold leg
COMBO	Continuous Measurement of Boron Concentration
CSNI	Committee on the Safety of Nuclear Installations
CVCS	Chemical and volme control system
DC	Downcomer
DCP	Downcomer pipe
DCV	Downcomer vessel
ECC	Emergency core cooling
ECCS	Emergency core cooling system
EOT	End of test
EVU	German utilities
FAP	Facilities and Programmes (in SESAR/FAP)
HL	Hot leg
HP	High pressure
HPSI	HP safety injection
JDH	Extra borating system
JEB	Reactor coolant pump system
JNA	LP safety injection system (also: LPSI)
JN(A)	Residual heat removal system (also: RHRS)
JND	HP safety injection system (also: HPSI)
JNG	Accumulator system

KBA	Volume control system
KKP 2	Nuclear power plant Philippsburg 2
KWU	Kraftwerk Union AG
LAB	Feedwater system
LAR	Emergency feedwater system
LB	Large break
LBA	Main steam system
LCQ	SG blowdown system
LOCA	Loss of coolant accident
LP	Low pressure; lower plenum
LPSI	LP safety injection
LS	Loop seal
MB	Management Board
ME	Elevation level of measurement
MS	Main steam
MST	Measurement point
NC	Natural circulation
NEA	Nuclear Energy Agency
NPP	Nuclear power plant
OECD	Organization for Economic Cooperation and Development
PANDA	Passive Nachwärmeabfuhr und Druckabbau (test facility)
PAZ	Cooling circuit for RCPs, spool pieces and lower plenum
PKL	Primärkreislauf (test facility)
PRG	Program Review Group
PRZ	Pressurizer
PWR	Pressurized water reactor
RC	Reflux-condenser
RCL	Reactor coolant line
RCP	Reactor coolant pump
RCS	Reactor cooling system
RCV	Relieve control valve
RELAP	Reactor Excursion Leak Analysis Program (computer code)
RHRS	Residual heat removal system
RPV	Reactor pressure vessel
SB	Small break

SESAR	Senior Group of Experts on Nuclear Safety Research
SETH	SESAR Thermalhydraulics
SG	Steam generator
SIP	Safety injection pump (SIP = HPSI pump)
SL	Swell level
SOT	Start of test
SV	Safety valve
TBT	Turbine bypass tank
TC	Thermocouple
TH	Thermalhydraulics
TRAM	Transients and Accident Management
UPTF	Upper Plenum Test Facility
1Φ	single phase
2Φ	two-phase

Latin and Greek Symbols

[B]	ppm	Boron concentration
$\dot{m}$	kg/s	Mass flow
p	bar, Pa	Pressure
Δp	bar, Pa	Pressure difference
P	kW	Power
t	s	Time
T	°C, K	Temperature
ρ	kg/m^3	Density

Subscripts

el	Electrical
prim	Primary
sec	Secondary

10 Index of Appendices

		E1.1 *	E2.1	E2.2	E2.3	E3.1
Scenario		**Inherent Boron Dilution during SB-LOCA**				**Loss of RHRS**
Topics of investigation		Symmetry of natural circulation start-up and consequences for boron concentration		Maximum condensate accumulations and minimum boron concentrations		Evolution of heat removal, flow pattern boron distribution and interrelation between each other
Break / RCS integrity		40 cm² break in hot leg		32 cm² break in cold leg	50 cm² break in hot leg	RCS intact and closed
ECCS	**HPSI**	4 SIPs, **cold** legs	4 SIPs, **hot** legs	2 SIPs, **cold** legs	2 SIPs, **hot** legs	Not in operation
	ACCs	---	---	---	All 4 hot leg ACCs	Successive injection in late test phase
	LPSI	Into all 4 cold legs	Into all 4 hot legs	Into 2 cold legs	Into 2 hot legs	Not in operation
CVCS		Not in operation				
Extra bor. system		Not in operation				
RHRS		Not in operation				In operation in final test phase
SG sec. sides		100 K/h (all 4 SGs connected by main steam header)				SG1 controlled at 2 bar, others isolated

Tab. 1: PKL III E - Test Matrix

* performed within the preceding national program

		E1.1 *	E2.1	E2.2	E2.3
Break size		40 cm²		32 cm²	50 cm²
Break positon		Hot leg in loop 2 with pressurizer		Cold leg 1	Hot leg 1
ECC	**HPSI**	All 4 SIPs into **cold** legs	All 4 SIPs into **hot** legs	2 of 4 SIPs, **cold** legs (1 in affected loop)	2 of 4 SIPs, **hot** legs (1 in affected loop)
	ACCs	---	---	---	All 4 hot leg ACCs
	LPSI	Cold leg inj. into all 4 loops	Hot leg inj. into all 4 loops	Cold leg inj. into 2 of 4 loops	Hot leg inj. into 2 of 4 loops
SG sec. sides		100 K/h (all 4 SGs connected by main steam header)			
Central topics of investigation		Investigation of basic issues: Symmetry of natural circulation start-up Coincidence of condensate slugs at RPV inlet Boron concentration in all 4 loops		Maximum condensate accumulation during design basis accident with cold leg ECC injection	Most penalizing scenario with-in design basis with respect to condensate production in individual loops and mixing for hot leg ECC injection

Tab.2: PKL III E - Tests on Inherent Boron Dilution during SB-LOCA

* performed within the preceding national program

		E1.1	E2.1	E2.2	E2.3
Coolant inventory	[kg]	870	771	1440	1340
	[%][1]	39	34	64	60
Boron conc. in loop seals	[ppm]	< 50	< 50	< 50	50 - 400 (only in loops 2 & 4)
Boron conc. at core outlet	[ppm]	3500	4250	> 2000	2500 (as in loops 1 & 3)
Heater rod bundle power (decay heat)	[kW]	515	510	530	1100[2]
Primary pressure	[bar]	40.0	39.5	40.5	36.4
Core outlet temperature	[°C]	250	249	251	245
Subcooling at core outlet	[K]	0	0	0	0
Pressurizer fluid temperature	[°C]	250	249	251	245
Pressurizer level	[m]	0.9	1.1	1.1	0.8
Flow pattern		Symmetrical heat transfer by all four SGs under reflux-condenser conditions			Loops 2 & 4: RC; loops 1 & 3: NC (total redirection of ECC water injected into hot legs 1 & 3 towards SGs)

Tab. 3: Initial Conditions of the PKL III E Tests on Post SB-LOCA Boron Dilution, Comparison

[1] 100 % ≙ 2250 kg; this mass is based on the PKL primary volume but corresponds to a mean coolant density of 709 kg/m^3 and a pressurizer level of 7.5 m, values which are typical for PWR operation at full power
[2] decreased short time after SOT to 600 kW

		E1.1	E2.1	E2.2	E2.3
Time after start of the test	[s]	1780	3630	3000	470
Primary pressure	[bar]	17.0	7.1	8.5	29.2
Core outlet temperature	[°C]	204	149	174	234
Subcooling at core outlet	[K]	0	17	0	0
Pressurizer level	[m]	0.7	0.5	0.5	0.5
Coolant inventory	[kg]	2050	2150	1860	1540
	[%][1]	91	96	83	68
Heater rod bundle power (decay heat)	[kW]	435	391	408	585
Instantaneous injection conditions		4 HPSI pumps into cold legs	4 HPSI pumps into hot legs	2 HPSI pumps & 2 LPSI pumps into cold legs 1 & 2	2 HPSI pumps into hot legs 1 & 3
Flow pattern		No mass flow in all four loops			Loops 2 & 4: no flow; loops 1 & 3: NC (total redirection of ECC water injected into hot legs 1 & 3 towards SGs)
Mass flow to evolve		Forward	Slow reverse	Forward (loop 3 & 4)	Forward (loop 2 & 4)

Tab. 4: PKL III E Tests - Conditions Prior to First Flow in the Loops with Condensate Slugs, Comparison

[1] 100 % ≙ 2250 kg; this mass is based on the PKL primary volume but corresponds to a mean coolant density of 709 kg/m^3 and a pressurizer level of 7.5 m, values which are typical for PWR operation at full power

Test facility	Operator	Location	Reference design	Issue	Tracer	Scale Dia.	Height	Volume	Pressure [bar]
BORABORA	EDF	Chatou, France	French 3 loop 900 MW	RCP startup after clear water intrusion into RCS: mixing from cold leg to core inlet	Tempera-ture, salt	1:5	1:5	1:125	1
Vattenfall test facility	Vattenfall Utveckling AB	Älvkarleby, Sweden	Westingh. 3 loop 900 MW	RCP startup after clear water intrusion into RCS: mixing from cold leg to core inlet	Salt	1:5	1:5	1:125	1
UPTF (meanwhile dismantled)	Framatome ANP	Mannheim, Germany	German 4 loop 1300 MW	NC startup after inherent dilution and PTS for ECC injection into NC: mixing from cold leg to bottom of downcomer annulus	Tempera-ture	1:1	1:1	1:1	20
Gidropress test facility	OKB Gidropress	Podolsk, Russia	Russian 4 loop VVER 1000	RCP startup after clear water intrusion into RCS: mixing from cold leg to core inlet	Tempera-ture	1:5	1:5	1:125	n.a.
ROCOM test facility	Forschungs zentrum Rossendorf	Rossendorf, Germany	German 4 loop 1300 MW	RCP startup after external dilution & NC-startup after inherent dilution: mixing from cold leg to core inlet	Salt	1:5	1:5	1:125	1
UMCP 2x4 test facility	University of Maryland	College Park, MD, USA	Babcock & Wilcox 1300 MW	RCP startup after clear water intrusion into RCS (OECD-ISP 43): mixing from RCP to core inlet	Tempera-ture	1:10	1:5	1:500	1
PKL integral test facility	Framatome ANP	Erlangen, Germany	German 4 loop 1300 MW	NC-startup after inherent dilution in the course of SB-LOCA: slug formation, system influence and -behaviour, NC-startup transient, mixing	Boric acid	1:12	1:1	1:145	40

Tab. 5: Relation of the PKL III E Test Series to other Experimental Investigations with Relevance for Inhomogeneous Boron Dilution

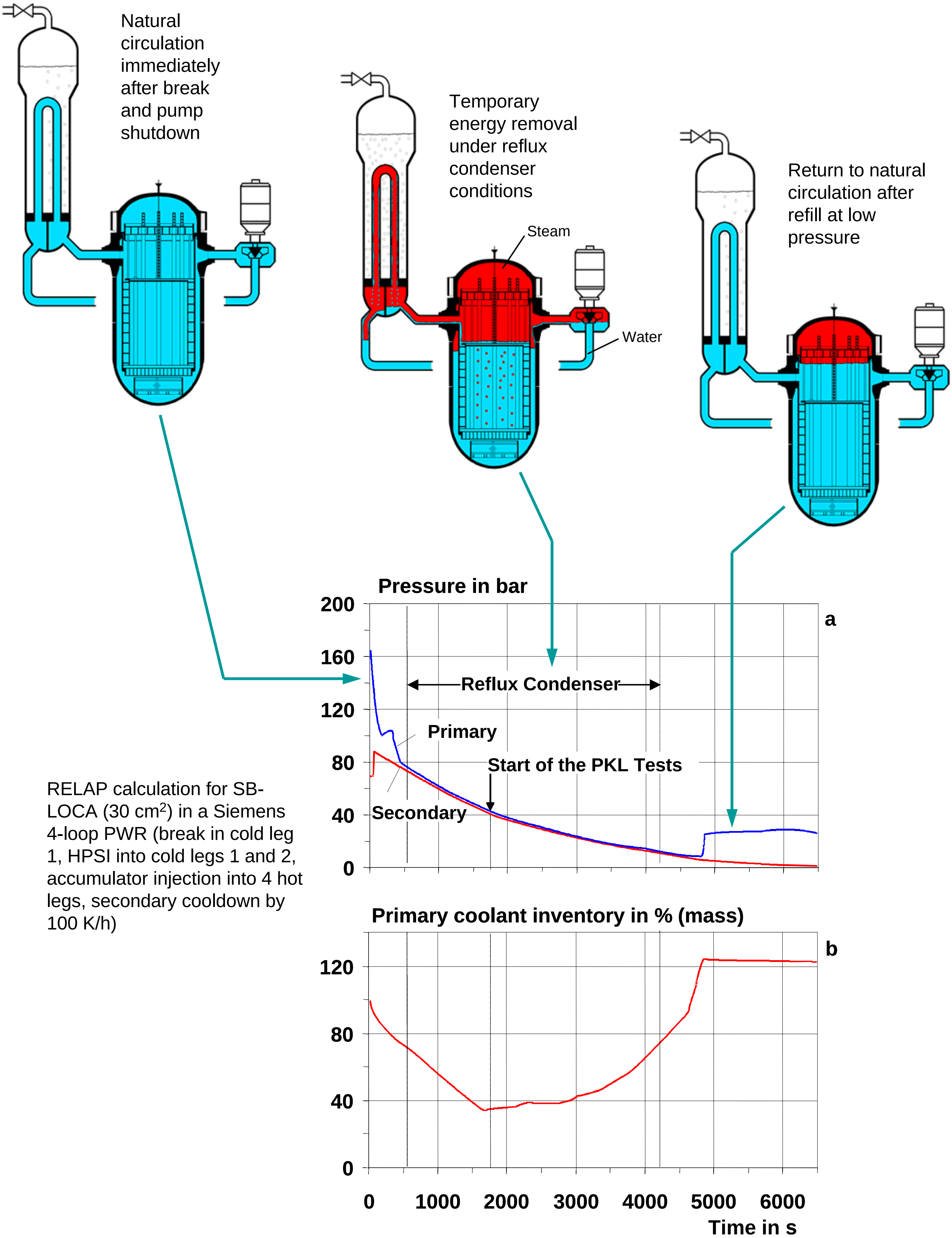

Fig. 1: Systematics of Inherent Boron Dilution during SB-LOCA: Temporary Occurrence of Reflux Condenser Conditions

Appendix to Report FANP NGTT1/04/en/04
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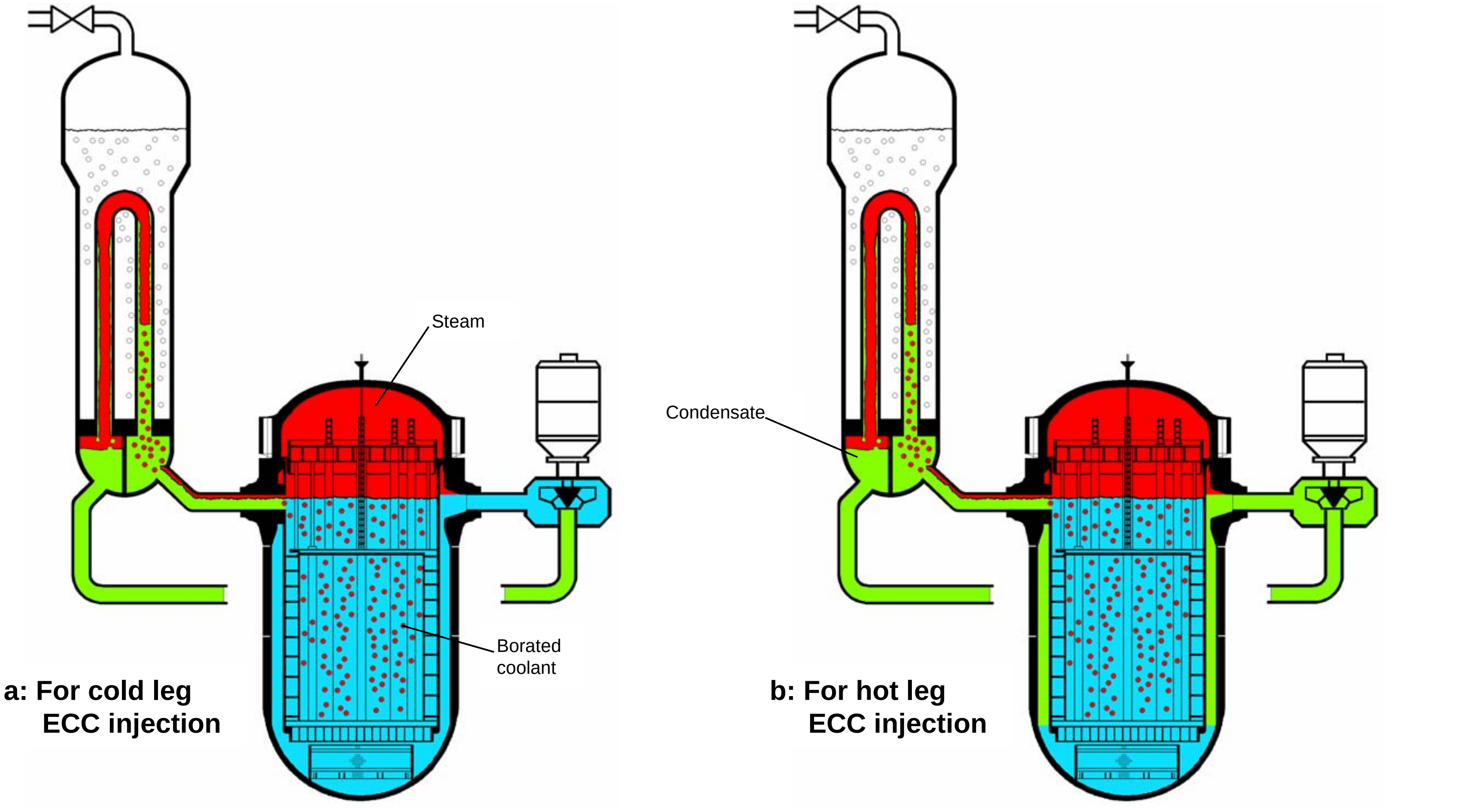


Fig. 2: Systematics of Inherent Boron Dilution during SB-LOCA: Possibilities of Condensate Accumulation during Reflux Condenser

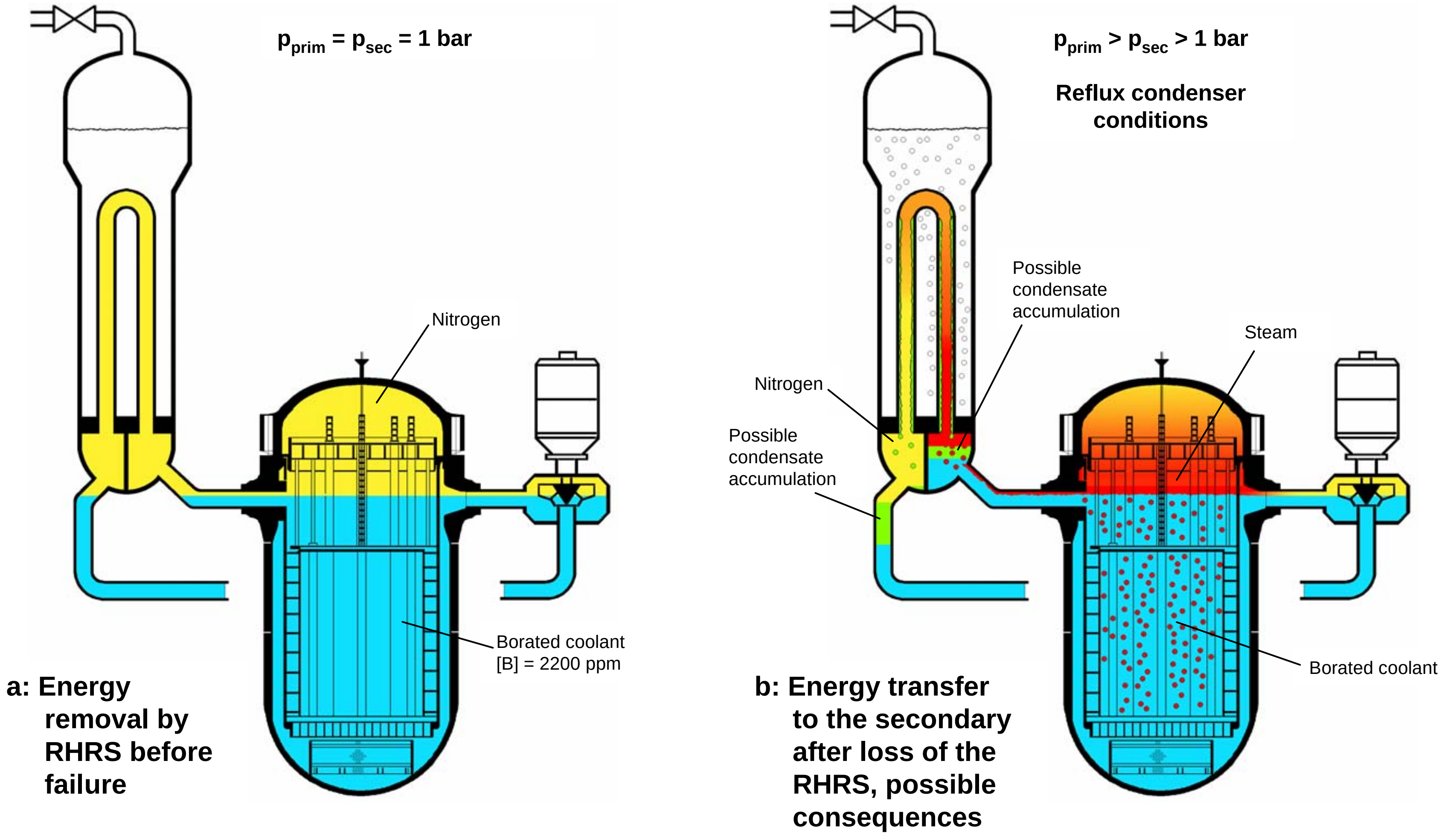
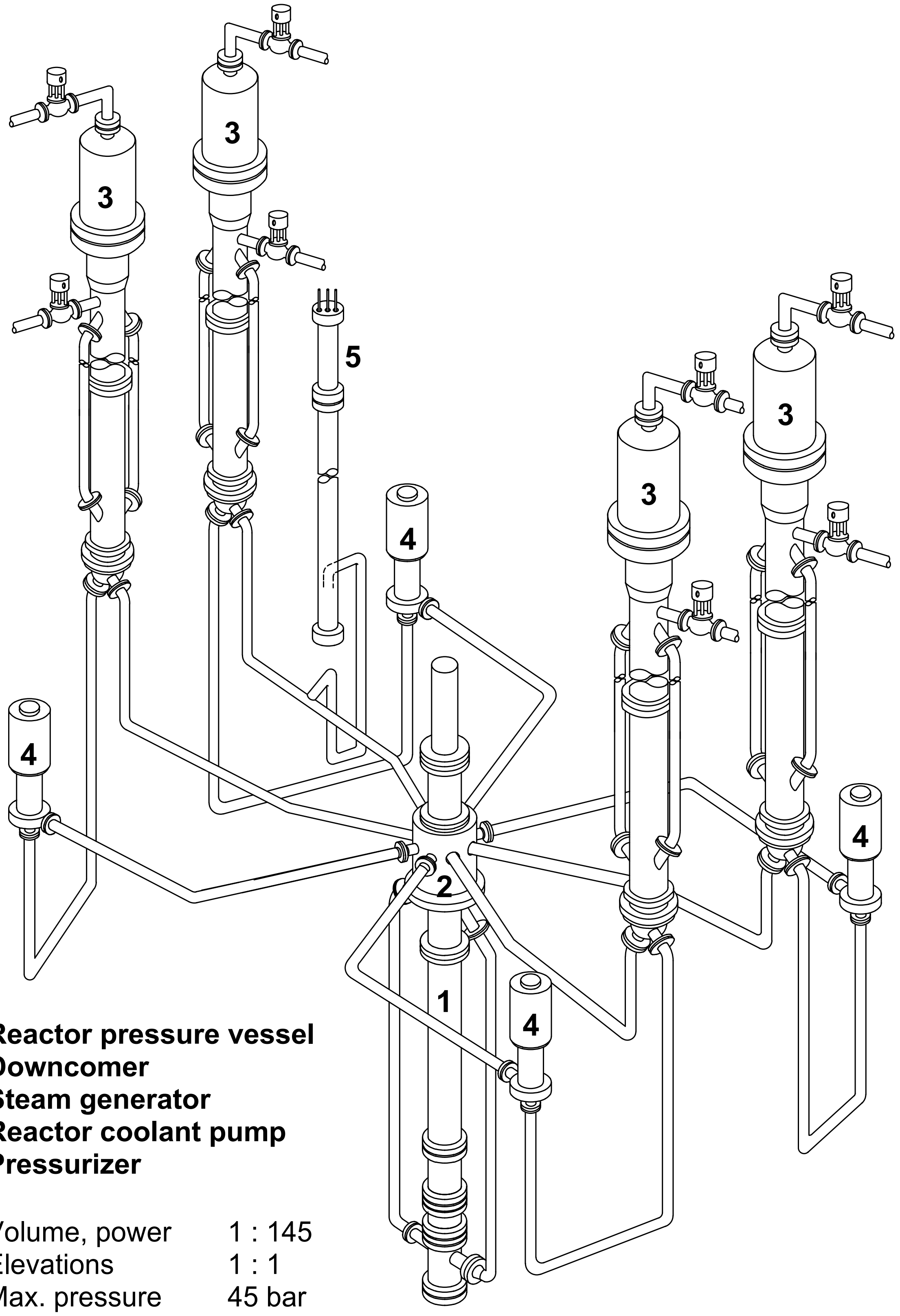


Fig. 3: Principle of Energy Removal after Loss of RHRS during 3/4-Loop Operation and Possible System Evolution



1 Reactor pressure vessel
2 Downcomer
3 Steam generator
4 Reactor coolant pump
5 Pressurizer

Volume, power	1 : 145
Elevations	1 : 1
Max. pressure	45 bar
Max. power	2.5 MW (10%)

Fig. 4: PKL III Test Facility

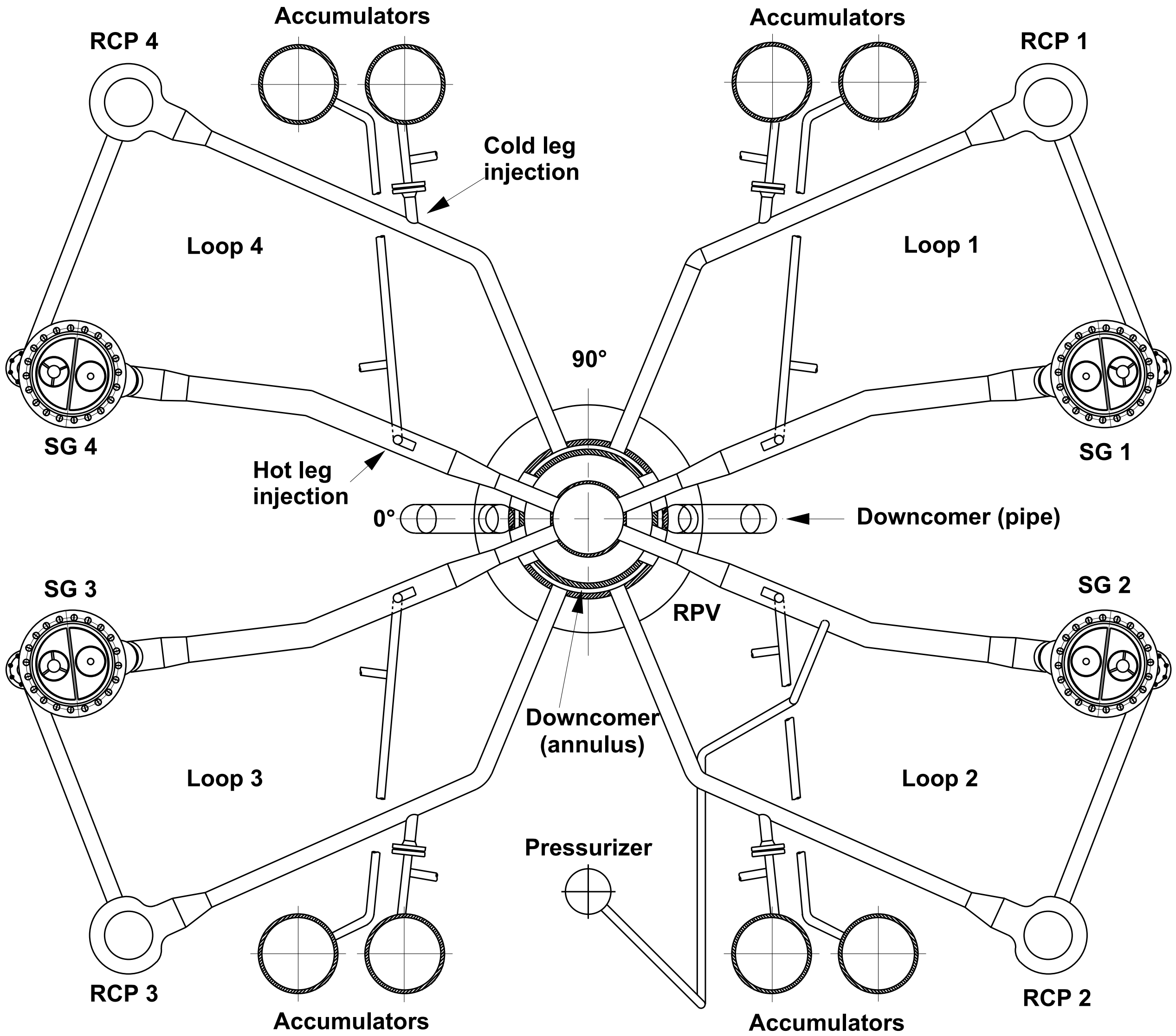


Fig. 5: PKL III Loop Arrangement

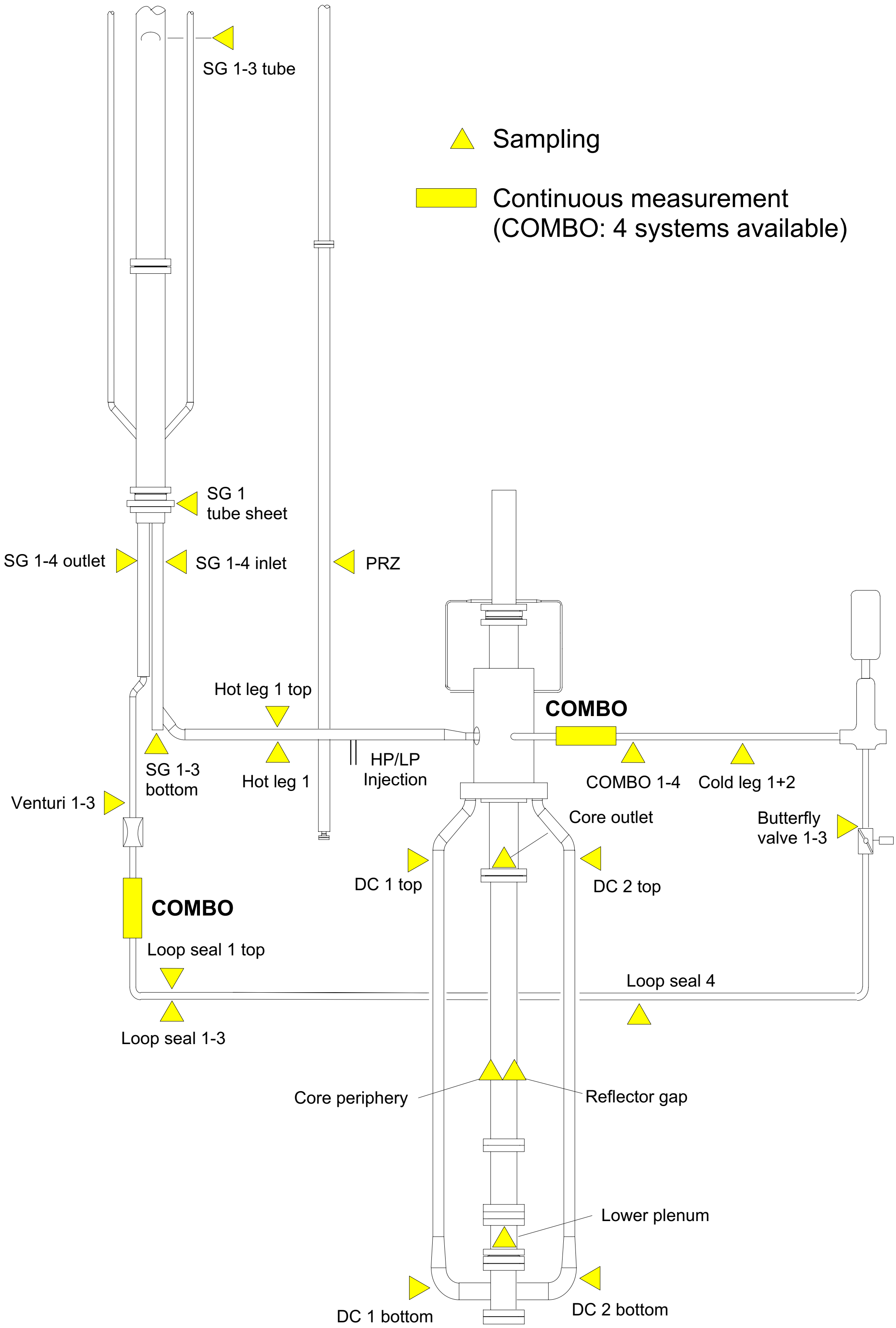


Fig. 6: PKL III E - Locations for Boron Concentration Measurements

Basic nuclear reaction:

$$^{10}B + n \longrightarrow {}^{7}Li + \alpha$$

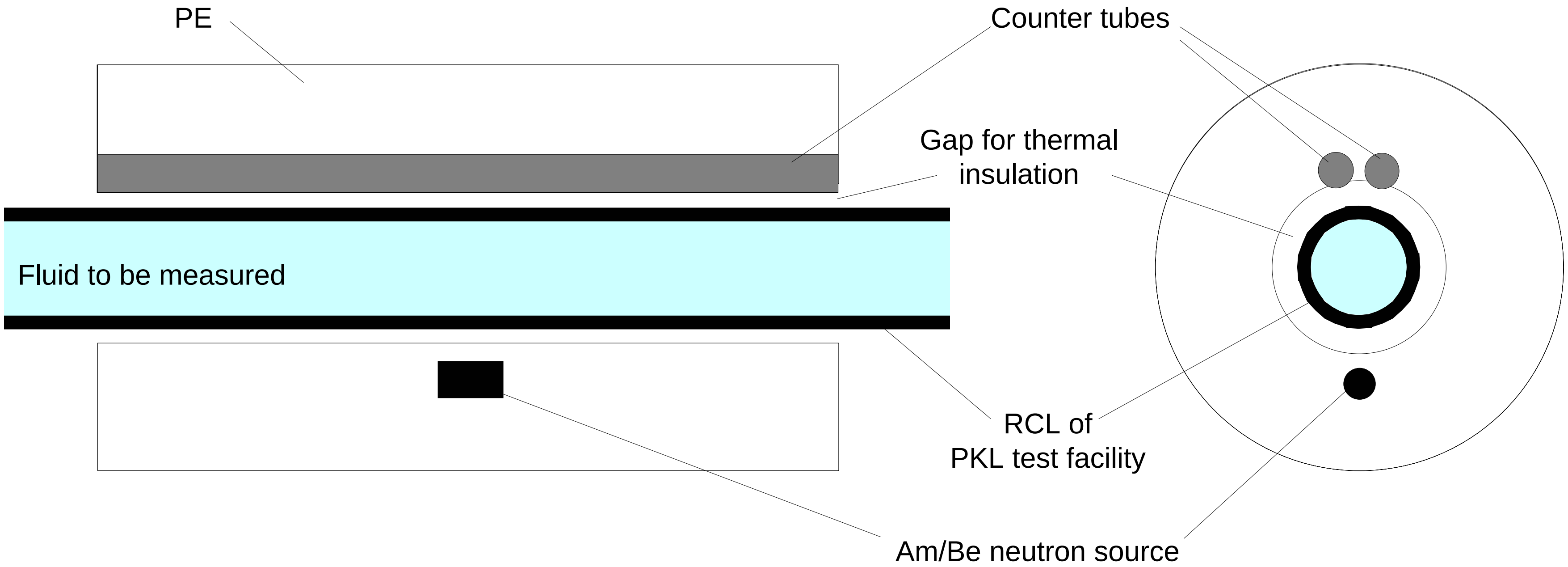


Fig. 7: Sketch of a COMBO Device

Appendix to Report
FANP NGTT1/04/en/04
EFRFig07.ppt
2004-03-12

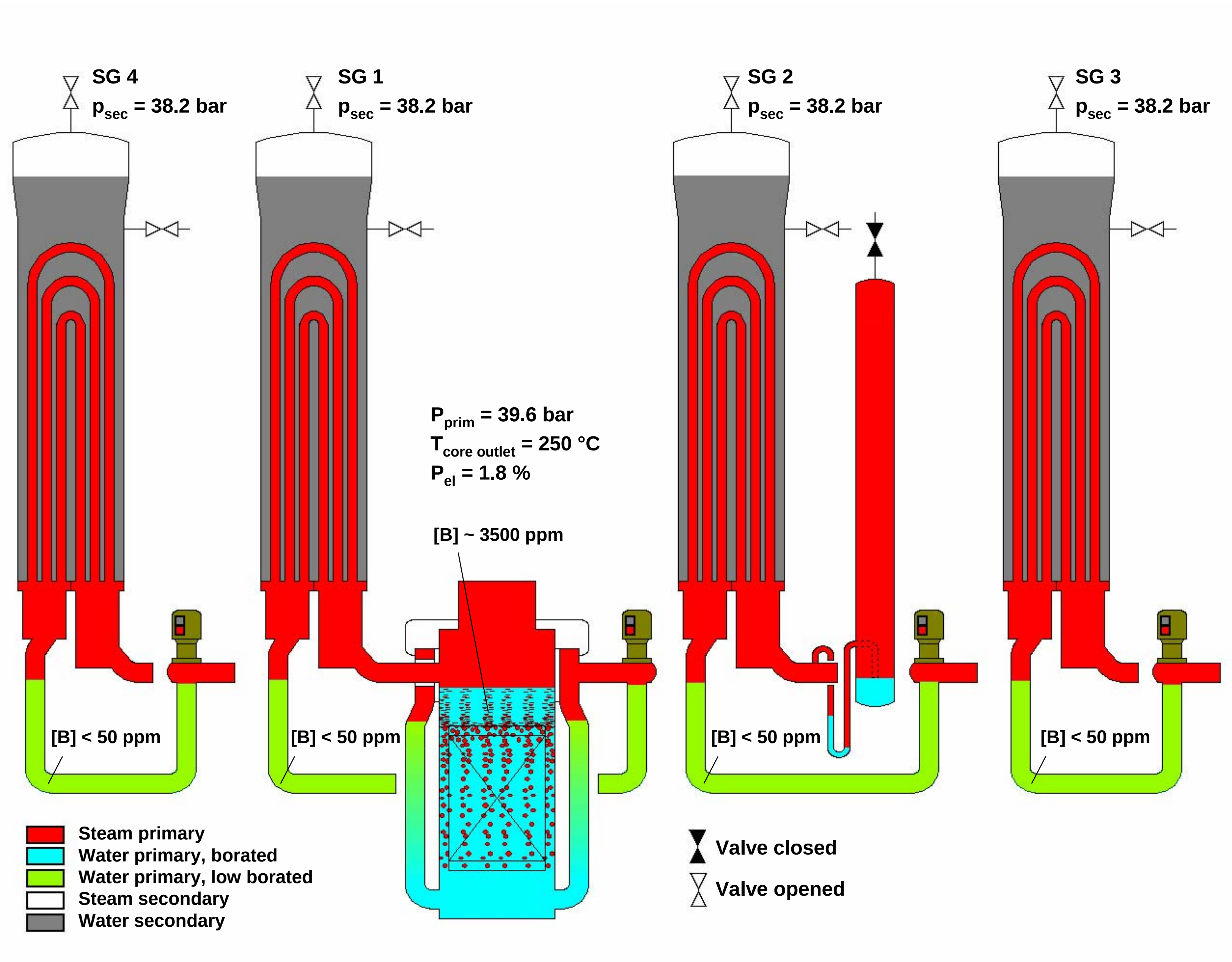


Fig. 8: PKL III E1.1 – Distribution of Inventory at Start of the Test (t = 0 s)

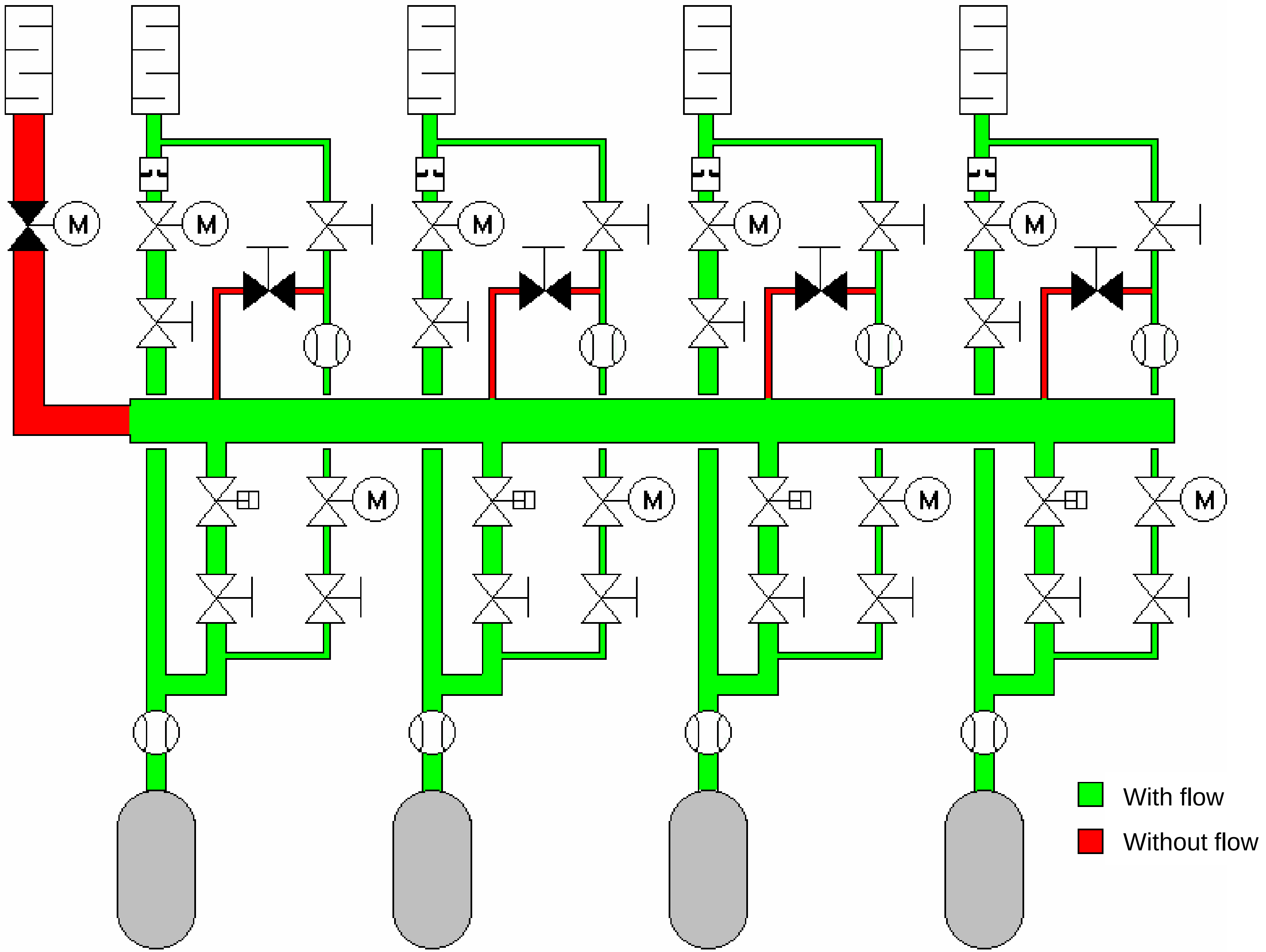


Fig. 9: PKL III E - Main Steam System during Tests E1.1/E2.1/E2.2/E2.3 (SB-LOCAs)

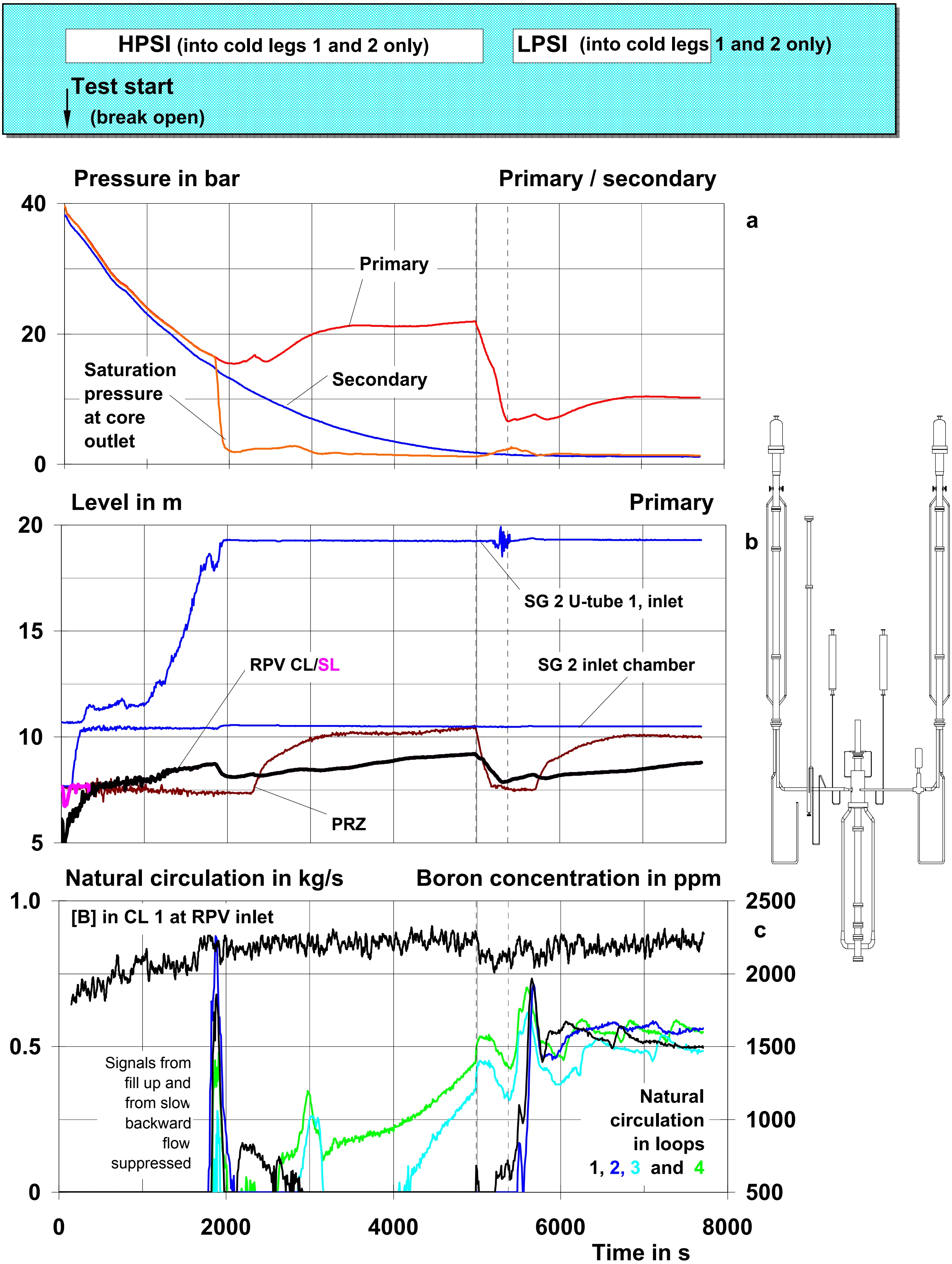


Fig. 10: PKL III E1.1 - Test Results (Overview)

Appendix to Report
FANP NGTT1/04/en/04
EFRFig10.xls
2004-02-16

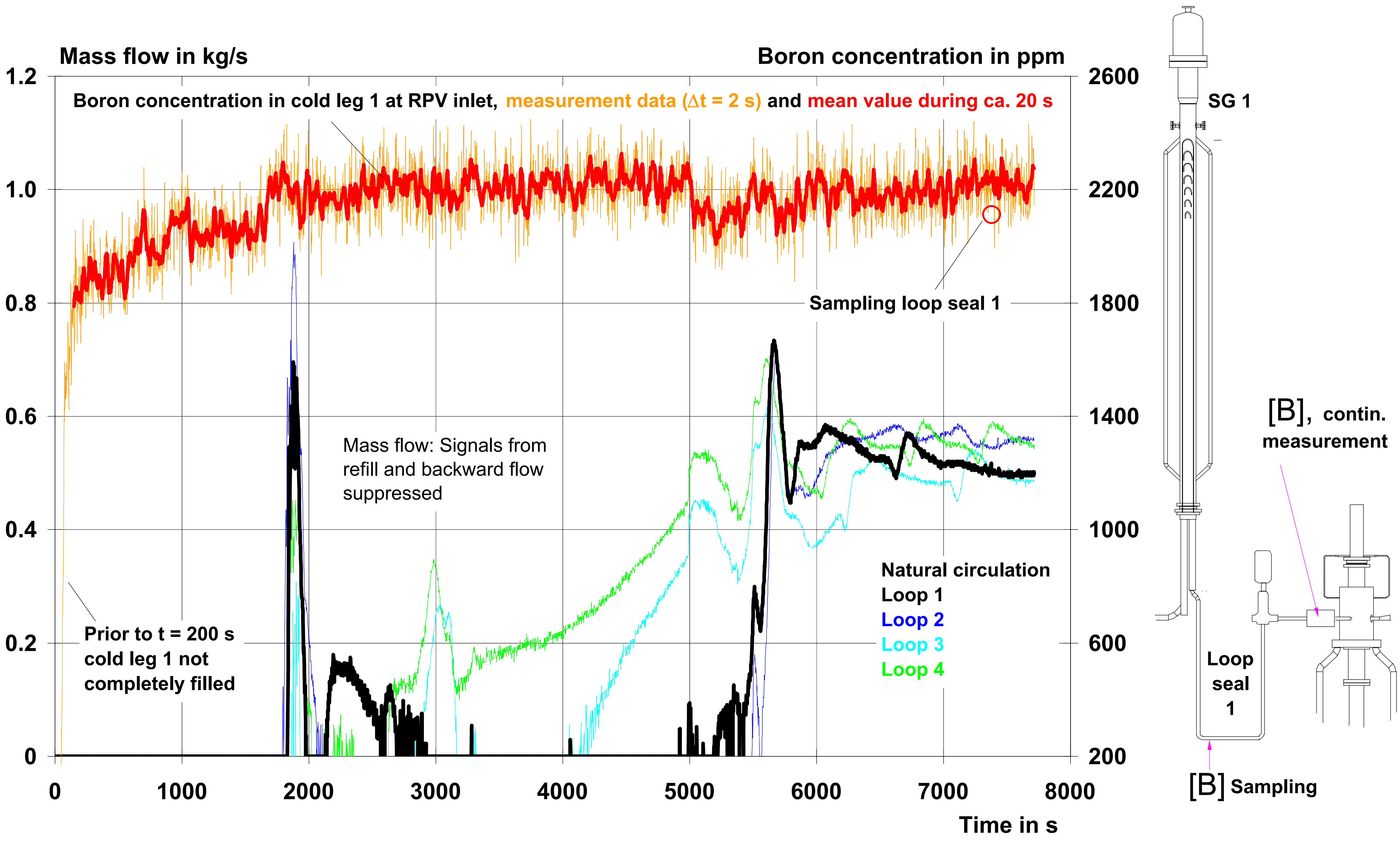


Fig. 11: PKL III E1.1 - Results of the Boron Concentration Measurements

Appendix to Report
FANP NGTT1/04/en/04
EFRFig11.xls
2004-02-18

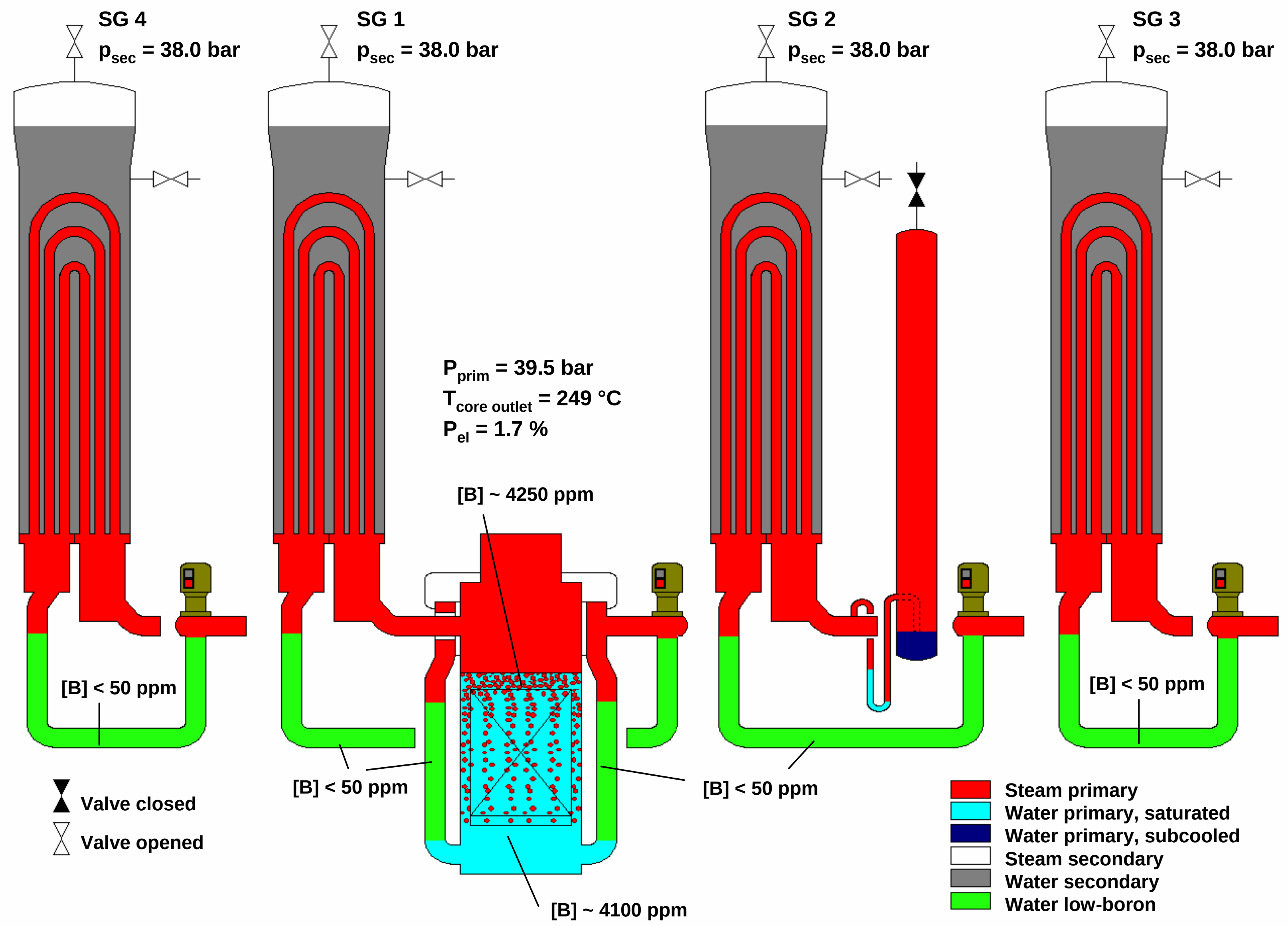


Fig. 12: PKL III E2.1 - Distribution of Inventory at Start of the Test (t = 0 s)

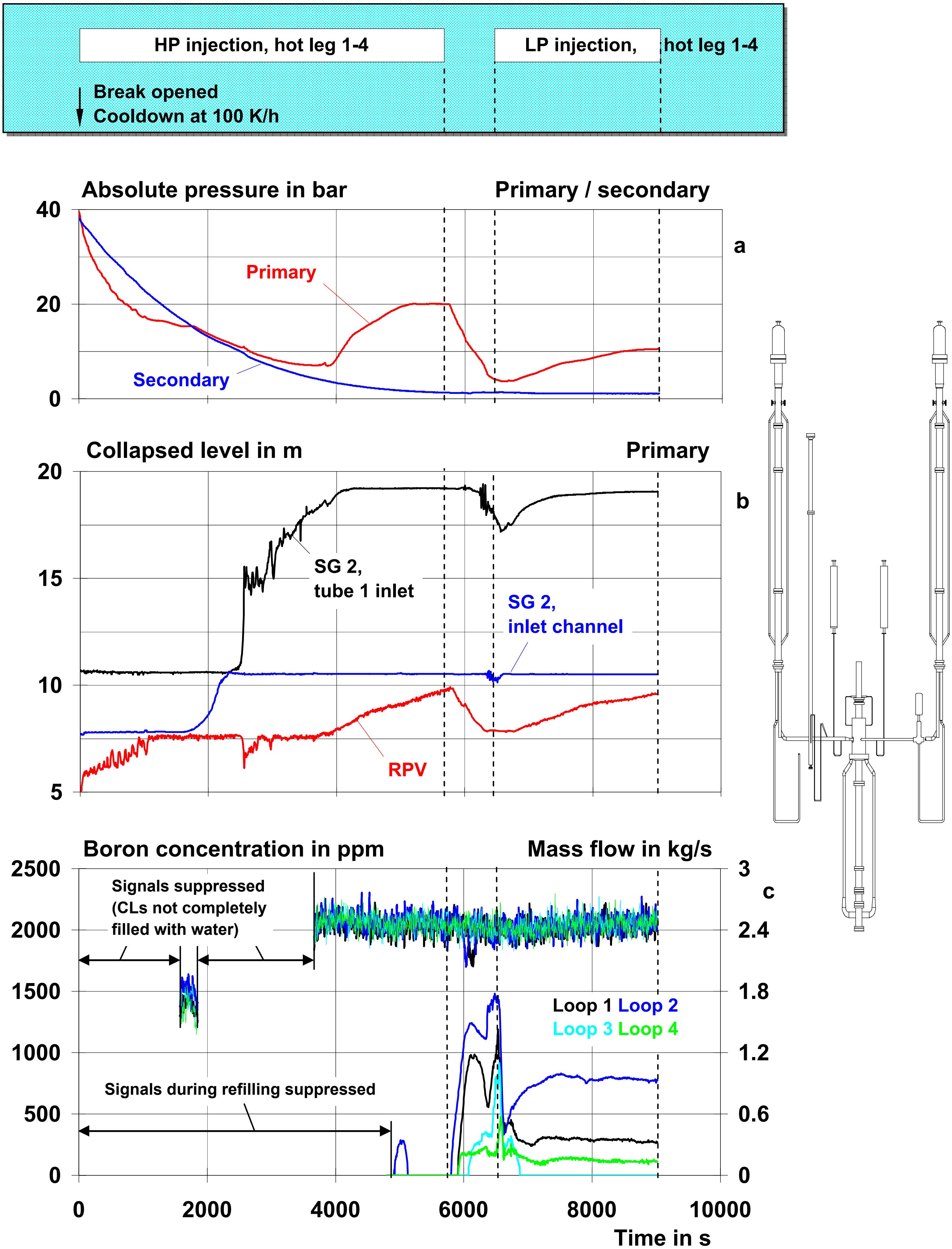


Fig. 13: PKL III E2.1 - Test Results (Overview)

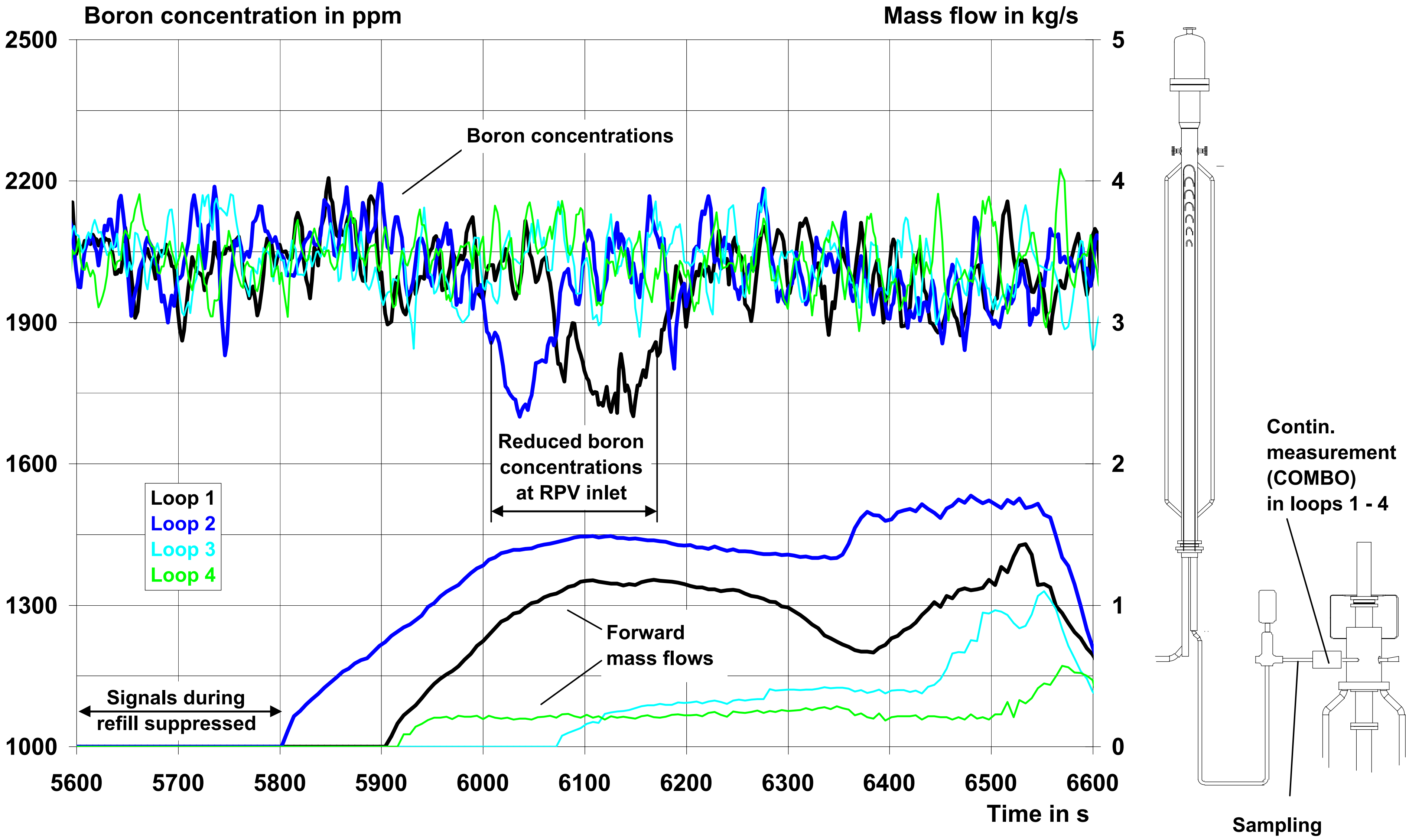


Fig. 14: PKL III E2.1 - Results of the Continuous Boron Concentration Measurements (COMBO)

Appendix to Report
FANP NGTT1/04/en/04
EFRFig14.xls
2004-02-18

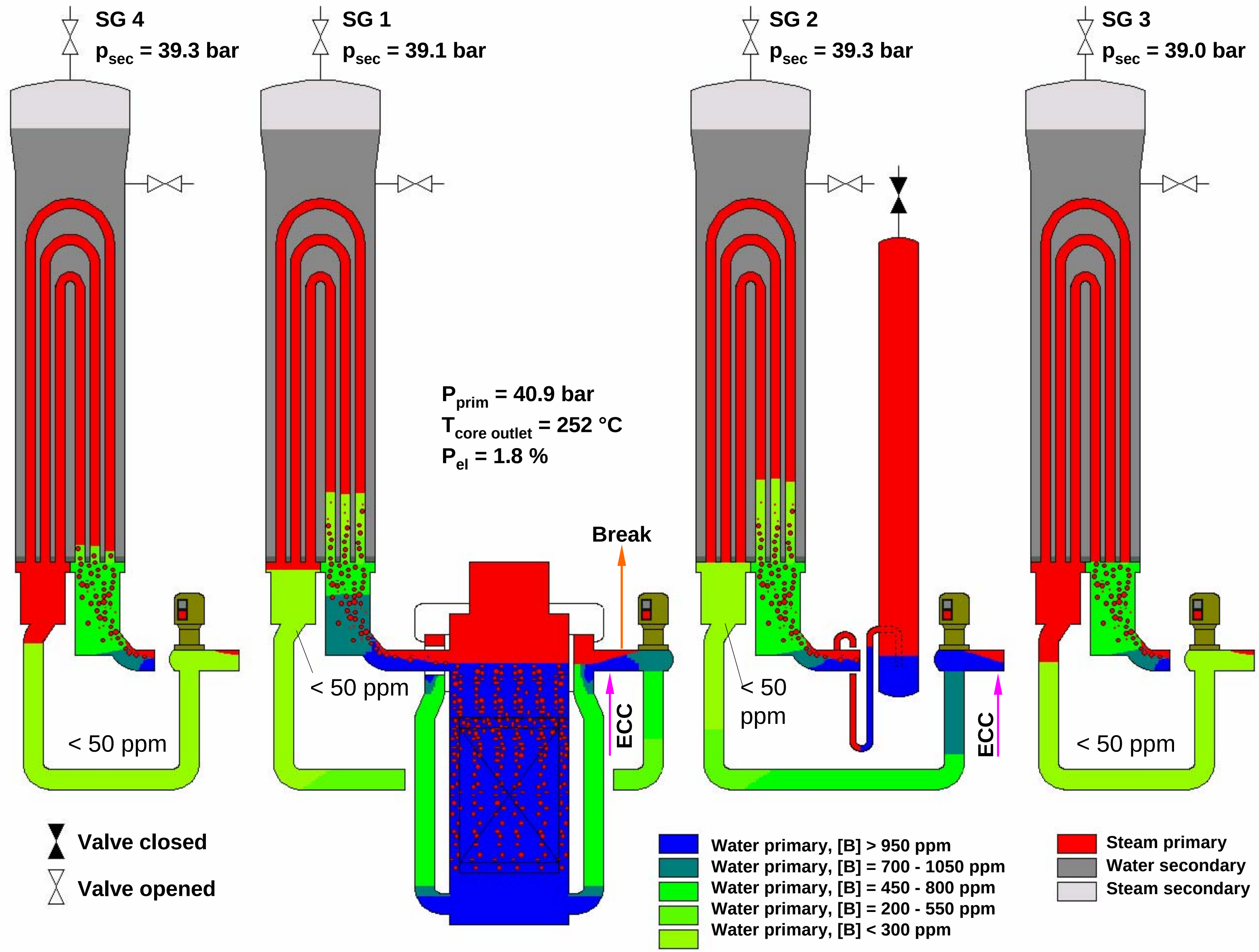


Fig. 15: PKL III E2.2 - Distribution of Inventory at Start of the Test (t = 0 s)

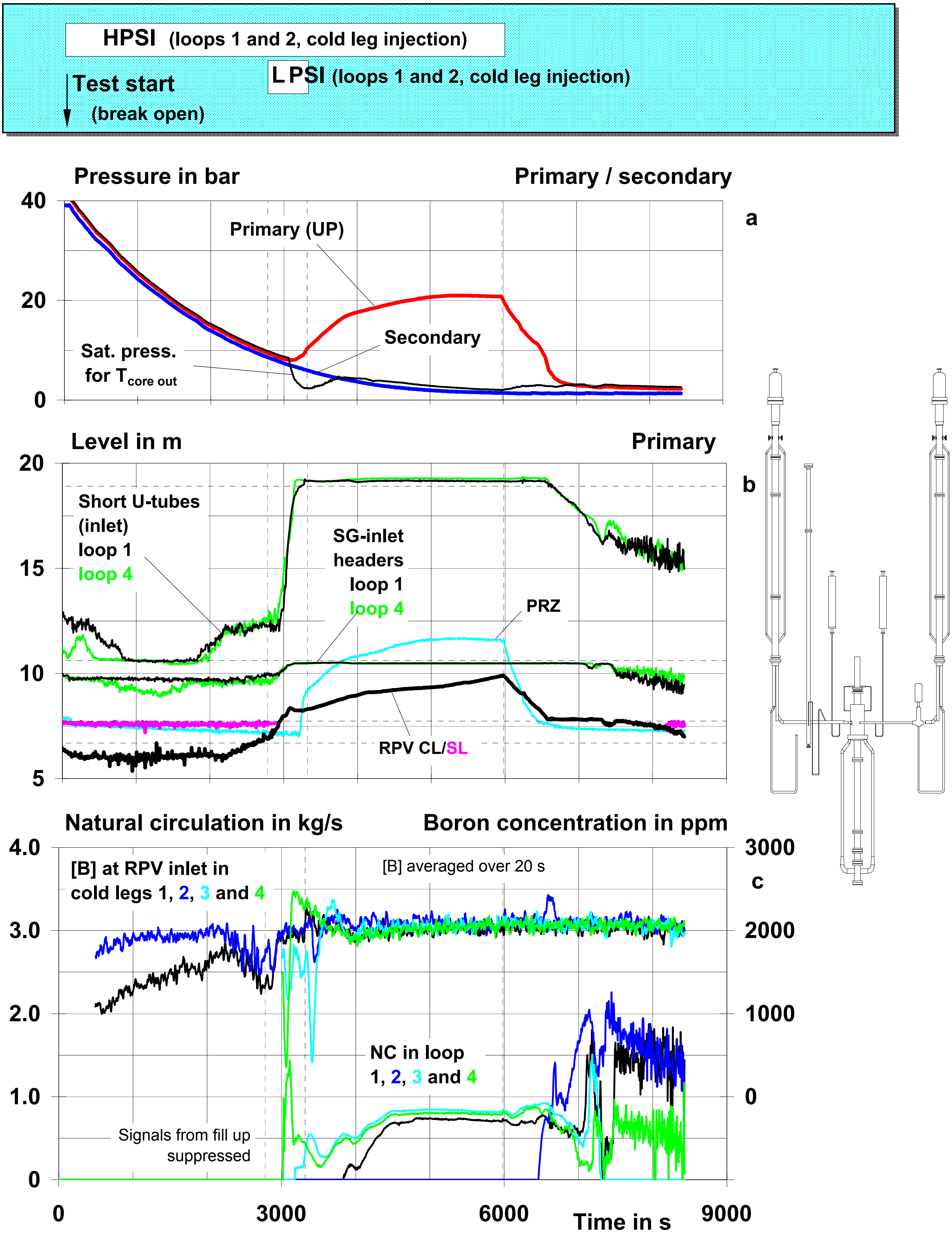


Fig. 16: PKL III E2.2 - Test Results (Overview)

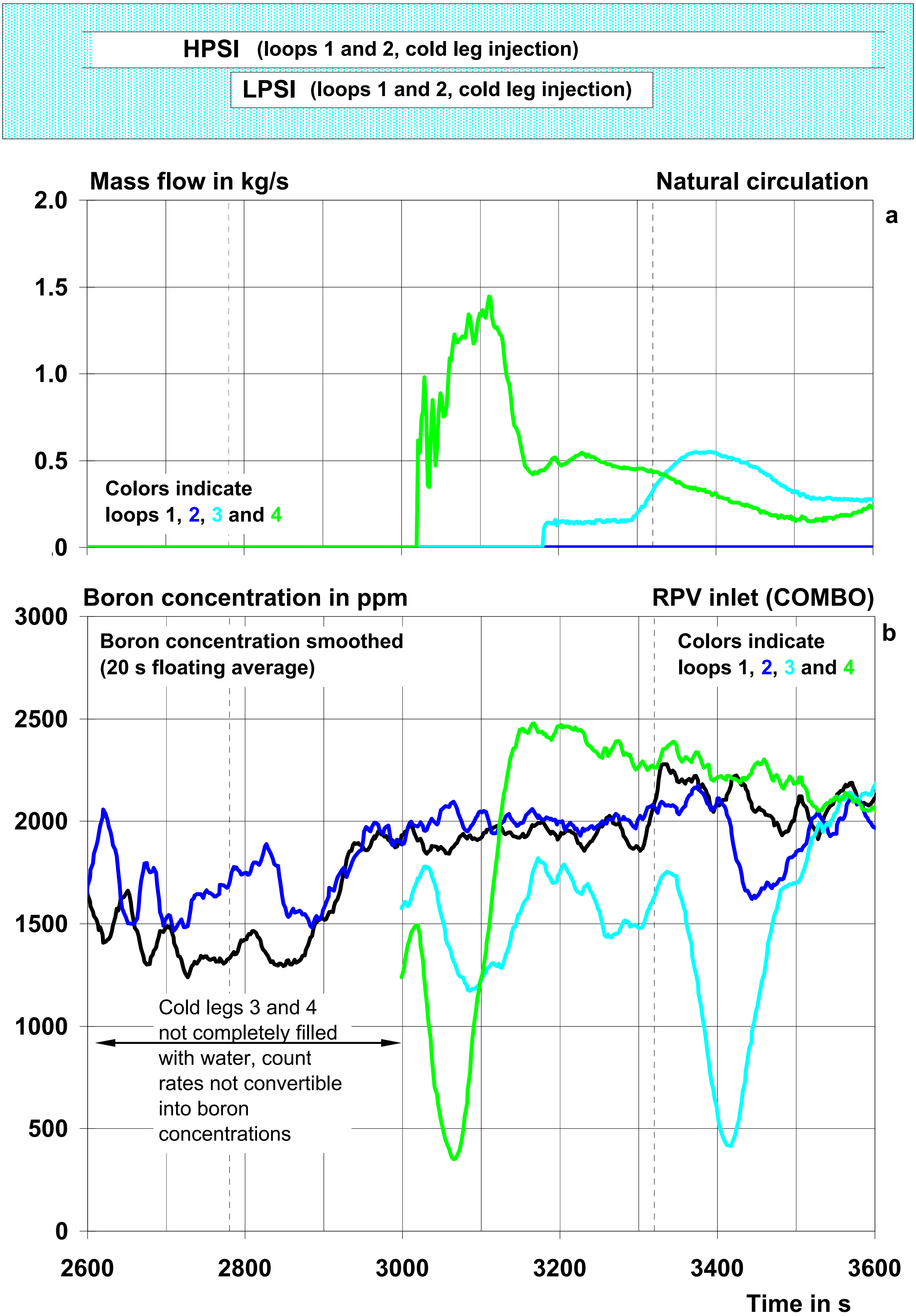


Fig. 17: PKL III E2.2 - Onset of Natural Circulation and Boron Concentration (Smoothed)

Appendix to Report
FANP NGTT1/04/en/04
EFRFig17.xls
2004-02-18

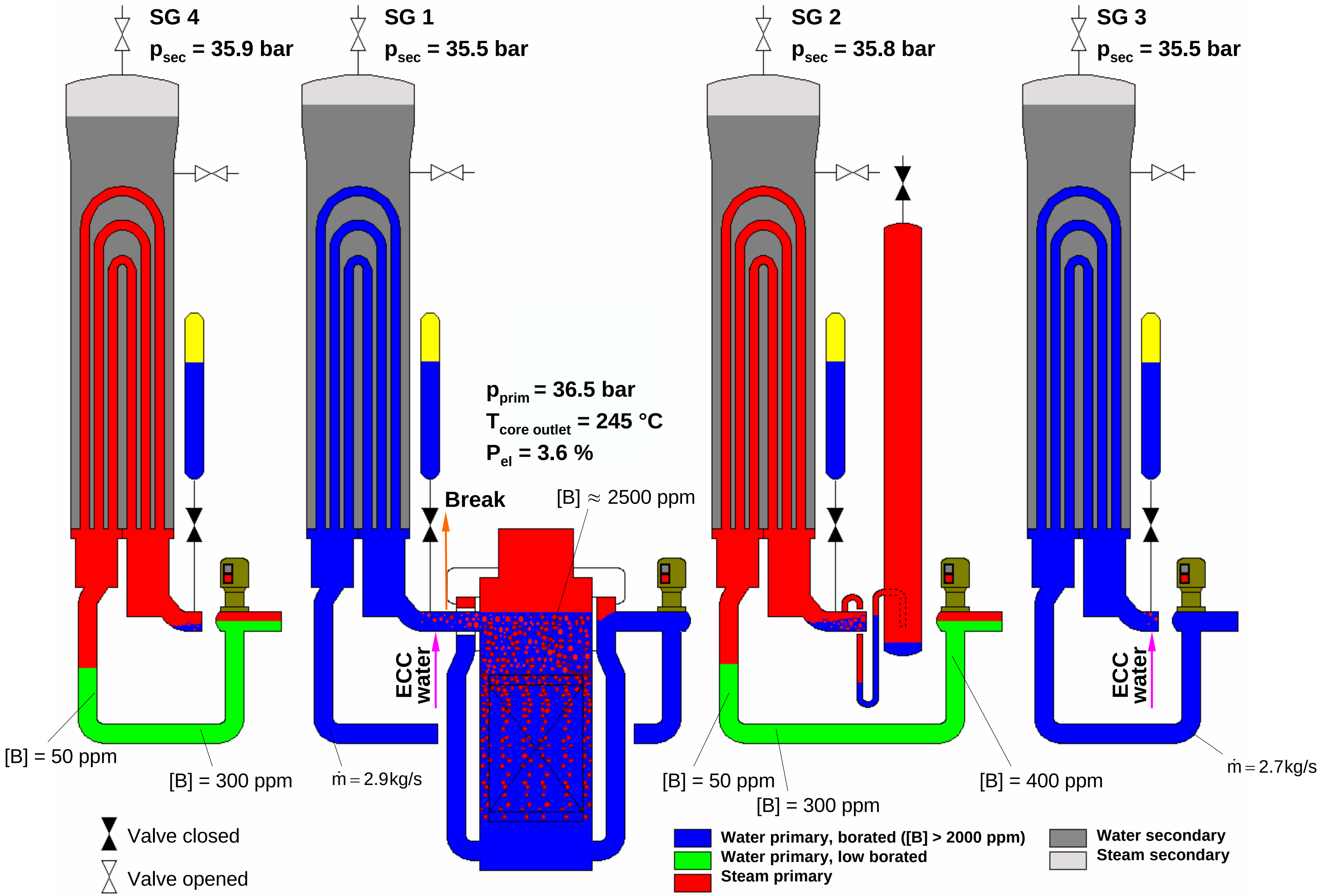


Fig. 18: PKL III E2.3 - Distribution of Inventory short before Start of the Test (t = -100 s)

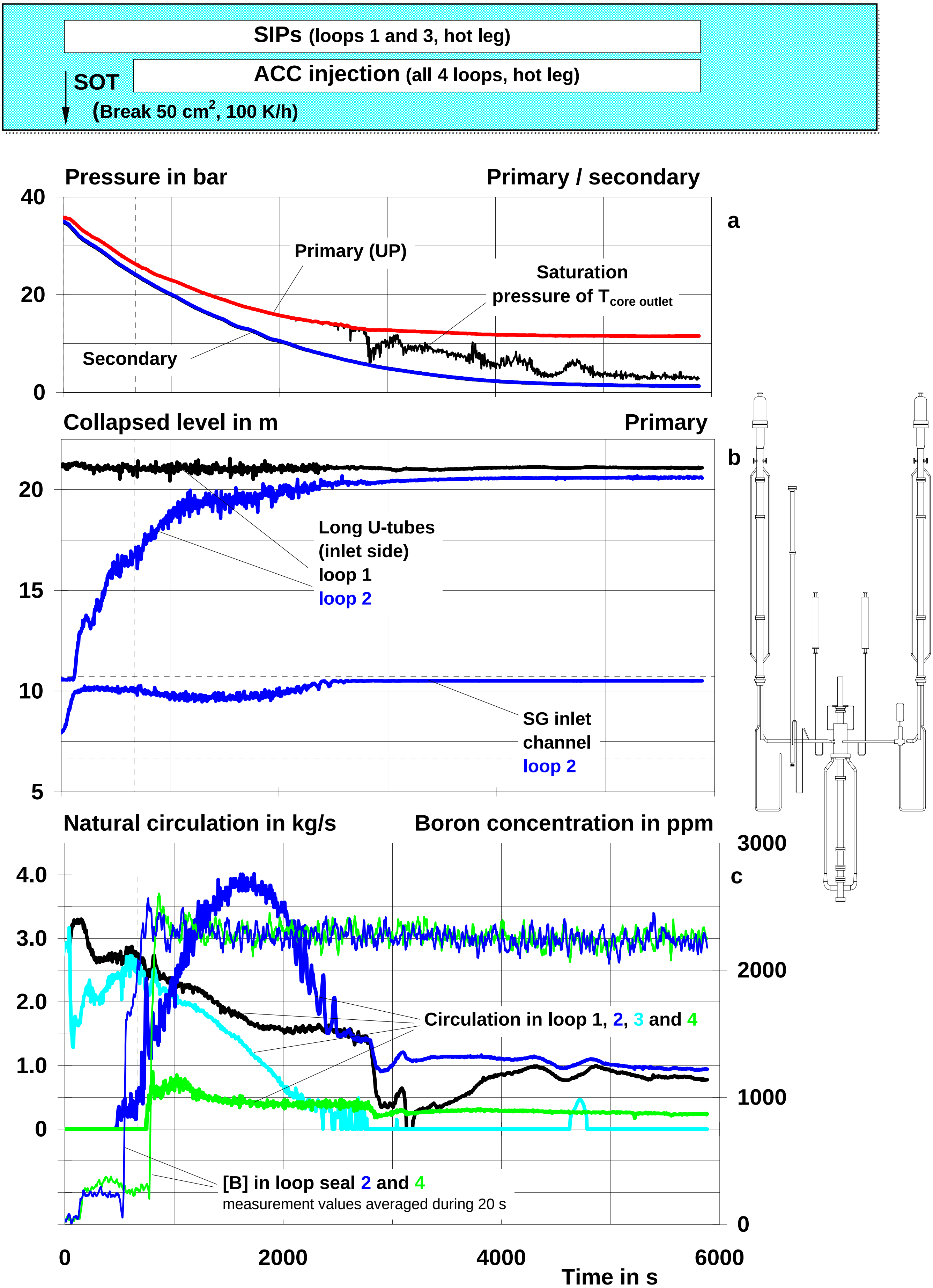


Fig. 19: PKL III E2.3 - Test Results (Overview)

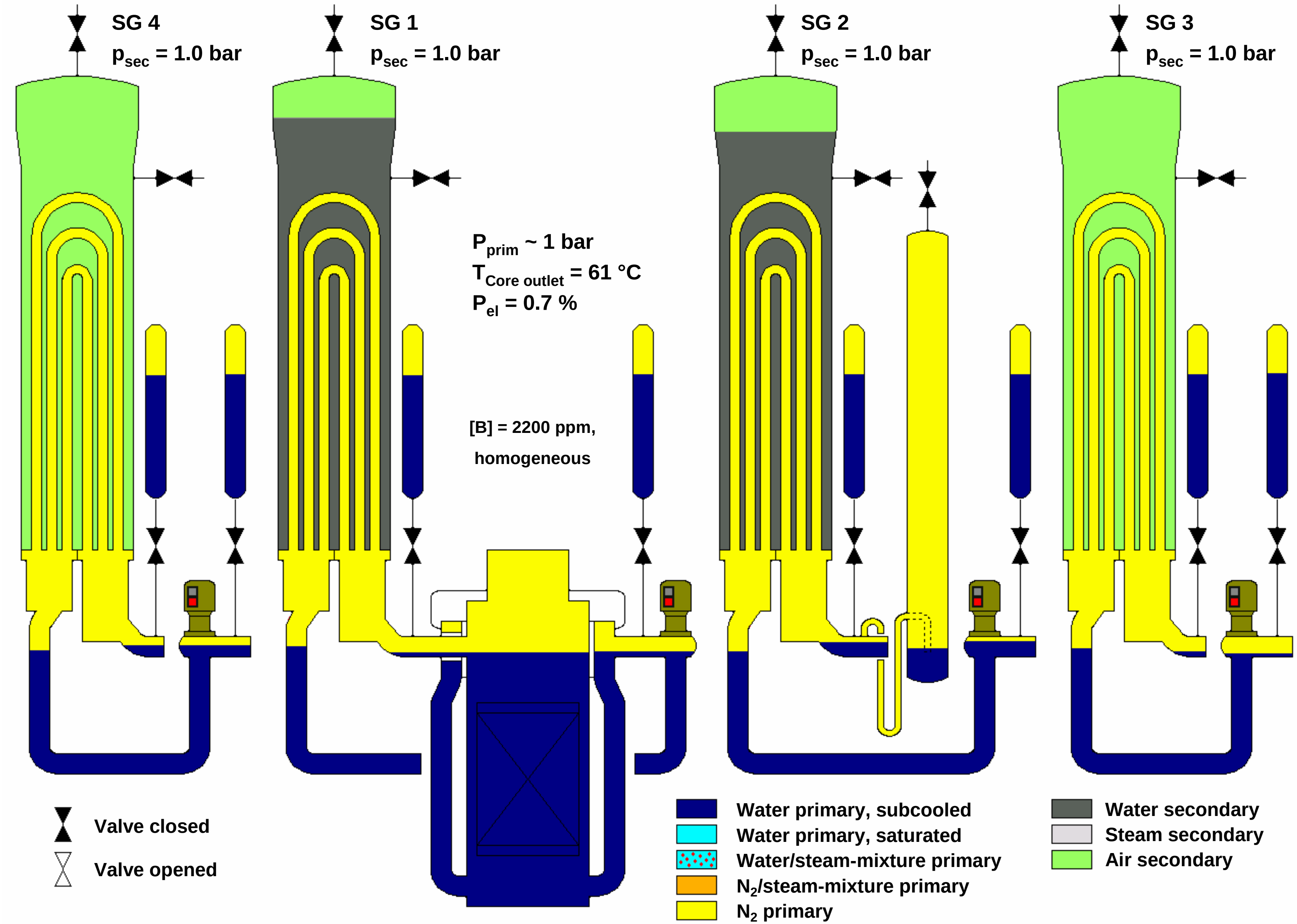


Fig. 20: PKL III E3.1 - Distribution of Inventory at Start of the Test (t = 0 s)

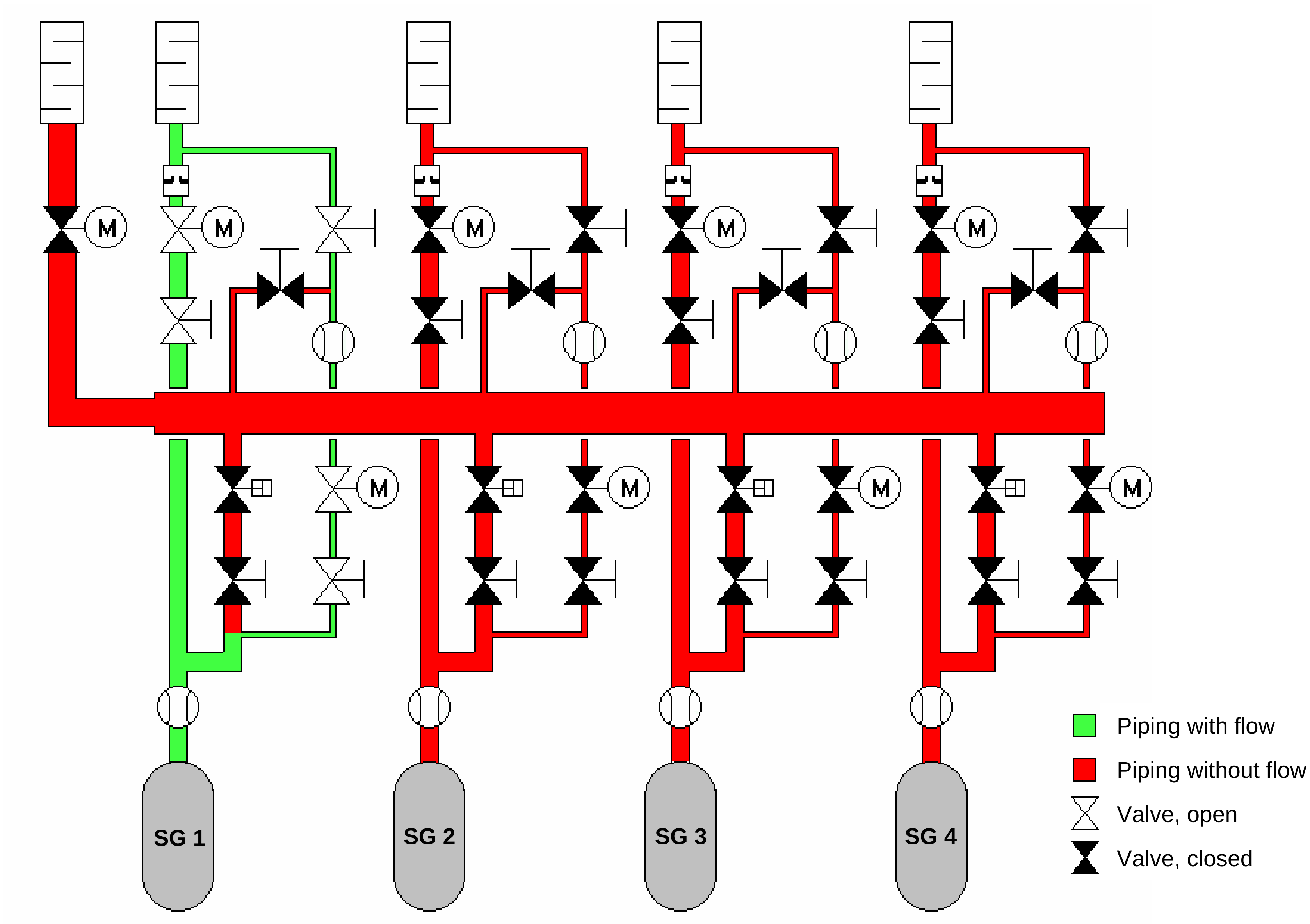


Fig. 21: PKL III E3.1 - Main Steam System during Test E3.1 (Loss of RHRS) after t = 8225 s

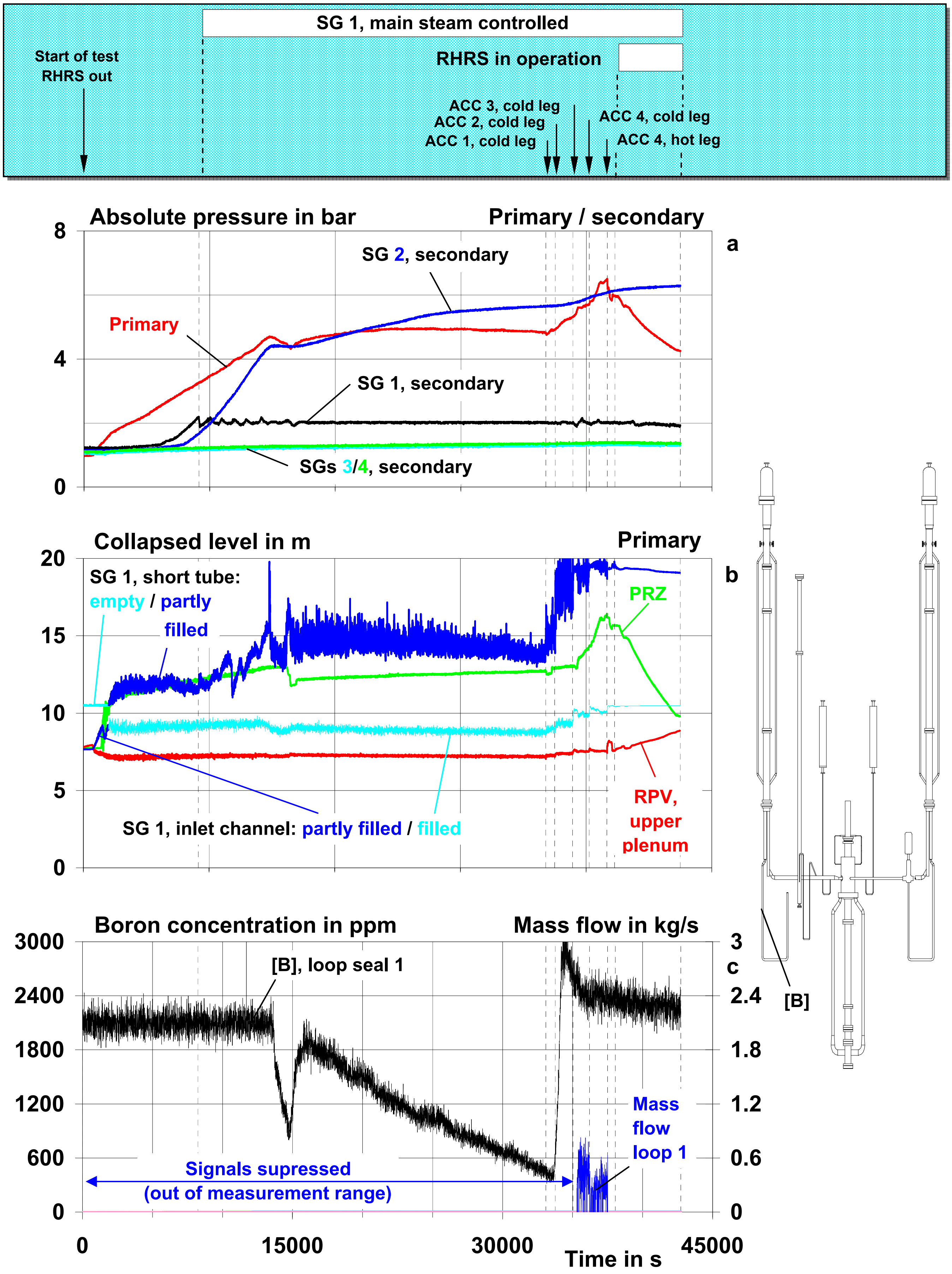


Fig. 22: PKL III E3.1 - Test Results (Overview)

Appendix to report
FANP NGTT1/04/en/04
EFRFig22.xls
2004-02-12