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Nuclear and INdustrial Engineering

RELAP5 Applications at GRNSPG-NINE: Thirty Years of Activities

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- Introduction and overview on the activities
- Recent participation to International Benchmark Activities
  - ITF, Research Reactor and NPP calculations
- Specific application of Relap5: ISP-42 – PANDA Facility
- Example of NPP calculations (safety analyses)
  - VVER-1000, CANDU
- Investigation on Relap5\CFX coupling
- Conclusions

- Main contributes in the TH-SYS code area
  - Code Assessment (internally / within International programs)
    - ✓ On-Going benchmarks : Oskarshamn-2, PKL-III H2.2 run2, ATLAS A5.1, EBR-II
  - Accuracy quantification
    - ✓ Code Assessment (FFTBM)
    - ✓ Database for deriving the Uncertainty Database (CIAU uncertainty method)
  - Characterization of transient scenarios in NPP
    - ✓ Design evaluation
    - ✓ **Licensing of NPP (BEPU)**

- List of Experimental Facilities and Test Analyzed (not Exhaustive List)

#	FACILITY	TEST ID	TYPE OF TEST	FRAMEWORK	MAIN FINDINGS	REF.	YEAR	OBJECTIVE CA	OBJECTIVE AQ	OBJECTIVE UD
1	ATLAS	DVI-05	DVI line break	OECD-ATLAS Project, ISP50	Satisfactory results obtained by fictitious 3D nodalization	[11], [12]	2012	X	X	
2	BETHSY	9.1B	SBLOCA	OECD, ISP27	Proven code capabilities under BDBA conditions	[13], [14]	1992	X	X	
3	BFBT / PSBT	Several tests	Void distribution and critical power	OECD Benchmark	Use of RELAP5-3D as subchannel code with MULTIDIM component. Fine resolution not possible, general agreement obtained	[15], [16], [17]	2007	X		
4	FIX-II	3061, 5052 2032	LOCA & Pump Trip	OECD, ISP15	Proven code applicability to BWR design	[18]	1983-84	X	X	
5	LOBI Mod I	14 tests	LBLOCA, IBLOCA	LOBI Project	Proven code applicability to Large LOCA scenarios	[19]	1979-82	X	X	
		A1-06	LBLOCA			[20], [21]	1981	X	X	X
6	LOBI Mod II	42 tests	NC, SBLOCA, SLB, SGTR, LOFW, ATWS, FWL break	LOBI Project	General code capabilities in predicting large variety of scenarios proven. Limited capabilities for specific situations (hardware driven) highlighted (e.g. SG behavior in LOFW)	[19]	1984-91	X	X	
		A2-81	SBLOCA	OECD ISP18		[22], [23]	1984	X	X	X
		BL-34	SBLOCA	LOBI Project		[24]	1990	X	X	X
		BL-44	SBLOCA high power			[25]		X	X	X
		A1-93	SBLOCA			[26]		X	X	X
		BL-06	SBLOCA			[27]		X	X	X
		BT-02	LOFW			[28]		X	X	X
		BT15-16	LOFW			[29], [30]		X	X	X
7	LOFT	8 Tests	SBLOCA, LOFW, ATWS	Internal activities	Proven code applicability to Large LOCA scenarios including nuclear feedback	[31]	1990-2000	X		
		L2-5	LBLOCA	OECD, ISP13 OECD BEMUSE		[32], [33], [34]	1983	X	X	X
		L2-3	LBLOCA	CIAU DB Expansion		[35]	2000	X	X	X
8	Neptune	N° 5002	Low-Pressure Boil Off	Internal activity	Use of RELAP5 as subchannel code by a fictitious nodalization. Good agreement achieved	[36]	2002	X	X	
9	PANDA	Phases A, B, C	Containment Pressurization	ISP42	Proven capabilities of RELAP to simulate containment behavior (large volumes at low pressure) by suitable nodalization technique	[37]	2000	X	X	X
10	PIPER-ONE	PO-SB-7	SBLOCA	OECD ISP21	Proven code applicability to BWR design including stability issue	[38]	1989	X		
		PO-ST-1	Stability	PIPER-ONE Project		[39]	1994	X		
		PO-IC-2	Investigation on isolation condenser			[40]	1995	X	X	
11	PKL-I		Boron dilution accidents and Loss of RHR in mid-loop operation	OECD-PKL-I Project	Proven code capabilities to simulate long lasting tests. Some issues identified for the simulation of boron transportation and for the impact of non-condensable	[41]	2004-07	X	X	
12	PKL-II	E2.2, F4.1, G3.1	NC during SBLOCA	OECD-PKL-II Project		[42]	2008-11	X	X	
13	PKL-III	E3.1	Boron dilution during shutdown condition	OCED-PKL-III Project		[43]	2011	X	X	
		F4.1	Boron dilution during reflux condensation			[44]	2012	X	X	
		H2.1, H2.2	SBO and Non-condensable			[45]	2014	X	X	
		G3.1	MSLB				2012	X	X	
		G7.1	SBLOCA in Hot Leg					X	X	

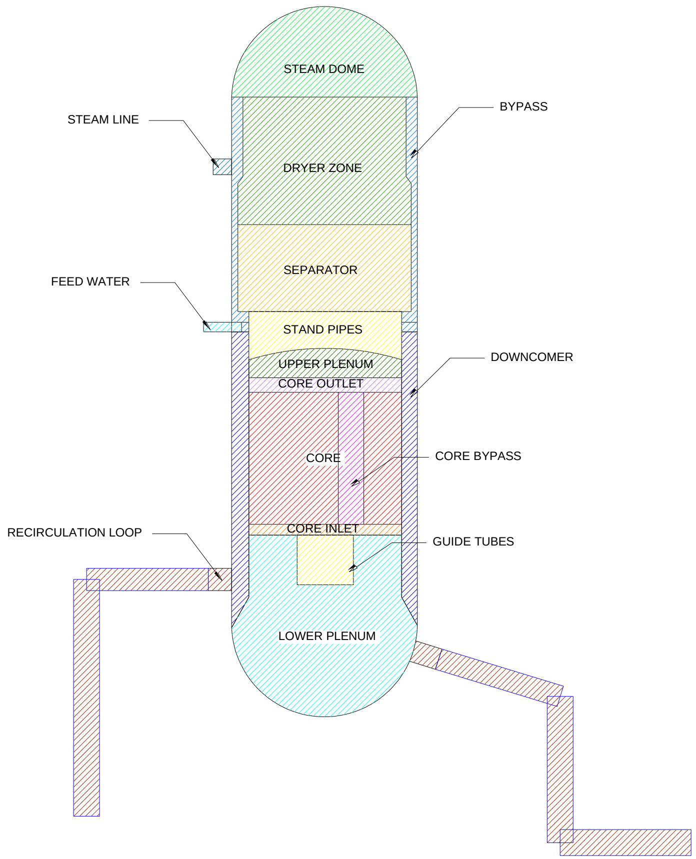
- List of Experimental Facilities and Test Analyzed (not Exhaustive List)

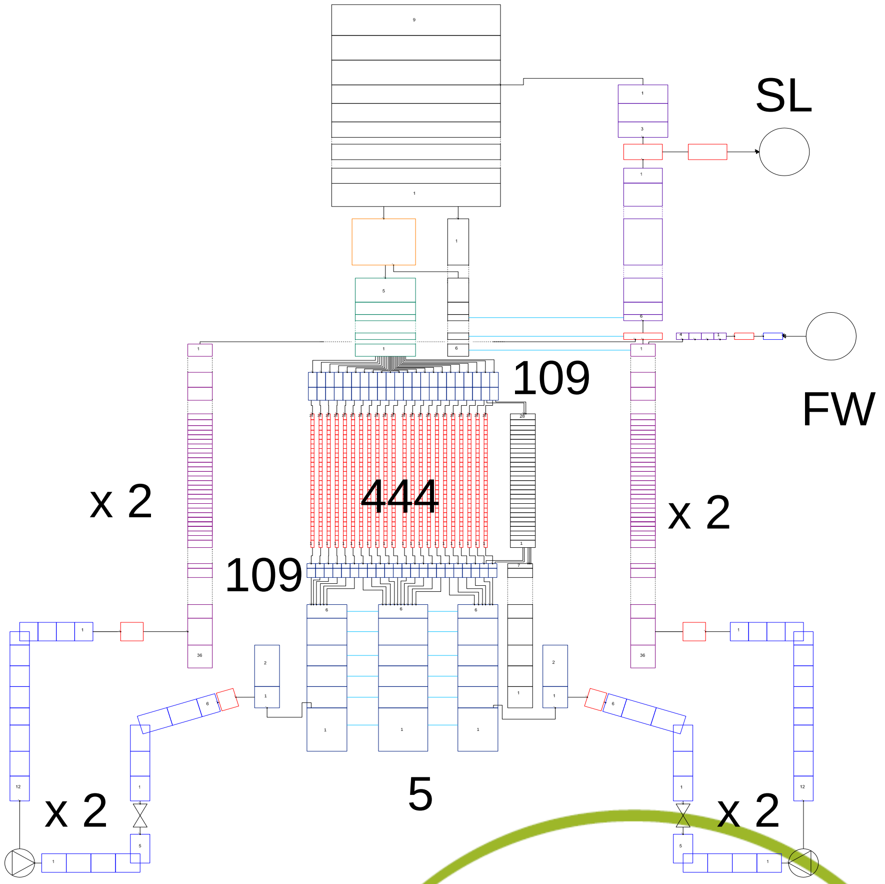
#	FACILITY	TEST ID	TYPE OF TEST	FRAMEWORK	MAIN FINDINGS	REF.	YEAR	OBJECTIVE		
								CA	AQ	UD
14	PSB-VVER	5 tests	LBLOCA, UPI line break, SBLOCA, PRISE	OECD-PSB-VVER Project	Proven code capabilities to simulate long lasting tests including complex thermal-hydraulic scenarios with accident management actions. Proven code applicability to VVER design	[46]	2003-08	X	X	X
		16 tests	SBLOCA, LOFW, SBO, PRISE, PORV stuck open	TACIS project		[47], [48], [49], [50]	2004-06	X	X	X
		CT41	SBLOCA				2005	X	X	X
		T#04, T#08, T#11 T#12	SBLOCA					X	X	X
		T#10	NC					X	X	X
		11up	IBLOCA					X	X	X
		PSH1	SGTR					X	X	X
		Test#14	PRISE				2006	X		
		Test#3	PORV stuck			[51], [52]	2005	X		
		Test#5	Main Steam Line Break plus SGTR			[53], [54]		X		
15	PWR-PACTEL	SBL-50	SBLOCA	International exercise	Good agreement between experiment and simulation obtained, degradation of heat exchange due to non-condensable presence not well predicted	[55]	2002	X	X	
16	RD-14m	B9401	LBLOCA	IAEA	Proven code applicability to CANDU design. Issue related with horizontal stratification identified	[56]	2000	X	X	X
17	ROSA-III	Run 912	5% SBLOCA	OECD, ISP12	Proven code capabilities to simulate accidents in large scale facility. Very good accuracy of the predicted results	[57]	1982	X	X	
18	ROSA-IV-LSTF	SB-CL-18	5% CL SB LOCA	OECD, ISP26		[58]	1990	X	X	X
		SB-CL-21	SBLOCA	CIAU DB Expansion		[59]	1995	X	X	X
		LSLW	Delayed activation of AFW	CIAU DB Expansion		[60]		X	X	X
19	SEMISCALE	2 tests	LOCA	Internal activity	Evaluation of natural circulation in 1- and 2-phase flow and core thermal-hydraulics	[61]	1998	X	X	
20	SPES	SP-SW-02	LOFW	OECD, ISP22	Proven code capabilities in simulating PWR design. Code scaling independence demonstrated through counterpart test simulation	[62]	1991	X	X	X
		SP-SB-03	SBLOCA	SPES project		[63]	1997	X	X	X
		SP-SB-04	SBLOCA full power			[64], [65], [66]	1998	X	X	X
21	UPTF	Test 05/06/07	Blowdown and refill phases	2D-3D Program	Proven code applicability at full scale. Reasonable results obtained both by 3D fictitious nodalization and by specific 'MULTID' component	[67], [68]	2000	X	X	X
22	VVER-PACTEL		NC	OECD, ISP33	Good agreement against experimental evidences, proven code applicability to VVER design, development of NC flow map	[69]	1994	X	X	X

- List of Code Applications for NPP (not Exhaustive List)

#	NPP TYPE	NPP NAME	TRANSIENT/ACCIDENT	FRAMEWORK	YEAR	OBJECTIVE			
						BM	SS	IR	LV
1	BWR	La-Salle 2	Stability analysis	OECD	1995	X			
		Leibstadt BWR-6	LOFW	Consultancy	1990		X		
		Oskarshamn-2	Stability originated by LOFW pre-heater	OECD	2012-on going	X			
		Peach Bottom-2	Turbine Trip, Low flow Stability	OECD	2001-2003	X			
		Ringhals-1	Stability analysis	OECD	1994-1996	X			
2	PHWR-Konvoi	Atucha-II	83 scenarios including AOO, DBA, SBDBA	Consultancy	2007-2013				X
3	PHWR-CANDU	Darlington	Loss of Flow Accident	Consultancy	2009-2010		X		
4	PWR	Angra-2	NC, LBLOCA	Consultancy	2001-2004		X	X	
		AP-600	SGTR	IAEA	1998	X			
		Krsko	DBA	Consultancy	1991			X	
		TMI-1	Main Steam Line Break	OECD	1999-2000	X			
5	RBMK-1000	Smolensk-3	NC, GDH blockage, SPTR, MPTR, including ALS response	TACIS project	2005-2006		X		
		Ignalina	DBA	Consultancy	2001			X	
6	VVER-440	Metsamor	LOCA	Consultancy	2000		X		
		Kozloduy-3	LBLOCA	Consultancy	2002		X		
		Mochovce	LOCA	Consultancy	2003		X		
7	VVER-1000	Balakovo-3	12 BDBA scenarios focused on AM	TACIS project	2005-2007		X		
		Kalinin-3	MCP switch off	OECD project	2009-2013	X			
		Kozloduy-6	MCP restart	OECD project	2002	X			
		Temelin	PTS	Consultancy	2004		X		
			MSLB	Consultancy	2002-2003		X	X	
		Zaporozhye	PORV stuck open	Consultancy	1986		X		

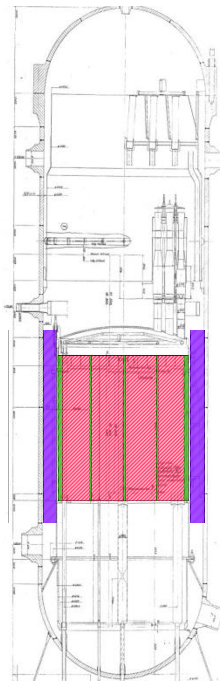
- Oskarshamn-2 OECD Benchmark: February 25, 1999 stability event
  - Loss of FW pre-heating & Control System failure: High FW flow, low temp, no SCRAM
  - Power and flow control system interaction: low flow, high power
- Nodalization Scheme (Draft)

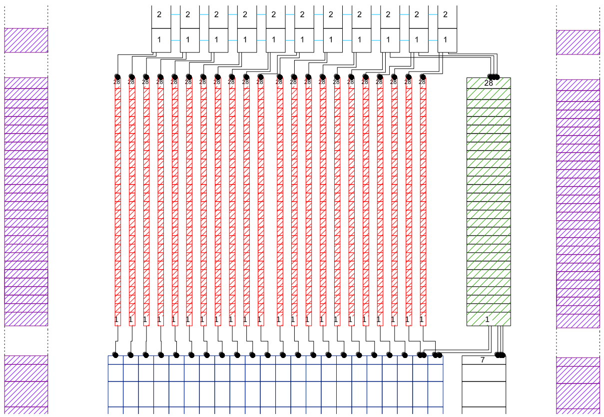


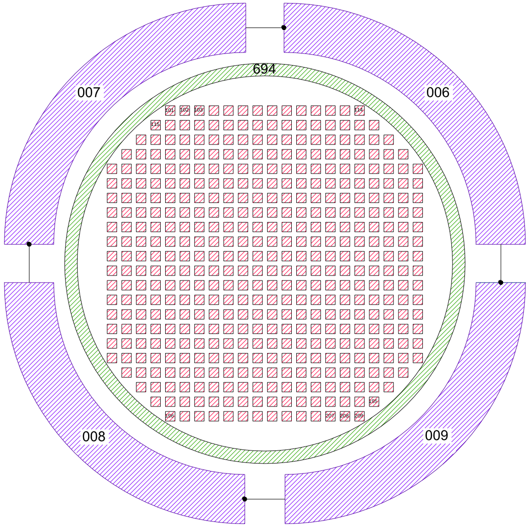


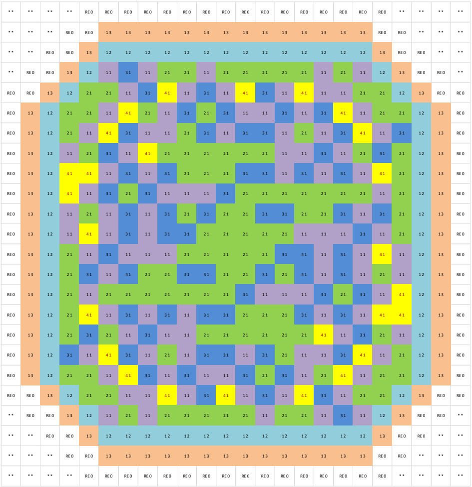
- Oskarshamn-2: Core

Downcomer
Core bypass
Core channels

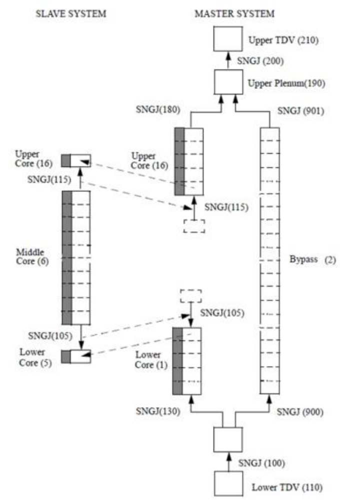


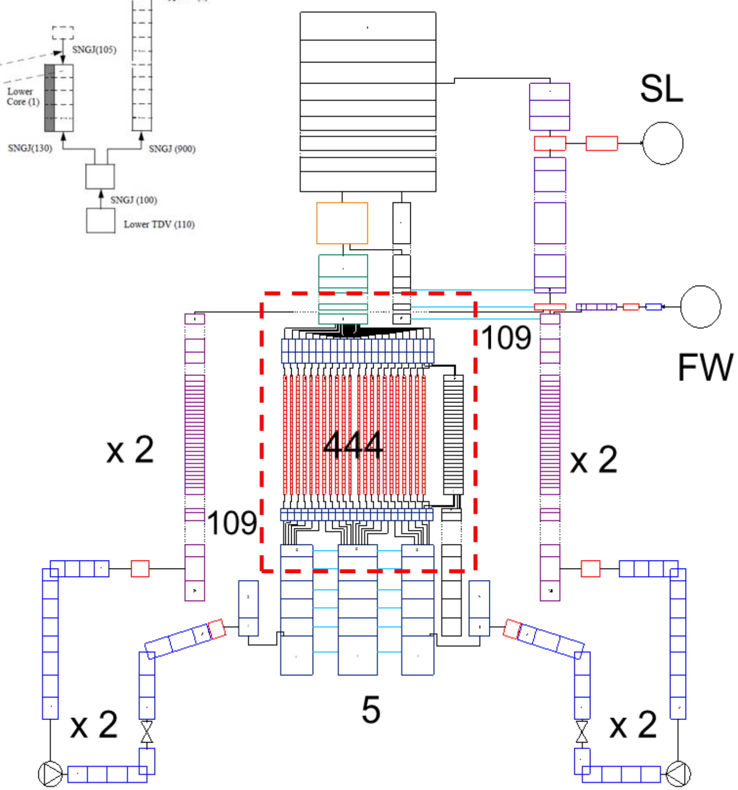






- Considerable use of code resources
  - ≈800 1D components
    - ✓ ≈ 13500 volumes
    - ✓ ≈ 14500 junctions
  - Possible use of 3D components
  - Detailed thermal model
    - ✓ ≈ 11100 active heat structures (about 20000 nodes)
  - Detailed 3D NK model (limitation embedded in NESTLE exists)
    - ✓ Careful description of TH feedback





- Opportunity to investigate the coupling via **PVMEXEC** (NPP calculation)
  - TH-TH (semi-implicit scheme)
  - TH-3DNK

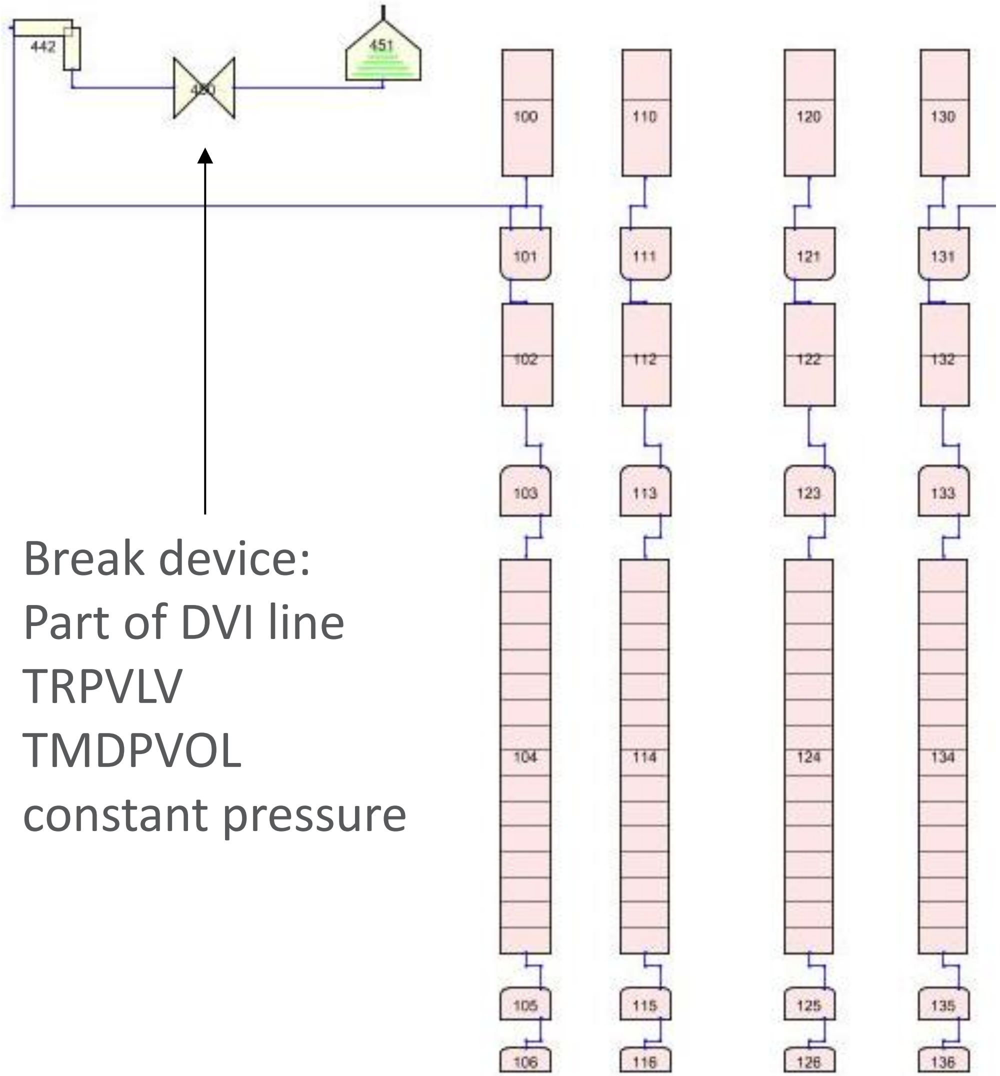
ATLAS benchmark

- Within the OECD-ATLAS project - Under OECD/NEA working group
- UNIPI-NINE asked for coordination (together with the OA [KAERI]) of a benchmark
- UNIPI-NINE nodalization qualification methodology adopted
- UNIPI-NINE interact with the OA during the design of the test
- Selected test
  - ATLAS A5.1 (Counterpart with LSTF SB-CL-32) - 1% SBLOCA
  - Operator action – SS depressurization

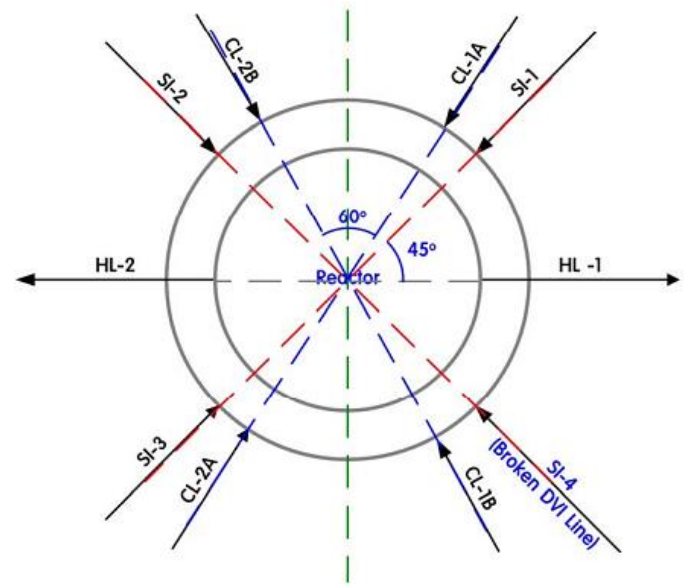
Action\Event	Date
Selection of the test	J0 (Oct. 2014)
Decision of specification	J0+6m (April 2015)
Test conduction	J0+8m (June 2015)
Pre-test data collection	J0+15m (Jan. 2016)
Pre-test data comparison & release of data	J0+17m (March 2016)
Post-test data collection	J0+19m (May 2016)
Post-test data comparison	J0+21m (July 2016)
Draft benchmark report	J0+23m (Sept., 2016)
Review by benchmark participants	J0+24m (Oct., 2016)
Final benchmark report	J0+25m (Nov, 2016)

ATLAS benchmark

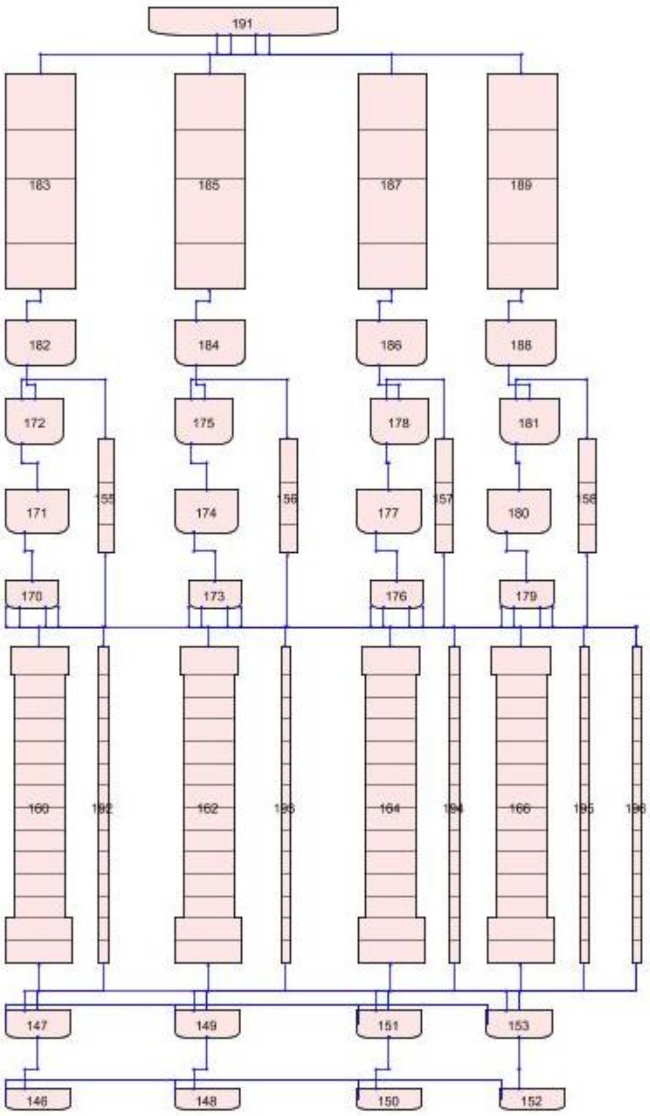
- UNIPI-NINE involved in previous ATLAS OECD based project: ISP-50
  - Participated to both blind and open phases
  - Adoption of FFT-BM
- RELAP5/MOD3.3 nodalization features:
  - Fictitious 3D approach
  - Slice approach
  - Both loops represented
  - Heat losses simulation
- RELAP5-3D nodalization adopted to simulate A5.1 is actually under development (based on the one adopted for the ISP-50)
  - Main improvement interests the secondary side
  - Use of MULTID component
    - ✓ ATLAS DC instrumentation is capable to capture 3D phenomena



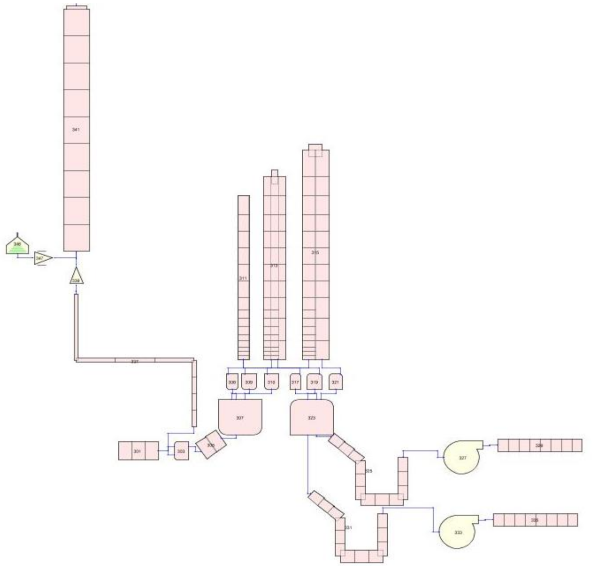
Break device:
Part of DVI line
TRPVLV
TMDPVOL
constant pressure

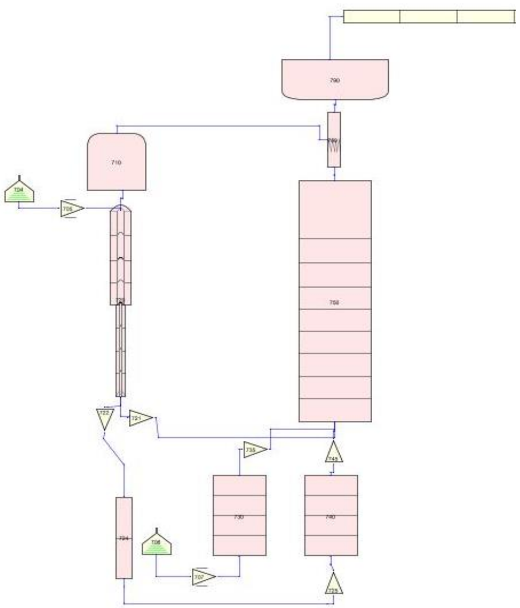


4 downward pipes covering 90° linked by MULTIPLE JUNCTION (not represented)
BRANCH in correspondence of connections with CL and DVI line



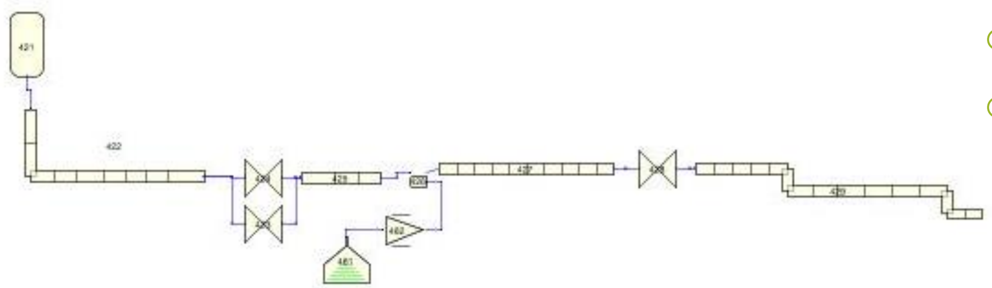
- Core
  - 4 upward pipes (14 subvolumes) covering 90° linked by MULTIPLE JUNCTION (not shown)
- LP & UP follow the same approach
- UH unique BRANCH



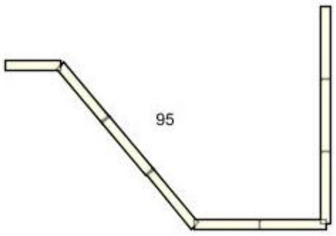


- Both loops nodalized
- SG UT represented by 3 equivalent pipes
- PRZ level and pressure control used for initialization purpose only

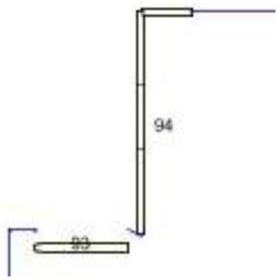
- SS nodalization includes
  - SG Downcomer
  - SG Riser
  - Economizer
  - Two FW connections



- SIT and ECCS line fully nodalized
  - Accumulator
  - TIME DEPENDENT JUNCTION



DC-HL bypass

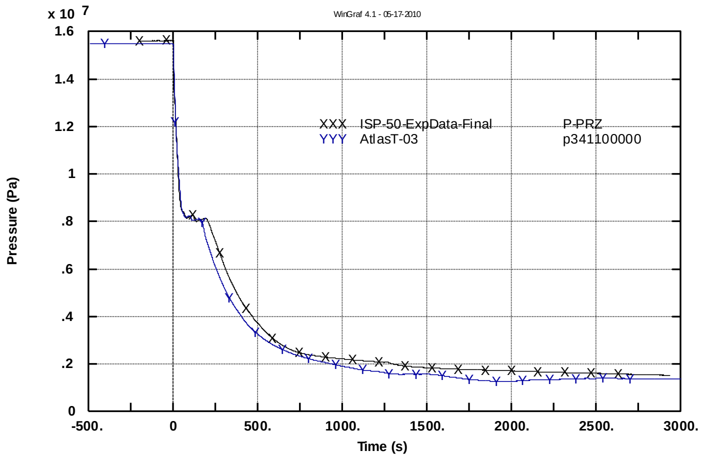


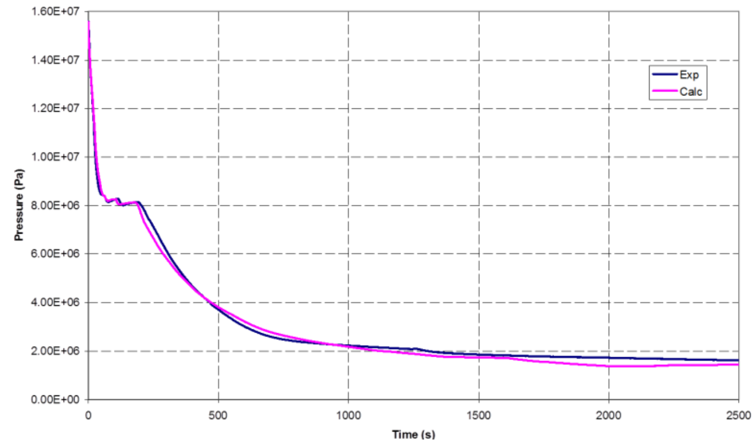
DC-UH bypass

- DC-HL bypass (two paths)
- DC-UH bypass (two paths)
- Core Guide Tube bypass (five paths)
- Core-UP bypass (four paths)

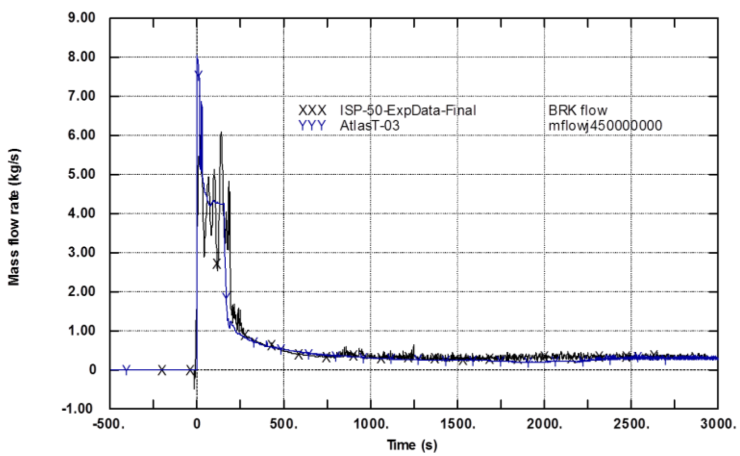
ATLAS benchmark

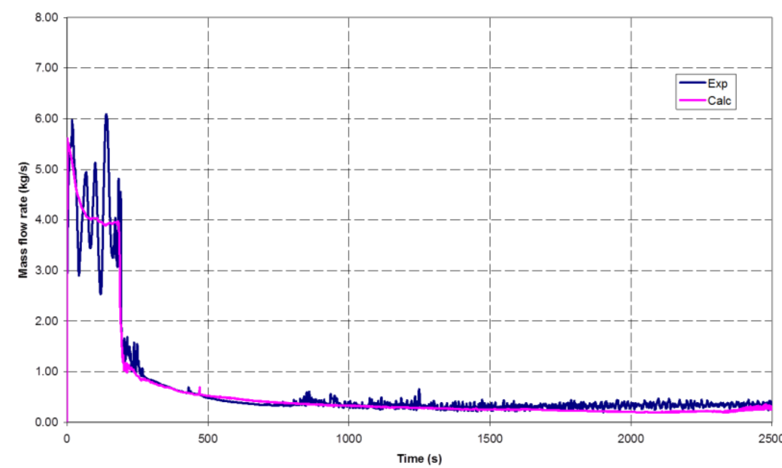
- ISP-50 Selected results: comparison between Blind and open Phases
  - ISP-50 used to qualify the (improved) nodalization at “on-Transient” level





Primary side pressure (Blind and Open calculation)





Break mass flow rate (Blind and Open calculation)

PKL III H2.2 run2 benchmark

- UNIPI involved in several OECD/NEA PKL project benchmarks
  - Benchmark coordinator
  - Participated to both blind and open phases (TRACE, RELAP5, CATHARE)
- Test H2.2 - Station-Blackout
  - Station-Blackout AM based on CET measurement
    - ✓ Secondary-side Depressurization (SDE)
    - ✓ Primary side Depressurization (PDE)
    - ✓ Mobile Pump (SS) & Emergency RHRS pump (PS)
- RELAP5-3D nodalization features (under improvement)
  - Fictitious 3D approach (UP)
  - Slice approach
  - Four loops represented
  - Heat losses simulation
  - Detailed modelling of PRZ and SGs (7 UT bundles)
- H2.1 and H2.2 run 1 (and the conditioning phases)will be investigated by UNIPI-NINE to qualify the nodalization

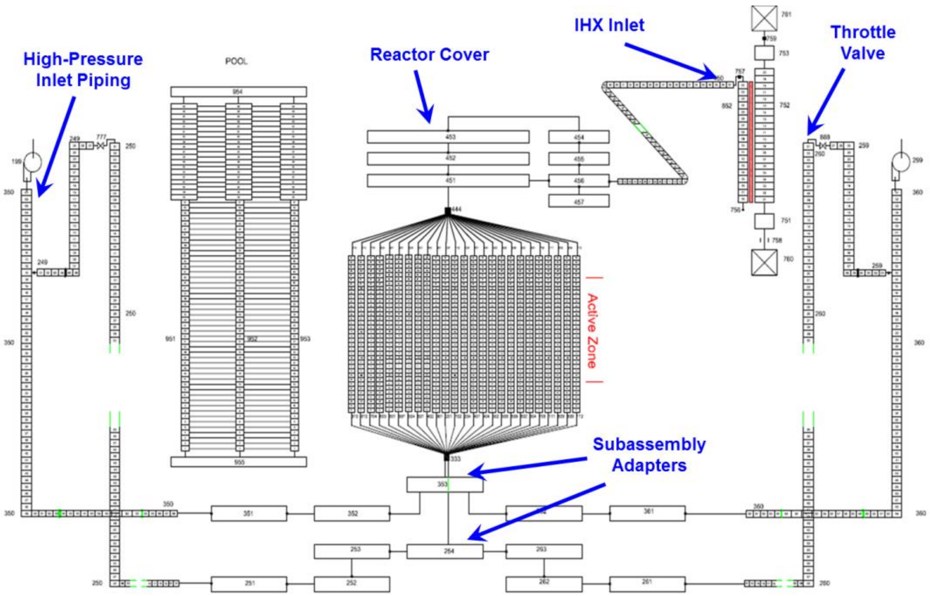
- H2.2 run2 benchmark involves more than 15 participants
- Time schedule

Action\Event	Date
Deadline for blind calculation and collecting data from participants	by October 31, 2015
Deliver of the Blind Benchmark report	by December 31, 2015
Decision about a possible open phase (distribution of the benchmark specification for the open phase)	by January 15, 2016
Deadline for open calculation and collecting data from participants (if needed)	by March 25, 2016
Blind (and if needed the Open) Benchmark Meeting (in Pisa) ✓ UNIPI will present the Blind Benchmark report ✓ Presentation of open calculation from participants (if needed)	April 2016

PKL III H2.2 run2 benchmark

- Adoption of UNIPI-NINE nodalization qualification methodology
- Special focus put on
  - CET and PCT behavior
  - PRZ behavior (PRZ RV&SV)
  - Accumulator behavior
  - Loop seal behaviour
  - SG behavior (N2 presence)
    - ✓ PRZ RV&SV closure after PDE in H2.2 run2
- UNIPI suggested improvements of the test specification
  - Radial core power distribution
  - Additional measurements to investigate the ACC behavior

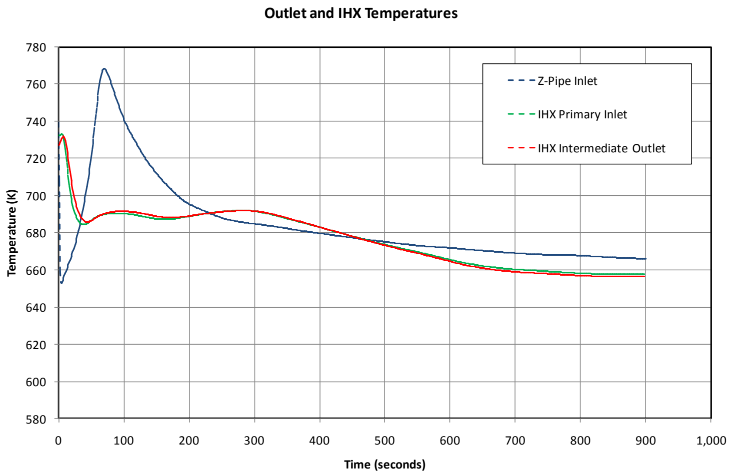
- SHRT-17 (1984)
  - Protected Loss of Flow Test (PLOFT)
  - Simultaneous trip of sodium pumps and control rod scram (@ full power)
  - Demonstrated effectiveness of natural circulation cooling characteristics to remove residual heat and keep core cooled during accident
    - ✓ Temperature rose to high, but acceptable levels
    - ✓ Thermal expansion and thermal inertia of sodium effective in protecting reactor from potentially adverse consequence from PLOF
  - Coupling of thermal hydraulic phenomena in core and primary loop created challenging benchmark problem

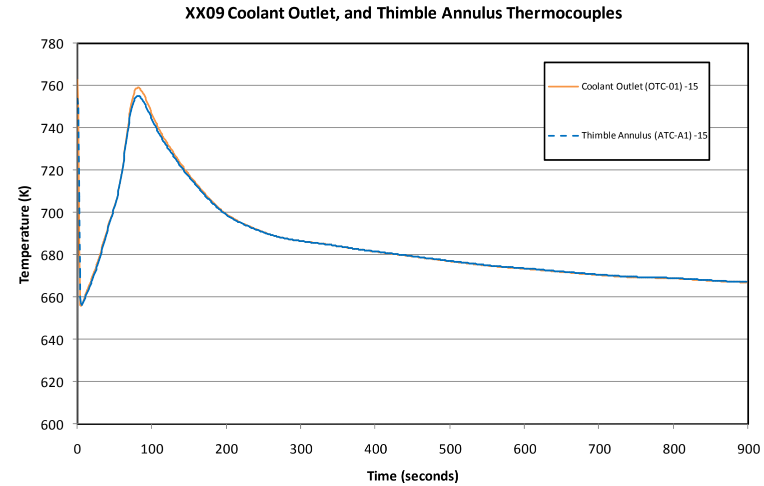


N°	Parameter	Value
1	Total number of volumes (i.e. points where balance equations are solved)	1804
2	Total number of mesh points (i.e. points where heat conduction eq. are solved)	991
3	Number of volumes per modelling the primary side (without the pool)	1348
4	Number of volumes for modelling the intermediate side	24
5	Number of volumes for modelling the pool	432
6	Number of hydraulic components for the whole core	98
7	Number of axial volumes per driver/subassemblies	36
8	Number of heat structures for the whole core	3332
9	Number of mesh points for the whole core	> 20000

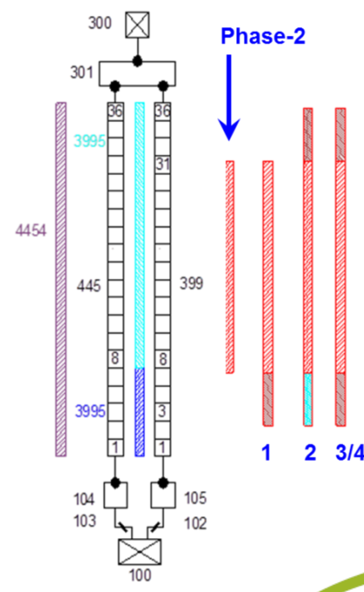
- Heterogeneity in the reactor core
  - 10 types of assemblies modelled
- Sodium Tank (open pool type reactor with immersed components)
  - “Fictitious 3D” approach
  - Use of MULTID (turbulent shear stress)
- UNIPI-NINE qualification methodology adopted in the benchmark

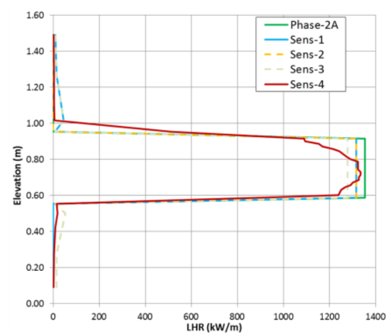
EBR-II benchmark

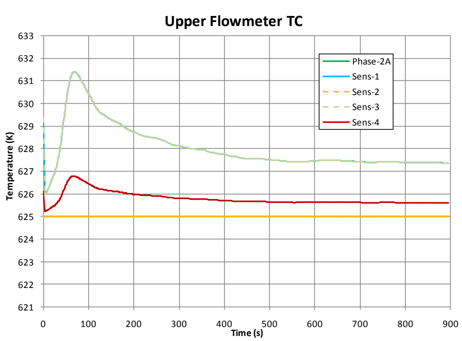


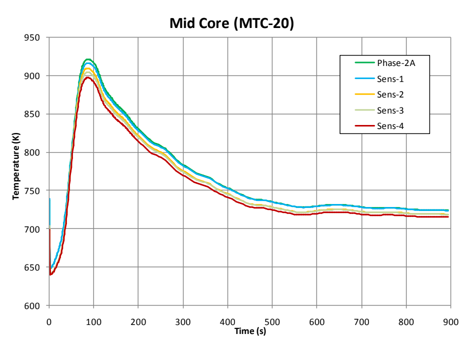


- Several sensitivities carried out to address selected issues. E.g.:
  - Power supplied also above and below the active part of the core (Gamma heating)
  - Axial power distribution (as in SHRT-45)



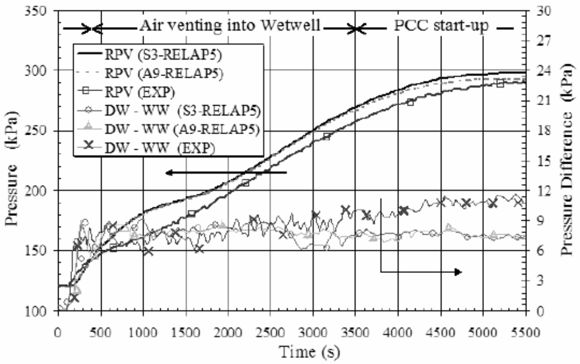




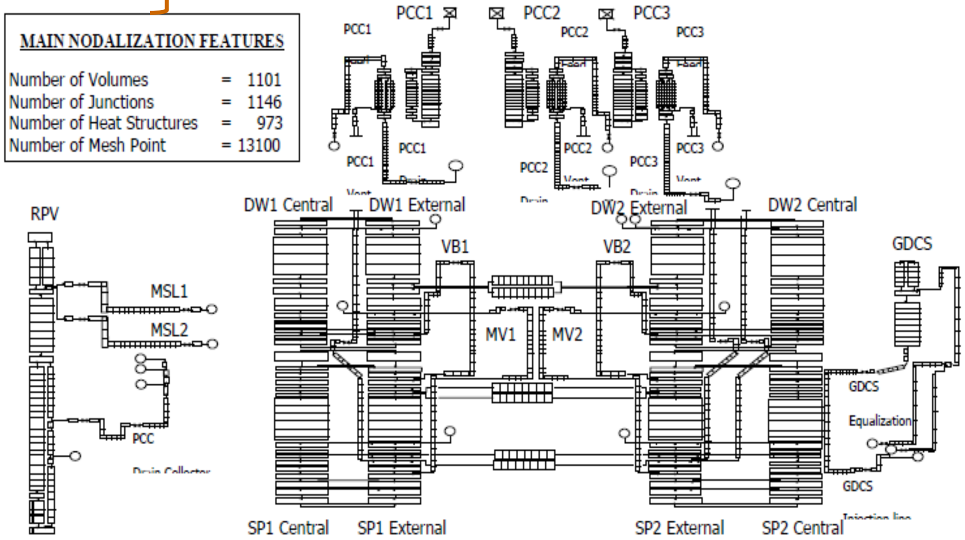


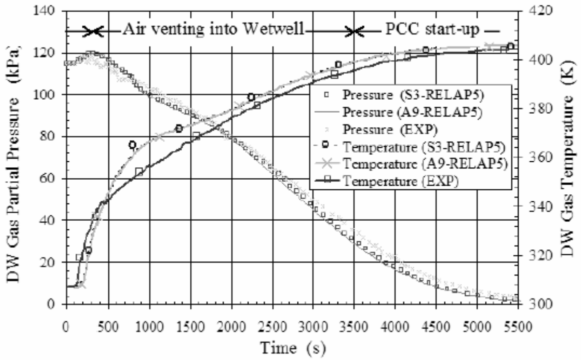
- Application to Containment: ISP-42 in PANDA Facility - (Passive Systems)
  - Phase A: Passive Containment Cooling System (PCC) Start-Up
  - Phase B: Gravity-Driven Cooling System (GDCS) Discharge
  - Phase C: Long-Term Passive Decay Heat Removal
  - Phase D: Overload at Pure-Steam Conditions
  - Phase E: Release of Hidden Air
  - Phase F: Release of Light Gas in RPV

Relap5 (Phases A–C)



a) *Pressure trends (phase A)*



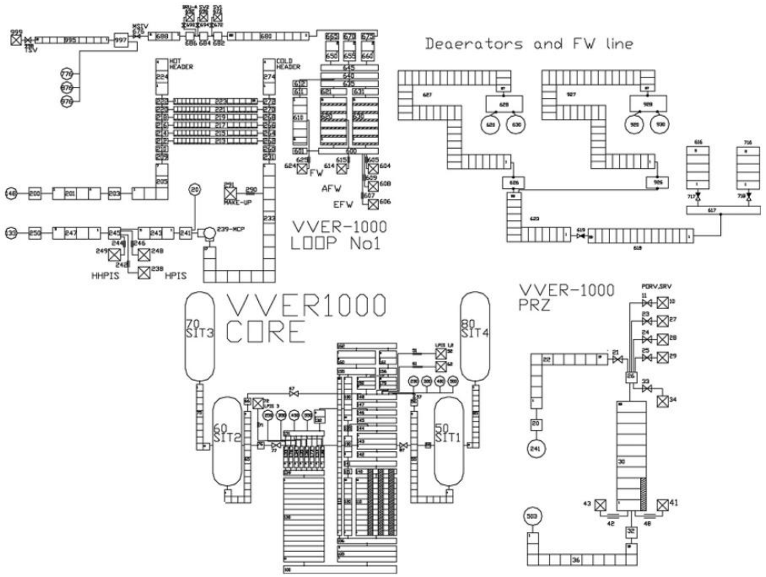


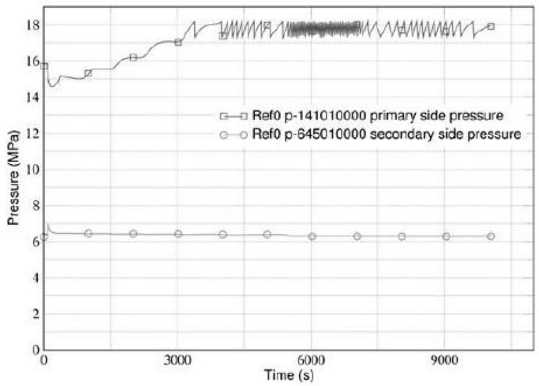
d) *Air Concentration in DW1 (phase A)*

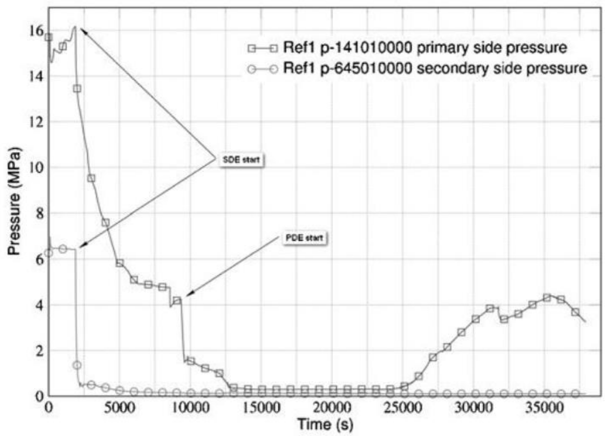
Parameter	AA
RPV pressure	0.053
DW1 pressure	0.054
WW1 pressure	0.063
DW1 partial pressure	0.051
DW2 partial pressure	0.428
SL1 mass flow rate	0.413
SL2 flow rate	0.445
PCC1 mass flow rate	0.443
PCC2 mass flow rate	0.461
PCC3 mass flow rate	0.447
Global Average Accuracy	***0.105***

NPP analyses: VVER-1000

- Several scenarios investigated VVER-1000 (e.g. LB-LOCA, MCP trip, MSLB, LOFW)
- Investigation and optimization of AM procedure to cope with SBO
  - Depressurization of SS (SDE) and PS (PDE)
  - Development of a methodology for AM procedure optimization

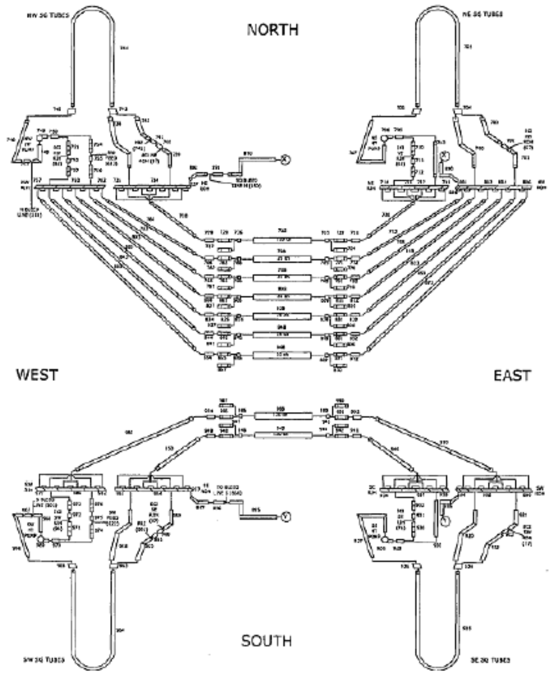


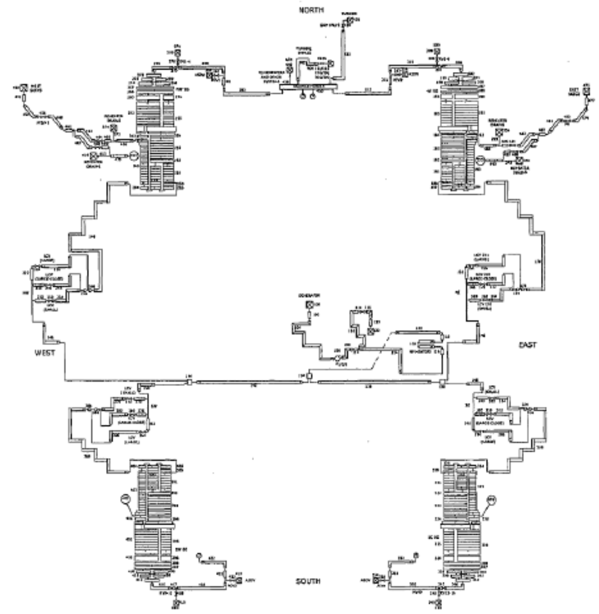




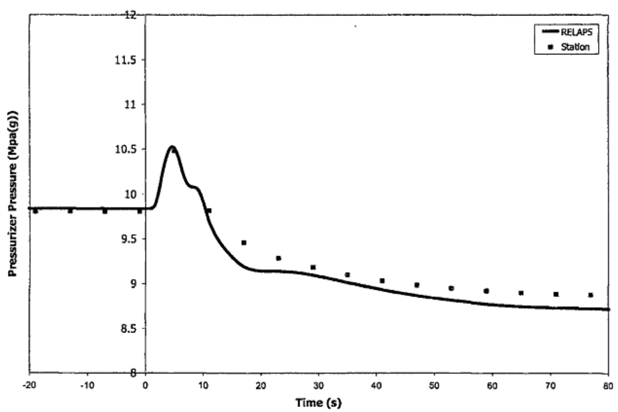
- LOFW scenario (Nov. 1993) in Darlington Nuclear Generating Station (CANDU)

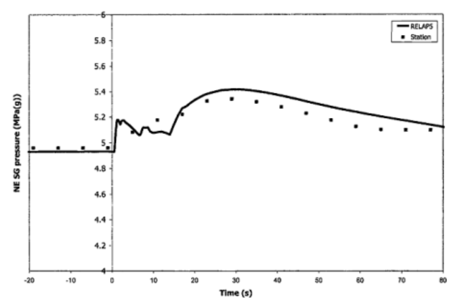
Heat Transport System	
Total number of hydrodynamic components	250
Number of volumes	1674
Number of junctions	1721
Number of heat structures	2470
Number of mesh points	31467
Secondary Side System	
Total number of hydrodynamic components	250
Number of volumes	1475
Number of junctions	1503
Number of heat structures	372
Number of mesh points	4986

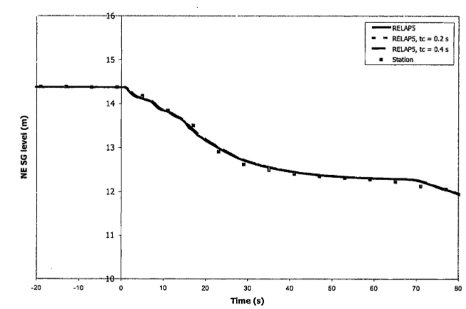




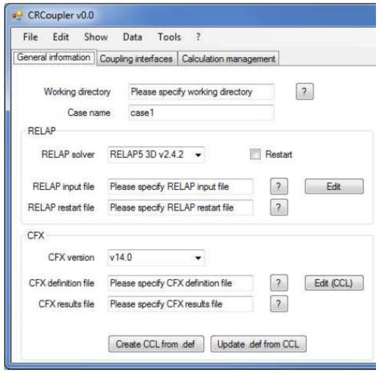
- Accurate modeling of
  - Channel end-fitting
  - Process control system
  - Emergency control system

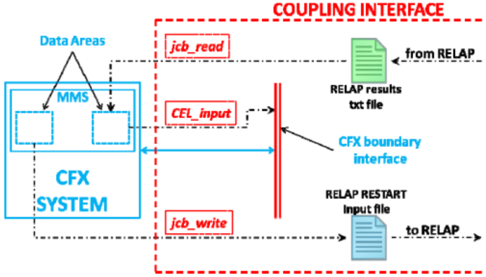


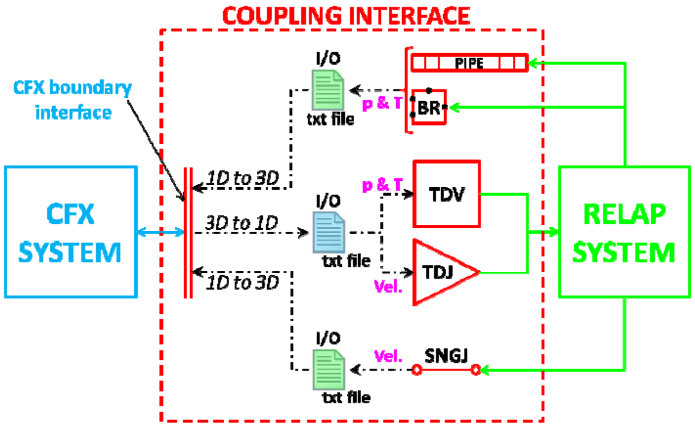




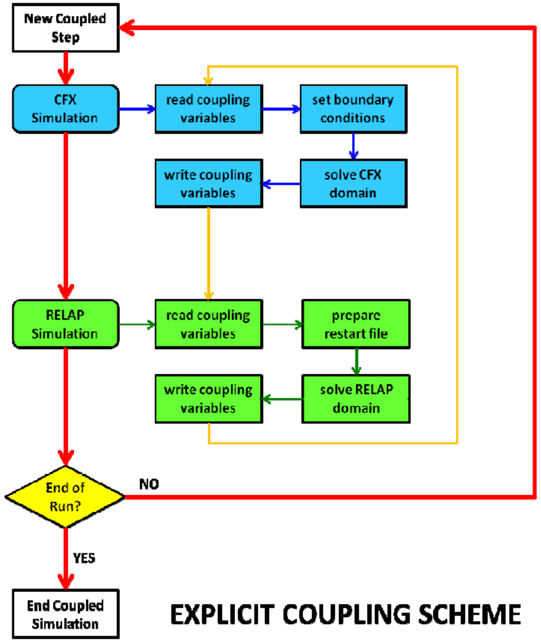
- Relap5-3D\CFX coupling: file dumping approach
  - Development of PERL and FORTRAN routines to allows and coordinate the data exchange
  - Development of a GUI

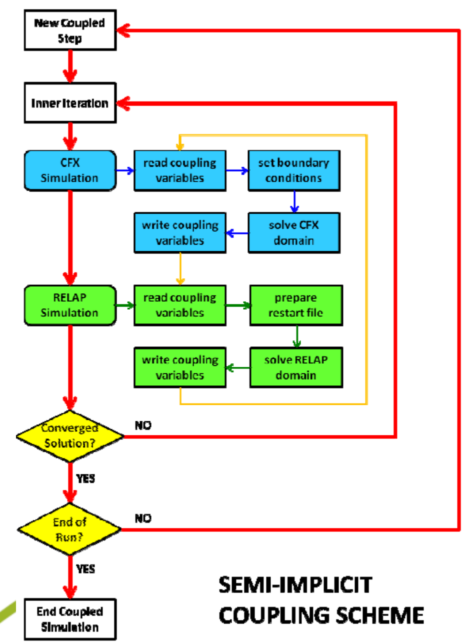




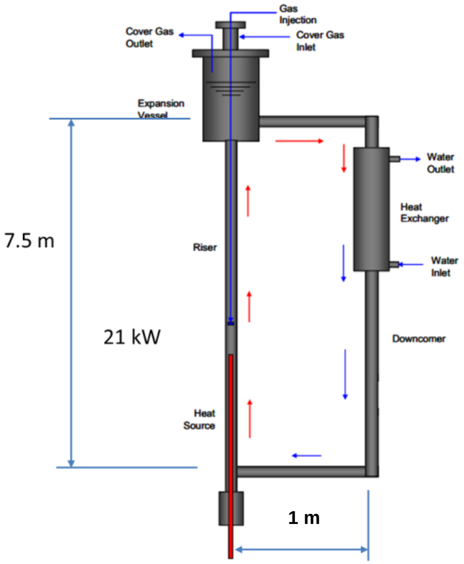


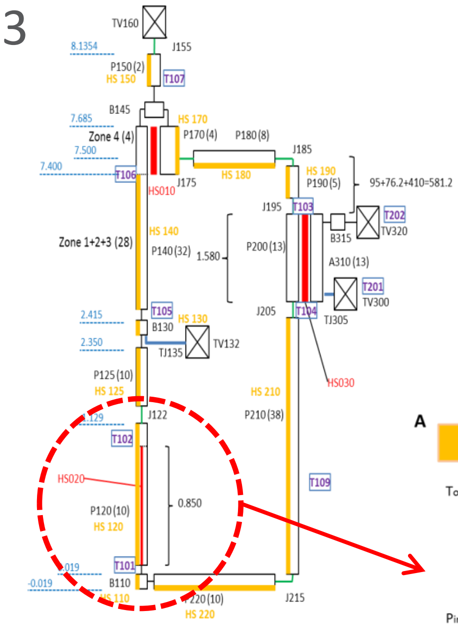
- Two different coupling schemes investigated
  - Explicit
  - Semi-implicit

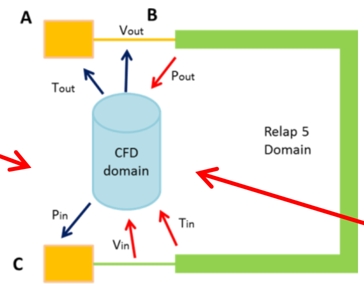


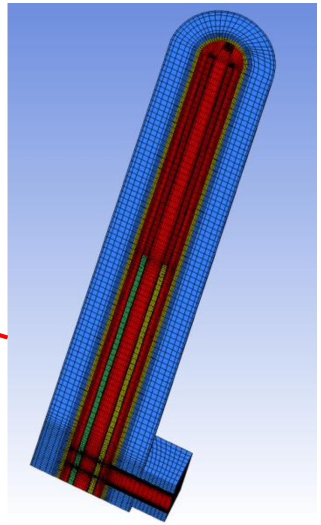


- NACIE Facility – Test ID: 303



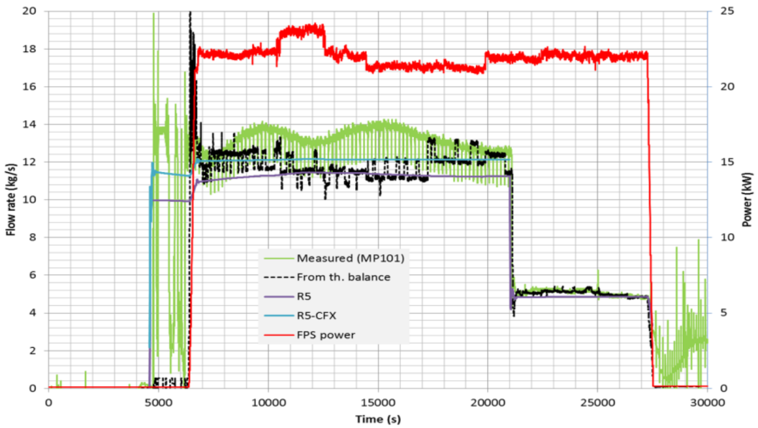






- Natural circulation (LBE loop)
  - Power: 21,5 kW (5 min ramp)
  - Average fluid temp: 300-350°C
  - Gas lift circ. → NC (@ 21000s)
  - Active heat sink

Preliminary results



- MP101 not fully reliable
- Improvement of the BIC and (coupled) models

- Summary of the experience gained on RELAP5 code at UNIPI-NINE
- Simulation of several ITF and SETF, different NPP design and scenarios
  - ITF simulating PWR and VVER
  - SETF: e.g. sub-channels analyses and containment behavior
  - Different NPP design: HWR, PHWR, BWR, VVER, RMBK
  - Different framework: Benchmarks, Safety Support Analysis, **Licensing**
  - LOCA and Non-LOCA scenarios
- Qualitative and quantitative accuracy evaluation
- Consolidation of procedure for nodalization development and qualification
  - Qualified results for Safety Analyses in Licensing (BEPU)

Strong bases on code use are the starting point for new challenges

(BEPU, coupling, …)