ENERGY AND ENVIRONMENT DEPT. «DIPARTIMENTO DESTEC» – GRNSPG (San Piero a Grado)

UNIVERSITA' DI PISA
56100 PISA – ITALY

FONESYS
FORUM & NETWORK OF SYS-TH CODES IN NUCLEAR REACTOR THERMAL-HYDRAULICS

SILENCE Network
SIGNIFICANT LIGHT & HEAVY WATER REACTOR THERMAL-HYDRAULIC EXPERIMENTS NETWORK FOR THE CONSISTENT EXPLOITATION OF THE DATA

REVERSE NATURAL CIRCULATION VIRTUAL BENCHMARK ACTIVITY

Vincenzo Zingales, Qingling Cai,

Francesco D'Auria, Klaus Umminger, Dominique Bestion

IRUG meeting
INL meeting center, Idaho Falls, ID
December 4-8, 2023

THE BACKGROUND

IT IS DIFFICULT TO ADVANCE IN PREDICTIVE CAPABILITIES OF THERMAL HYDRAULIC SYSTEM CODES

- *Several motivations at the basis of the above statement.*
- *Disagreement among experts' opinions.*
- *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 (for WCNR) was published (Ref [4]) and pressure drops are unquestionably important parameters in more than half of them.*
- *Large errors in predicting Local (mainly) and Distributed pressure drops, as a function (mostly) of void fraction, Re, and geometry.*

THE OBJECTIVE-TARGET

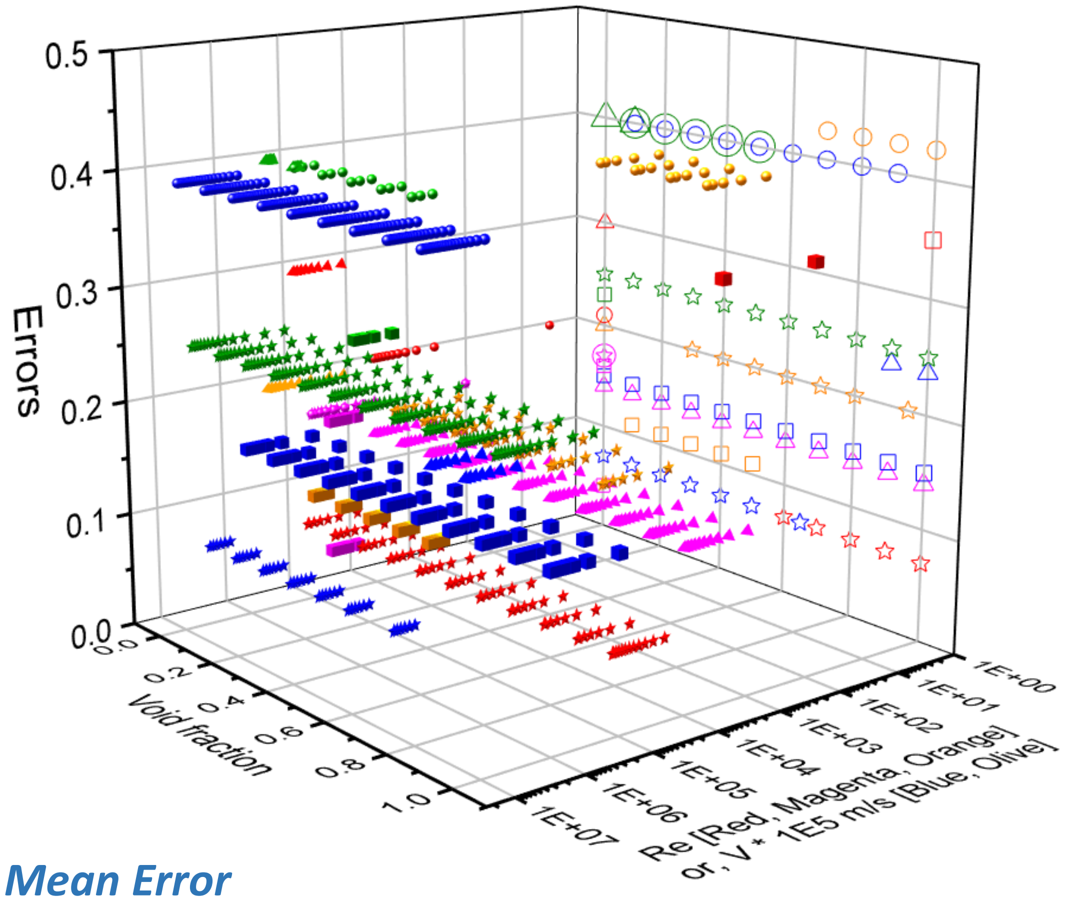
- ***To investigate to what extent improvements of pressure drop modeling are essential for the new generation of SYS TH codes.***

- **To demonstrate the importance of accurate values for individual local pressure drop coefficients a Reverse Natural Circulation (RNC) calculation benchmark in the PKL facility has been conducted.**
- ***To obtain*** **RNC, power has been moved from core to down-comer region.**

- ***Moving the progress in NTH (transient DBA conditions) needs improvement in predictive capabilities for pressure drop.***

PRESSURE DROP PREDICTIVE CAPABILITIES

Pressure drops Mean Errors vs Void fraction range vs Re number (or velocity) range



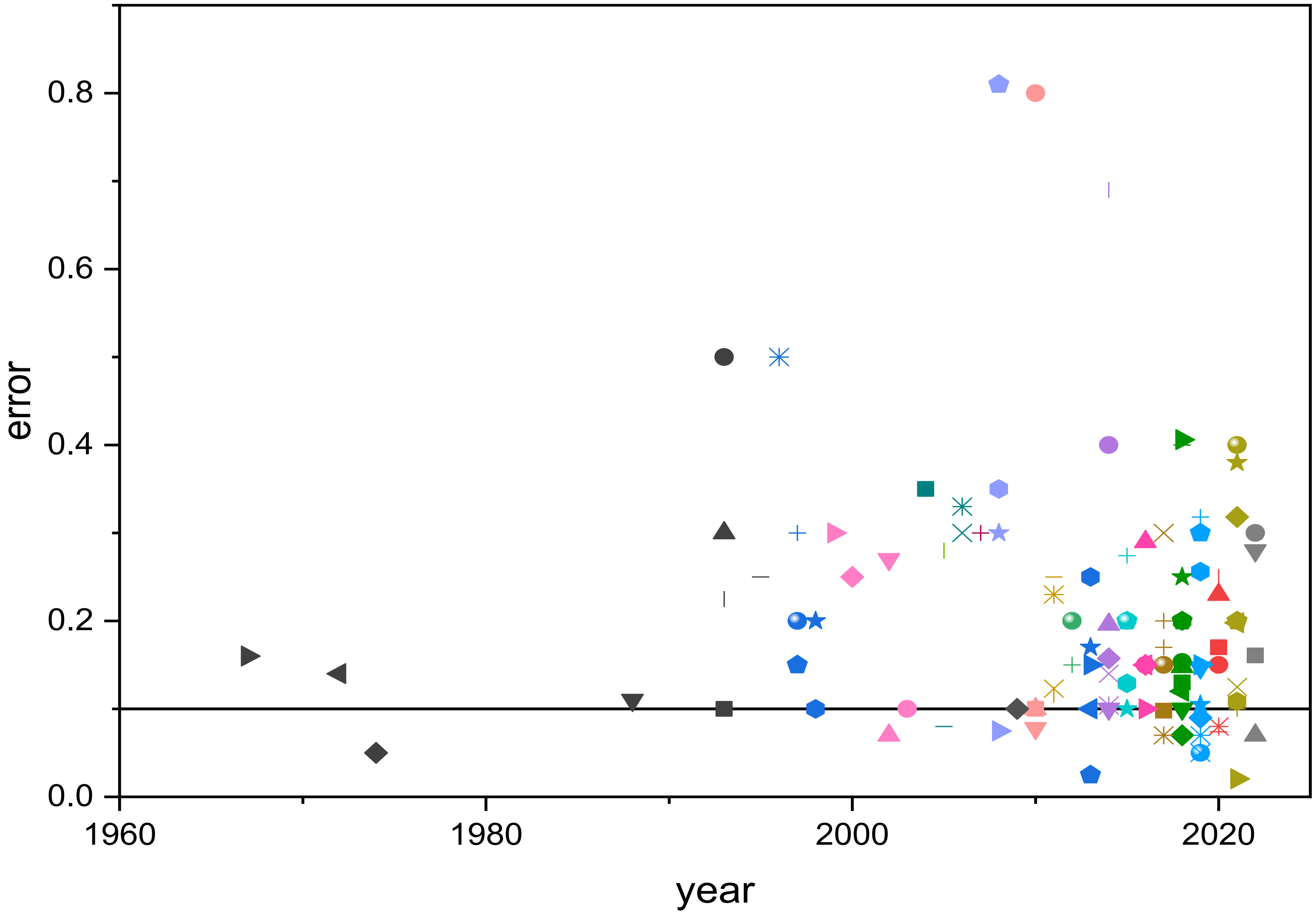
REFERENCE	Re (or Velocity) range	Void fraction range	MODEL (N-newly proposed model)	Error
Wu et al., 2022	30000-170000	0	N	30%
Liu et al., 2022	100-3000	1	modified CTD	35%
du Toit et al., 2021	10-10000	0	ERDIM	20.50%
Ferraris and Marcel, 2020	20000-124000	0-1	FEMA	7.40%
Ma et al., 2020	0-10000	0-1	RNG k-ε	13.80%
Demagh et al., 2020	20000-50000	0	Gnielinski	16%
Liang et al., 2020	300-100000	0	UCTD	17%
Chen et al., 2019	300-100000	0	UCTD	17%
Wang et al., 2018	30000-450000	0	N	19.70%
Bowden and Yang, 2016	158000-245000	0.1-0.5	N	11%
Yoo et al., 2022	690-5600	0.1-1	N	42.50%
Shi et al., 2018	10000-100000	0.02-0.5	N	20%
Hsu and Ferng, 2021	0.31-0.41(m/s)	0-0.1	N	40%
Li et al., 2020	0-0.02(m/s)	0	Ergun	23%
Wang et al., 2020a	0.2-0.4(m/s)	0.1-0.5	Sun-Mishima	40%
Wang et al., 2020c	0.25-6(m/s)	0-1	Lockhart-Martinelli	25%
Wang et al., 2020b	3-15(m/s)	0.9-1	Ishii-Zuber	23.67%
Zhou et al., 2019b	0.1-1(m/s)	0-1	Muller and Heck 1986	15%
Porter and Avramova, 2018	2.75-19.5(m/s)	0.1-0.9	CTF code	40%
Qiao and Kim, 2018	2-4(m/s)	0-0.65	Kim	7%

Mean Error

$$\bar{E} = \frac{1}{N}\sum_{i=1}^{N}\frac{(\Delta P_c - \Delta P_m)}{\Delta P_m}$$

PRESSURE DROP PREDICTIVE CAPABILITIES

Pressure drops Mean Errors vs year



REFERENCE	MODEL (N-newly proposed model)	ERROR
(Bovati et al., 2022)	CFD	16.1%
(Wu et al., 2022)	N	30.0%
(Liu et al., 2022)	N	35.0%
(Gui et al., 2022)	N	28.0%
(Al-Ani and Al-Dahhan, 2021)	Ergun	31.8%
(Arabi et al., 2021)	N	19.8%
(du Toit et al., 2021)	ERDIM	20.5%
(Kim et al., 2021a)	artificial neural network	10.8%
(Lopes et al., 2021)	CFD	38.0%
(Zhang et al., 2021)	N	20.0%
(Hsu and Ferng, 2021)	N	40.0%
(Kim et al., 2021b)	N	10.0%
(Cruz et al., 2021)	CFD	12.5%
(Sun et al., 2020)	N	8.0%
(Ferraris and Marcel, 2020)	FEMA	7.4%
(Jin et al., 2020)	N	25.0%
(Tairov and Khan, 2020)	N	17.0%
(Liang et al., 2020)	UCTD	15.0%
(Li et al., 2020)	Ergun	23.0%
(Guo et al., 2019)	CFD	14.7%
(Ewim and Meyer, 2019)	Carey 1992	9.0%
(Zhou et al., 2019b)	Muller and Heck, 1986	15.0%
(Ramesh and Gedupudi, 2019)	J.Yan et al. 2017	25.6%
(Chen et al., 2019)	UCTD	10.5%
(Loyola Lavín et al., 2019)	Blasius correlation for round ducts	30.0%
(Pereira et al., 2019)	N	5.0%
(Dang et al., 2019)	Kim	31.8%
(Bashir et al., 2019)	Poiseuille	5.0%
(Zhou et al., 2019a)	El-Genk	7.0%
(Porter and Avramova, 2018)	CTF code	40.0%
(Emadur Rahman and Singh, 2018)	N	15.0%
(Park et al., 2018)	N	13.0%
(Tikadar et al., 2018)	CFD	15.3%
(Chen et al., 2018)	UCTD	14.8%
(Guo et al., 2018)	N	10.0%
(Qiao and Kim, 2018)	Kim	7.0%
(Zhang et al., 2018)	N	12.0%
(Kim et al., 2018)	Warrier et al., 2002	40.6%
(Shi et al., 2018)	N	20.0%
(Wang et al., 2018)	N	25.0%
(Xiao et al., 2018)	N	20.0%
(Guo et al., 2017)	N	15.0%
(Shin and NO, 2017)	Thom	17.0%
(Kumar et al., 2017)	N	30.0%
(Kumar and Singh, 2017)	N	7.0%
(Zhu et al., 2017)	N	20.0%
(Yan et al., 2017)	N	20.0%
(Ma et al., 2017)	Filonenko	9.8%
(Cioncolini and Santini, 2016)	N	15.0%
(Chen et al., 2016)	N	29.0%
(Zhang et al., 2016b)	N	15.0%
(Zhang et al., 2016a)	N	15.0%
(Li et al., 2016)	CFD	10.0%
(Colombo et al., 2015)	N	12.9%
(Di Marcello et al., 2015)	ATHLET code	10.0%
(Osgouei et al., 2015)	modified Lockhart-Martinelli model	20.0%

REFERENCE	MODEL (N-newly proposed model)	ERROR
(Edvardsen et al., 2015)	CFD	20.0%
(Nilpueng and Wongwises, 2015)	Kakac and Liu	27.4%
(Chen et al., 2014)	CTD	14.0%
(Lee et al., 2014)	N	10.4%
(Wang et al., 2014)	N	19.1%
(de Oliveira and Barbosa, 2014)	Padilla	69.0%
(Yan et al., 2014)	Lee-Lee	35.0%
(Xia and Liu, 2014)	N	19.6%
(Manavela Chiapero et al., 2014)	Colebrook	10.0%
(Joyce and Soliman, 2014)	N	15.7%
(Li et al., 2013)	N	10.0%
(Baburajan et al., 2013)	N	15.0%
(Arment et al., 2013)	modified Kanizawa	25.0%
(Huang et al., 2013)	Mishima and Hibiki	17.0%
(Celen et al., 2013)	N	2.5%
(Fang et al., 2012)	N	20.0%
(Qin et al., 2012)	N	15.0%
(Asok et al., 2011)	CFD	12.3%
(Bai et al., 2011)	N	23.0%
(Venkatesan et al., 2011)	N	25.0%
(Ferroni et al., 2011)	N	11.6%
(Dedov et al., 2010)	Filonenko	10.0%
(Hejazi et al., 2010)	Lockhart-Martinelli	80.0%
(Shannak, 2010)	N	10.0%
(Qi et al., 2010)	N	7.8%
(Bharadwaj et al., 2009)	N	10.0%
(Pendyala et al., 2008)	N	7.5%
(Shannak, 2008)	N	35.0%
(Cioncolini et al., 2008)	corrected Lockhart–Martinelli	30.0%
(Biswas and Das, 2008)	N	81.0%
(Cheng and Chen, 2007)	N	30.0%
(Spedding et al., 2006)	N	30.0%
(Nilpueng and Wongwises, 2006)	Lockhart–Martinelli	33.0%
(Olekhnovitch et al., 2005)	N	8.0%
(Jamialahmadi et al., 2005)	N	28.0%
(Wen and Kenning, 2004)	Lockhart–Martinelli	35.0%
(Hwang et al., 2003)	Blasius	10.0%
(Yu et al., 2002)	modified Chisholm	7.0%
Warrier et al., 2002	N	27.0%
(Martin et al., 2000)	N	25.0%
(Chen and Guo, 1999)	N	30.0%
(Ogino and Yamamura, 1998)	N	10.0%
(Fukano and Furukawa, 1998)	N	20.0%
(Kojasoy et al., 1997)	N	15.0%
(Conlin et al., 1997)	neural network.	20.0%
(Tong et al., 1997)	N	30.0%
(RAVIGURURAJAN and BERGLES, 1996)	N	50.0%
(Wang et al., 1995)	N	25.0%
(Sakaguchi et al., 1993)	N	22.5%
(Manglik and Bergles, 1993)	N	10.0%
(Panchal and France, 1993)	N	50.0%
(Buel et al., 1993)	N	30.0%
(Chun and Oh, 1988)	N	11.0%
(Lawn, 1974)	N	5.0%
(Novendstern, 1972)	N	14.0%
(Lopina and Bergles, 1967)	N	16.0%

PKL RNC

Why RNC…

- *Flow reversal (FR) occurs in many DBA accident scenarios*

  (e. g. LBLOCA in cold leg, RCP shaft break).

- *RNC scenario implies low-flow (low Re) pressure drops that are sensitive and subject to large prediction errors.*

- *No adjustments could be made to the input decks, because RNC was not experimentally investigated in the PKL facility.*

Why PKL…

- *PKL is owned by a member of SILENCE (FRAMATOME, Germany).*

- *The facility may be eventually modified to reproduce RNC.*

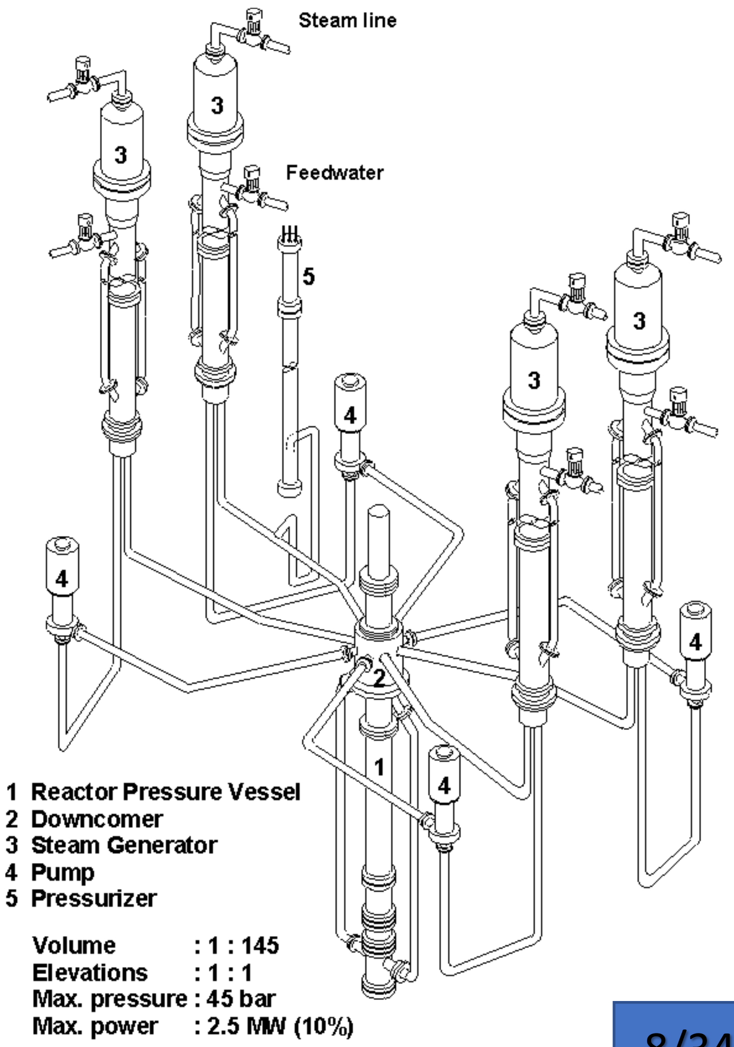
- *BICs can be retrieved from the DNC experiment PKL test F1.2, which was conducted in 2004*

- *For the PKL test F1.2 qualified code calculations and nodalizations are available.*

KEY RESULTS FROM PKL RNC CALCULATION

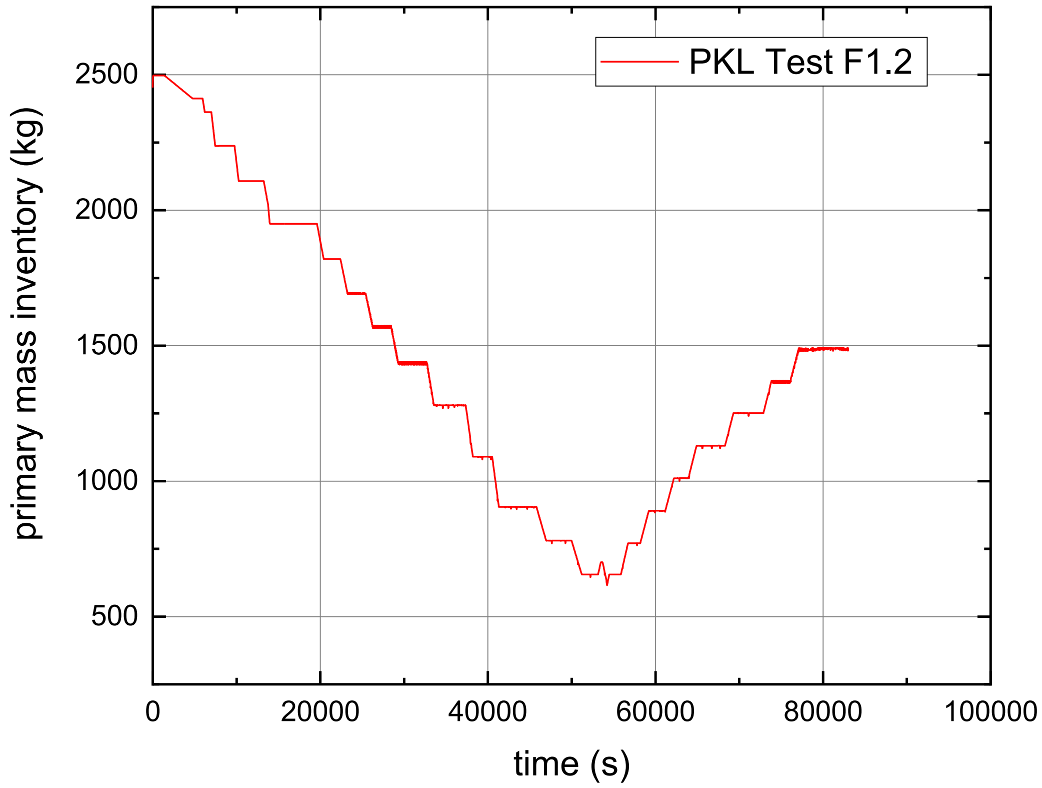
RNC Boundary and Initial conditions

	Experimental Data of Direct Natural Circulation (PKL Test F1.2 in 2004)	Initial Conditions [1] of RNC (Reverse Natural Circulation)
Primary coolant inventory	2540 kg (40 kg in PZR)	2540 kg
Core power/DC power	600 kW	600kW
Primary pressure	12 bar	12 bar
Temperature at core outlet	457 K	457 K
Subcooling at core outlet	4 K	4 K
Fluid temperature pressurizer	461 K	461 K
Pressurizer Pressure	12 bar	12 bar
Pressurizer level	1.3 m	1.3 m
Mass flow in all 4 loops	1.23 kg/s per loop	1.25 kg/s per loop
Main steam pressure in all 4 SGs	5.9 bar	5.9 bar
Main steam temperature	431 K	431 K
Collapsed level in all 4 SGs	12 m	12 m
Mass Flow Rate of Feedwater	0.2kg/s in total	0.2kg/s in total
Total Heat Loss	100kW	100kW



KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

Primary Mass Inventory



In F1.2 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**.

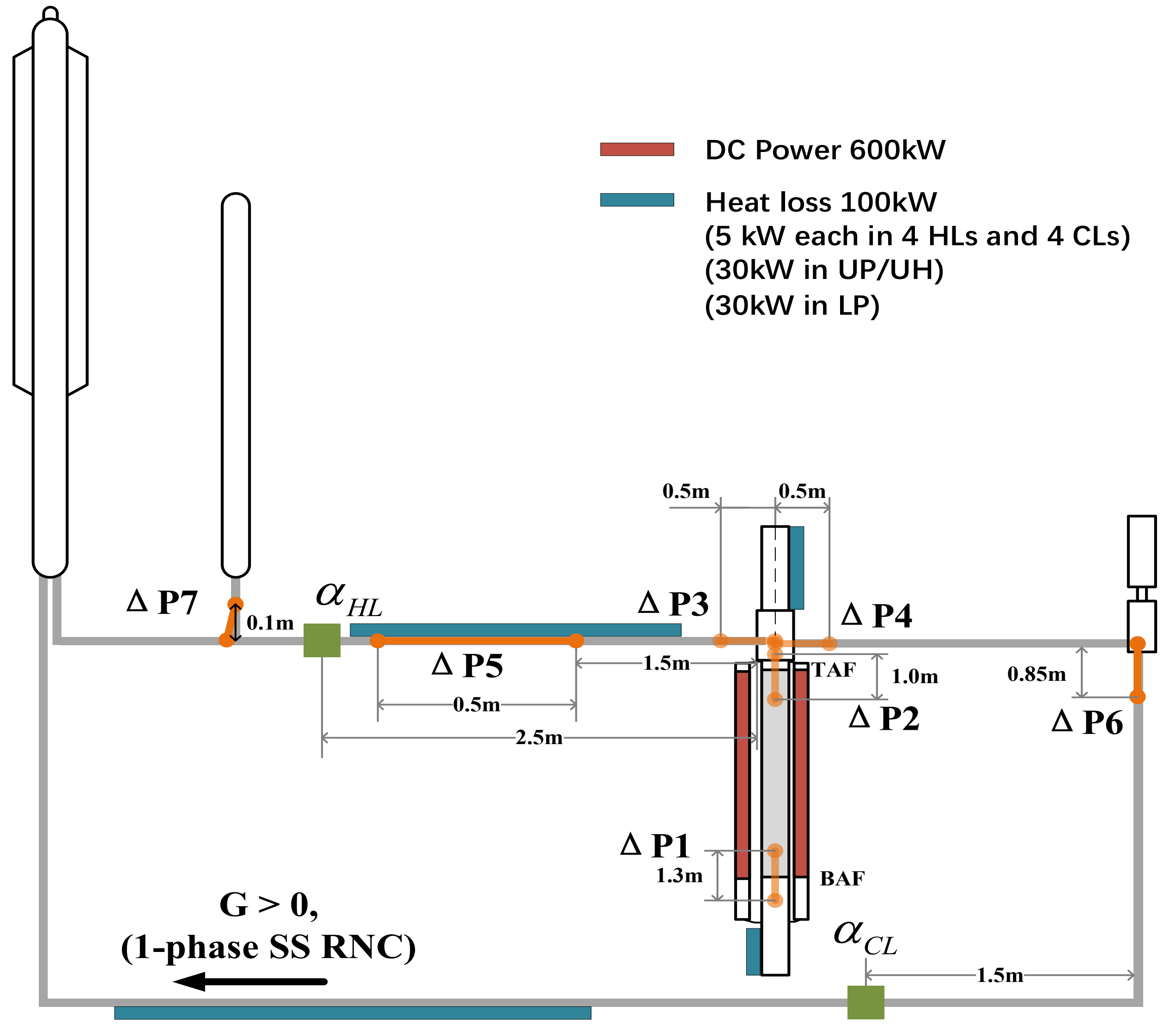
KEY RESULTS FROM PKL RNC CALCULATION

OUTPUT PARAMETERS (every 1 second)

1	Core Flow Rate (kg/s)
2	Collapsed level in all 4 SGs
3	Liquid temperature at the left downcomer pipe outlet (K)
4	Liquid temperature at the left downcomer pipe inlet
5	CL flow rate, G(CL) (4) in kg/s
6	HL void fraction of volume 2.5m from core outlet, $\alpha(HL)$
7	CL void fraction at loop seal bottom, $\alpha(CL)$
8	$\Delta P1 = P(LP) - P(\text{active core}) - \rho g \Delta h1$ in Pa, $\Delta h1=1.3m$ as in Page 12
9	$\Delta P2 = P(\text{active core}) – P(UP/UH) – \rho g \Delta h2$ in Pa, $\Delta h2 = 1.0m$ as in Page 12
10	$\Delta P3 = P(\text{core outlet}) - P(\text{HL, 0.5m from core outlet})$
11	$\Delta P4 = P(\text{CL, 0.5m from DC vessel}) - P(\text{downcomer vessel})$
12	$\Delta P5$ = Pressure drop on HL within 0.5m, 1.5m to core outlet as in Page 12
13	$\Delta P6 = P(\text{pump outlet}) - P(\text{pump inlet}) + \rho g \Delta h6$, $\Delta h6$ is the pump length
14	$\Delta P7 = P(PRZ) - P(HL) – \rho 7 g \Delta h7$, shown in fig. 3

KEY RESULTS FROM PKL RNC CALCULATION

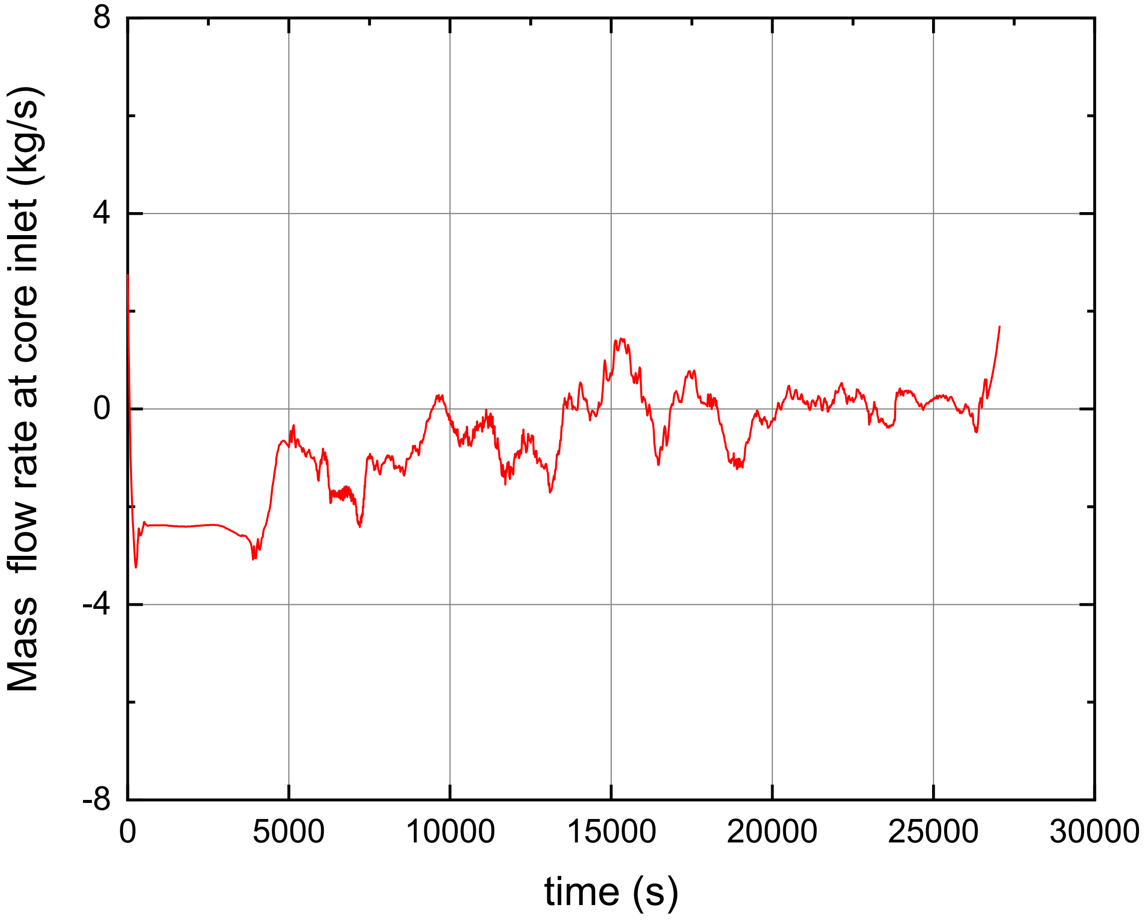
PKL sketch with requested quantities namely ΔP1 to ΔP7



In RELAP5 input deck, MCPs are vertically upward.
Elevation change (length) is 0.565m.
ΔP6 is the pressure drop between pump inlet and outlet.

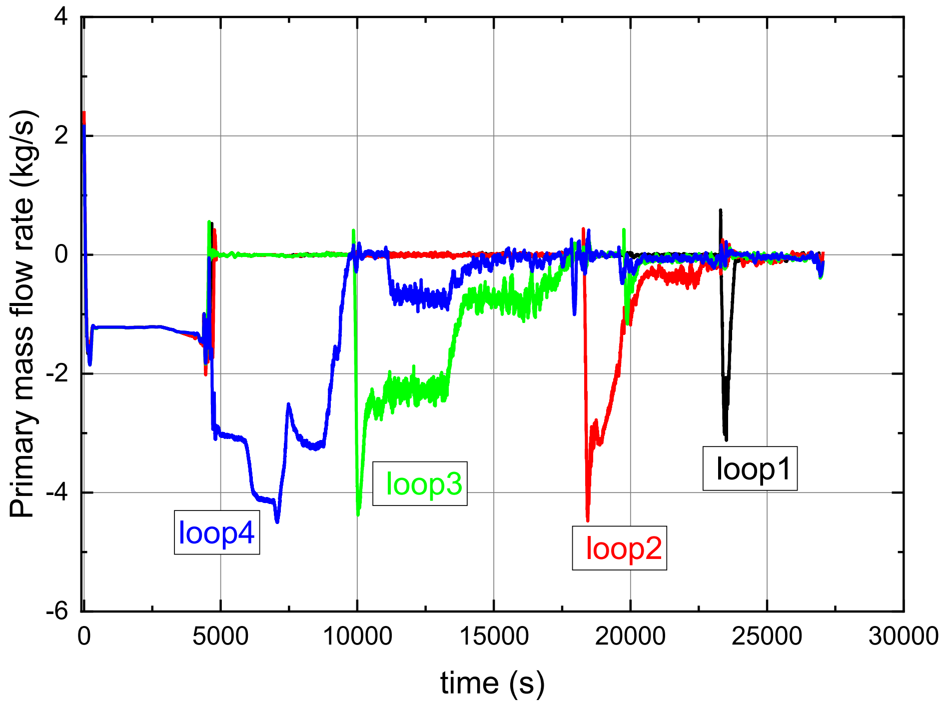
KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

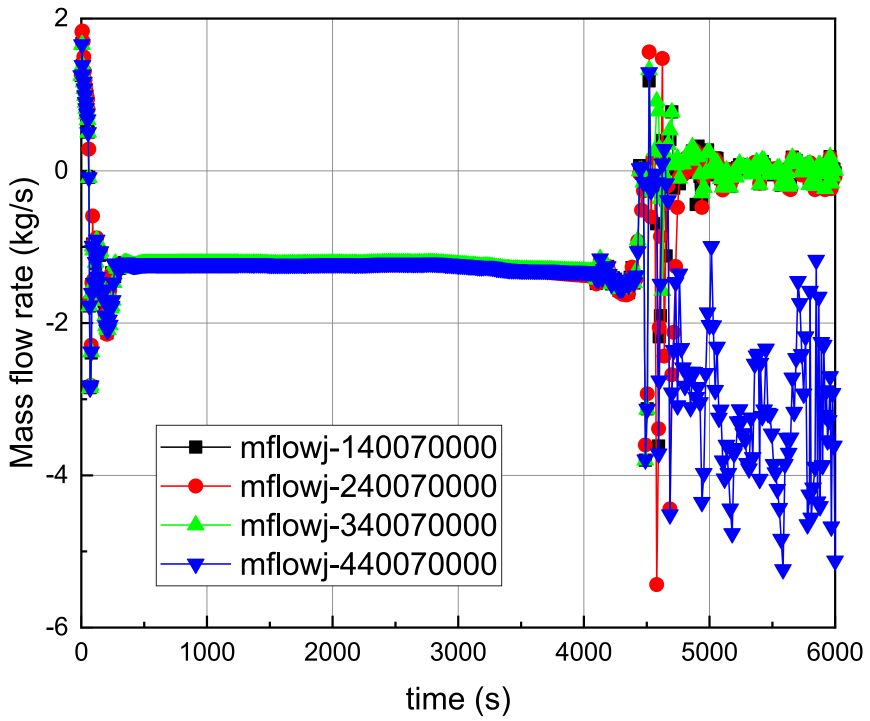
Core Mass Flow



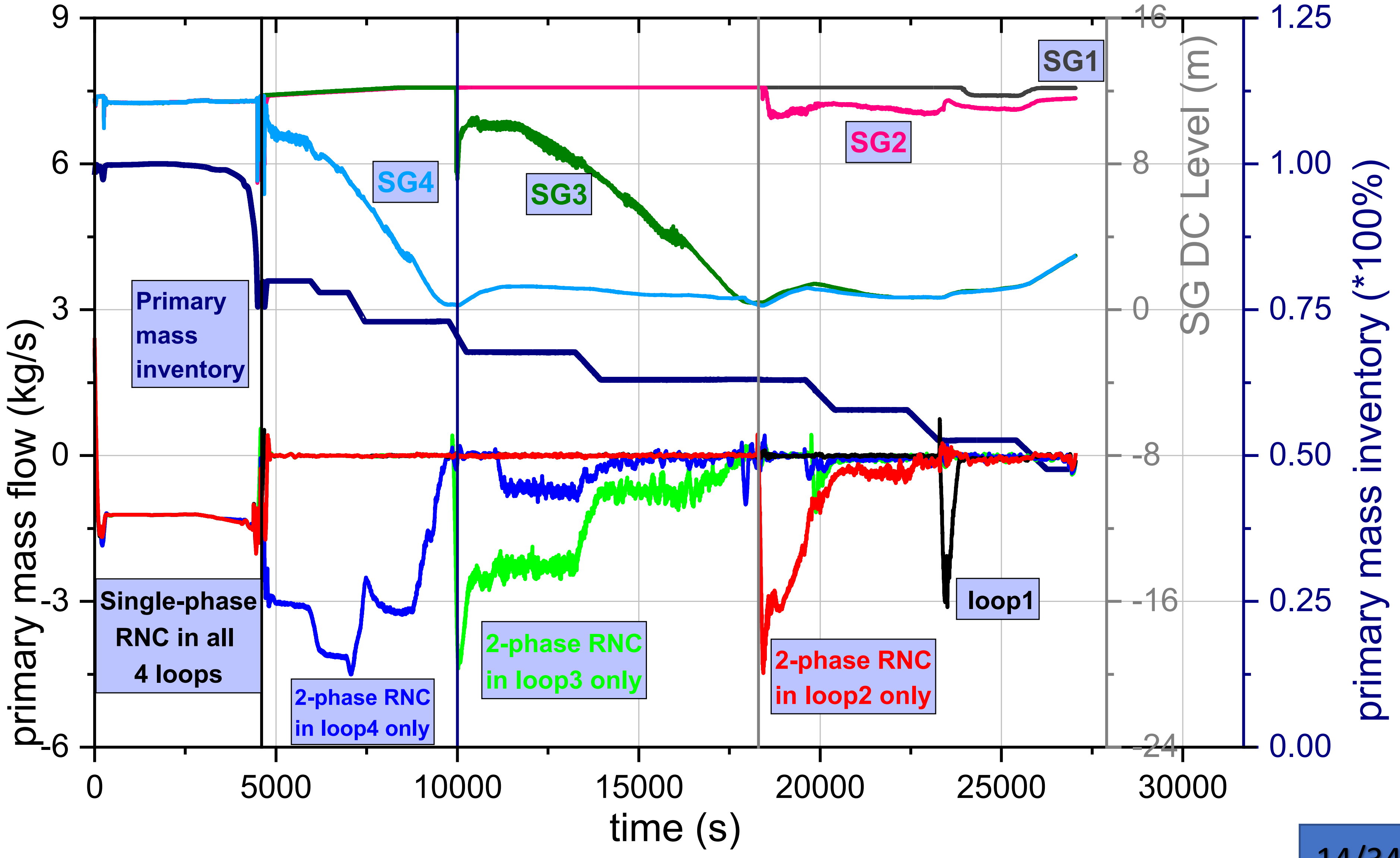
KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

Mass Flow Rate in HLs





KEY RELAP5 RESULTS FROM PKL RNC CALCULATION



KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

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
- Following the stop of NC, the heat transfer to secondary circuit steeply decreases and the **primary pressure increases, changing the gravity head equilibrium.**
- After a short period of time, the **circulation is reestablished in one of the loops**. It happens in a specific loop **because of 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.**
- **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 necessarily due to the pressure losses model and would remain even with a “perfect” model.
- The calculation stops because of CHF in the downcomer heat structures.

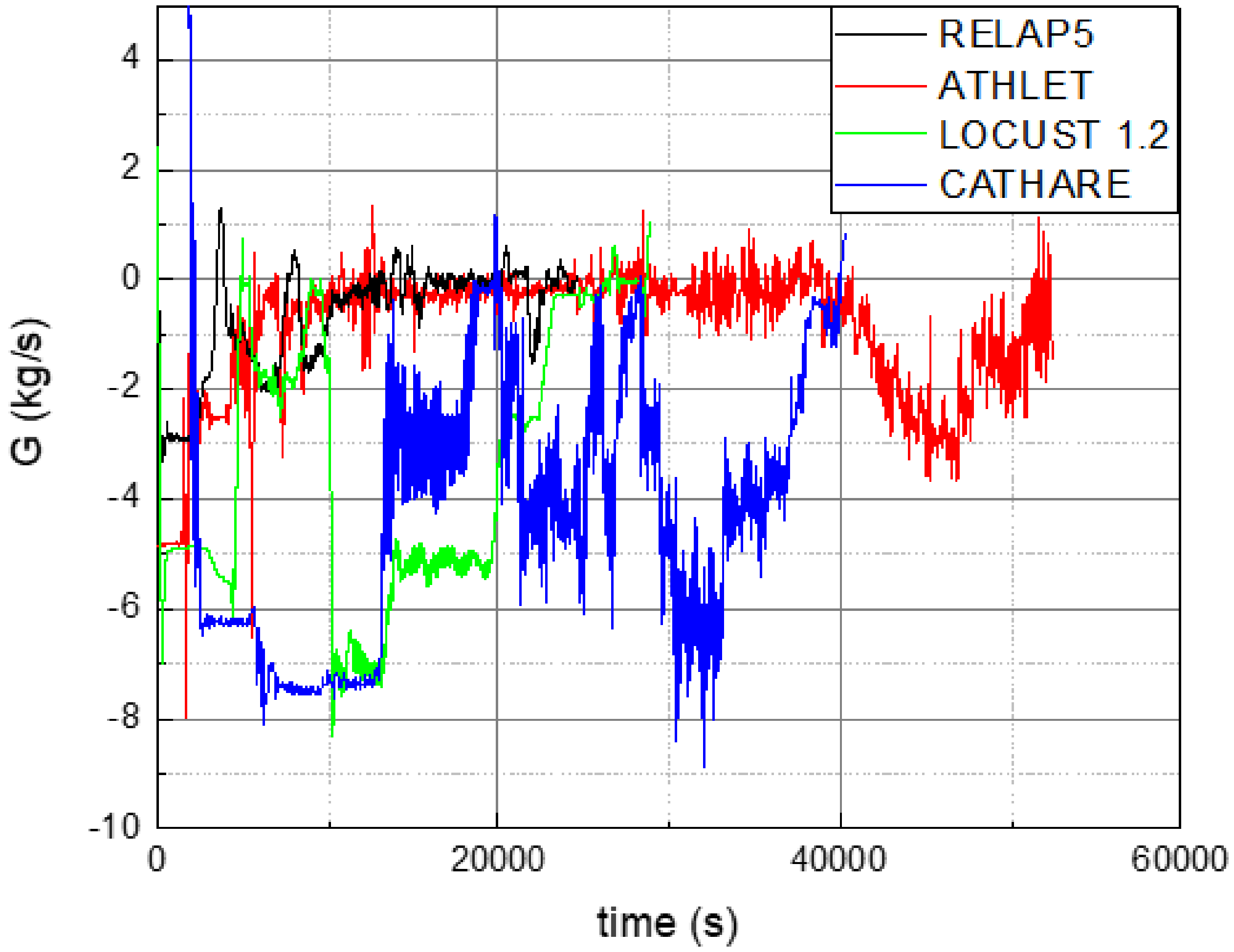
KEY RESULTS FROM PKL RNC CALCULATION

Participants and Submission record

Country/Organization	Code	Submission date
Italy/UNIPI	RELAP5/mod 3.3	Dec 1, 2022
Germany/GRS	ATHLET	Dec 16, 2022
France/EDF	CATHARE	Dec 22, 2022
China/CNPRI	LOCUST 1.2	Jan 11, 2023

KEY RESULTS FROM PKL RNC CALCULATION

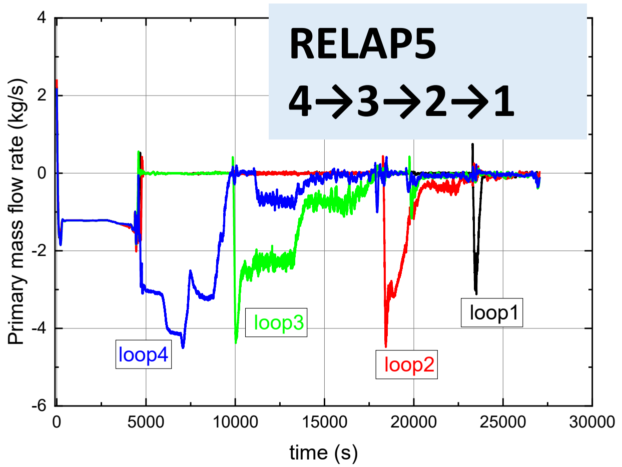
Core mass flow rate

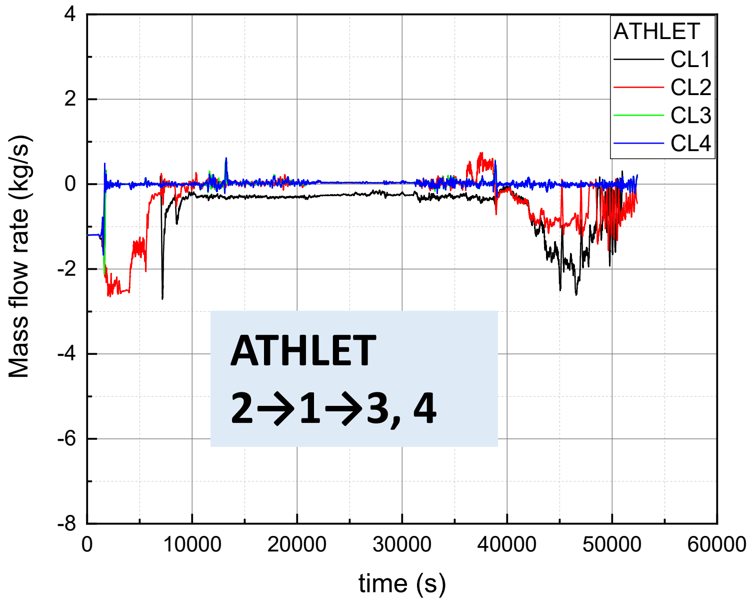


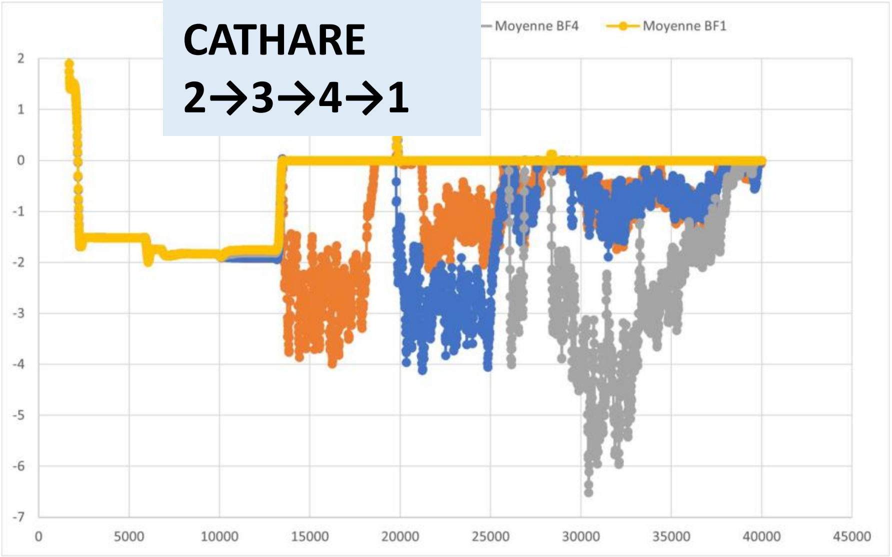
CATHARE calculation includes core bypass flow

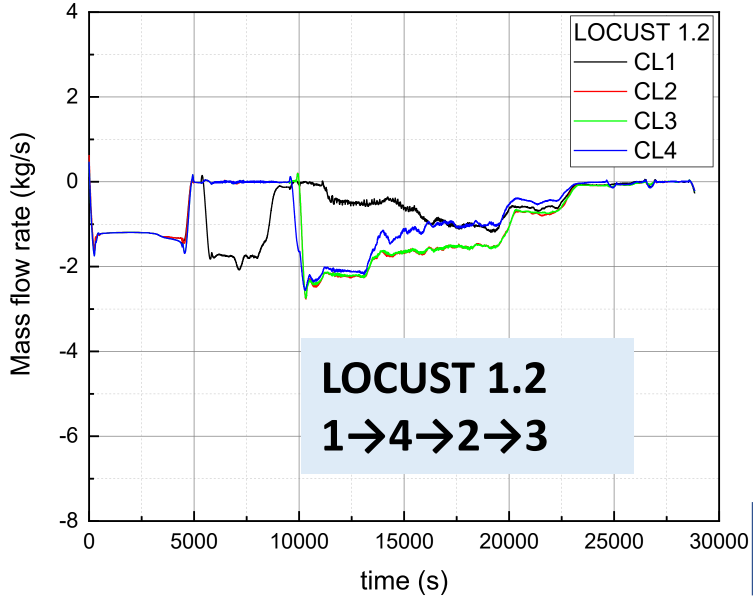
KEY RESULTS FROM PKL RNC CALCULATION

Mass flow rate in CLs



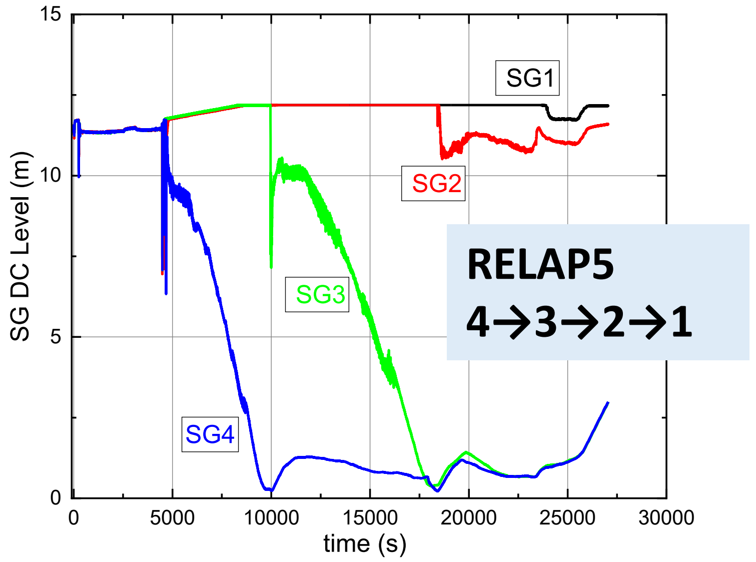


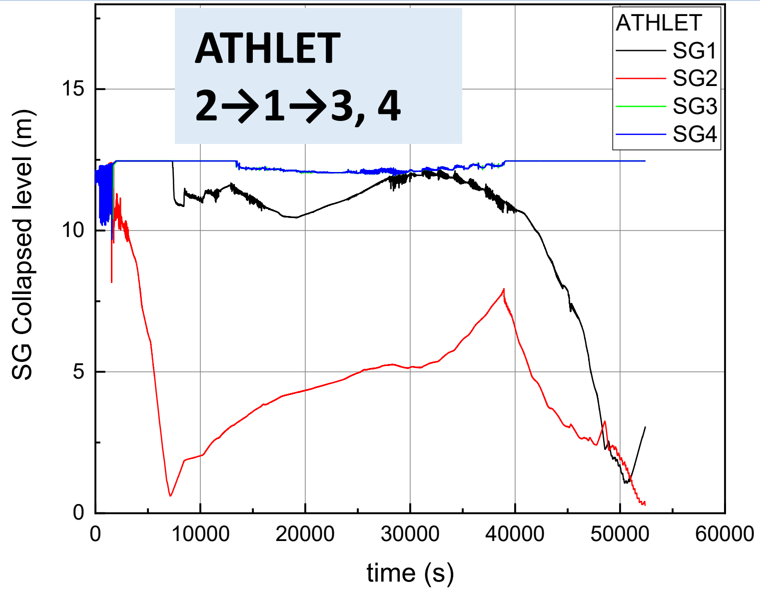


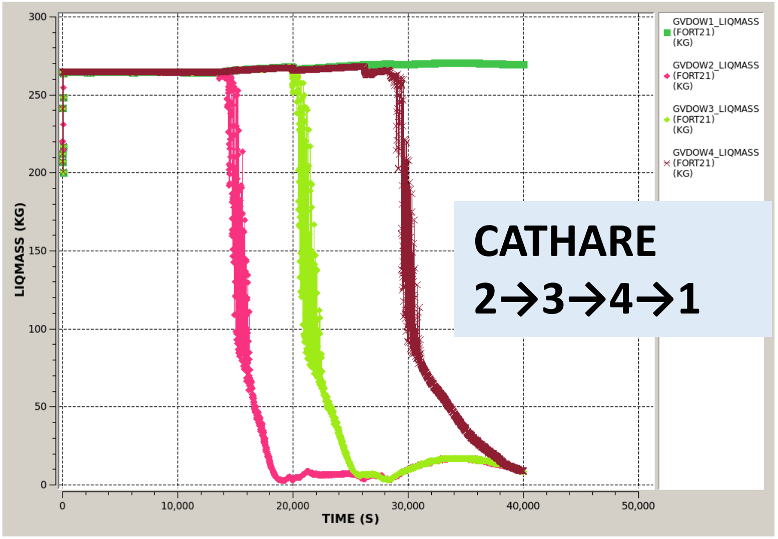


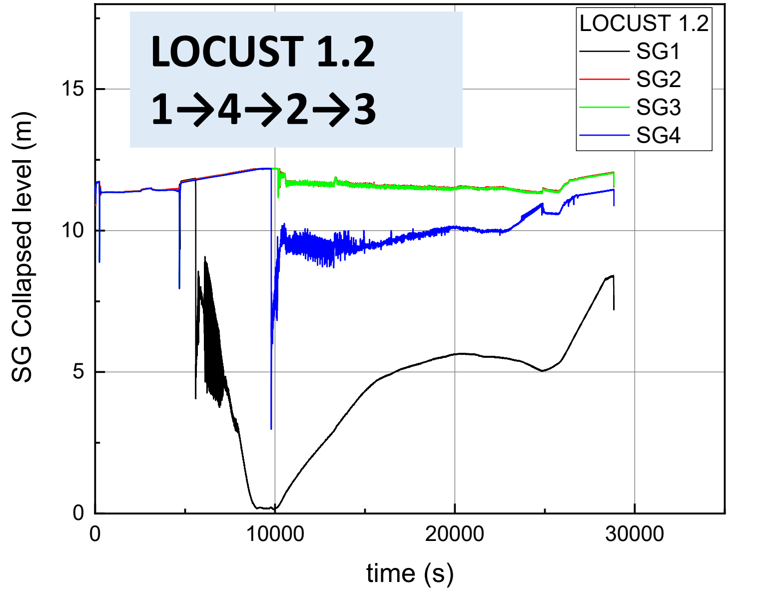
KEY RESULTS FROM PKL RNC CALCULATION

SG collapsed level



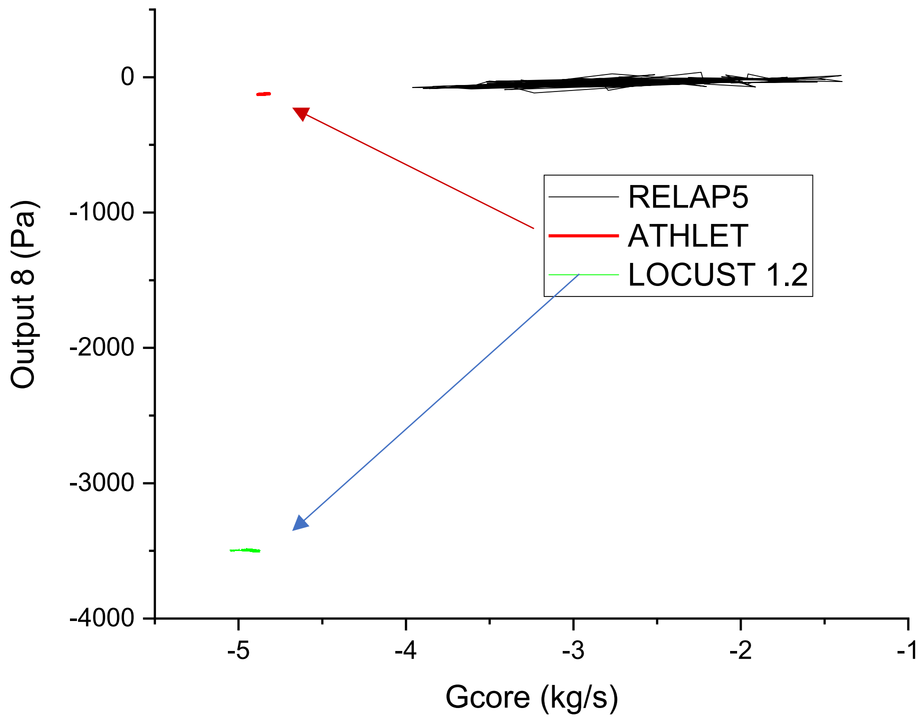




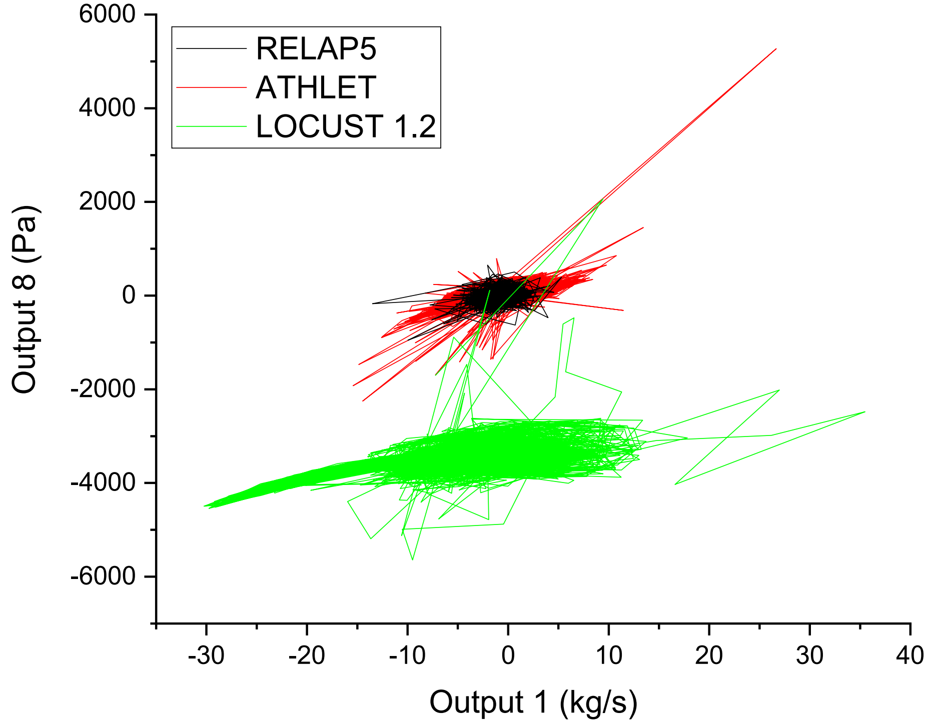


KEY RESULTS FROM PKL RNC CALCULATION

ΔP1(ΔP between core and lower plenum) vs. Gcore



Single-phase



Two-phase

RELAP5 RESULTS FROM PKL RFC CALCULATION

Pressure line

We believe that differences in code results in RNC can be attributed not only to errors in two-phase pressure drops but also to the possibly different "pressure lines" (static pressure + hydrostatic pressure along the loop) predicted.

To provide substantiation to this idea, a calculation was performed on single-phase steady state RFC (Reverse Forced Circulation).

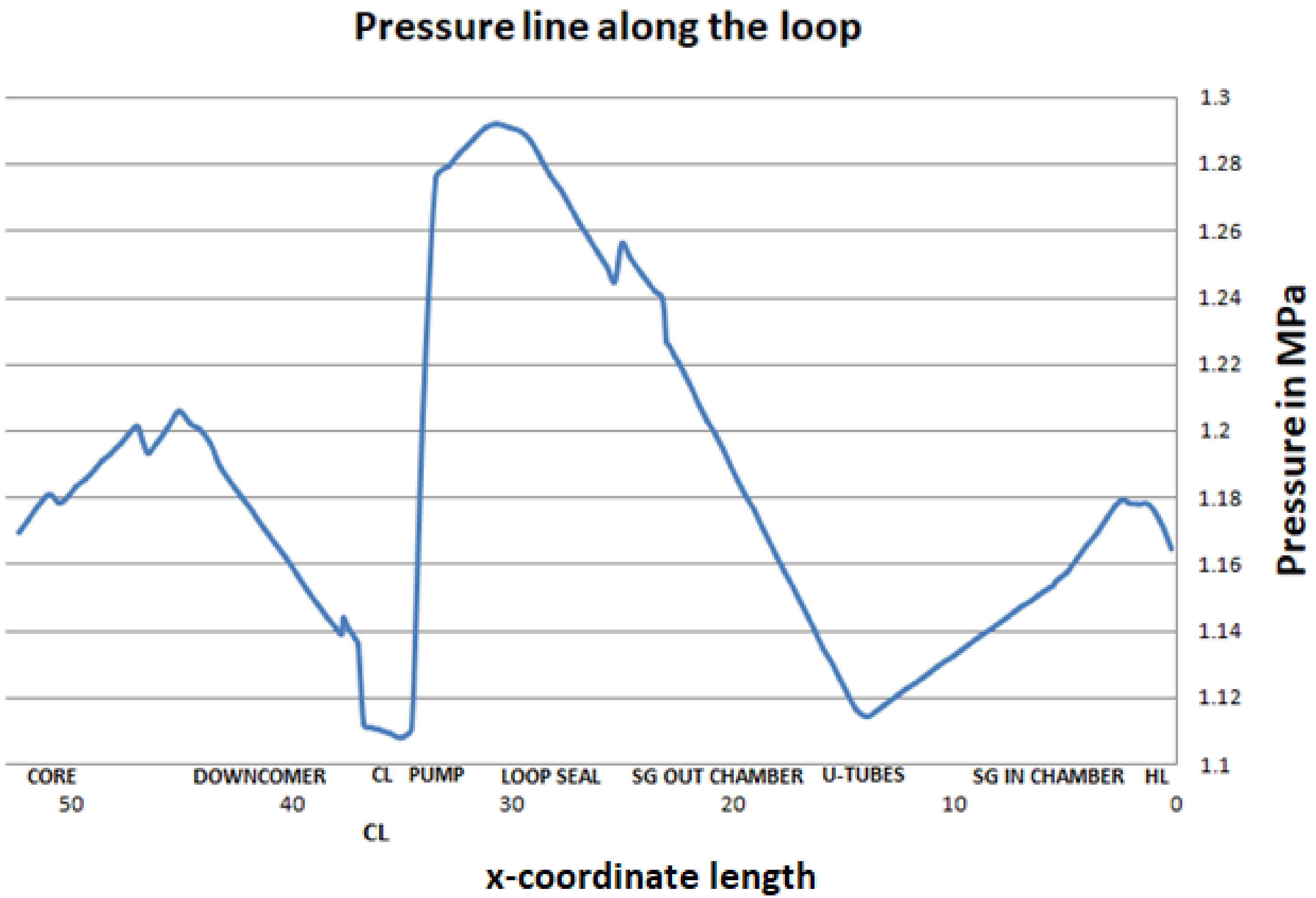
- **Single-phase:**
  Smaller errors in correlations
  Better precision in measurements

- **The nodalization of the PKL facility has been kept as in F1.2, except for the directions of the pumps.**

- **Feedwater flow and pumps speed have been adjusted in order to get one-phase steady state RFC.**

RELAP5 RESULTS FROM PKL RFC CALCULATION

Pressure line by RELAP5



ON THE RELEVANCE OF THE PRESSURE LINE

Design of experimental facilities:

Plant and facility should have the same pressure line.

Different pressure lines may bring different dynamic behaviour of a system (even if the total pressure drops along the loop are the same).

Code validation:

If the code is not able to predict the pressure line in the facility in forced circulation, then it would not be reasonable to assume that the prediction of the system behaviour in NC is correct.

KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

Four sensitivity studies have been carried out to better understand the dependence of RNC results on nodalization detail and time step choice.

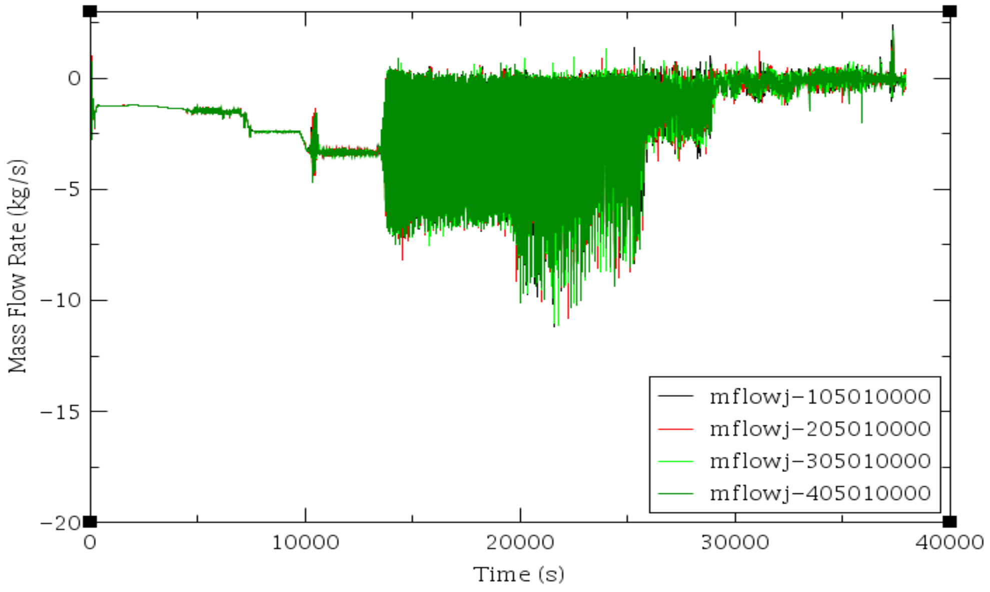
1. Horizontal loop seal impact on RNC
2. Time step choice impact on RNC
3. 2x7 U-tubes SG impact on RNC
4. 4x7 U-tubes SG impact on RNC

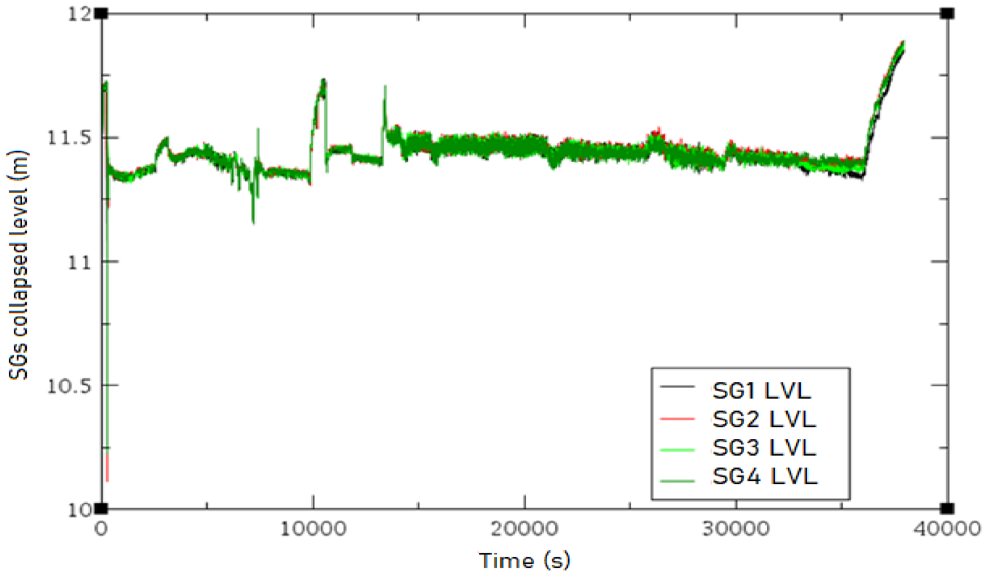
KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

1. Horizontal loop seal impact on RNC

The loop seals were replaced by pipes at the same elevation as the pumps and with a length such that the total pipe length from the SG outlet to the pump inlet is preserved.
In this study we get a **symmetrical** behavior of the four loops, hence asymmetry and bifurcation can be attributed to the loop seal.

This nodalization has been adopted because, as shown in **ISP33**, the presence of loop seal in hot leg (Pactel facility for VVER-440, same situation of loop seal in RNC in PWR) causes bifurcation instabilities.

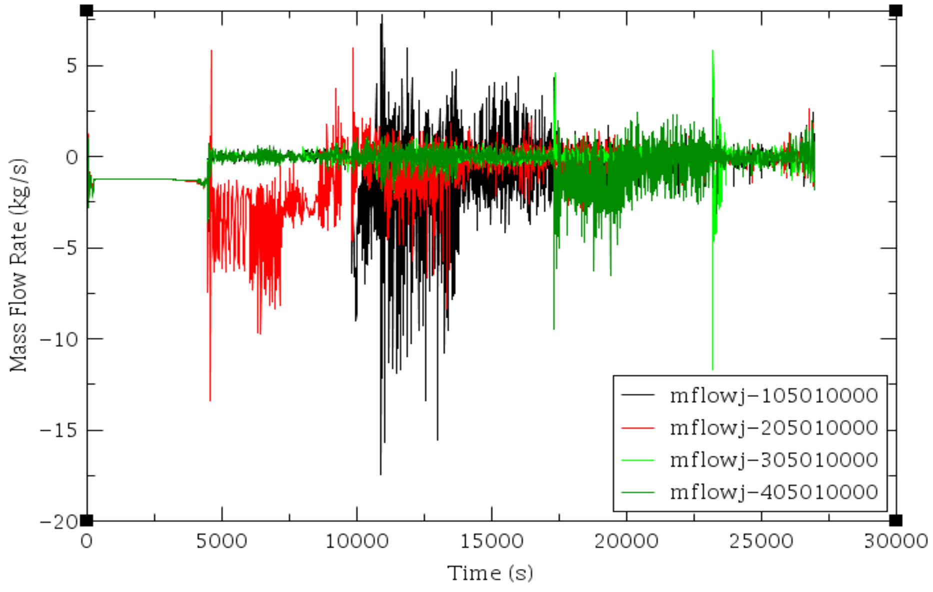


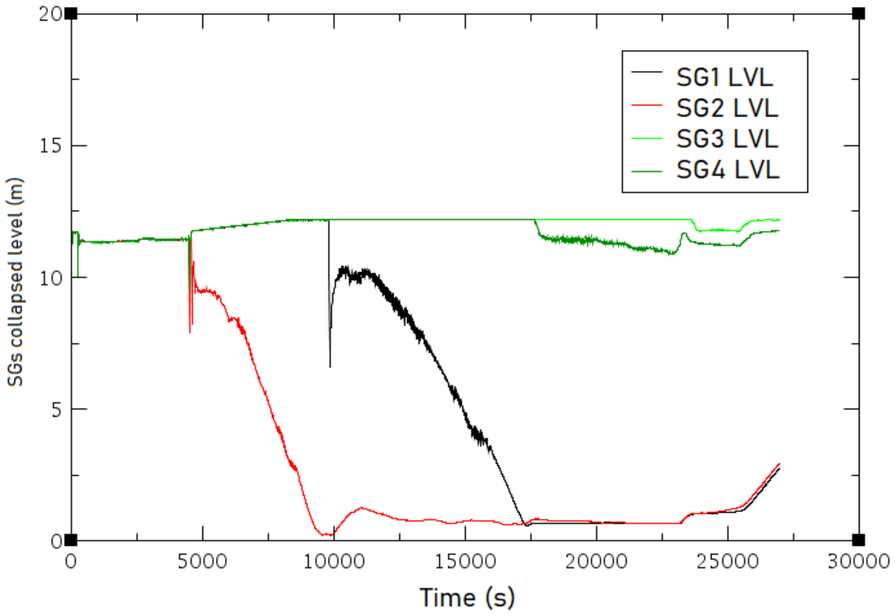


KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

2. Time step impact on RNC

- **Nodalization as the reference case, time step as horizontal loop seal case.**
- **Modified time steps from 0.1s to 0.01s at time window 2400s-7700s.**
- **Asymmetrical loops (2→1 → 4 → 3).**

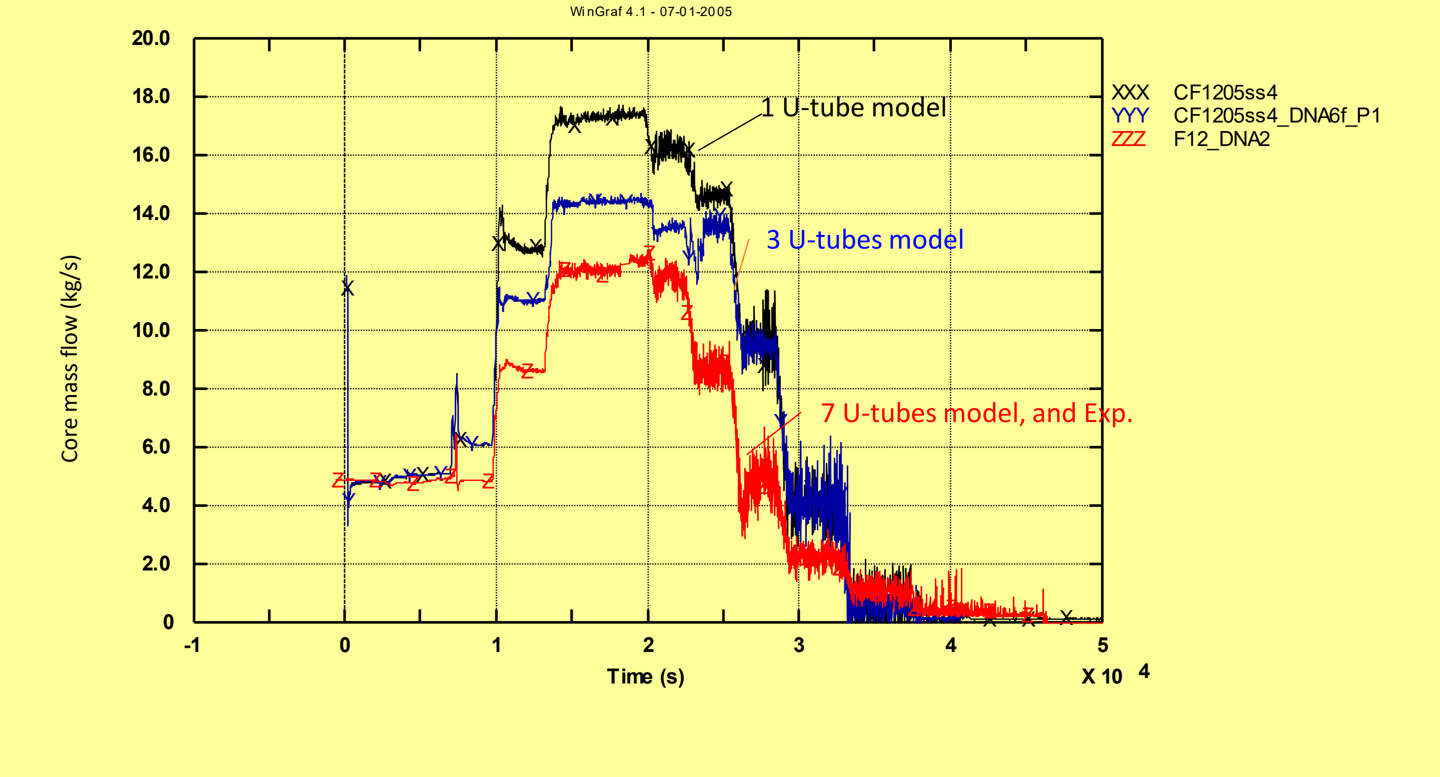




KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

7 U-tubes SG impact on RNC

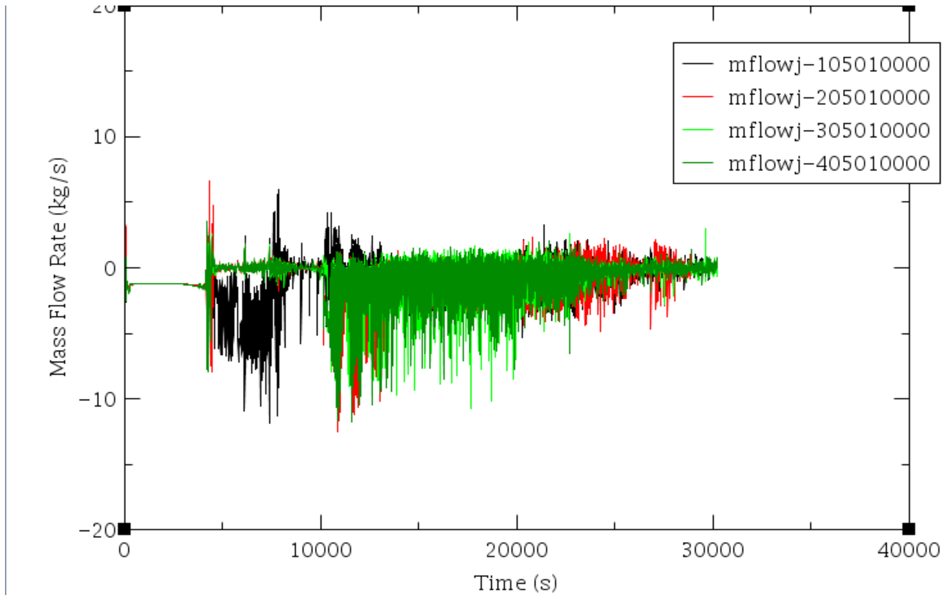
DNC Core flow rate

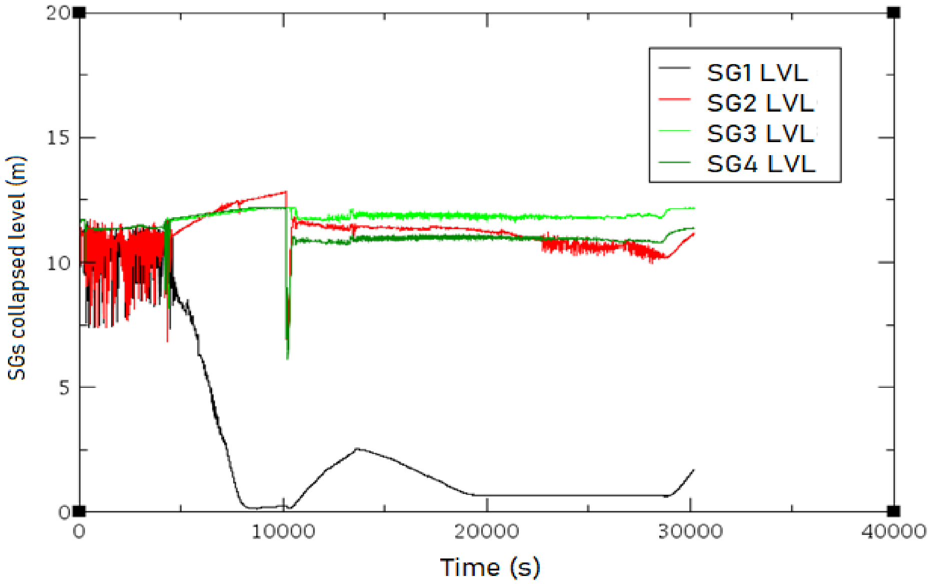


KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

3. 2x7 U-tubes SG impact on RNC

- **7 U-tube model in loop 1 and loop 2**
- **1 U-tube model in loop 3 and loop 4**
- **Asymmetrical loops (loop 1 starts).**

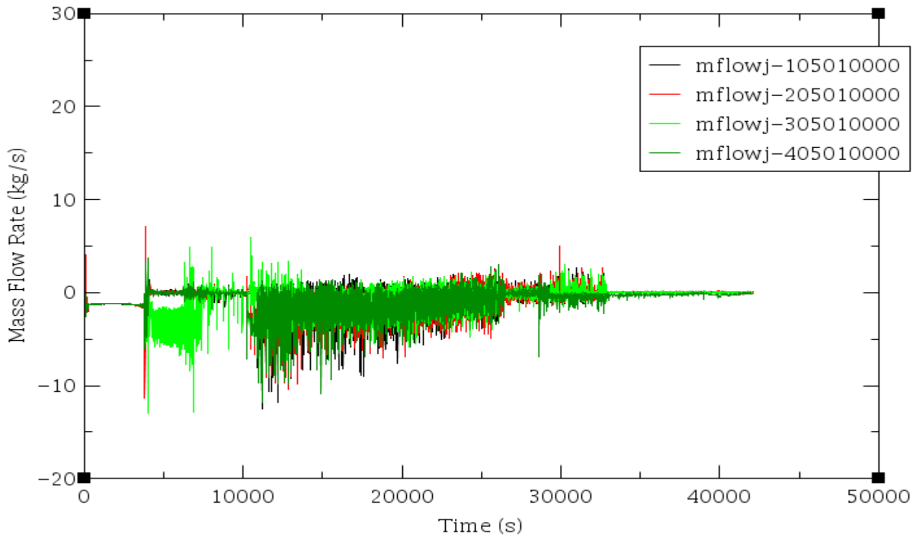


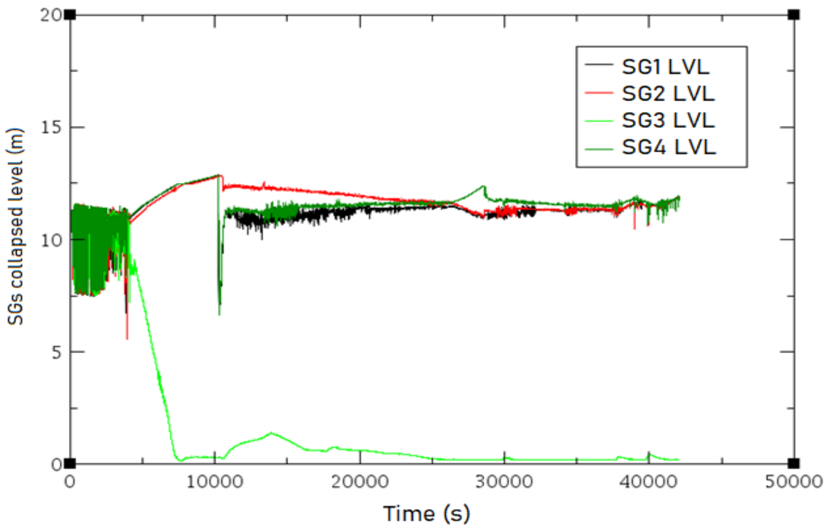


KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

4. 4x7 U-tubes SG impact on RNC

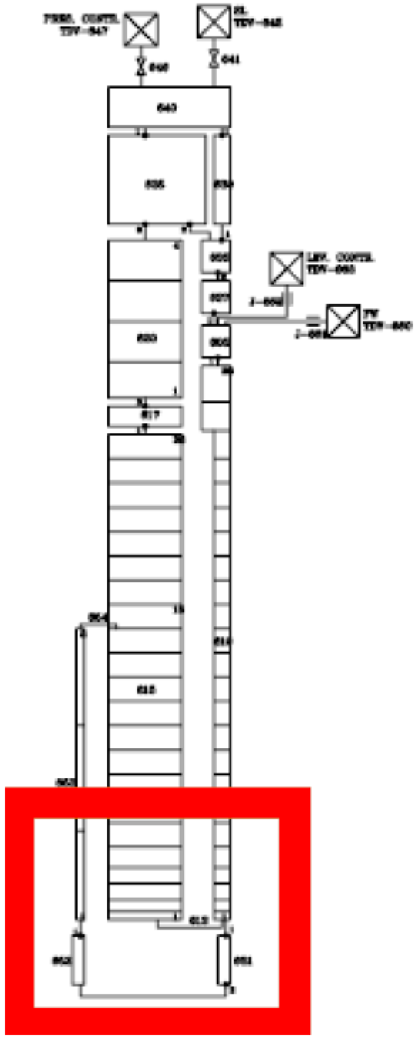
- 7 U-tube model in all 4 loops.
- Modified the length and the number of volumes in each SG to deal with stack overflow.
- Modified the reverse loss coefficient at the bottom of SG downcomers, from 1000 to 0.1, in order to reach convergence and avoid an unphysical pressure spike in the secondary side itself.
- Asymmetrical loops (loop 3 starts).

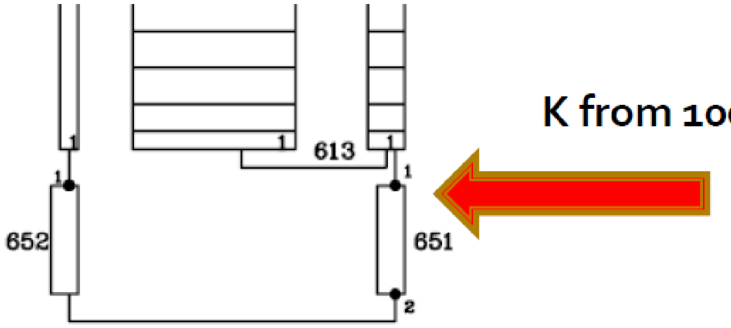




KEY RELAP5 RESULTS FROM PKL RNC CALCULATION

4. 4x7 U-tubes SG impact on RNC





K from 1000 to 0.1

CONCLUSIONS ON THE SENSITIVITY STUDIES

Final results of RNC showed large dependence on nodalization and time step choice.
When the loop seal is present, bifurcations and asymmetries always appear in our calculations.
Bifurcations and asymmetries are also connected to differences in pressure drop models, namely when circulation flow is very small and a new flow configuration-scenario will develop (i.e. transition from 1 to 2 phase flow).

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 nodalization, in pressure losses or any other change.

CONCLUSIONS ON THE RNC VIRTUALBENCHMARK

- ***RNC calculations by RELAP5, CATHARE, ATHLET and LOCUST 1.2 showed:***
  Same single-phase reverse flow rates
  Large difference in two-phase core mass flow and two-phase asymmetrical loops

- ***ΔP vs. G curves are different among codes (RELAP5, ATHLET and LOCUST 1.2) in both single-phase and two-phase conditions***

- ***CURRENT MODELING CAPABILITIES FOR PRESSURE DROPS NEED IMPROVEMENT: IN EACH CASE, KΔP = f(GEOM, RE, ALPHA, FLOW REGIME) .***

- ***THIS APPEARS MANDATORY AS IMPROVEMENT, IN PARALLEL WITH OTHER MODELING IMPROVEMENTS***

REFERENCES

[1]. Qingling Cai, Francesco D'Auria, Klaus Umminger, Dominique Bestion and Jianqiang Shan, Prioritizing pressure drop research in nuclear thermal hydraulics. Progress in Nuclear Energy, 2022. 153: p. 104358.
[2]. Klaus Umminger, Lars Dennhardt,Simon Schollenberger and Bernhard Schoen, Integral Test Facility PKL: Experimental PWR Accident Investigation. Science and Technology of Nuclear Installations, 2012. 2012: p. 1-16.
[3]. SILENCE network, Virtual RNC benchmark Comparison Report .
[4]. Aksan, N., D'Auria, F., Glaeser H., 2018. Thermal-hydraulic phenomena for water cooled nuclear reactors. Nucl. Eng. Des. 330, 166–186
[5]. J. Freixa, C. Pretel, L. Batet, F. Reventós, Post-Test Thermal-Hydraulic Analysis of PKL Tests F1.1 and F1.2. 2014, U.S. Nuclear Regulatory Commission.
[6]. Purhonen, H.; Kouhia, J.; Holmstrom, H., ISP 33. OECD/NEA/CSNI International Standard Problem n. 33. Pactel natural circulation stepwise coolant inventory reduction experiment. Comparison report. Volume1+2
[7]. Internal document (DNC)
[8]. F. D'Auria (2023): Scaling, Passive Systems, and the AP-1000, Nuclear Science and Engineering
[9]. Sensitivity Studies on Reverse Natural Circulation in the PKL Facility by Using RELAP5mod3.2mz (2023): Vincenzo Zingales, Qingling Cai, Francesco D'Auria, Dominique Bestion, Klaus Umminger, NENE 2023

Thanks for your attention!

Questions are welcome