CONCLUSIONS ON BORON PRECIPITATION FOLLOWING A LARGE BREAK LOSS OF COOLANT ACCIDENT

K. Umminger, B. Schoen, and S.P. Schollenberger
AREVA GmbH
Paul-Gossen Strasse 100, 91058 Erlangen, Germany
klaus.umminger@areva.com, bernhard.schoen@areva.com; simon.schollenberger@areva.com

ABSTRACT

Wide experimental investigations on the system responses of pressurized water reactors (PWR) under off-normal condition have been conducted at the integral test facility PKL for many years. PKL is operated at AREVA's unique thermal hydraulic testing platform in Erlangen, Germany, which comprises large-scale thermal-hydraulic systems and components testing facilities.
The PKL test rig replicates the entire primary-side operational and safety systems and relevant parts of the secondary side of a 1300 MW PWR plant with elevations scaled 1:1 and diameters reduced by a factor of 12 (volume and power scaling factor 1:145). With its total of around 1600 measuring points, the PKL facility is well instrumented, which permits detailed analysis and interpretation of the phenomena observed in the tests. One major goal of the experiments is to provide an extensive database for use in the further development and validation of thermal-hydraulic computer codes.
This presentation will focus on results from PKL experiments dealing with boron precipitation processes that may occur in the long-term cooling phase following a large cold-leg break LOCA in PWR plants due to continuous boiling in the reactor pressure vessel (RPV). The PKL experimental results on boron precipitation demonstrated the size of the mixing volume to comprise the entire hot side coolant volumes leading to a slow boron enrichment process, as well as the effectiveness of the changeover from cold-leg to hot-leg ECC injection in reversion of the boron enrichment process.

KEYWORDS
PWR, LB-LOCA, PKL, thermal-hydraulic system behavior, integral tests, boron precipitation

1. INTRODUCTION

1.1 The Boron Precipitation Phenomenon Following LB-LOCA

Boron precipitation may occur in the long-term cooling phase following a large cold-leg break LOCA in PWRs [1]. Continuous boiling in the reactor pressure vessel (RPV) is expected during the long-term phase of a large cold leg break LOCA in PWR plants with sole cold leg ECC injection. In this state, the reactor core is rewetted and covered by two-phase mixture of water and steam but due to mixing of cold ECC water with steam in the upper downcomer (DC) the coolant fed to the core in compensation for the evaporation is almost at saturation temperature. The limitation of the ECC flow from the cold side via DC to the core is a consequence of the pressure balance between hot (core, upper plenum (UP)) and cold side (break location); the hot side UP pressure acts against the flow and thereby avoids a subcooling of the core volumes. In doing so, the ECC flow theoretically only compensates for the evaporation rate in the core, regardless of the cold-side ECC flow rates as any excess ECC is lost via the break.
Thus, **the boiling process in the core continues in the long term**.

During evaporation, the boron (B) injected with the ECC water remains in the liquid phase in the RPV and accumulates continuously. At concentration values of boric acid (cB) which exceed that of the ECC water by a factor of 20 or more the temperature-dependent limit of boron solubility in water may be reached and even exceeded. Locally initiated crystallization then effectuates the formation of solid boron particles which may compromise core cooling by impeding the heat transport from the rods through plate-out of boric acid at the rod cladding surfaces. In the long-term cooling phase the containment pressure (= RCS pressure) is assumed to vary around 2.5 bar (T_{sat} ~127 °C), under these conditions the solubility limit for boron in water varies around 66000 ppm.

The most decisive parameters for the speed of the boron enrichment process are the core power (residual heat) and the size of the mixing volume, i.e. the amount of liquid water in the RPV available for mixing with the continuously accumulating boric acid. The mixing volume is directly connected to the enrichment process, whereas small mixing volumes effectuate a fast enrichment process. The direct impact of the residual heat manifests in an increased evaporation rate on one hand and an increased amount of steam (void volumes) in the core region on the other hand; the consequences of both mechanisms are relatively easy to determine. A mechanism whose impact is not so easy to quantify lies within the magnitude of the flow resistance of the cross-over legs and its possible increase during the transient: In a cold-leg break scenario, a high flow resistance between upper plenum (close to steam source) and cold side (break, heat sink) results in a high differential pressure between UP and break location. The hot-side swell level accounts for this pressure differential: The higher the flow resistance, the higher the pressure differential between upper plenum and cold leg and the lower the swell level in the RPV and the mixing volume available.

Certain effects may contribute to the increase of the overall pressure differential between hot and cold sides. A partial or complete blockage of one or multiple cross-over legs by ECC or two-phase mixture increases the flow resistance. Plate-out of boric acid in the steam generator (SG) U-tubes resulting from the evaporation of coolant entrained into the U-tubes (the secondary side is at a higher temperature level) may also slowly increase the flow resistance across the SG and contribute to the overall pressure differential. In this way, high steam loads (comparably high core power in the early long-time cooling phase) in conjunction with the built-up flow resistances along the loops cause a decrease of the swell level in the core (“swell level depression”) and thereby a significant reduction of the mixing volumes in the RPV. The scenario – as theorized – is depicted in Fig. 1.

1.2 Reversion of Boron Precipitation

An effective measure to avoid or reverse a present or developing boron enrichment process in the core is the switch-over to hot-leg ECC injection. A hot-leg ECC flow high enough may create a net flow that displaces the high boron coolant inventory from the RPV riser side via DC towards the break (“flushing” of the core).

However, in some PWR an early switch to hot-leg injection is inappropriate as high steam velocities present in the loops at the early state of the long-term cooling phase are assumed to divert the ECC injected in the hot legs into the SGs. An evaporation of the coolant entrained into the SGs (temperature level significantly higher than core exit) generates additional contribution to the hot-side pressure built-up and may aggravate the swell level depression. Furthermore, the boron injected with the ECC may accumulate in the U-tubes as a result of evaporation in the U-tubes and favor the development of boric acid plate-out in the U-tubes. Consequently, for PWR preferably featuring cold-leg ECC injection, the switch to hot-leg injection for a reversion of the enrichment process in the core has to be delayed until the steam velocities have reduced according to the decrease of the decay heat.

Associated with the partial switchover to hot-leg injection are questions on sudden local crystallization in the upper plenum when highly subcooled ECC water is added to the upper plenum and core region and if the concentration is simultaneously reduced in the entire mixing volume or if there are localized regions near the core periphery where concentration is not reduced.

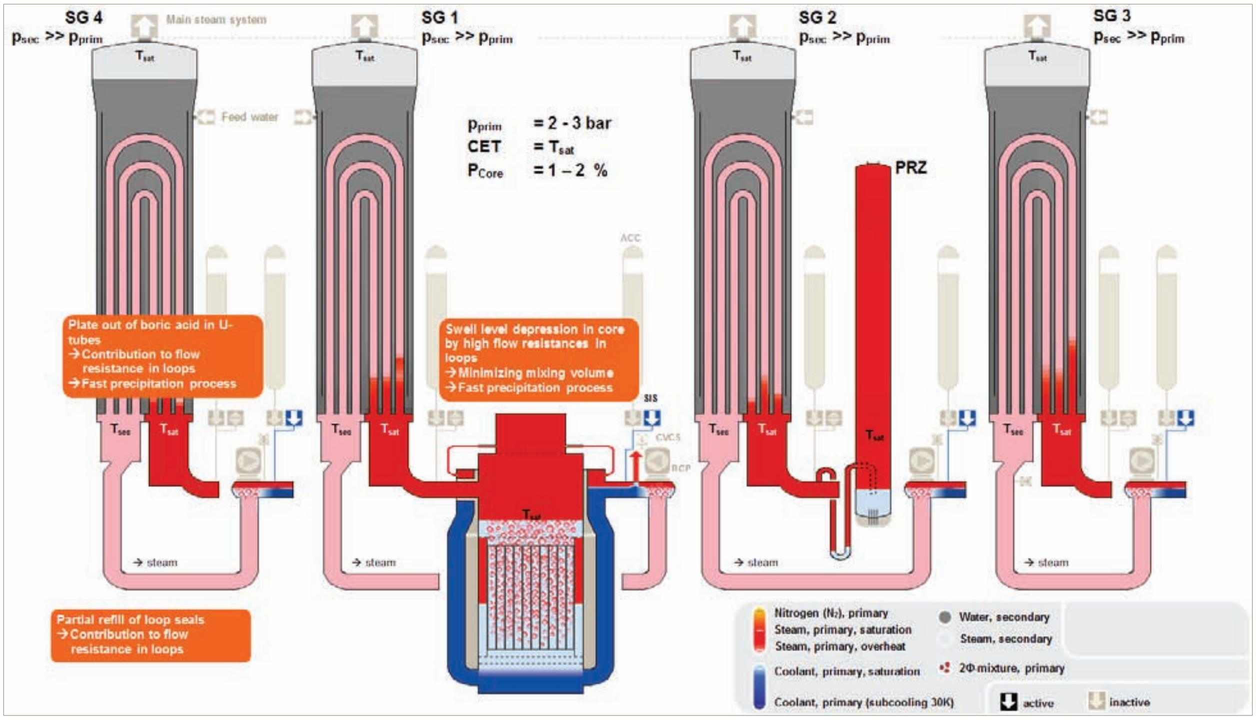

Figure 1. Postulated Scenario: Long-Term Cooling Phase Following LB-LOCA

2. PKL III TEST FACILITY

The PKL (German acronym for “Primärkreislauf”, primary circuit) (see Fig. 2, [2]) is a scaled-down replication of the nuclear steam supply system of a 1300 MW KWU-type pressurized water reactor (PWR). Reference plant is the Philippsburg 2 nuclear power plant. The PKL test facility is operated at AREVA Germany to experimentally investigate the thermal-hydraulic behavior of PWRs under off-normal conditions for design and beyond-design basis accidents (e.g. efficiency of accident management measures).

The PKL test facility replicates the entire primary and the most significant parts of the secondary side (no turbine, no condenser) in 1:1 heights. Volumes, power input and mass flows of safety and operational systems are scaled 1:145. The core is modeled by a bundle of 314 electrically heated rods, arranged with original rod pitch and lengths, able to deliver 2.5 MW of power (corresponding to 10 % of nominal core power).

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 demand:

- Simulation of all four loops, identical piping lengths and 1:1 heights (full-scale hydrostatic head)
- Power, volume, and cross-sectional area scaling factor of 1:145
- Core bypass flows and the reflector gap volumes are replicated accordingly.
- Full-scale frictional pressure loss for single-phase flow
- 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 according to the overall volume scaling factor of 1:145.

In cases of conflicting requirements, the simulation of the phenomena was given preference over consistent simulation of the geometry, e.g. in order to account for important phenomena in the hot legs such as flow separation and countercurrent flow limitation, the geometry of the hot legs is based on the 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 1600 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 concentrations (conductivity probes) were used for the experiments described below.

The maximum operating pressure of the PKL test facility is 50 bar on the primary side and 60 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 below 50°bar and with initial conditions corresponding to those present in a real plant at that 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.

Since 2001 the PKL tests conducted at the PKL test facility are involved in international collaborations organized via the OECD/NEA. Since then, the PKL-project advanced the development in nuclear technology and reactor-safety research on an international level by providing a large database of experimental results for the international project partners to validate thermal-hydraulic computer programs.

3. EXPERIMENTAL SET-UP

The abovementioned considerations on the theoretical background of the post LB-LOCA long term core cooling phase return the following important points as subjects to be clarified by the PKL experiments:

- **The impact of core power** - manifesting in evaporation rate, void volumes and two-phase head loss in the core on the enrichment process is quantified in the PKL experiments by a variation of the core power level within the power range typical of the scenario: 1 – 2 %.

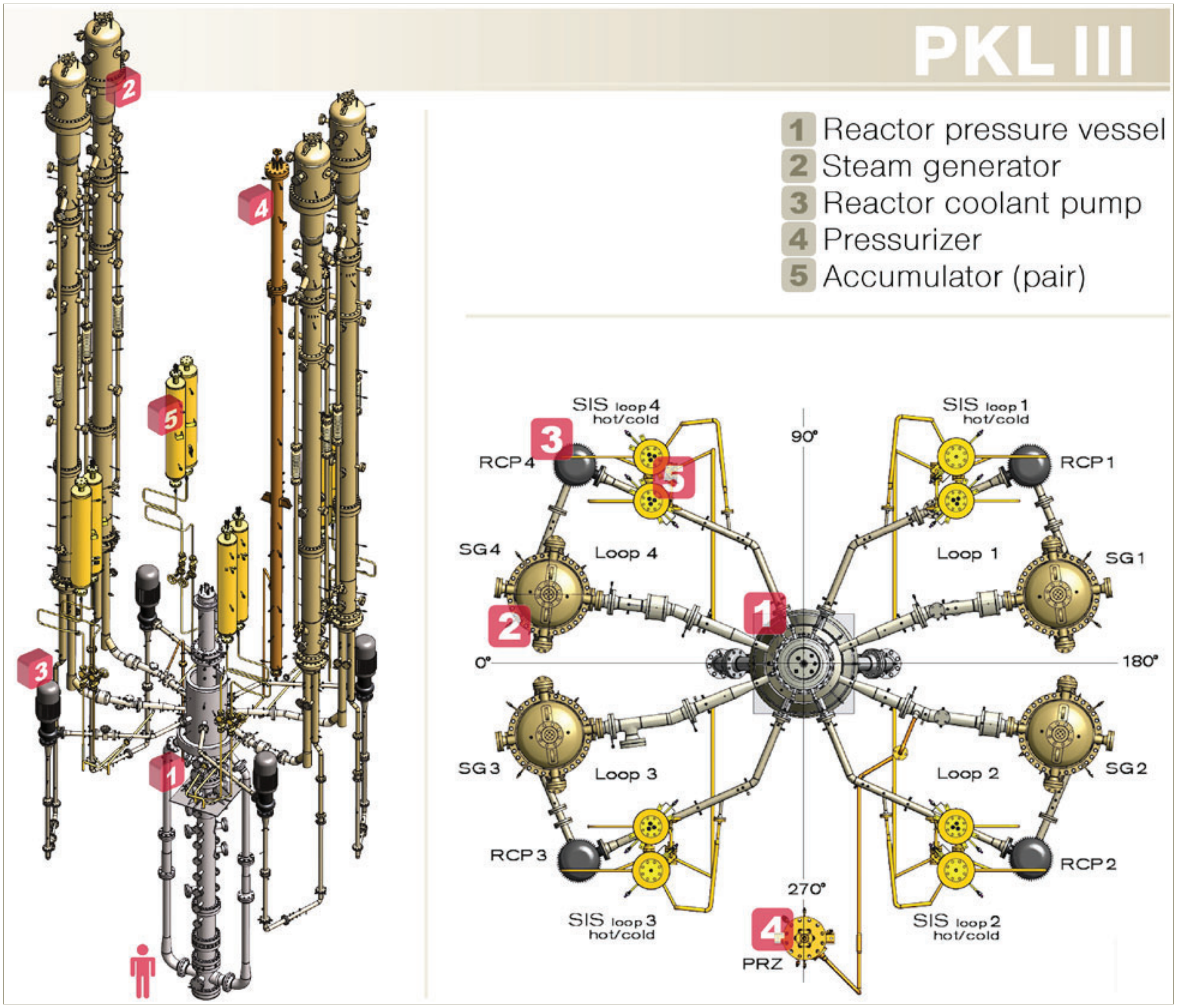

Figure 2. PKL III Test Facility

- **Size of the mixing volume in the RPV**. The amount of RPV sections and volumes which contribute to the mixing volume (i.e. that display an increase of cB) is analyzed by boron concentration measurement positions in all relevant RCS sections. The larger the amount of liquid coolant, the slower the progress of the boron enrichment process. The mixing volume is determined by the pressure differential between hot and cold side, whereas the flow resistance along the loops play the major role. The reduction of the hot-side swell level resultant from increase of differential pressure between hot and cold sides is referred to as "**swell level depression**".
  The impact of the flow resistances of the cross-over legs on the size of the mixing volumes in the core, that is, the extent of swell level depression, was analyzed by a variation of the cold-side ECC flow rates and injection sequences and - in the most recent experiment - by newly installed additional butterfly valves in all cross-over legs below the SGs. The closing of the valves induces additional singular K-factors in the cross-over legs that add up to the total loop flow resistance and thereby effectuate decreasing mixing volumes on the hot side (swell level depression). While in the PWR, the RCP (main source of flow resistance in the loops) as well as different effects such as two-phase head in core, hydraulic friction along the loops, potential plate-out of boric acid in SG U-tubes and cross-over legs being partly or completely filled with liquid or two-phase coolant each contribute to the

overall differential pressure, the impact of these effects on the swell level on the hot side is simulated in PKL by closing of the butterfly valves in the cross-over legs. In this way, the PKL experiments aim at the determination of the amount of pressure differential required for a notable swell level depression in the RPV.

As the speed of the boron enrichment process mainly depends on core power level and the size of the mixing volumes, a determination of the time span up to the necessary switch-over to hot-leg ECC injection ("core flushing") for the PWR has to take into account a realistic estimation of the extent of swell level depression in the PWR. In respect thereof, the PKL experiments provided a trend for the magnitude of the K-factor needed for a significant reduction of the mixing volume, a basis on which conclusions on the prospect of a safety issue arising from a possible quick boron enrichment in the PWR may be stated.

- **Effectiveness of hot-leg injection in the reversion of the boron enrichment process ("core flushing)".** At a later stage of the experiments (core power 1 % and lower) after having reached a considerable cB in the mixing volume (> 20000 ppm) the ECC injection is partially switched to combined hot-and cold-leg injection for a mitigation or reversion of the enrichment process. In effect, "Core Flushing" is more a displacement of high boron coolant from the hot side through the break by a net flow of coolant (from hot-leg injection point via UP, core, LP and DC to the break) than an actual reversion of the enrichment process (i.e. dilution). The flow required for a flushing of the core was roughly determined by a stepwise increase of the hot-leg ECC injection.

The boron concentrations are measured at different locations in the RPV, hot leg, and SG inlets. Conductivity probes, calibrated for high boron concentrations have been installed at the most relevant points (core exit, reflector gap, SG 1 inlet and lower plenum) to provide continuous recording of data for those points. Discretely taken grab samples and analyses by titration serve as diverse measurement technique, partly in support of the conductivity probes

The central topics of interest are summarized in Fig. 3.

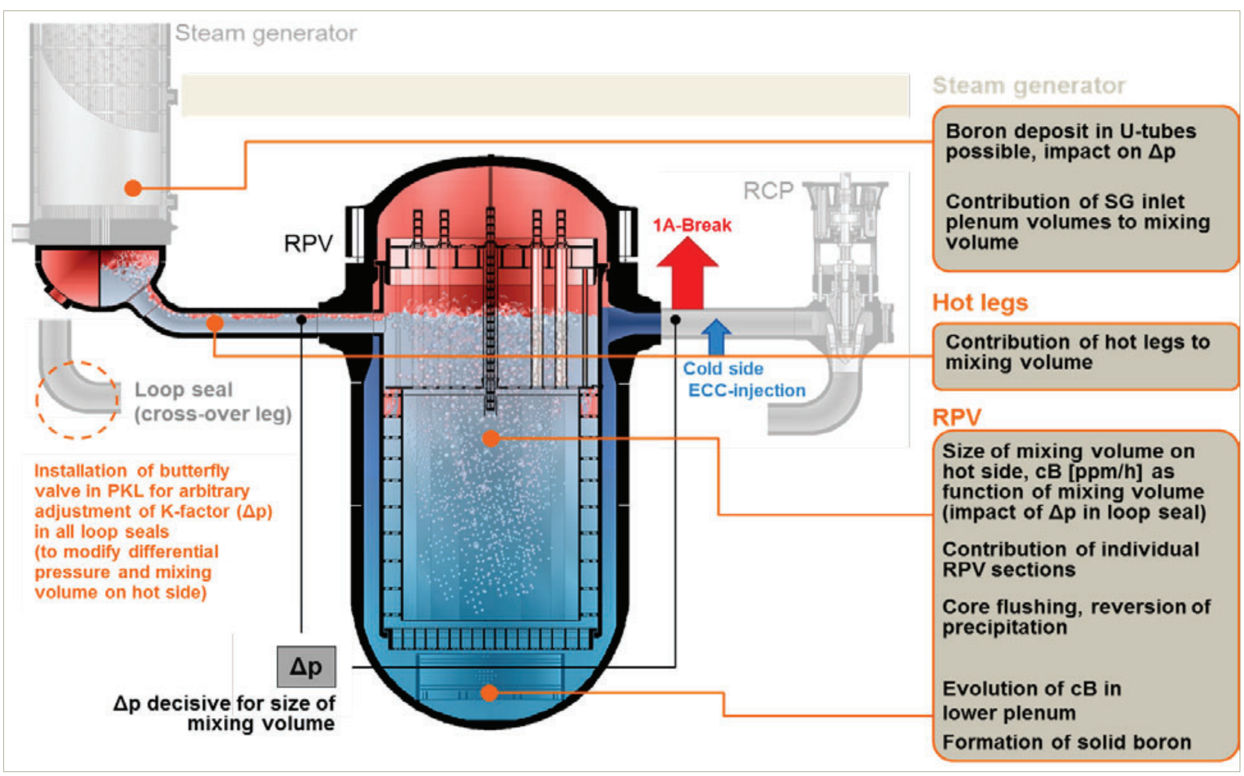

Figure 3. RCS Section of Interest and Test Objectives

4. EXPERIMENTAL RESULTS

4.1 Mixing Mechanisms in the RPV

From different experiments, the measured boron concentrations (grab samples and conductivity probes) indicated that the mixing volume (sections with almost simultaneous increase of cB) consists of the entire hot-side coolant volumes, i.e. the volumes of the core section, the reflector gap (RG), the lower plenum (LP) and the hot leg and SG inlet plenum volumes (Fig. 4). Mixing mechanisms assure the interconnection of the volumes for a simultaneous increase of cB in most of the hot-side coolant volumes (Fig. 4 and 5); as regards the lower plenum some particularities apply:

- For the lower plenum, the exceeding of a certain difference in cB between core and lower plenum (ΔcB ~ 8000 ppm) is required to balance the temperature-induced density differences between core and LP. The impact of dissolved boric acid on the coolant density is eventually large enough to overcome the temperature-induced density difference between core and LP. In this way, even the lowermost regions of the RPV, i.e. the region with the coldest water at the lowermost region of the RPV eventually become part of the mixing volume. Local crystallization in the bottom region of the RPV was not observed for cB up to approx. 35000 ppm in the LP.
- For swell levels that reach into the SG inlet chambers, intense fluid exchanges between upper plenum and SG inlet plenums via hot legs assure the contribution of the inlet plenums to the mixing volume.

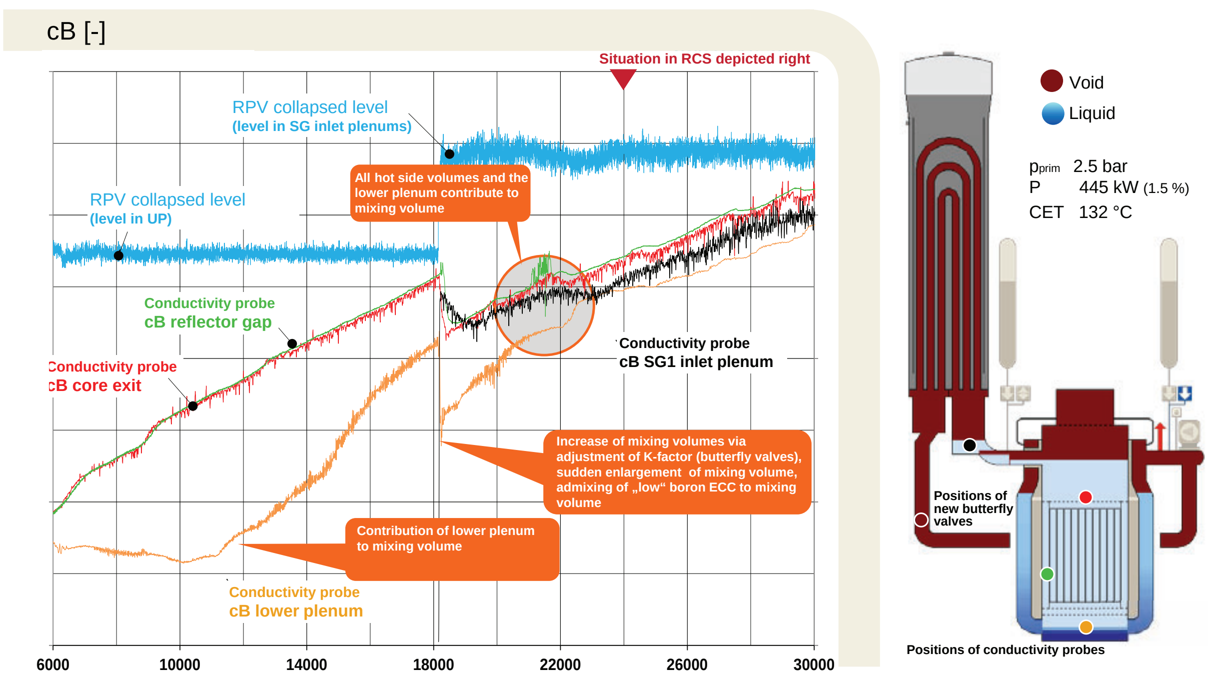

Figure 4. Increase of cB in RCS Sections During Core Cooling with Two-Phase Mixture.

The mechanisms of mixing in the RPV (see Fig. 5) were found to include the volumes of the core region, the reflector gap even for swell levels that just cover the core (by overflow across the grid plate) and the lower plenum. For higher swell levels, the volumes of the upper plenum or the hot legs and SG inlet plenums also participate in the enrichment process. In sum, regardless of the height of the swell level in the core, as long as the core is covered by two-phase mixture, the mixing volumes in the RPV comprise much larger RPV sections than just the core region.

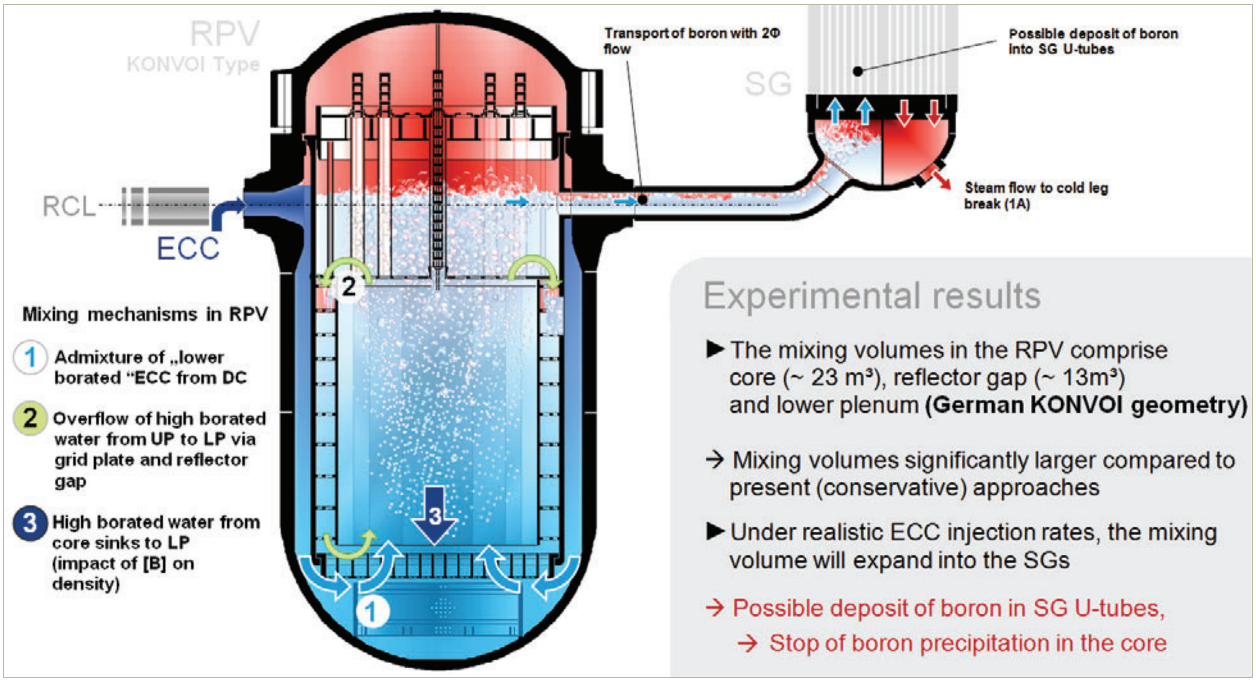

Figure 5. Mechanisms Interconnecting the Hot-Side Volumes (experimental results applied to PWR).

4.2 Size of the Mixing Volume and The Swell Level Depression Phenomenon

Being of significant importance for the size of the mixing volume (and the speed of the enrichment process) the investigations on the swell-level depression phenomenon constituted a major objective within the experimental campaigns. The experimental results indicated the following tendencies for the influence parameters on the prospect of swell level depression:

A considerable pressure differential (K-factor) between hot and cold side is required for a notable swell level depression, e.g. the head losses at singularities such as reactor coolant pump impellers at standstill or of U-tube bundles are not sufficient to induce swell level depression to a relevant extent. The order of magnitude required for the pressure differential to induce a depression of the swell level in the RPV to fasten the boron enrichment in such a way to exceed the solubility limits within 4 hours after scram - as theorized in the postulated scenario (Fig. 6A) is beyond the usual boundaries imposed by the K-factors of the RCS components. An increase of the overall K-factor by a factor of around 10 would be required to depress the swell level to obtain such a shortening of the time period. With the KONVOI RCS and flow resistances and its hydraulic friction factors (including the RCP), simulated in PKL experiments without the employment of additional butterfly valves, the flow resistance across the loop towards the break is too low to maintain the swell level in the core at low levels while downcomer level in parallel is high (postulated scenario in beforehand, Fig. 6A).

Therefore, for RCS geometries and K-factors similar to KONVOI and realistic ECC flow rates (exceeding the evaporation rate by far), it must be assumed that the mixing volumes always extend into UP, hot legs and SG inlet plena (Fig. 5 and 6 C). In this way, large grace periods for the enrichment process may always be obtained until precipitation occurs, long enough to allow the switchover to hot leg injection at significantly decreased decay power level (distinctly below 1 % for $t > 6$ h after scram)

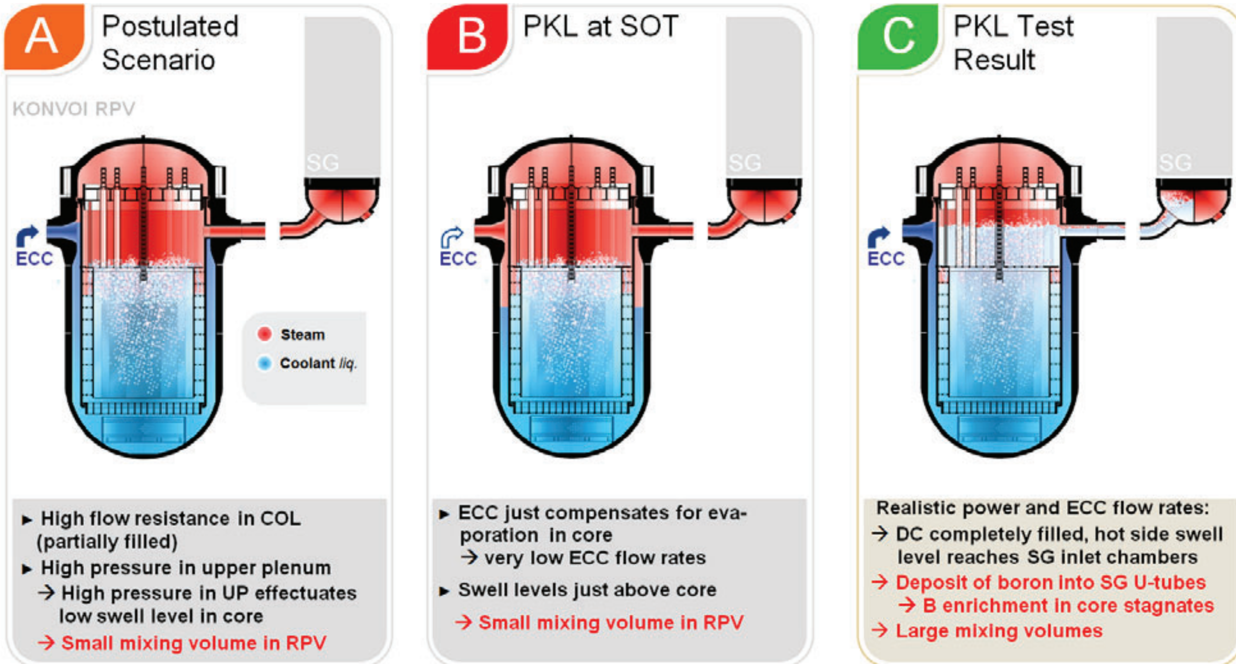

Figure 6. Postulated Scenario vs. Results for Low Flow Resistances (KONVOI geometry) without the employment of additional butterfly valves in the cross-over legs

- **Boric acid plate-out in U-tubes**: For hot side swell levels that reach into the U-tubes, the evaporation of coolant due to the secondary side being at higher temperature the U-tubes presumably causes the deposit of boron on the inside surfaces of the U-tubes. In the PKL experiments, the enrichment process was found to significantly slow down for such high swell levels, which evidenced the transfer of boric acid from the mixing volume, most likely into the U-tubes. Although being instrumented with highly sensible differential pressure detectors, an increase of the pressure differential across the U-tube bundles was not measured, not even if operated in this condition for several hours.
  So apart from enlarged mixing volumes, a high hot-side swell level provided a further mitigation of the precipitation process in the core by a partial boron displacement towards the SG-U-tubes. The occurrence of additional head losses resultant from plate-out in the U-tube could not be confirmed in PKL.

4.3 Reversion of Precipitation – Core Flushing

According to the theoretical assumptions, core flushing is more a displacement of high boron coolant from the hot side through the break than an actual reversion of the enrichment process (dilution).
A sudden local precipitation in the upper plenum as a result of subcooled water being added to the upper plenum was not observed due to good mixing in the hot legs at the injection nozzles or in the upper plenum, despite the ECC is being injected via a scoop in the hot legs as in the KONVOI type PWR.

5. CONCLUSIONS

The PKL experiments provided new and valuable data on boron precipitation phenomena that may occur during the long-term phase of a LB-LOCA with only cold-side ECC injection. Significantly high boron concentrations beyond 30000 to 40000 ppm can be obtained within about 4 hours, if mixing volumes in the primary system with boron enrichment are assumed small enough and only comprise the core region.

Contrarily, the mixing volumes have found to be significantly larger, yielding a grace period in the order of 6 h until exceeding to the solubility limit.
If no additional K-factors are introduced in the loops, the flow resistance provided by the KONVOI RCS geometry (simulated in PKL) is too low to induce notable swell level depression for a distinct reduction of the time period until the solubility limit is met. Plate-out of boric acid in the SG U-tubes may occur for large mixing volumes but does not provide a measurable contribution to the overall flow resistance along the loops.

To obtain notable swell level depression on the hot side an increase of the loops overall K-factor by a factor of around 10 must be realized. A comparison of the conditions in the individual PWR with the PKL results may be helpful in the estimation of the contribution of swell level depression to the evolution of the mixing volume. It has to be analyzed and checked, if an increase of the overall K-factor of such a magnitude can technically be realized by the phenomena associated with the scenario (e.g. cross-over legs partly filled by two-phase mixture).

In sum, the PKL experimental results indicated that under the conditions investigated, boron precipitation seems unlikely to produce conditions that compromise core cooling in the first 6 h after reactor scram, a time period sufficient to await the decrease of the core power to 1 % and below for a safe switch-over to combined hot and cold leg safety injection to obtain core flushing.

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