
Validation of thermal-hydraulic codes for boron dilution transients in the context of the OECD/SETH Project

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Abstract: The scope of the OECD/SETH project is twofold: (1) to provide experimental data at system level for the boron redistribution in the reactor cooling system after a SB-LOCA and after loss of RHR system at mid-loop operation and (2) to provide experimental data for CFD code assessment for plumes and jets in multi-containment geometry. This paper deals exclusively with part 1 presenting the main results obtained in a specific workshop and the status of an ongoing benchmark. The workshop showed that the problematics relative to the correct predictions of the boron behaviour were closely linked to the non-precise prediction of the thermal-hydraulic phenomena. For SB-LOCA calculations most of the participants had problems with obtaining the start-up 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 and the correct splitting of the safety injection flow (to the vessel and to the loop). For the mid-loop calculations the experimental phenomenology (loop deboration, condensate overspill in short U-tube and transport) was predicted qualitatively only when using 3 U-tubes per SG but the heterogeneous behaviour of the U-tubes after unplugging was still not clearly identified. An international benchmark is currently ongoing relative to the mid-loop test.

1 INTRODUCTION

The experimental data delivered by the OECD/SETH project relative to the boron dilution at system wide level part was extensively used by the participants to validate their thermo-hydraulic codes.

This data originated from the four experiments performed at the PKL facility; three dealing with SB-LOCA and one with loss of RHR at mid-loop operation.

The SB-LOCA series was focused on investigating the effect of multiple configurations of the Safety Injection (SI) system (i.e. symmetric/asymmetric, hot/cold leg) on a deborated slug displacing in the loop after refilling and restart of natural circulation.

The mid-loop experiment was instead focused on the analysis of the progression of deboration in a loop subject to reflux-condenser mode after loss of RHR in a closed circuit.

This paper will present the main findings obtained by the participants during their code validations.

2 BORON DILUTION PROBLEMATIC

Inherent boron dilution can take place if a SB-LOCA occurs in the reactor 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 SI pumps, the primary coolant inventory will decrease. As a result, energy may temporarily be transported from the primary to the secondary side under reflux-condenser conditions. In this situation only small amounts of boron are transferred to the vapour phase. Therefore the condensate produced in the SGs is nearly boron free. This condensate may accumulate locally in the reactor coolant system, especially in the loop seals. After refill of the primary system and with SGs cooling down the plant natural circulation starts and the low-boron water inventories could be transported towards the RPV. The main problem will therefore be to determine whether these clear water slugs may cause recriticality.

Possible recriticality will depend mainly on the following aspects:

1. Size of the "condensate slugs" formed in each loop
2. Effective boron concentration after the mixing process during refill and transport (in the SGs, in the loops)
3. Intensity of the natural circulation
4. Time difference between the startup of natural circulation between the different loops
5. Effective boron concentration after the mixing with highly borated water in the annular gap of the RPV downcomer 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.

The above-mentioned aspects are dominated by boundary conditions such as break size, break location, injection rates, injection locations and cooldown rate that have been investigated within the experimental campaign.

Inherent boron dilution can also take place if the loss of RHR system occurs at mid-loop operation with a closed primary circuit and with at least 1 SG available for cooling. Reflux-condenser conditions arise and the previously described "boron distillation" phenomenon occurs.

3 PKL FACILITY

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

Similarly to other test facilities of this size, the scaling concept aims to simulate the thermal hydraulic system behaviour 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 phenomena 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).

- The RPV downcomer is modelled as an annulus in the upper region and continues as two 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 the only test facility worldwide 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. Modelling 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 modelled 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 behaviour 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, permitting detailed analysis and interpretation of the phenomena observed in the tests. Besides conventional measurements of temperature, pressure and mass flow rates, also special measurement techniques for the determination of the boron concentration were used for the OECD/SETH experiments.

The maximum operating pressure of the PKL test facility is 45 bars on the primary side and 56 bars on the secondary side. Due to this pressure limitation, it is not possible to simulate the high-pressure portion of accident sequences (such as SB-LOCAs) starting from a PWR's actual operating pressure (155-160 bar) under original conditions. Hence, the PKL tests "starts" 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 SB-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 centred above all on the theoretical and experimental analysis of LB-LOCA, focusing on verifying the effectiveness of the ECCS required for controlling these accidents. In line with this original objective, 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 that were sponsored by the 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 and the BMBF and the BMWi. 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 analysed within the German Risk Study, phase B.

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 development 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.

4 SUMMARY OF THE OECD/SETH PKL TESTS SERIES

4.1 SB-LOCA series

PKL tests concerning post SB-LOCA inherent boron dilution can be classified into two conservative categories:

1. With respect to the time difference between startup of natural circulation in the different loops: for these tests the boundary conditions are chosen in such a way that a simultaneous startup of natural circulation is favoured (E1.1, E2.1).
2. With respect to the amount of condensate accumulated in individual loops: for these tests the boundary conditions are chosen in such a way that the mass of condensate produced is large and the influence of mixing processes is small (E2.2, E2.3).

For the first category of tests all four loops of the RCS are fed symmetrically with ECCS water. For the second category tests (at least at high pressure) all loops are not fed by the SI pumps while the size of the break is chosen to maximize the amount of condensate.

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

4.1.1 Objectives of tests E1.1 and E2.1

The purpose of tests E1.1 and E2.1 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 (E2.1) injection of ECCS water.

The aim of these tests was to verify whether the simultaneous restart of natural circulation in two or more loops can be ruled out after ECCS cold-leg (E1.1) or hot-leg (E2.1) injection and to determine the minimum boron concentrations at the RPV inlet.

The symmetry between the loops (uniform injection) favours 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 effect together with the large amounts of condensate initially present in all the loops can be regarded as a conservative assumption with respect to recriticality.

4.1.2 Objectives of test E2.2

Test E2.2 consists of a small break in cold leg 1 with 2 out of 4 SI pumps injecting into cold legs 1 and 2.

Analyses over the entire range of small break sizes show that the largest condensate masses accumulating in the event of a cold-side break are to be expected if ECCS water is also injected by the SI pumps 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 reflux-condenser phase. As a result of the high filling level, the computations and estimates predict that zones with under-borated water will form in the loop seals. Test E2.2 modelled precisely this scenario and about 800 kg of condensate was formed during the conditioning phase (before start of the test). This value is significantly greater than the 240 kg that correspond to the mass of condensate predicted by RELAP computations to be formed in the PWR before 40 bars are reached. The test is thus conservative in terms of the amount of condensate accumulating in the event of a cold-side SB-LOCA.

The aim of this test was to verify the size of the condensate slugs, to evaluate the mixing effects in the SGs and in the RCL, and to determine the minimum boron concentrations at the RPV inlet.

4.1.3 Objectives of test E2.3

Test E2.3 was designed to investigate a scenario involving a hot-side break with unfavourable mixing conditions for the accumulated condensate with highly borated water, and with accumulation of large condensate masses in individual loops.

The break was postulated in hot leg 1. Only 2 out of 4 SI pumps were postulated to be available and injecting into hot legs 1 and 3. A conservative assumption was that natural circulation was not yet interrupted in the two loops with HPSI at a pressure of 40 bars (departure point of the PKL-test). It was also 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 ECCS 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 safety injection and with reflux-condenser conditions.
- If natural circulation resumes in these loops 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 unfavourable (simultaneous flow through all loops at similar flow rates and absence of plumes of ECCS water penetrating the core and reaching the lower plenum).

The main investigated points were:

- General system behaviour 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.

4.2 Loss of the RHR system during mid-loop Operation

The purpose of this test was to investigate the system response following loss of residual heat removal in mid-loop operation with a closed RCS. In this plant condition the PWR has already been cooled down for refuelling. 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 RHR system fails. Loss of residual heat removal in mid-loop operation can produce reflux-condenser 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 mass 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 primary 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 deborated condensate
 - Displacement of water with low boron content into the RPV before or after the accumulator injections.

5 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 the prediction of the following phenomena:

Thermal-hydraulic related

- Natural circulation startup sequence after SB-LOCA
- Symmetric and asymmetric loop behaviour (due to: break location, pressurizer connection, ECCS injection location)
- Different behaviour of U-tubes having different lengths
- Heat transfer between primary and secondary during natural circulation taking into account a redirection of the hot leg ECCS injection to the SGs (CCFL)
- System behaviour 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

Boron related

- Formation of a deborated slug (Test E3.1)
- Limitation of the slug size
- Boron slug mixing and transport
- Mixing of differently borated masses of water in different sections of the reactor coolant system

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

5.1 Performed Thermal-Hydraulic Code Analyses

The “First workshop on analytical activities related to OECD-SETH project” held in Barcelona on the 2nd and 3rd September 2003 brought together participants of the project to compare various simulations of the PKL experiments using their own codes. The codes that were used were: RELAP, ATHLET and CATHARE.

Table 2 summarizes the analysed transients by the participants

5.1.1 Main Results from the SB-LOCA Tests

The code results related to boron dilution after SB-LOCA showed in general a qualitative agreement with the experiments with respect to the overall system behaviour (e.g. evolution of pressure, break flow rate, fill-up of the primary system). However, it still seems to be a challenge for all the codes to correctly reproduce the restart and establishment of natural circulation, which is for this kind of scenario one of the key parameters. As demonstrated by the experiments, the restart of natural circulation is in fact a very sensitive mechanism, which is strongly influenced by the prevailing boundary conditions in the individual loops (break, connection of pressurizer, ECCS-injection). In contrast to the experiments, all the calculations tend to result in a simultaneous restart of natural circulation in the individual loops. Discrepancies between calculations and experiments also occurred with respect to the evolution of the local boron concentration. This is partly a consequence of the above-mentioned problems in reproducing the natural circulation behaviour but also due to the currently used boron transport models. In most cases, the boron transport and the local boron concentration could be only qualitatively reproduced. Other problems that encountered in the calculations are related to fill-up of the reactor pressure vessel upper head and the pressurizer 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) a possible non mixing between the low cold safety injection flow and the slow hot deborated slug transiting in the cold leg and (b) 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.

General recommendations for improvements which have been discussed during the meeting and which should be dealt with in future calculations can be summarized as follows:

- Modelling improvements for upper plenum/upper head and pressurizer to deal with stratification and saturated layers (fill- up behaviour)
- Use of a 4 loop-configuration instead of a lumped approach
- Improved boron transport model
- Sensitivity studies on the influence of parameters dominating natural circulation behaviour
- Finer nodalization and coupling of system codes with CFD calculations.

5.1.2 Main Results from the Mid-Loop Test

The calculation related to the PKL mid-loop test E3.1 demonstrated that the experimental results (U-tube unblocking and condensate overspill in short SG U-tubes, transport of low borated water via the pump seal into the reactor pressure vessel) could only be reproduced when using at least 3 U-tubes per SG (instead of 1 U-tube).

6 BENCHMARK ON TEST E3.1

In order to better coordinate the comparison of results by the participants performing analytical calculations an OECD internal benchmark has been proposed at the end of 2004 on the assessment of test E3.1 of the OECD SETH project.

AVN was set as leader of the exercise. The deadline for sending results was set for end of September 2005 and by spring 2006 a report should be available to the participants.

The objective of this benchmark is to evaluate and compare the best-estimate system codes capabilities relative to boron dilution/concentration transients during a loss of residual heat removal (RHR) system accident at mid-loop operation.

Focus is set on both the correct prediction of the T-H parameters and on the boron dynamics in the system.

The documentation relative to this test was available to all the participants via the specific E3.1 CD delivered by FRAMATOME ANP.

The participants will have to answer to various questionnaires providing: general information, nodalization choices, lumping strategy, etc. They will also have to perform two steady state calibration runs (at 2 different loopflows) and a heat transfer calibration run to pre-assess their model.

Sensitivity studies are also proposed to investigate potential problematics.

About 40 curves will be compared between the participants (e.g. pressures, levels, boron concentrations, temperatures).

The countries that have agreed to participate are the following:

- AVN, Belgium
- GRS, Germany
- Framatome ANP, Germany
- KAERI, Korea
- JNES, Japan
- PSI, Switzerland
- University of Pisa, Italy
- UPV, Spain
- UPM, Spain
- UJV, Czech Republic
- VTT/STUK, Finland

7 CONCLUSIONS AND OUTLOOK

The participants of the OECD/SETH project have performed an extensive validation of thermal-hydraulic codes for boron dilution transients.

The participants agreed that boron prediction capabilities of T-H codes are strongly dependent on correct T-H prediction of the transient.

The main T-H prediction problematics relative to SB-LOCA transients were: the correct sequence and entity of the restart of natural circulation, the refilling of the pressurizer and the upper head and the splitting of the SI flow towards the vessel and the loop seal.

The main T-H prediction problematics relative to the Loss of RHR transient were relative to the prediction of the heterogeneous behaviour of the SG U-tubes during reflux-condenser mode. A multi U-tube model seems to qualitatively predict the observed unplugging phenomenon.

An international benchmark is currently ongoing relative to test E3.1.

Since the boron prediction capabilities of the T-H codes have been shown to be still premature to be used for plant calculations it is necessary in the future to continue to

investigate experimentally this domain in order to determine systematically the influence of different relevant parameters which will help to validate such codes.
 The ongoing OECD/PKL project, mainly focused on accidents at mid-loop operation will contribute in this task.

8 REFERENCES

1. „Final Report of the PKL experimental Programme within the OECD/SETH Project“, Mull, Schoen, Umminger, FRAMATOME ANP, FANP NGTT1/04en/04, August 2004
2. „First workshop on analytical activities related to SETH-OECD project – Summary and Conclusions“, Barcelona, Spain , 2 - 3 September 2003
3. Specifications of the OECD SETH/PKL benchmark on boron dilution during loss of the residual heat removal at Mid-loop operation, A. Bucalossi, AVN, Nov 2004

Acronyms

ATHLET	Analyse der THERmohydraulik von LEckstörfällen und Transienten (computer code)
BMBF	German Federal Ministry for Education, Science, Research and Technology
BMWi	German Federal Ministry for Economy and Technology
CCFL	Counter Current Flow Limitation
CFD	Computational Fluid Dynamics
ECCS	Emergency Core Cooling System
LB-LOCA	Large Break - Loss Of Coolant Accident
NC	Natural circulation
OECD	Organization for Economic Cooperation and Development
KWU	KraftWerk Union AG
PKL	PrimärKreisLauf (test facility)
PWR	Pressurized water reactor
RELAP	Reactor Excursion Leak Analysis Program (computer code)
RC	Reflux-condenser
RCL	Reactor coolant level
RCS	Reactor Cooling System
RPV	Reactor Pressure Vessel
RHR	Residual Heat Removal
SB-LOCA	Small Break - Loss Of Coolant Accident
SESAR	SENIor group of experts on nuclear SAFety Research
SETH	SESAR Thermalhydraulics
SG	Steam generator
SI	Safety Injection
T-H	Thermal-Hydraulics

	E1.1*	E2.1	E2.2	E2.3
Break Size	40 cm ²		32 cm ²	50 cm ²
Break Location	Hot leg 2 (pressurizer loop)		Cold leg 1	Hot leg 1
ECCS (HP and LP)				
N° of SI pumps	All 4	All 4	2 out of 4	2 out of 4
Location	Cold legs	Hot legs	Cold legs, (1 in break loop)	Hot legs, (1 in break loop)
Accumulators	-	-	-	All 4
SG sec side	100 K/h cooldown (all 4 SG connected by header)			
Central Investigation topics	Symmetry of NC startup ; evolution of boron concentration in all 4 loops		Max Condensate accumulation during DBA with cold leg ECCS injection	Max Condensate accumulation during DBA with hot leg ECCS injection

* Performed within the German national programme.

Table 1: SB-LOCA test matrix summary

Calculation	PKL Test					Code Version
	E 1.1*	E 2.1	E 2.2	E 2.3	E3.1	
FANP, Germany			PoT			Modified version of RELAP5 Mod2.5 and Mod 3
University of Manchester, UK			PoT			CFX-5
UPV, Spain		PoT				RELAP5/mod3 Model
UPC, Spain	PoT		PoT			RELAP5
GRS, Germany			PoT			ATHLET Mod 2.0 Cycle A
NRI, Czech Republic		PoT A	PrT A PoT A PrT R	PrT R	PrT R	A = ATHLET Mod1.2 Cycle D R = RELAP5 Mod 3.2
NUPEC, Japan		PoT	PoT	PoT		RELAP5 Mod 3.2.2 beta
PSI, Switzerland		PoT	PoT		PoT	RELAP5 Mod3.3 gamma
IRSN, France	PoT					CATHARE 2v1.5b
AVN, Belgium					PoT	CATHARE 2v1.5a mod7.1

PoT = Post-test analysis

PrT = Pre-test analysis

Table 2: Participant analysis summary

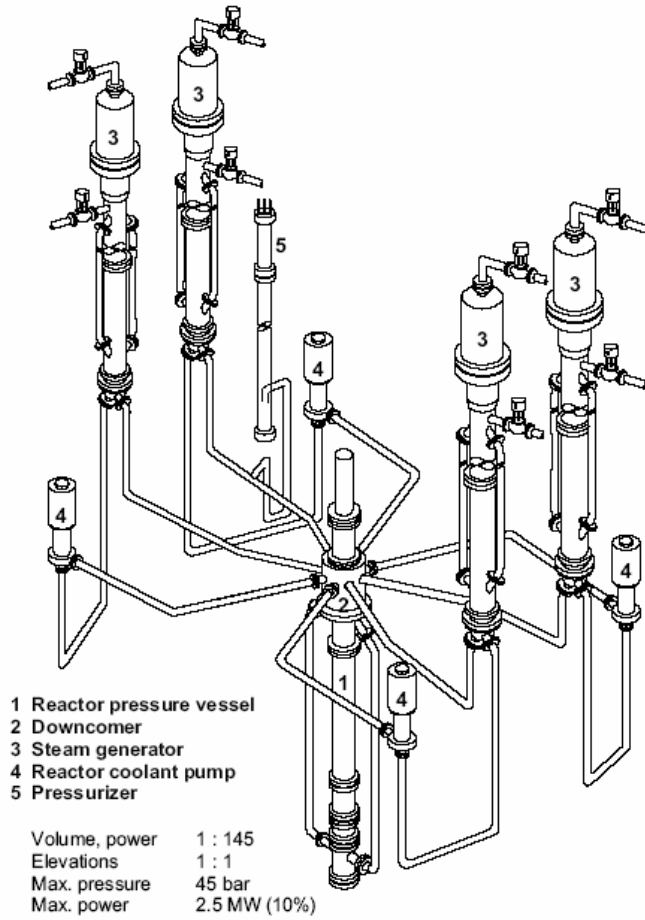


Figure 1: PKL test Facility

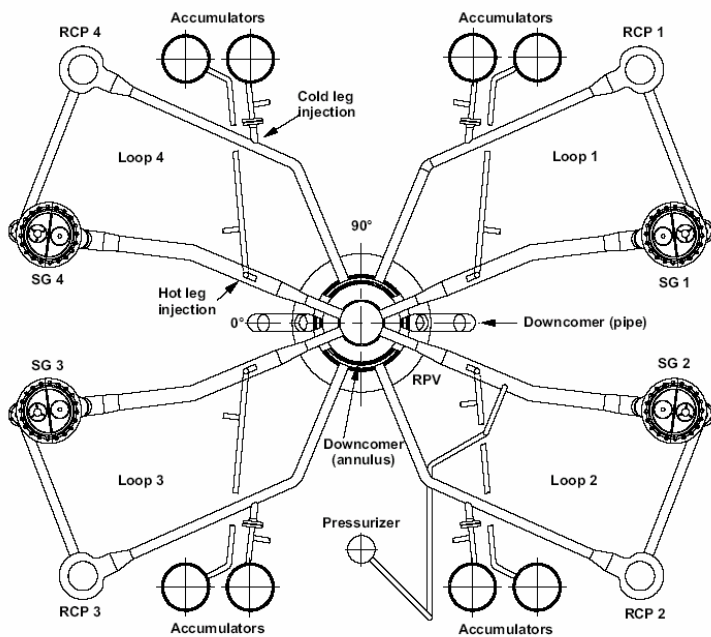


Figure 2: PKL test Facility (top view)