Sensitivity Studies on Reverse Natural Circulation in the PKL Facility by Using RELAP5mod3.2mz

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ABSTRACT

Prediction of pressure drops by wall friction and at geometric discontinuities is important in nuclear thermal hydraulics simulation. Pressure-drop models were established and upgraded for decades; however, errors in predictions of experimental data are up to 40%, namely in low flow and two-phase conditions and particularly at geometric discontinuities. In order to clarify the impact in situations of interest for nuclear reactors, noticeably accident scenarios investigated in scaled experimental facilities, a virtual benchmark on Reverse Natural Circulation (RNC) in the PKL test facility is being carried out (Ref. [1]), (Ref. [3]).

Since asymmetries between loops and bifurcations occurred in such virtual RNC, in this article sensitivity studies on the impact of the elimination of the loop seal, the impact of the adopted time step and the impact of the nodalization details have been performed by using RELAP5mod3.2mz.

1 INTRODUCTION

In water-cooled nuclear reactors (WCNRs), accident analysis using system thermal-hydraulic codes is important for confirming the adequacy and efficiency of the provisions in the defense in depth concept to cope with challenges to plant safety. Confidence in the code results depends strongly on the capability of modeling related thermal-hydraulic phenomena (THP) and validation through relevant experimental programs and/or real plant operational data. In 2018, a list of 116 THP was published (Ref [4]) and pressure drops are unquestionably important parameters in more than half of them. Flow Reversal (FR) condition in the entire primary loop or in selected parts of the primary loop is expected during several accidents belonging to the design basis condition (DBC) envelope. For example, in small break loss of coolant accidents (SBLOCAs), there is natural circulation (NC) at low flow rate in primary loop, causing reverse flow in some steam generator tubes or even in all tubes in the reflux condenser mode. Flow reversal occurs also in case of SBLOCA or large break loss of coolant accidents (LBLOCAs) in the cold leg of a pressurized water reactor (PWR) or again in case of reactor coolant pump (RCP) shaft break. Correlations for irreversible pressure drop coefficients have necessarily an empirical nature. The currently available database seems not to cover the whole range of parameters relevant to reactor conditions. In integral test facilities and in reactors, the available pressure measurements provide some information on irreversible pressure drops in positive flow conditions but not in reverse flow. In addition, the coverage of two-phase conditions is much less complete than for the single-phase case. Also, the quality of two-phase pressure loss models in two-fluid models and in three-field models is not very good. The current models are often based on old models developed for a mixture momentum equation with some arbitrary repartition between phases or between fields. No data are available to measure the actual friction force or wall pressure forces on each phase or each field. Therefore, inadequacies in predictive capabilities of pressure drop modeling risk to overshadow improvements and demonstration of qualification for various models in nuclear thermal hydraulics.

To clarify the impact in situations of interest for nuclear reactors, a virtual experiment (or benchmark) in Reverse Natural Circulation (RNC) in the PKL facility (Primary Coolant Loop Test Facility or, in German, Primärkreislauf-Versuchsanlage) (Ref. [2]) has been launched (Ref. [1]). RNC has been chosen because there are no measured pressure loss data available to determine the singular pressure drops coefficients in reverse flow. The PKL facility has been selected because BICs can be retrieved from direct natural circulation (DNC) studies performed in 2004 (F1.2 experiment) (Ref. [5]) and because the facility may be modified to obtain RNC.

Previous simulations (Ref. [3]) have predicted bifurcation events in two-phase NC and an asymmetrical behavior of the loops. In order to better understand the origin of the bifurcation and of the asymmetry, this work presents sensitivity studies performed by using RELAP5mod3.2mz on the impact of eliminating the loop seal, the impact of the adopted time step and the impact of the nodalization details.

2 BRIEF REVIEW OF THE PKL TEST FACILITY

The PKL facility models the nuclear steam supply system of a 1300 MW (electric) nuclear power plant on a scale of 1:145, and most of the secondary system (except for the turbine and condenser). Detailed design was based to the largest possible extent on the specific data of Philippsburg nuclear power plant, unit 2. As for other test facilities of this size, the scaling concept aims to simulate the overall thermal hydraulic behavior of the full-scale power plant.

The following features serve to meet the above requirement:

• Full-scale hydrostatic head (elevations scaled 1:1)

• Power, volume, and cross-sectional area scaling factor of 1: 145 (diameters scaled by a factor 12)

• Full-scale frictional pressure loss for single-phase flow (direct circulation)

• Simulation of all four loops

• 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 number of rods and U-tubes is scaled down by a factor 145 (314 electrically heated fuel rods, 28 U-tubes per SG).

• In cases of conflicting requirements, simulation of the phenomena was preferred over consistent simulation of the geometry, e.g., in order to account for important phenomena in the hot legs such as flow stratification and counter current 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 Reactor Pressure Vessel (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.

The operating pressure of the PKL facility is limited to 45 bar on the primary side and to 56 bar on the secondary side. This allows simulation over a wide temperature range (250°C to 50°C) that is particularly applicable to the cooldown procedures investigated.

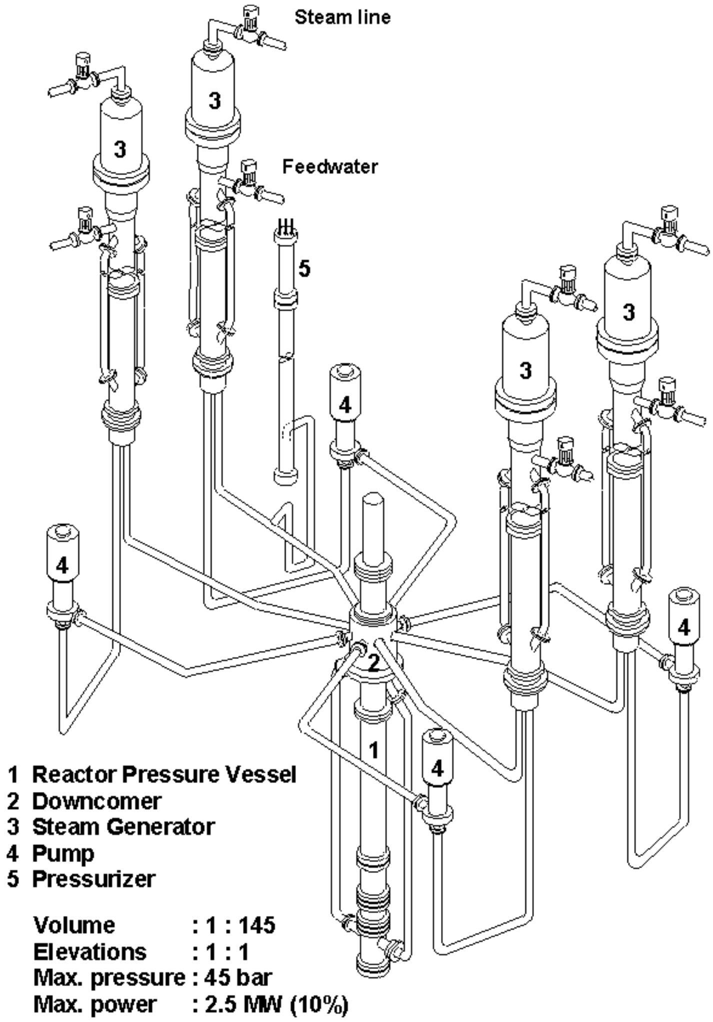

Figure 1. PKL test facility

2.1 Boundary and Initial Conditions

The Boundary and Initial Conditions (BICs) of the code calculations are based on a NC experiment performed in the PKL test facility in 2004 (Ref. [5]). In this test, the NC behavior in the primary loop was systematically investigated within a parametric study by a stepwise reduction and replenishment of the primary loop coolant mass. Water is drained as in F1.2 test from the vessel, in such a way to obtain the mass inventory shown in Figure 2. The BICs of this test are adopted for the calculations with the main difference that heat input is not considered in the core region (as in the experiment) but by an artificial heating system in the RPV downcomer (600kW in total) in order to establish RNC conditions.

Power in downcomer is equally subdivided in two downcomer pipes. Axial power profile is kept as in PKL core. The thermal power is supplied between the same elevation as the bottom of active fuel (BAF) and top of active fuel (TAF).

The pressurizer level is controlled till 4750s, after that instant the surge line is closed. Steam generators (SGs) pressure is kept as in F1.2 test. SGs level is controlled for 80s (12m as reference), then feed water (FW) keeps injecting during the whole transient 0.2 kg/s of water in total (differently from F1.2 test where the level was kept constant by manually adjusting the FW flow rate). The simulation starts with a steady state calculation for 1000s, in order to achieve stable one phase RNC.

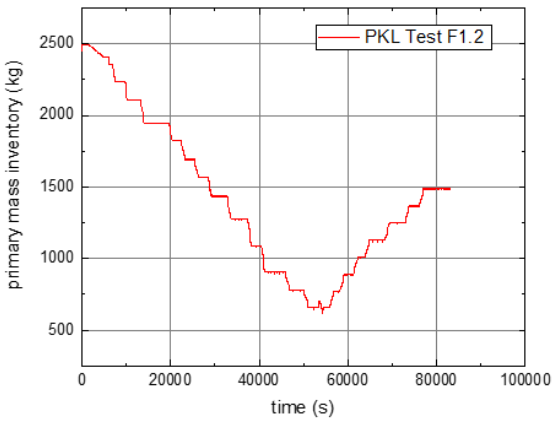

Figure 2. Primary mass inventory versus time

2.2 Adopted nodalizations

Five different nodalizations have been adopted.

1) In the reference nodalization the steam generator 28 U-tubes have been collapsed into one, with arrangements taken to preserve mass flow rate and pressure drops in one phase flow as well as heat transfer towards the secondary side. In figure 3 a sketch of the nodalization is reported.

2) The second nodalization is identical to the reference one with exception of the loop seal, which here has been virtually removed. The part of intermediate leg which is below the pump was replaced by a horizontal pipe at the same elevation as the pump and with a length such that the total pipe length from the SG outlet to the pump inlet is preserved. This nodalization has been adopted because, as shown in a previous research (Ref. [6]), the presence of loop seal in hot leg (VVER-440, same situation of loop seal in reverse natural circulation in PWR) causes bifurcation instabilities.

3) The third nodalization is as the first one but the steam generator U-tubes of the loop one and two have been modeled by 7 groups of U-tubes having different lengths. This modeling reproduces the 7 different U-tubes lengths present in the PKL facility. The reproduction of the U-tubes length has been proved to be necessary to correctly predict DNC (Direct Natural Circulation) flow rate evolution versus mass inventory , even if in that case it was of course applied to all four loops. Because of the limitations of the code version used, it wasn't possible to run the simulation by applying the mentioned level of detail to all four loops.

4) In the fourth nodalization, the steam generator U-tubes number has been increased to 7 for each loop. Respect to the previous case anyway the number of nodes used to represent each of the 7 U-tubes has been decreased, as well as the number of nodes used to depict the SGs secondary side.

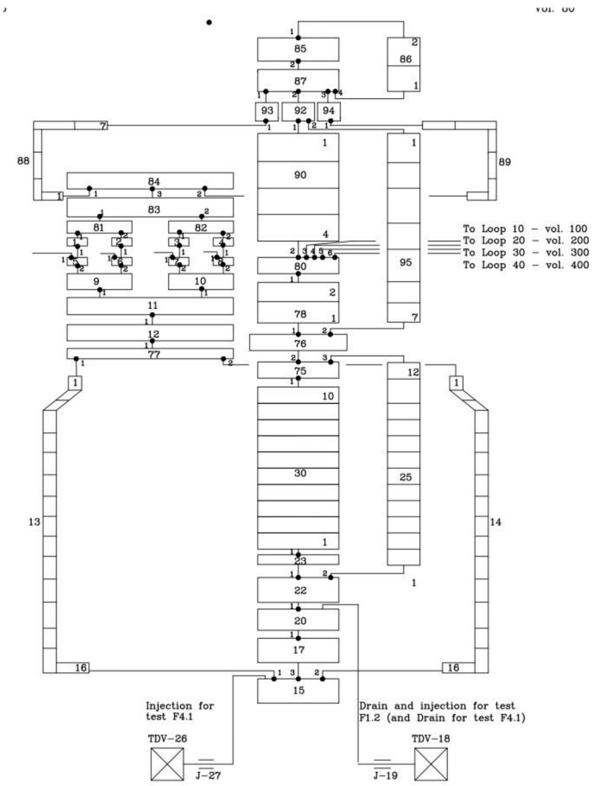

Figure 3. Reactor pressure vessel nodalization

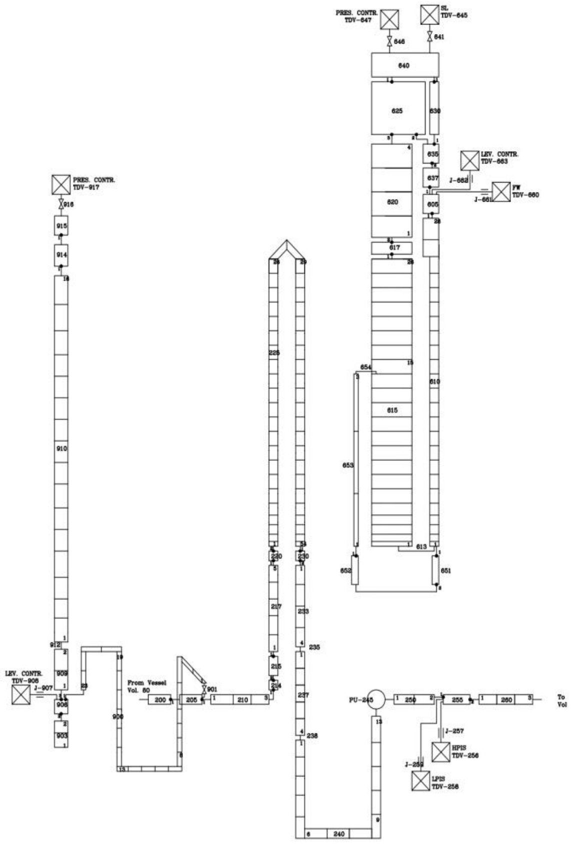

Figure 4. Loop 2 and SG secondary side nodalization, 1 U-tube SG

3 SENSITIVITY STUDIES

3.1 List of sensitivity studies

A. The reference case uses nodalization 1)

B. The first sensitivity study deals with the simulation of the transient performed by using the nodalization 2); in order to get the code running for a time long enough to see the SGs draining, the maximum time step in a specific time window (2410s-7700s) had to be reduced with respect to the one used in the reference case (from 0.1s to 0.01s).

C. The second sensitivity study uses the nodalization 1). The time step used is the same as in case B)

D. In the third sensitivity study, nodalization 3) is used.

E. In the fourth sensitivity study, nodalization 4) is used. During preliminary calculations, an un-physical pressure spike occurred in the secondary side, causing the calculation to halt. The pressure surge was caused by a combination of reverse flow in the SG downcomers and the use of a high singular reverse pressure drop coefficient. As a result, it was necessary to modify the singular reverse pressure drop coefficient at the bottom of the SGs downcomer. Specifically, the coefficient was changed from 1000 to 0.1 in the branches 551, 651, 751, and 851. The branches 551,751,851 belong to loop 1, 3 and 4 respectively, and correspond to the branch in loop 2 designated as 651 in figure 4.

BICs are the same for all the studies.

Table of calculations

Case n°	Nodalization	Notes
A	1	Reference case RNC
B	2	No loop seal RNC
C	1	Time step impact on RNC
D	3	2x7 U-tubes RNC
E	4	4x7 U-tubes RNC

3.2 Key results

In the reference case, RNC starts first in all loops until t=4500s. Then in two-phase conditions, RNC stops and starts again in loop 4 only , followed, in order, by loop 3 only, loop 2 only and loops 1 and 2 only. This can be observed, for example, both by looking at the loops flow rate in figure 5 and at the SGs collapsed level in figure 6, which behave asymmetrically.

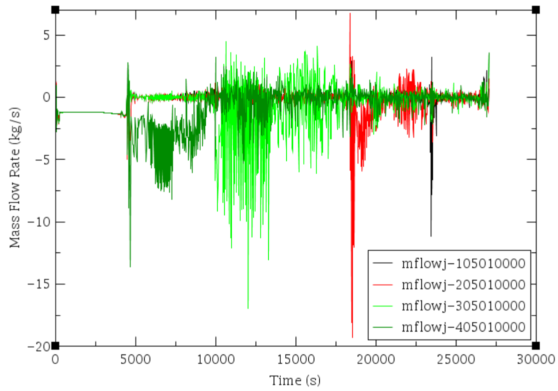

Figure 5. Mass flow rates in the four hot legs in case A

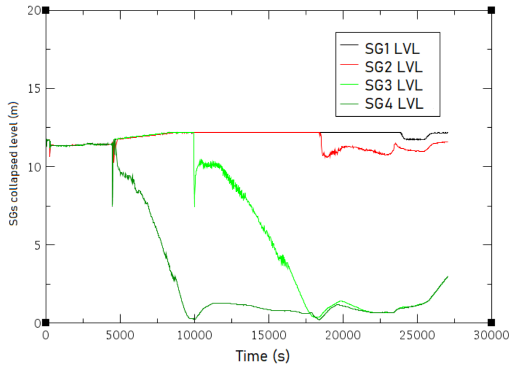

Figure 6. Steam generators collapsed level in case A

A. Horizontal loop seal impact on RNC

In this study we get a symmetrical behavior of the four loops, therefore asymmetry and bifurcation have to be attributed to the loop seal itself.

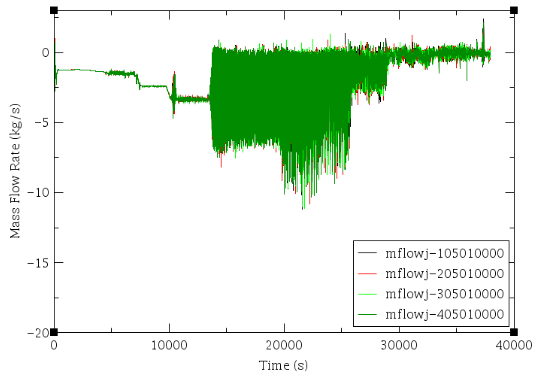

Figure 7. Mass flow rates in the four hot legs in case B

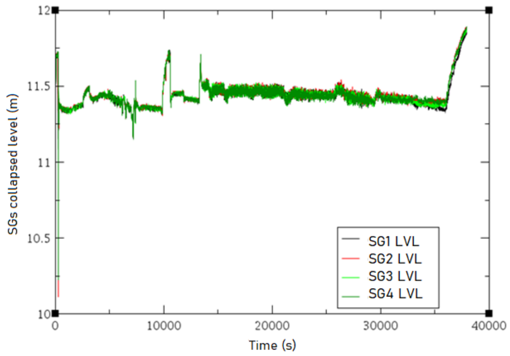

Figure 8. Steam generators collapsed level in case B

B. Impact of the time step adopted on RNC

In this case, after the restart of RNC we found again asymmetrical loops behavior but the order in which the loops start and stop working is now different from the reference case. In particular now the order is: 2, 1, 4, 3.

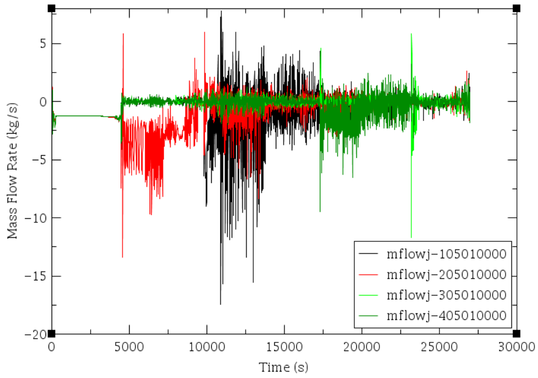

Figure 9. Mass flow rates in the four hot legs in case C

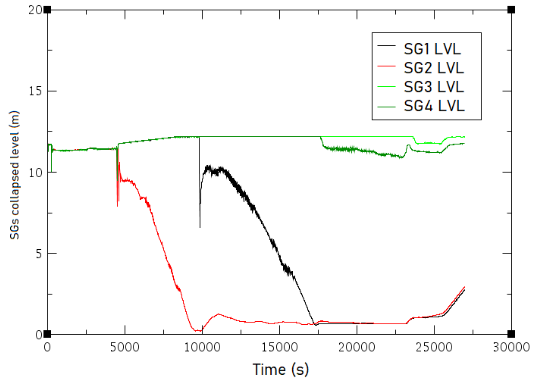

Figure 10. Steam generators collapsed level in case C

C. Impact of nodalization details: Two loops with 7 U-tubes mesh

Also in this case, after the restart of RNC we found asymmetrical loops behavior but now loop 1 starts, followed by some circulation in the other loops.

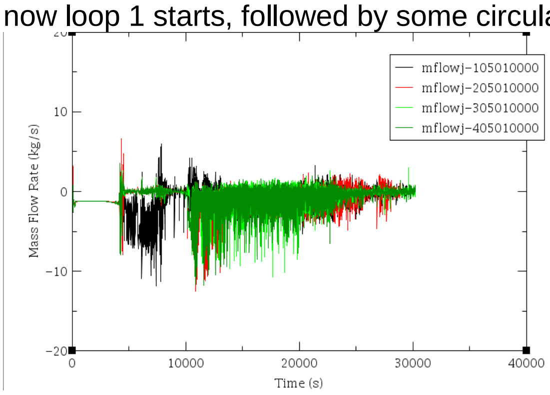

Figure 11. Mass flow rates in the four hot legs in case D

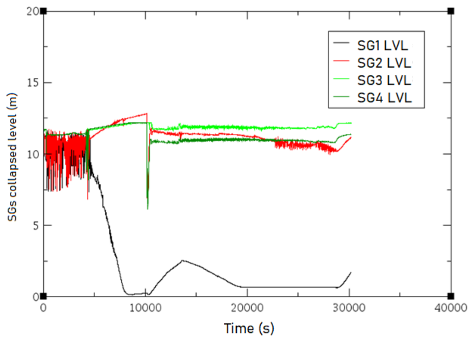

Figure 12. Steam generator levels in the four loops in case D

D. Impact of nodalization details: Four loops with 7 U-tubes mesh

The overall behaviour is qualitatively similar to case D but now circulation starts in loop 3. Moreover the code is able to simulate the transient for a time span 10'000s longer than in the previous case.

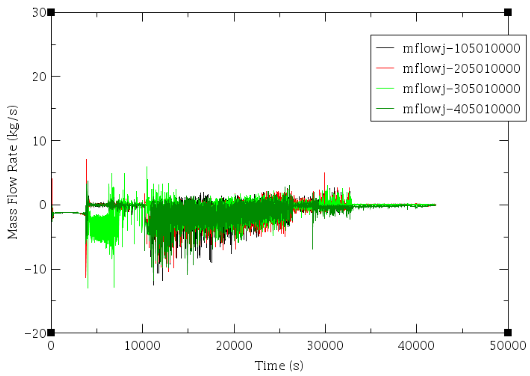

Figure 13. Mass flow rates in the four hot legs in case E

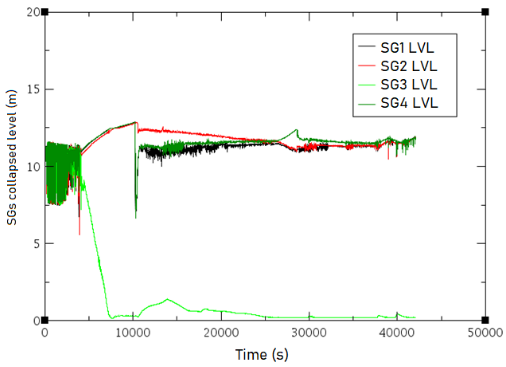

Figure 14. Steam generators collapsed level in case E

All the calculations stopped well before the replenishment phase of the coolant mass inventory because the flow rate in all the loops was very close to zero and this didn't allow heat removal from downcomer heat structures. Therefore critical heat flux occurred and heat structure temperature rose above 2000K, out of range for the thermal conductivity tables provided.

4 MAIN CONCLUSIONS

Final results of RNC showed strong dependence on nodalization and time step. When the loop seal is present, bifurcations and asymmetries always appear. The behavior may be explained as follows:

• The loop seal stops NC when the flow rate in cold legs becomes two-phase by creating an unfavorable gravity head (in upward and downward branches of the loop seal in the intermediate legs). This stop of NC and pressure increase was already observed in the ISP33 which investigated the NC in the PACTEL facility representing a VVER with a loop seal in the hot legs (Ref. [6])

• Following the stop of NC, the heat transfer to secondary circuit steeply decreases and the primary pressure increases, decreasing the void fraction in loops and changing the gravity head equilibrium.

• After a short period of time, the circulation is reestablished in one of the loops. The reason why it happens in loop 1 or 2 or 3 or 4 depends on very small differences between loops. But when it occurs in one of the loops it prevents circulation in the other loops until there is not enough water in the SG which received the whole power. A similar behavior is observed for the “loop seal plugging and clearing” during some SBLOCAs when the loop seal clearing occurs in one of the loops preventing loop seal clearing in the other loops (Ref [4]).

• The very small difference which decides that the NC starts in one of the loops first may be sensitive to changes in the time step, in the nodalization, in pressure losses, or any other change.

One may consider that the loop seal geometry creates a metastable state (stop of NC) that switches to another more stable state (NC with asymmetrical behavior). This bifurcation is not due to the pressure losses model and would remain even with a “perfect” pressure loss model.

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