International RELAP5-3D Users Group Meeting

December 4-8, 2023

Sapienza Contribution to the IAEA CRP on the "Benchmark Analysis of FFTF"

SAPIENZA
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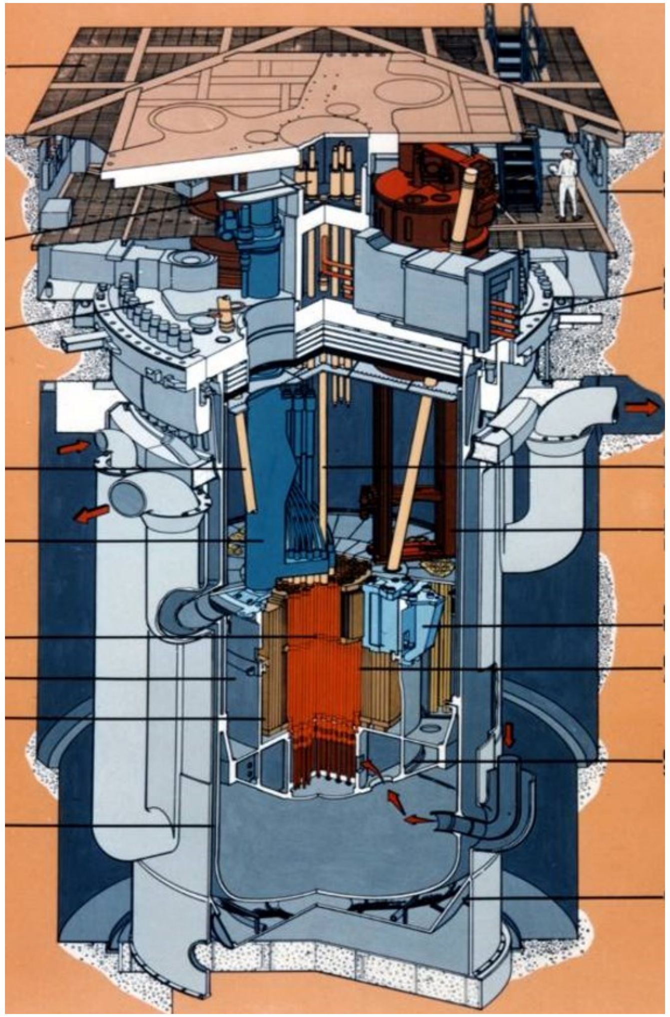
Framework

- A Coordinated Research Project on “Benchmark Analysis of FFTF Loss of Flow Without Scram Test” was launched by the International Atomic Energy Agency (IAEA) in 2018.
- A series of passive safety tests were conducted from 1980-1992 at the Fast Flux Test Facility (FFTF), 400 MW_{th} liquid sodium-cooled nuclear test reactor owned by U.S. Department of Energy (DOE) to demonstrate the potential of FFTF to survive severe accident initiators with no core damage.
- Amongst these tests was a series of Loss of Flow Without Scram (LOFWOS) tests from power levels up to 50%, also commonly referred to as Unprotected Loss of Flow (ULOF) tests, which were studied in the IAEA CRP.
- The data were provided by the Argonne National Laboratory (ANL) and Pacific Northwest National Laboratory (PNNL).
- *24 organizations from 12 Member States participated in the FFTF CRP*



Outline

- Adopted coupling methodology
- Overview of NK-TH modelling
- TH Nodalization
- FFTTF LOFWOS Test #13: transient analysis
- Conclusions and future works

ADOPTED COUPLING METHODOLOGY

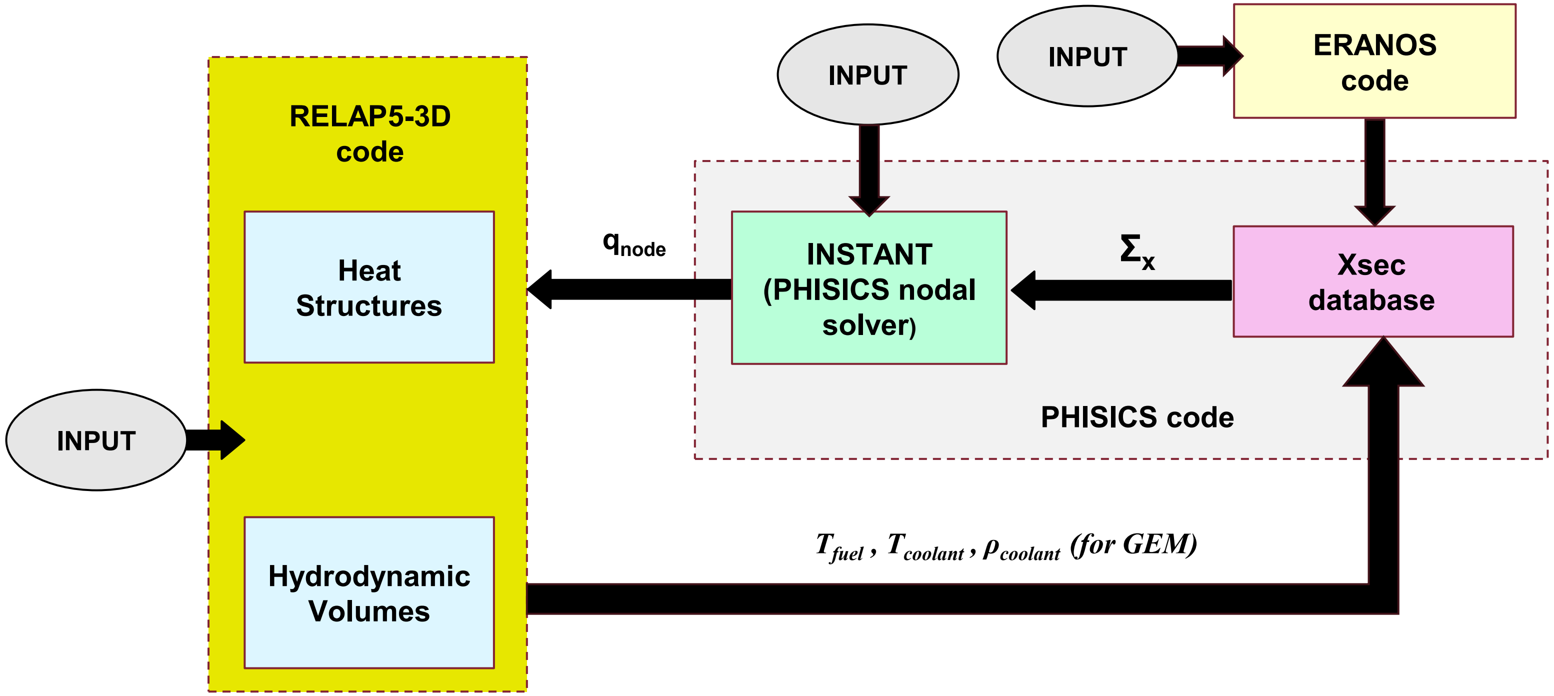
- **RELAP5-3D** is the latest version of RELAP5 series of codes developed at Idaho National Laboratory (INL). It provides the possibility to simulate **innovative working fluids** and to use a fully integrated **multi-dimensional nodalization**.

- **PHISICS**, developed since 2011 at INL and actually not supported, is a reactor analysis toolkit to perform advanced **neutron transport calculations** coupled with the 3D thermal-hydraulic system code RELAP5-3D. The nodal solver associated to PHISICS code is called **INSTANT** and allows to solve **transport equations** in an **unlimited number of energy groups**.

- **ERANOS** is a neutron calculation code system for fast reactors core design developed by the CEA (Commissariat à l’Energie Atomique). The code consists in **multigroup libraries of nuclear data** (**JEFF-3.1**), **calculation programs and procedures** that allow high flexibility and modularity. It is provided with a cell and lattice code called **ECCO**.

ADOPTED COUPLING METHODOLOGY

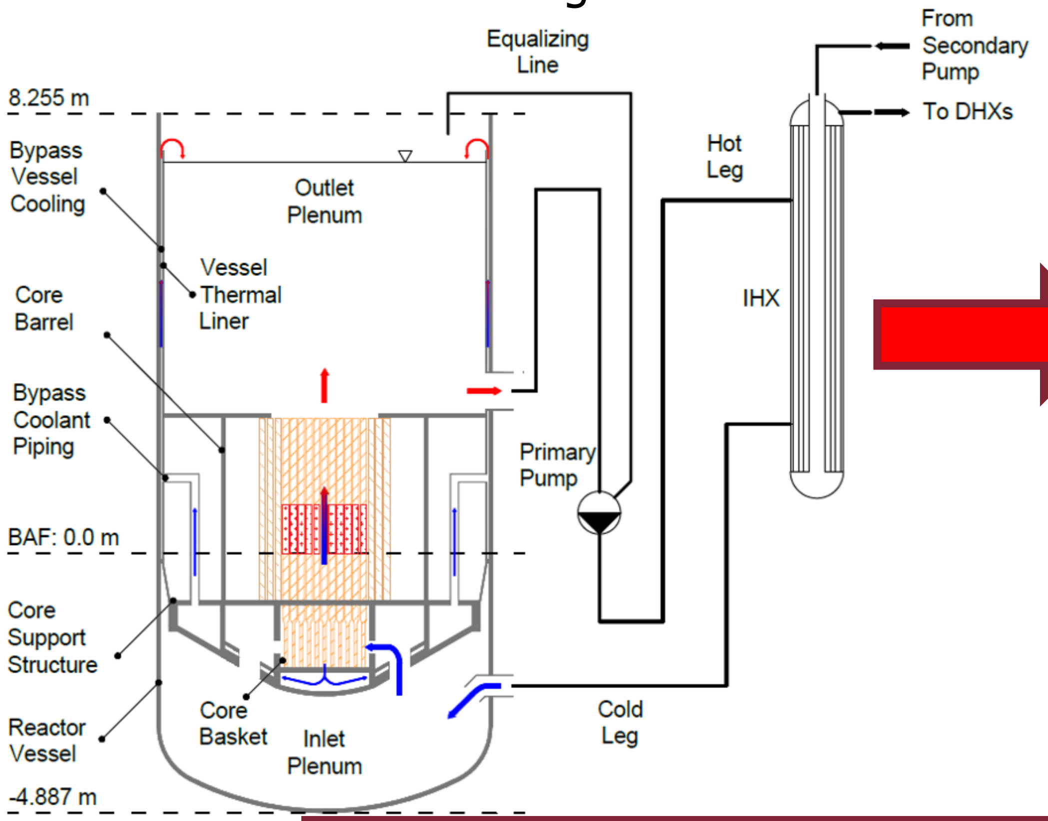
- **PHISICS** uses **TH parameters** provided by **RELAP5-3D** to interpolate the **self-shielded macroscopic cross sections** present in the **.xml file (Xsec database)** and calculates the **core power distribution (q_{node})**.
- The core power distribution is given to RELAP5-3D code to solve the **thermal fluid-dynamic problem** and compute the TH parameters for the next time step of iteration.
- The **.xml file** with the self-shielded cross sections is provided by the **ECCO** cell/lattice code (**ERANOS package**).

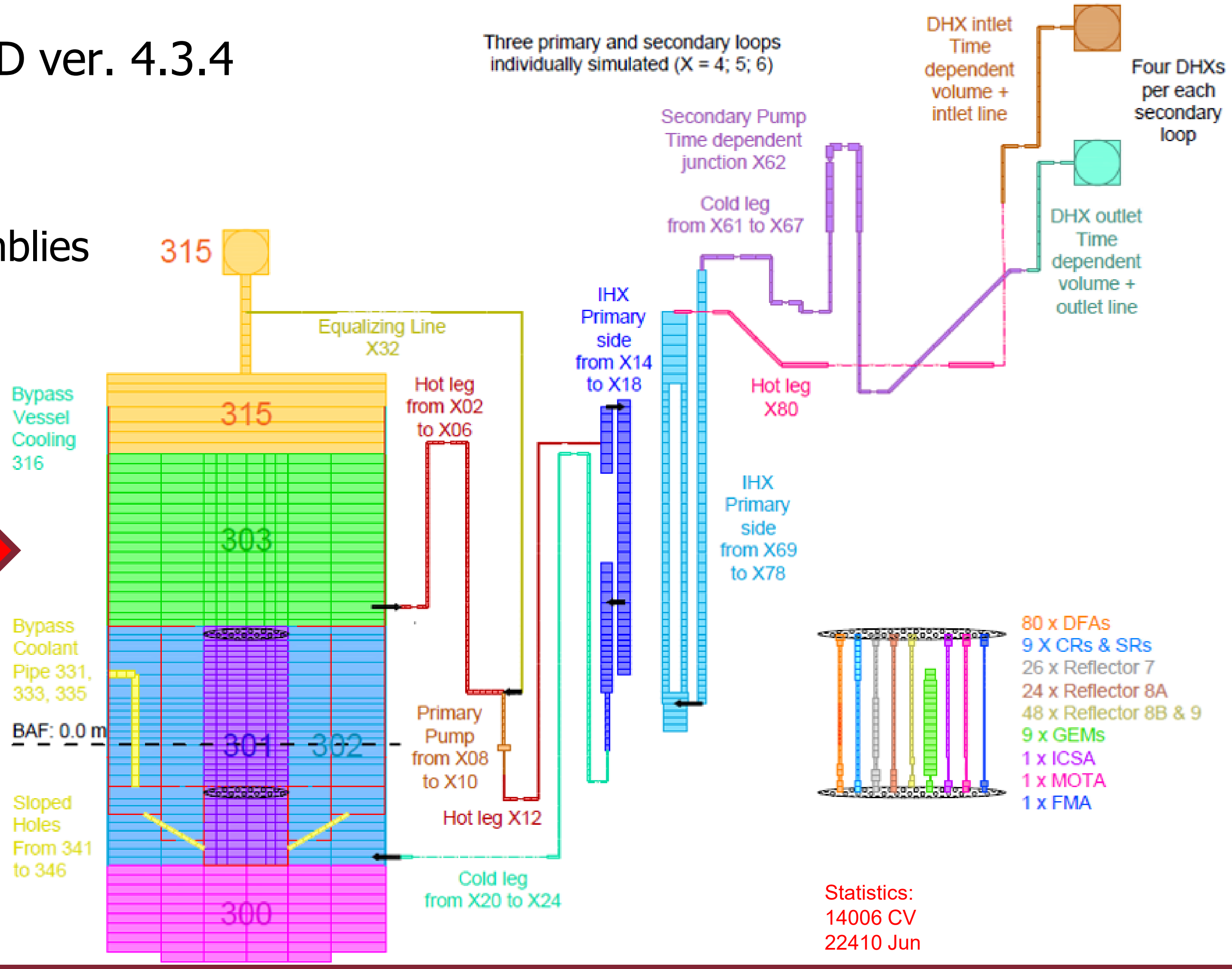


- Main focus is on the **Gas Expansion Module (GEM)** safety system, simulated with **the free level of sodium** and considered for **temperature and density feedback in the NK problem**, to physically evaluate the effect during the transient.

OVERVIEW OF NK-TH MODELLING

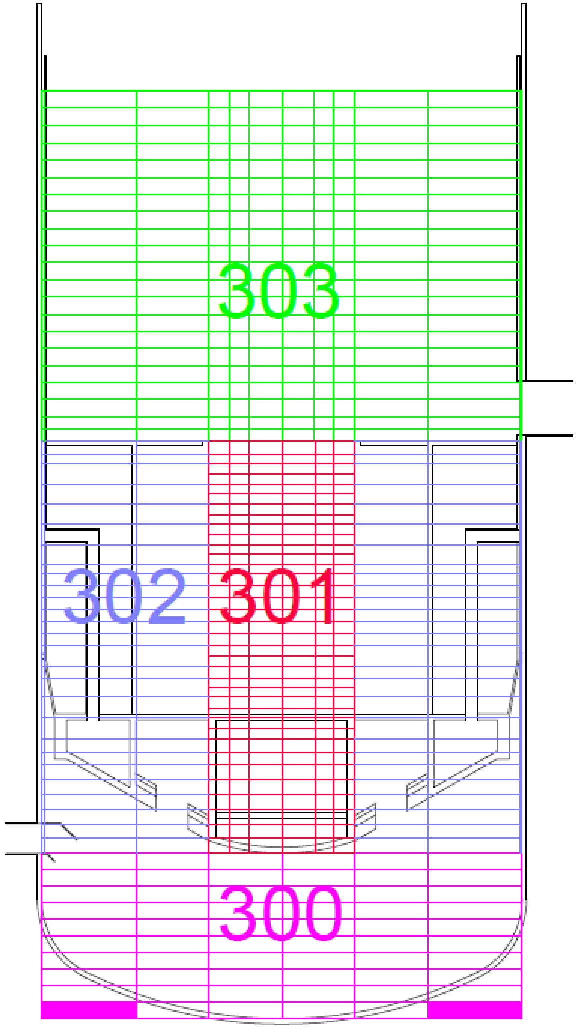
- TH Modeling developed with RELAP5-3D ver. 4.3.4
- Two macro regions:
  - "MULTID" nodalization of the RV
  - 1D modeling of HTS and core assemblies





OVERVIEW OF TH MODELLING: 3D NODALIZATION FOR RV

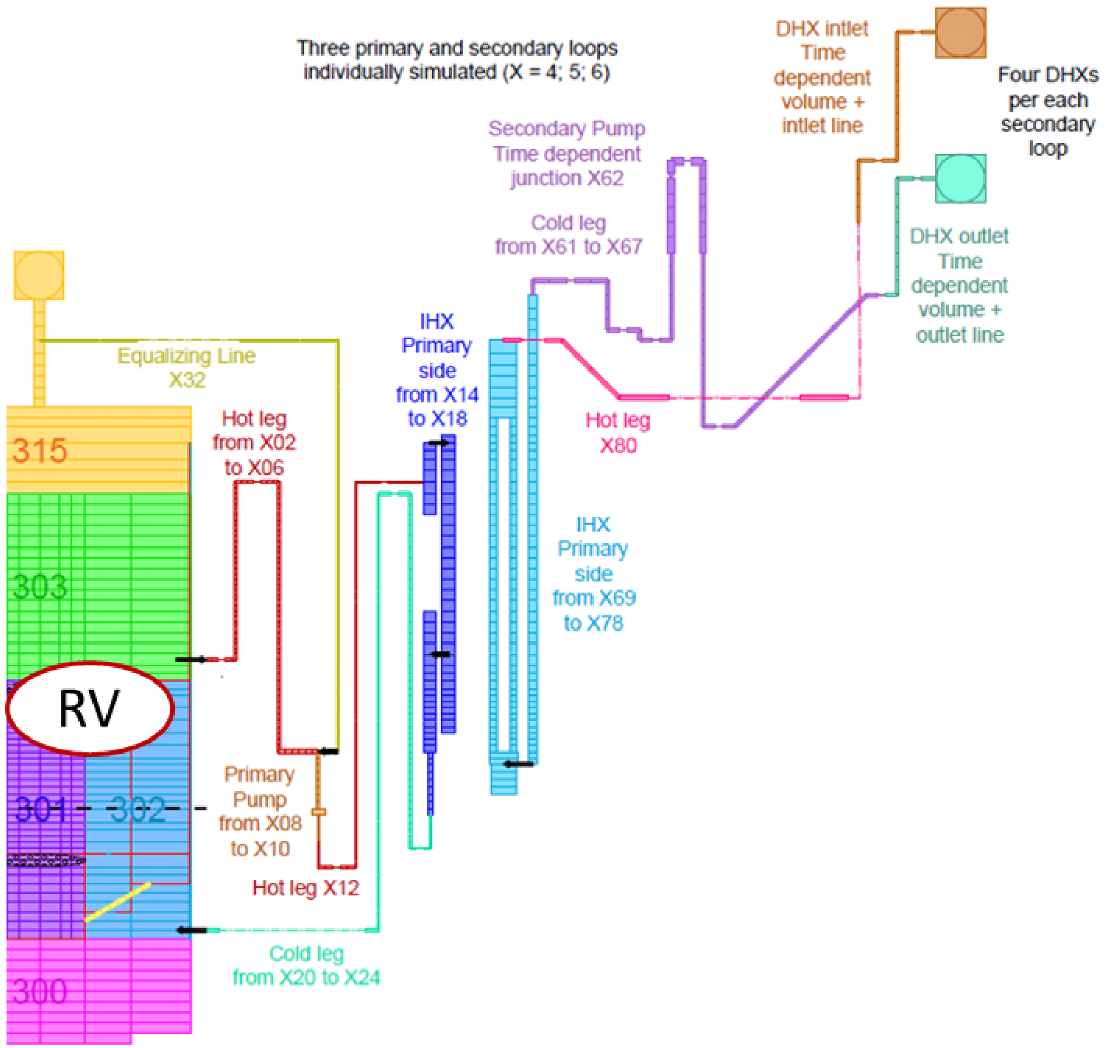
- Four MULTID components;
- Cylindrical geometry (r, θ, z);
- Six azimuthal intervals (θ-coordinate), based on actual symmetries;
- Radial and axial modeling ad hoc for each component;
- Sliced modeling approach;
- Volume and junction factors adopted to account for internals and lower plenum geometry;
- Heat structures account for heat exchange between different zones and material inventory.



MULT ID#	Description	Rad. Mesh N°	Azim. Mesh N°	Ax. Mesh N°	Total CVs
300	Inlet Plenum	3	6	10	180
301	Lower plenum, Core basket, Core bypass	3	6	36	648
302	Annular region between RV and core	3	6	27	486
303	Outlet Plenum	6	6	18	648

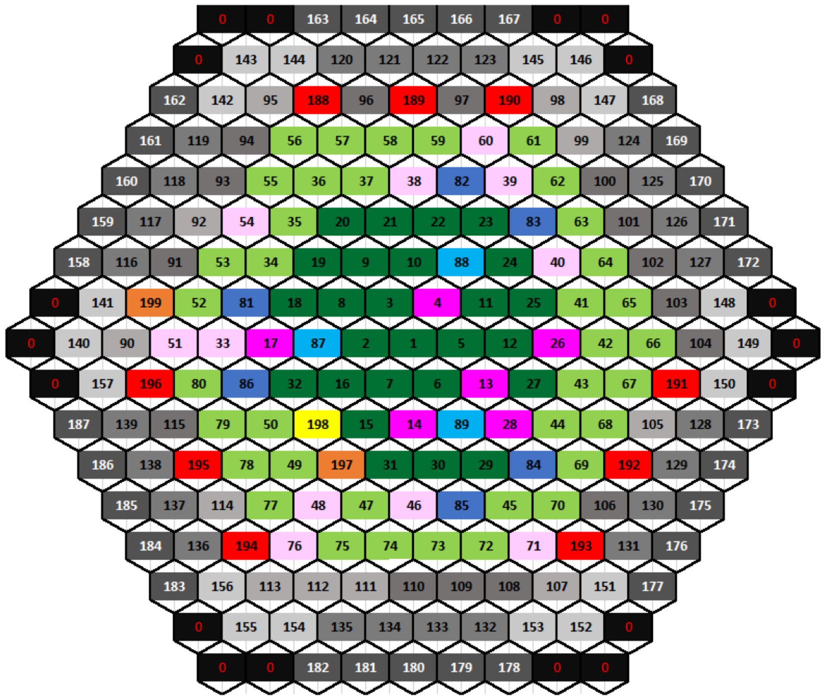
OVERVIEW OF TH MODELLING: 1D NODALIZATION FOR HTS

- Three primary loops and three secondary loops separately modelled;
- 1D nodalization scheme reflects actual elevations and geometries;
- Sliced modeling approach;
- Primary pumps simulated with pump components: homologous curves derived from benchmark specifications;
- Secondary HTS simulated as open loops, imposing sodium inlet temperature and outlet pressure, substituting for the DHXs;
- Secondary mass flow set as BC with dedicated TMDP JUN components;
- HTC correlations: Seban & Shimazaki (no bundle), Graber & Rieger (bundle).



OVERVIEW OF TH MODELLING: 1D NODALIZATION FOR REACTOR CORE

- Assembly-by-assembly modeling;
- Actual core arrangement kept by proper TH coupling with core bypass (MULTID #301);
- Geometrical features differentiated per each assembly type;
- Axial meshing consistent with assembly design and sliced modeling approach;
- GEM modeling allows the free level movement (useful for NK-TH);
- Pressure drops modeling developed to match Cheng & Todreas correlation;
- Calibrated inlet K-loss coefficient for shield orifice region;
- HTC correlations: Seban & Shimazaki (no bundle), Kazimi & Carelli (bundle).



Ass. Type	Label	Ass. N°	RELAP IDs
Driver Fuel Assemblies	DFA	80	1-80
Control & Safety Rods	CR & SR	9	81-89
Reflector Assemblies	REFL	98	90-187
Gas Expansion Modules	GEM	9	188-196
Materials Open Test Assembly	MOTA	1	197
In Core Shim Assembly	ICSA	1	198
Fracture Mechanics Assembly	FMA	1	199

OVERVIEW OF TH MODELLING: 1D NODALIZATION FOR REACTOR CORE

❖ The axial modelling referred to each assembly type is shown below.

DFAs

CV#	Region
26	HANDLING SOCKET
25	
24	PIN BUNDLE
23	
22	
21	
20	
19	
18	
17	
16	
15	
14	
13	
12	
11	
10	
9	
8	
7	
6	SHIELD OR. REG.
5	
4	
3	
2	INLET NOZZLE
1	

CR/SRs

CV#	Region
26	HANDLING SOCKET
25	
24	CONTROL ROD SHAFT
23	
22	
21	
20	
19	
18	ABSORBER REG.
17	
16	
15	
14	
13	
12	
11	
10	
9	
8	
7	
6	SHIELD OR. REG.
5	
4	
3	
2	INLET NOZZLE
1	

REFL. 7/8A

CV#	Region
26	HANDLING SOCKET
25	
24	TOP AD. BLOCK
23	UPPER SHIELD
22	
21	
20	
19	
18	
17	
16	AB. CORE LOAD PAD
15	REFLECTOR
14	
13	
12	
11	
10	
9	
8	
7	LOW AD. BLOCK
6	SHIELD OR. REG.
5	
4	
3	
2	INLET NOZZLE
1	

REFL. 8B/9

CV#	Region
25	HANDLING SOCKET
24	
23	TOP AD. BLOCK
22	UPPER SHIELD
21	
20	
19	
18	
17	
16	
15	AB. CORE LOAD PAD
14	REFLECTOR
13	
12	
11	
10	
9	
8	
7	
6	LOW AD. BLOCK
5	SHIELD OR. REG.
4	
3	
2	INLET NOZZLE
1	

GEM

CV#	Region
	HANDLING SOCKET
	UPPER SHIELD
20	EXPANSION VOLUME
19	
18	
17	
16	
15	
14	
13	
12	
11	
10	
9	
8	
7	
6	
5	
4	
3	SHIELD OR. REG.
2	INLET NOZZLE
1	

OVERVIEW OF NK MODELLING

- PHISICS interpolates macroscopic cross section from a N-dimensional Cartesian grid made up of core parameters (fuel T, coolant T, "coolant" ρ and CR position).
- The first "coolant" density simulates the presence of Ar in the CV. In this way, Na inserted into the GEM is treated as the BWR two-phase water.
- Cross sections calculated with ECCO cell code by considering: 15 energy groups; P1 approximation for scattering; Thermal expansion; Doppler effect; JEFF 3.1.1 nuclear data library.
- Material compositions derived from benchmark specifications.
- The NK nodalization foresees 30 axial meshes (all core height except for inlet nozzle and handling socket). Radially, a neutronic node associated to each assembly (5970 nodes).
- Zero-flux BC used at core edges.
- For each time step, convergence criteria are: 1 pcm for k-effective and 10^{-04} for neutron flux.
- Standard ANS73 curve used for gamma power.

Core Parameter	Unit	Values
Fuel Temperature	°C	443, 1950
Coolant Temperature	°C	300, 600
Coolant Density	kg/m^3	1.2*, 860, 1000
CR Position	-	inserted/not inserted

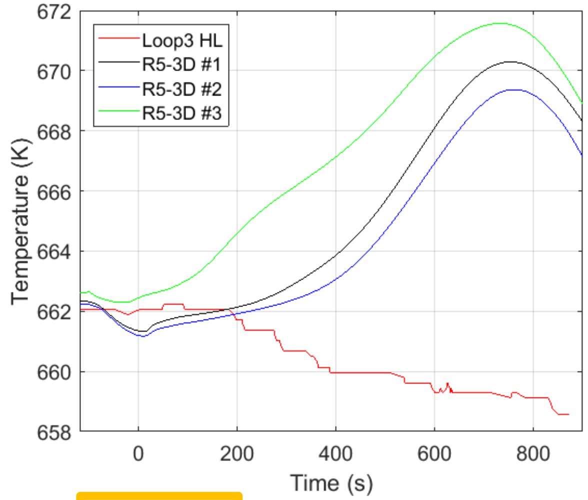
* the first one simulates the presence of Ar gas in the CV

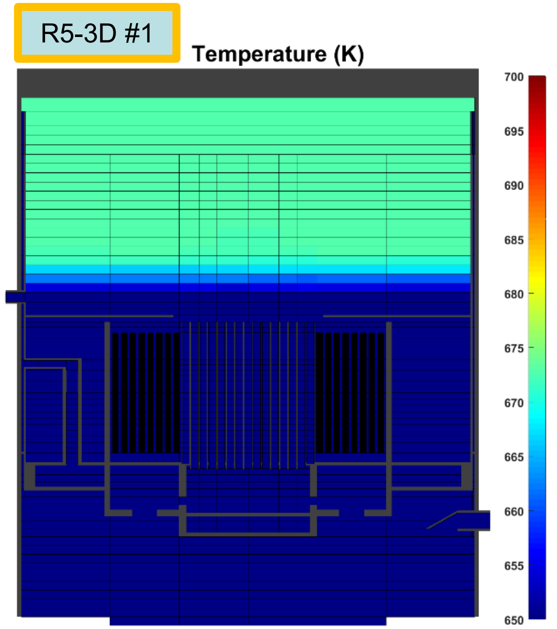
Pool mesh sensitivity

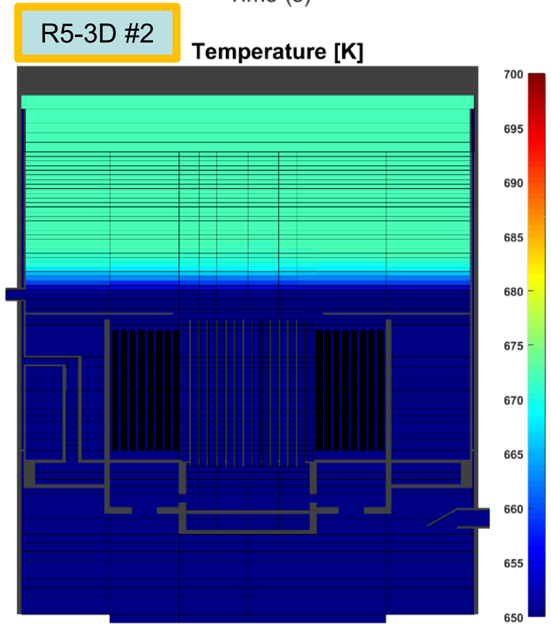
A **mesh sensitivity** has been performed for the **outlet plenum** to investigate effect on the primary hot leg temperature and on the thermal stratification and mixing phenomena:

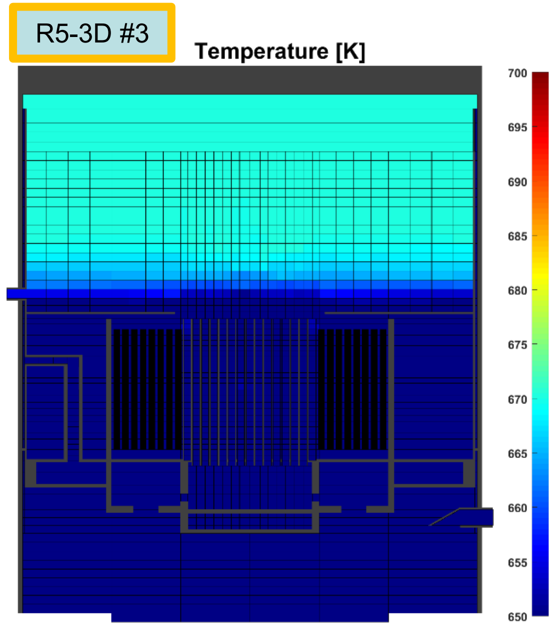
- **R5-3D #1**: 5 meshes along r-coordinate, 18 meshes along z-coordinate
- **R5-3D #2**: 5 meshes along r-coordinate, 36 (2x) meshes along z-coordinate
- **R5-3D #3**: 16 (3x) meshes along r-coordinate, 18 meshes along z-coordinate (this case also includes improved modeling of the core bypass);

- Although some quantitative differences, calculations provides same qualitative trend, keeping discrepancy with experiment







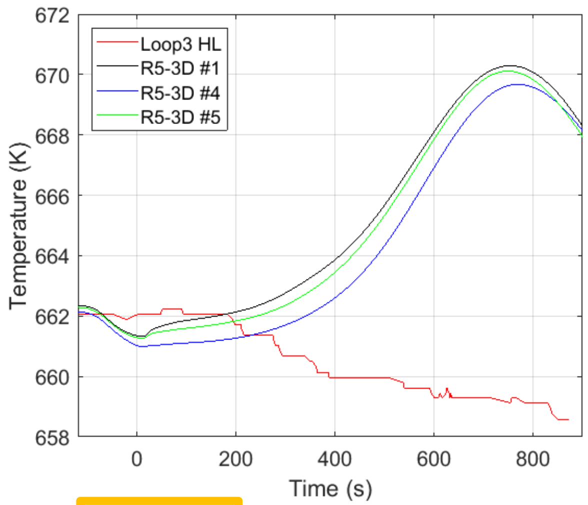


Pool mesh sensitivity

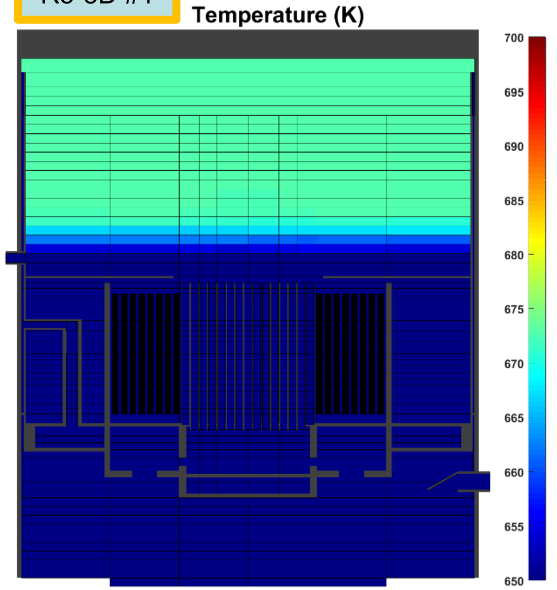
Further sensitivity analysis regarding the outlet plenum investigates the effect of **bypass flow between in-vessel storage and outlet plenum**, and of **axial thermal conduction** within outlet plenum:

- **R5-3D #1**: no bypass flow, no thermal conduction
- **R5-3D #4**: yes bypass flow, no thermal conduction
- **R5-3D #5**: no bypass flow, yes thermal conduction

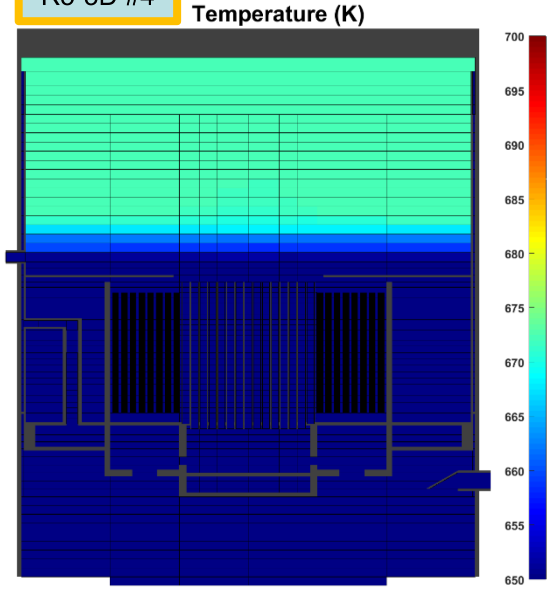
- Negligible differences are observed, while keeping the same qualitative results



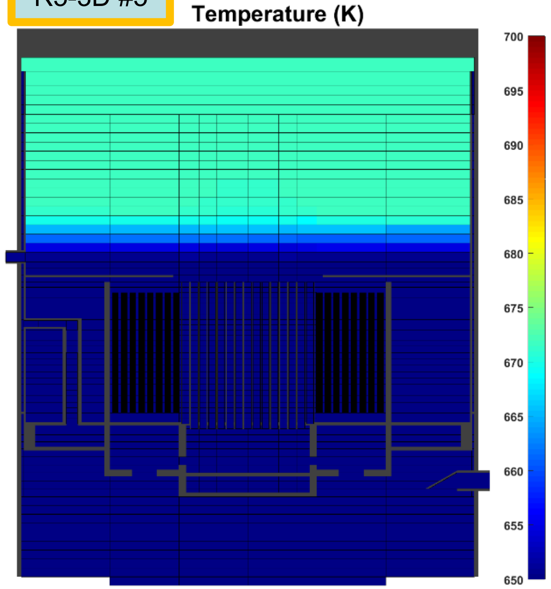
R5-3D #1



R5-3D #4

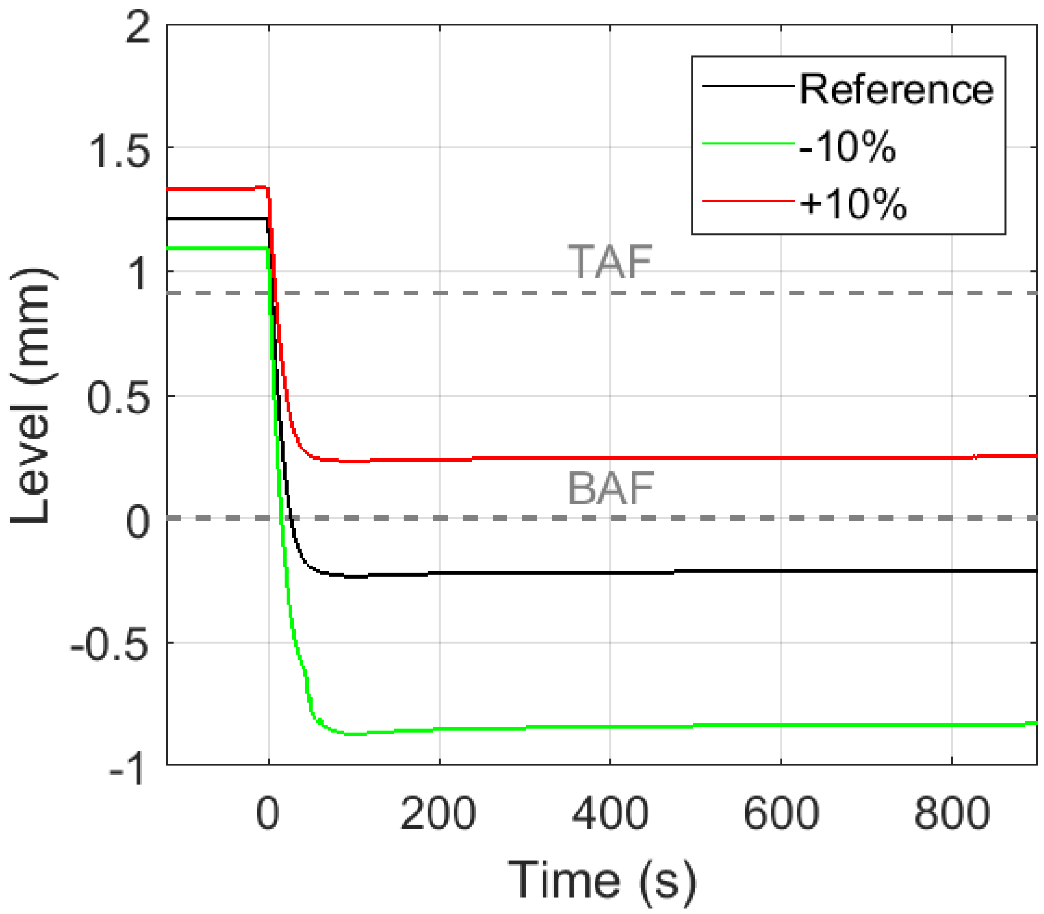


R5-3D #5



GEM level sensitivity

- The effect of several parameters on the **GEM free level motion** has been investigated: initial GEM and RV free surface level, RV cover gas pressure, GEM-to-bypass heat transfer
- Among these, initial free surface level within the GEMs has shown relevancy
- The reference case is assumed as declared in benchmark specifications
- Initial level change results in different initial amount of gas into the GEM
- It influences both the magnitude of level change (+10% case remains above BAF) and time for total reactivity injection (26 s in reference calculation and 15 s in -10 % case)



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FFTTF LOFWOS TEST #13: STEADY STATE RESULTS

- Firstly, a steady-state simulation was carried out to set the FFTF reactor initial state.
- Results are very similar to the blind phase.

Primary Loop Pressure Drops

Parameter	Exp. Value [kPa]	R5-3D Value [kPa]	Δ%
DFA (FZ 1 - 7)	623.56[1]	626.26	0.43%
Primary loop 1 (piping)	76.95[2]	74.90	-2.66%
Primary loop 2 (piping)	76.95[2]	74.65	-2.99%
Primary loop 3 (piping)	76.95[2]	73.44	-4.56%
IHX 1	52.11[2]	50.22	-3.63%
IHX 2	52.11[2]	50.04	-3.97%
IHX 3	52.11[2]	49.21	-5.57%

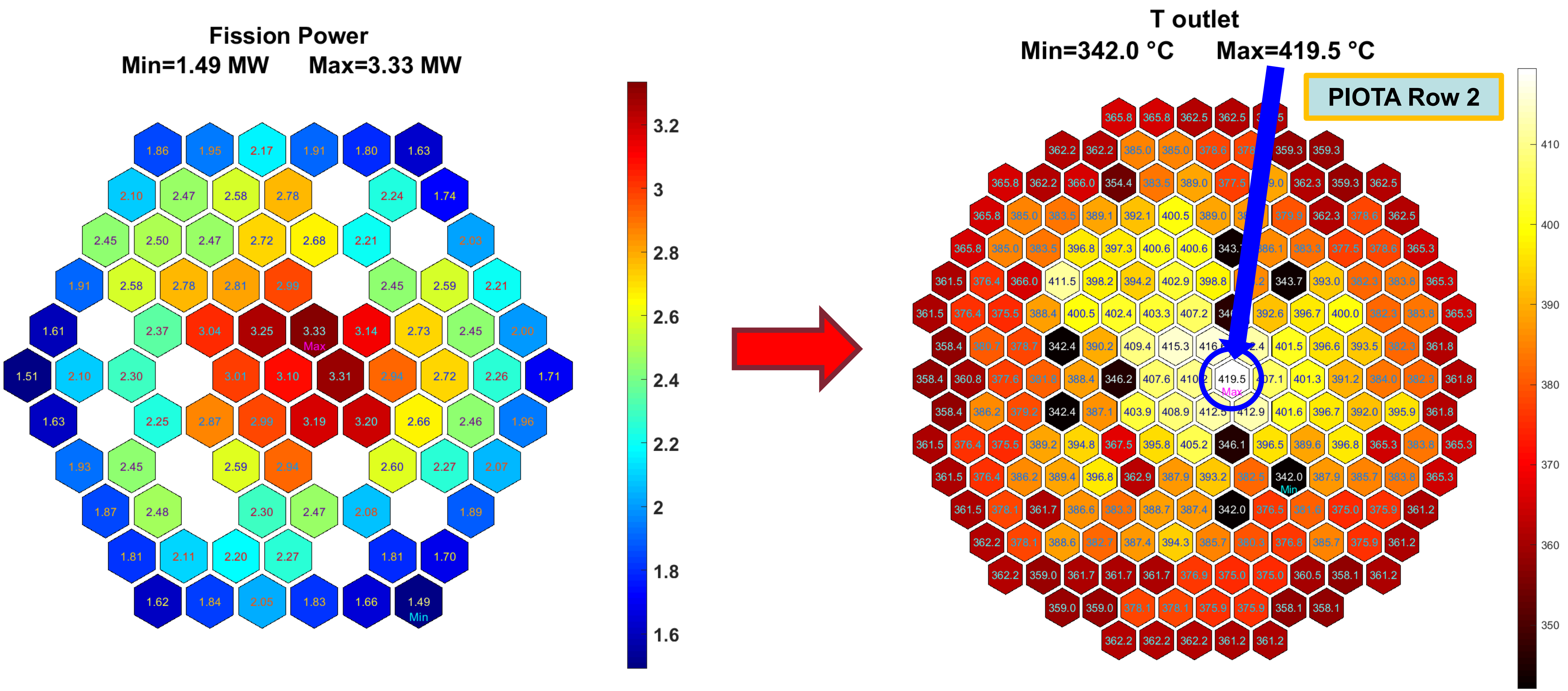
[1] 85% of nominal value reported in benchmark specifications;

[2] 90% of nominal value reported in benchmark specifications;

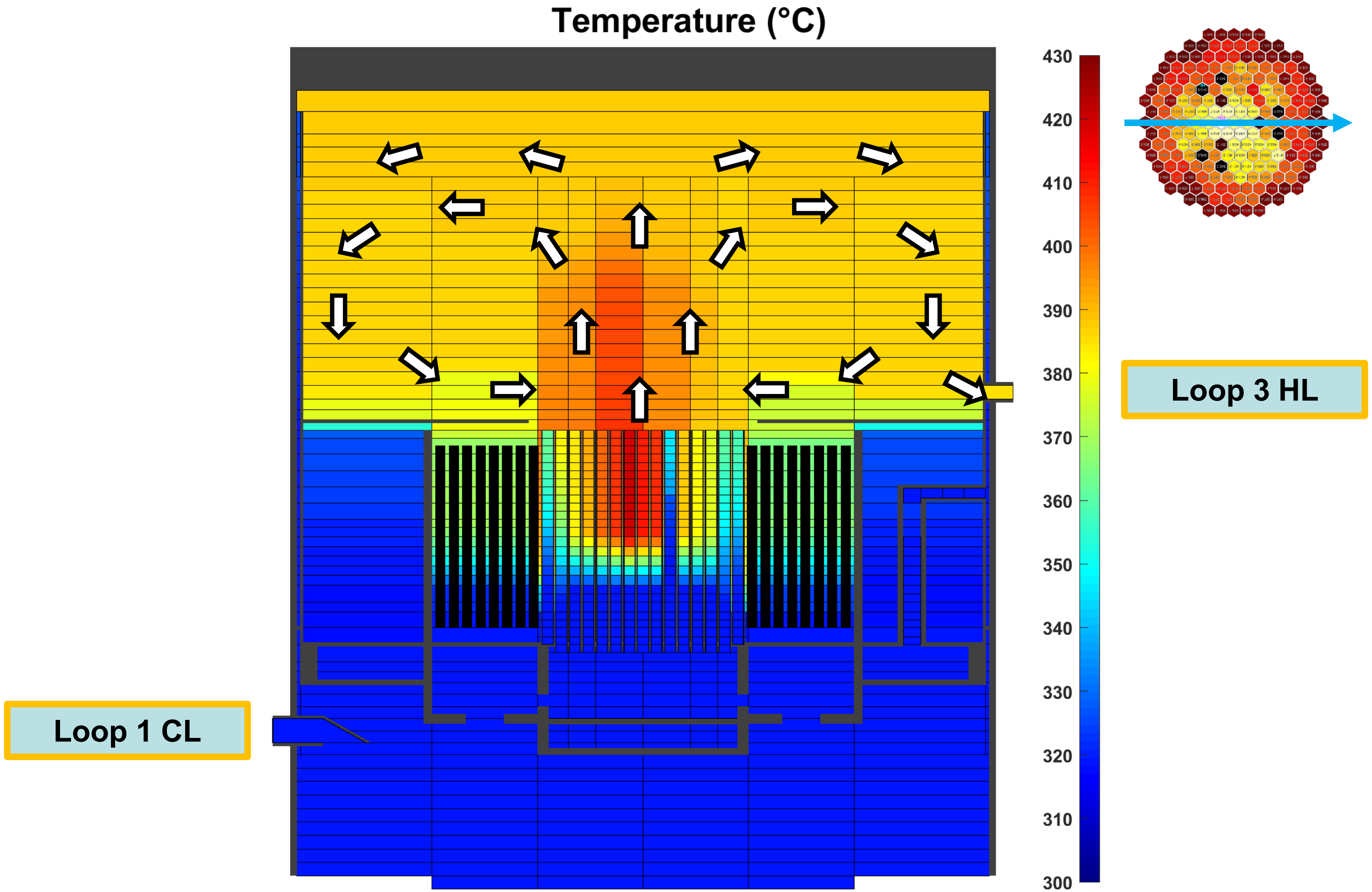
Primary Mass Flow Distribution

FZ#	Ass N°	Exp. MF [kg/s]	R5-3D MF Mean [kg/s]	R5-3D MF σ [kg/s]	Δ%	R5-3D Tot MF [kg/s]
1	22	25.39	25.25	4.5E-3	-0.54	555.54
2	12	24.14	23.97	3.4E-3	-0.70	287.64
3	22	20.82	20.80	3.0E-3	-0.10	457.59
4	12	25.39	25.34	1.55E-2	-0.21	304.04
5	5	19.97	19.79	2.8E-3	-0.90	98.95
6	4	24.82	24.64	4.8E-3	-0.73	98.56
7	3	20.50	20.47	5.1E-4	-0.13	61.42
8	1	1.79	1.78	-	-1.05	1.77
9	1	2.04	2.02	-	-0.80	2.02
10	9	4.55	4.51	2.6E-3	-0.89	40.59
11	1	0.65	0.64	-	-0.94	0.64
12	11	1.79	1.77	5.8E-5	-1.02	19.49
13	15	0.89	0.885	2.2E-5	-0.51	13.28
14	24	0.73	0.725	1.9E-5	-0.74	17.39
15	18	0.53	0.530	6.8E-6	-0.05	9.54
16	30	0.38	0.379	4.7E-6	-0.24	11.37
Total	190	1988.42	-	-	-0.43	1979.83

FFTTF LOFWOS TEST #13: STEADY STATE RESULTS



FFTTF LOFWOS TEST #13: STEADY STATE RESULTS



FFTTF LOFWOS TEST #13: PHENOMENOLOGICAL WINDOWS

- Five Phenomenological Windows (PhWs) have been identified

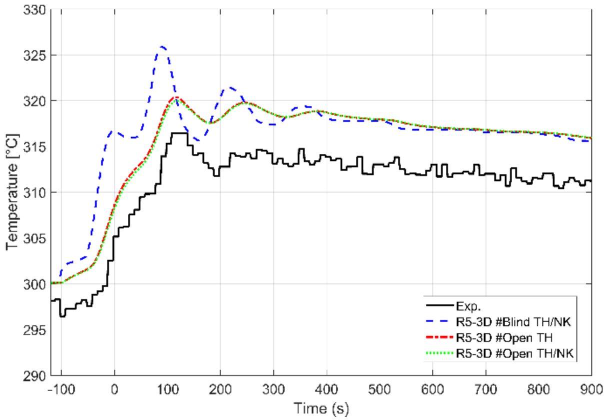
PhW	Time interval [s]	Description
1	-120 – 0	DHX fan speed decrease and temperature rise in secondary cold legs
2	0 – 9	Power-to-flow ratio increase; first peak temperature at the core outlet
3	9 – 25	Power coastdown governed by negative reactivity feedbacks; effective core cooling by pumps inertia
4	25 – 100	GEM level below BAF; primary system energy increase and core outlet temperature maximum peak
5	100 – EoT	Long-term cooling in natural circulation

FFTTF LOFWOS TEST #13: TRANSIENT ANALYSIS RESULTS

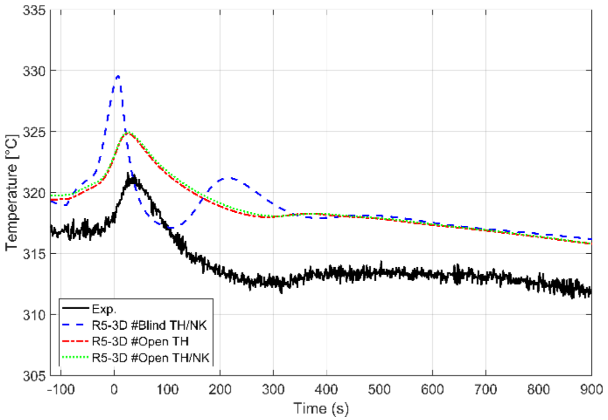
PhW 1

- Simulation results slightly overpredict the SL cold leg temperature, experimentally acquired downstream of the correspondent pump.
- Calculation outcomes approach the BC provided by Benchmark Specifications (BS);
- Discrepancy can be explained by the thermocouples' thermal inertia (added in Open).
- The deviation propagates to PL CL (through IHX) but not to core or HL, since suppressed by RV Inlet Plenum.
- Code well estimates PIOTA row 6 outlet temperature, but underpredicts the one of PIOTA row 2 of nearly ten degrees (lower power-to-flow ratio; TCs uncertainty; possible higher assembly-to-bypass heat transfer);

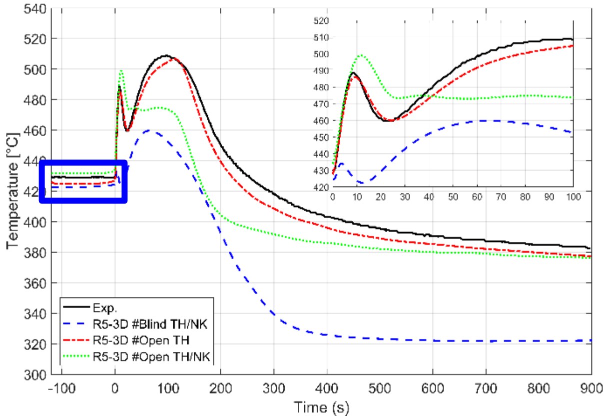
Secondary loop 1 CL



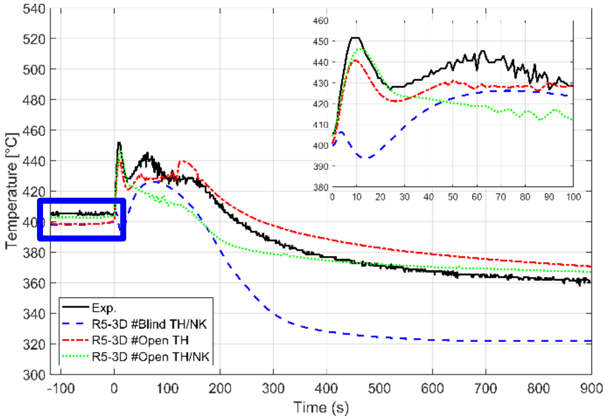
Primary loop 1 CL



PIOTA row 2



PIOTA row 6

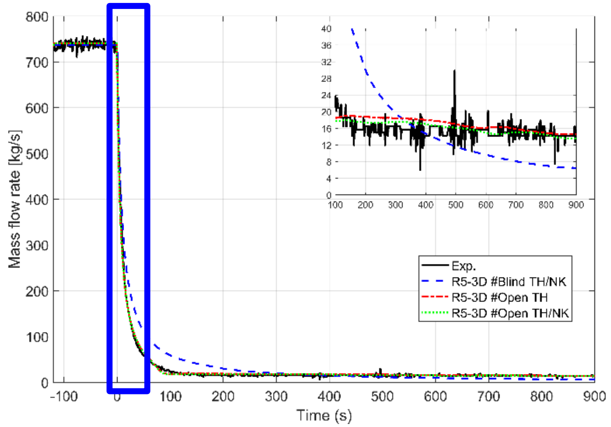


FFTTF LOFWOS TEST #13: TRANSIENT ANALYSIS RESULTS

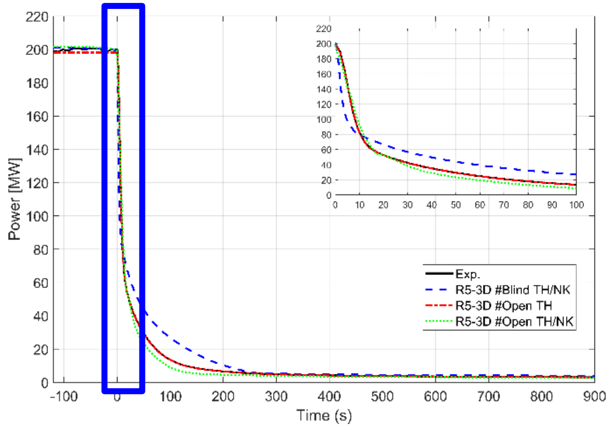
PhW 2

- The second PhW goes from PIE to the first peak in PIOTA temperatures (9 s).
- At the PhW end, sodium flow rate drops to 25% of the initial value, while total core power decreases slower (SCRAM not triggered), and, driven by reactivity feedbacks, is still about halfed the initial value.
- The increased power-to-flow ratio produces the first PIOTA temperature spike (+60 and +47 °C for PIOTA row 2 and 6, up to 480 and 447 °C, respectively).
- The trend is qualitatively well predicted by the code.
- Quantitatively, temperature excursion exactly reproduced in only TH for PIOTA 2, and also well reproduced for PIOTA 6 and adding the NK.

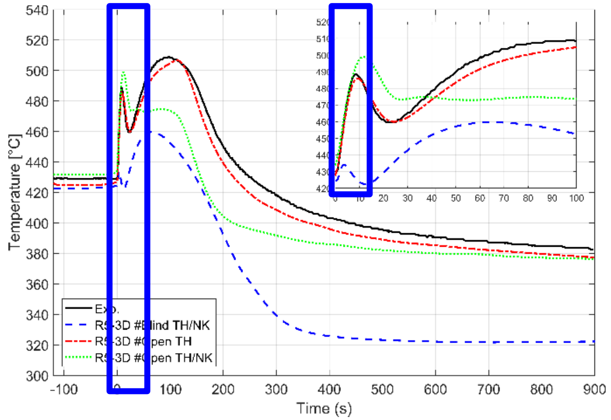
Primary loop 1 MF



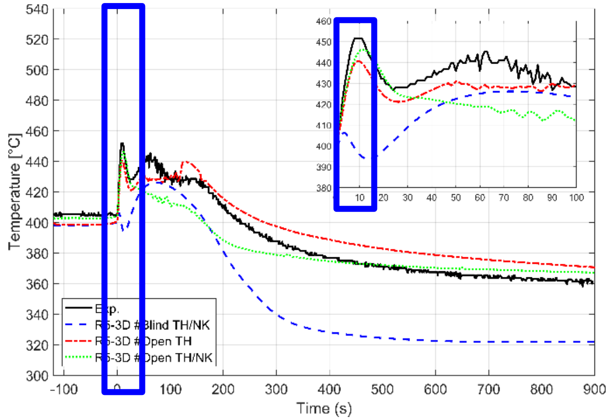
Reactor Power



PIOTA row 2



PIOTA row 6

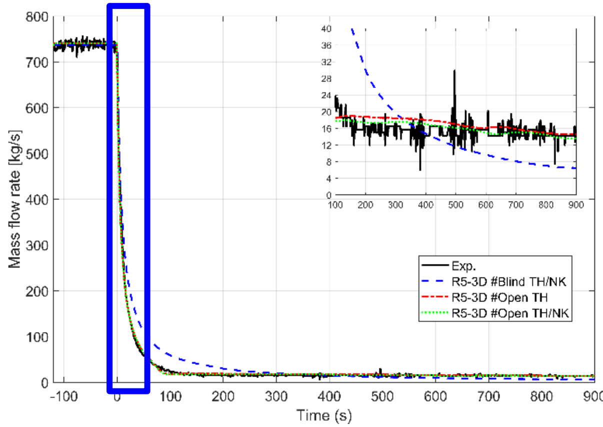


FFTTF LOFWOS TEST #13: TRANSIENT ANALYSIS RESULTS

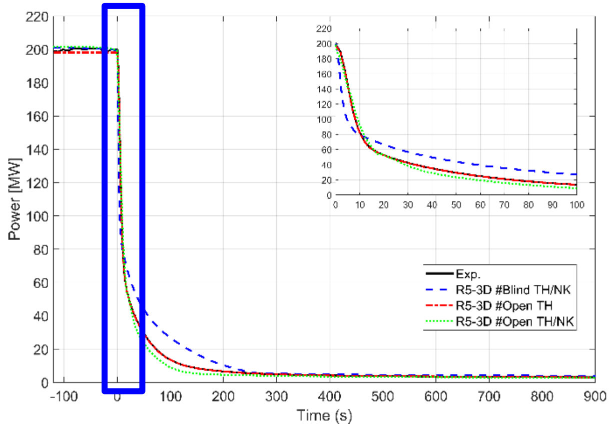
PhW 3

- The third PhW is ruled by the power reduction due to the insertion of large negative reactivity feedbacks.
- Pump coastdown controlled by the component inertia is well predicted by the code in Open.
- Core inlet flow rate (and pressure) reduces, allowing the gas expansion within the GEM. Sodium free level drops from above the TAF to below the BAF, enhancing radial neutron leakage and producing a negative reactivity feedback that shuts down the reactor.
- Following the power reduction, PIOTA temperatures decrease. This is qualitatively simulated by the code also with NK even if the magnitude of the temperature lowering is underpredicted. This is mainly due to the overestimation of the total reactor power.
- The power surplus calculated by the code is due to some negative reactivity feedbacks correlated to the core thermomechanical deformations not well considered in the NK model, such as diagrid and fuel expansion (a linear dilatation is actually considered).

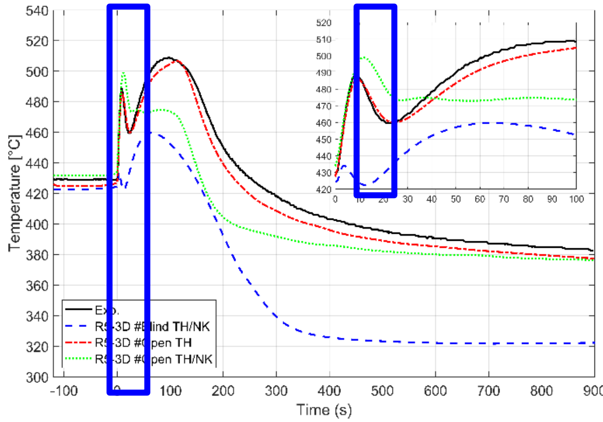
Primary loop 1 MF



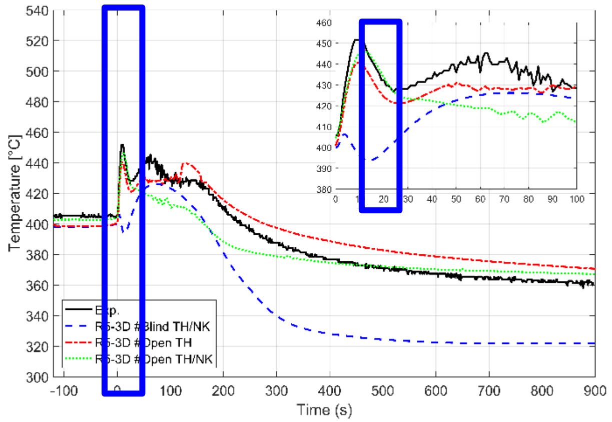
Reactor Power



PIOTA row 2



PIOTA row 6

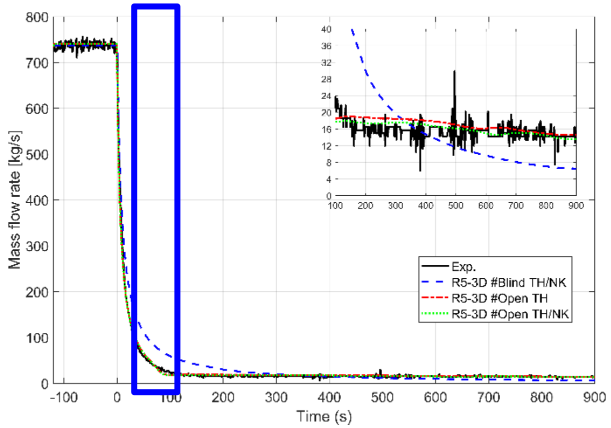


FFTTF LOFWOS TEST #13: TRANSIENT ANALYSIS RESULTS

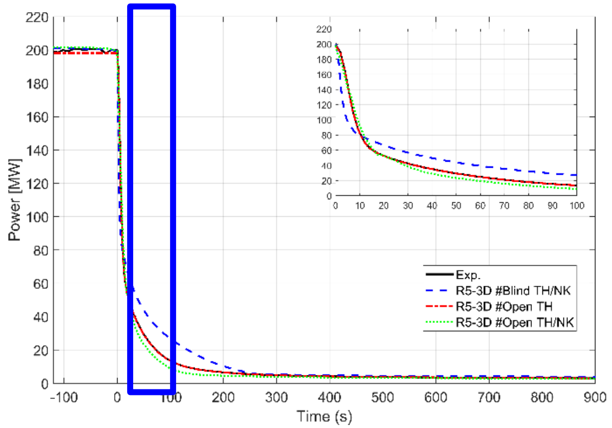
PhW 4

- The fourth PhW begins when the GEM level moves below the BAF and concludes when natural circulation is completely established.
- GEM negative contribution to core reactivity variation is terminated, and PIOTA outlet temperatures rise again.
- The code calculates PIOTA row 2 maximum value 20 °C above the initial one. The trend is qualitatively well reproduced but the peak temperature is undestimated with NK.
- PIOTA row 6 experiences a softer excursion but with different experimental behavior, only partially due to radial power distribution. Indeed, a significant role is played by assembly-to-bypass heat transfer.
- [Liu and Hu] preliminary investigated this contribution. It was recognized that PIOTA position in the core array could explain the dissimilarities acquired by the fast response TCs.

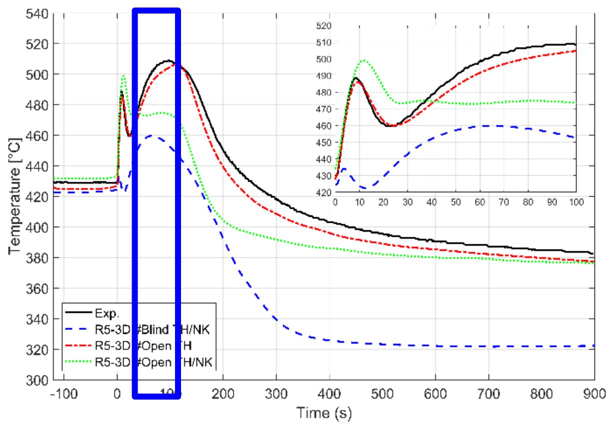
Primary loop 1 MF



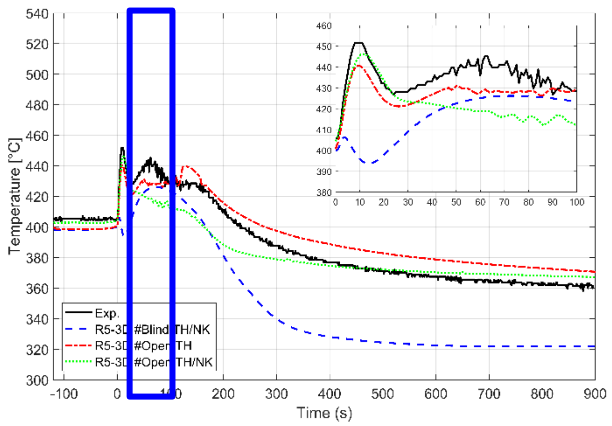
Reactor Power



PIOTA row 2



PIOTA row 6

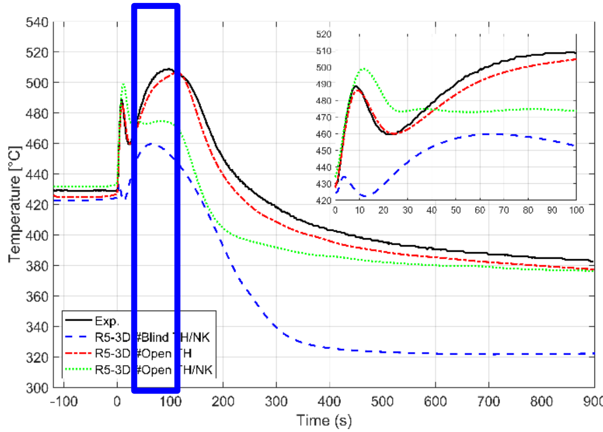


FFTTF LOFWOS TEST #13: TRANSIENT ANALYSIS RESULTS

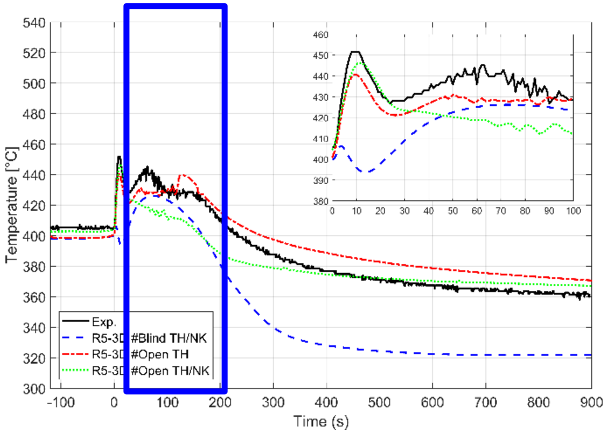
PhW 4

- ❖ PIOTA row 2 located in the core center, surrounded by DFAs (similar temperature axial profiles) → flat bypass temperature distribution in the correspondent region → low assembly-to-bypass heat transfer.
- ❖ PIOTA row 6 installed near non-fuel assemblies (reflectors and GEMs) → relevant gradient for bypass temperature in the surrounding region → significant assembly-to-bypass heat transfer.
- ❖ <u>Conclusion: needed core bypass detailed nodalization, accounting for the different radial regions.</u>
- ❖ For PIOTA row 6, code computes a temperature peak of 70 °C above the initial value. In addition, it predicts a parameter trend similar to PIOTA row 2.
- ❖ This means that the numerical model is not able to well reproduce the heat exchange with the core bypass and the nodalization adopted for this region results too coarse.

PIOTA row 2



PIOTA row 6



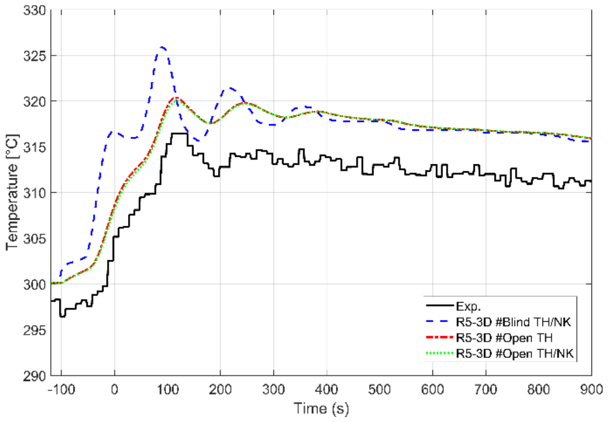
- ❖ Prediction of PIOTA row 6 outlet temperature is significantly increased when considering an improved bypass model (R5-3D #3) and the rated power is imposed as boundary condition (TH only simulation).

FFTTF LOFWOS TEST #13: TRANSIENT ANALYSIS RESULTS

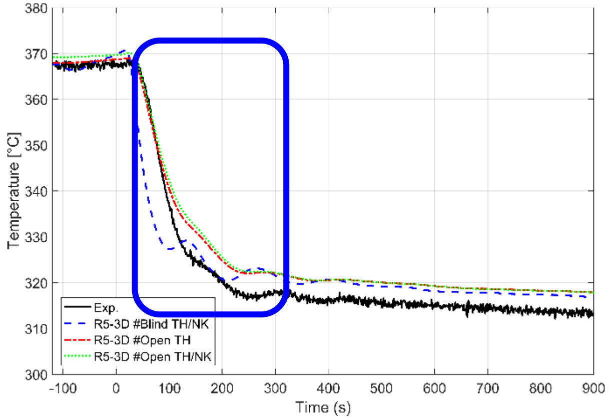
PhW 4

- Focusing on the SL, in the fourth PhW a large temperature decrease is experienced on the hot leg.
- This is due to the significant heat transfer reduction within IHXs. The decrease of the PL mass flow produces a relevant drop of the correspondent velocity and HTC profiles that inhibits the thermal exchange.
- R5-3D predicted an anticipated reduction of the hot leg temperature in Blind. Experimental acquisitions are performed just before the DHXs inlet. As for SL cold leg in PhW1, disagreement was reduced inserting in Blind the thermocouples thermal inertia.

Secondary loop 1 CL



Secondary loop 1 HL

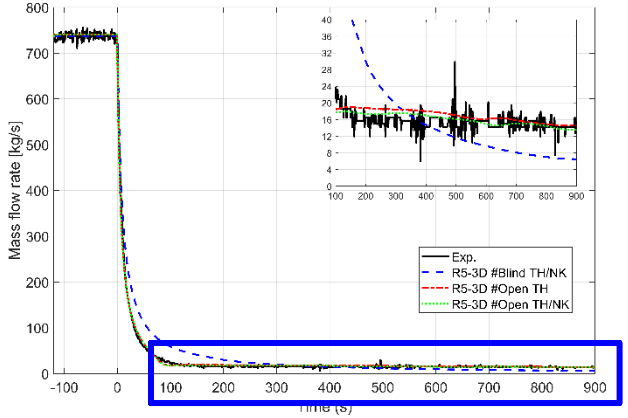


FFTTF LOFWOS TEST #13: TRANSIENT ANALYSIS RESULTS

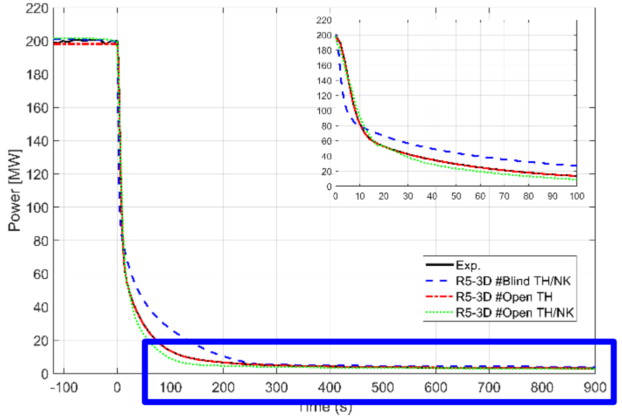
PhW 5

- The fifth PhW starts with the complete transition to natural circulation (nearly 100 s) and lasts up to EoT.
- R5-3D well predicts the transition. Later, experimental mass flow experiences large fluctuations around the mean value (2% of the initial one), higher than the uncertainty band. Good agreement between the average experimental data and the simulation outcomes (only a slight underestimation).
- PIOTA temperatures gradually decrease converging to a similar value. The exp. Acquisitions have more temperature differences in this PhW between PIOTA 2 and 6
- Several reasons explain this discrepancy, but the main one could be connected to the bypass heat transfer

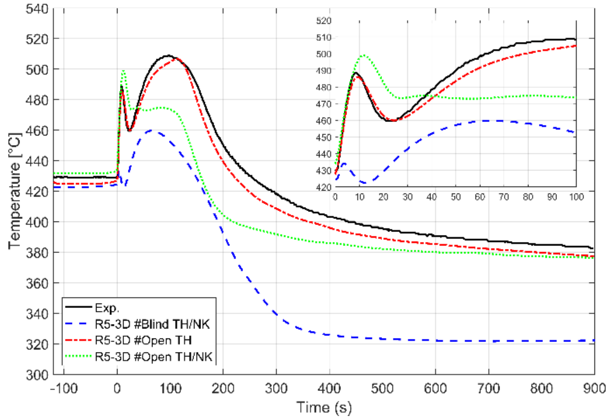
Primary loop 1 MF



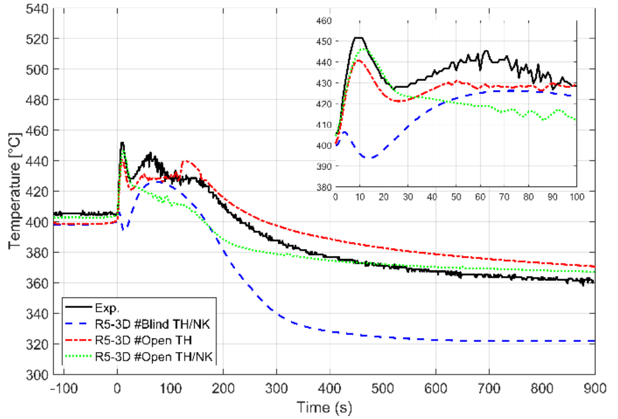
Reactor Power



PIOTA row 2



PIOTA row 6

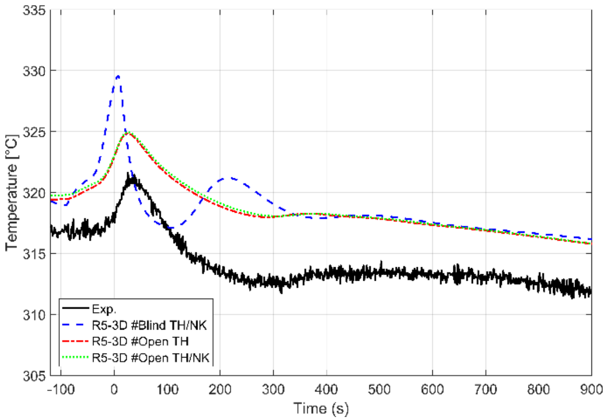


FFTTF LOFWOS TEST #13: TRANSIENT ANALYSIS RESULTS

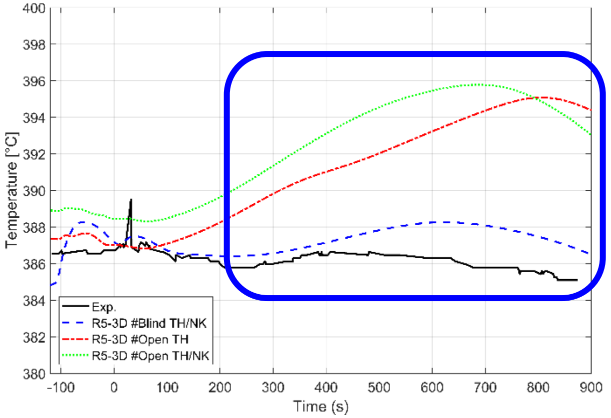
PhW 5

- TH code well reproduce the qualitative trend of the cold leg temperature (slight overprediction due to uncertainties in SL boundary conditions).
- Referring to the HL, numerical results agree with experimental data up to 200 s. Temperature is kept almost constant by RV outlet plenum large thermal inertia.
- Later, TCs observe a small temperature decrease. Instead, R5-3D predicts a temperature increase of few degrees (plateau at the EoT, 8 °C above initial value).
- Several phenomena affect the HL temperature: core outlet temperature, thermal stratification and mixing convection within RV outlet plenum, thermal inertia, and heat losses.
- BS do not provide TH data related to sodium flow path connecting core outlet and hot leg, making it difficult to identify the origin of such disagreement.

Primary loop 1 CL



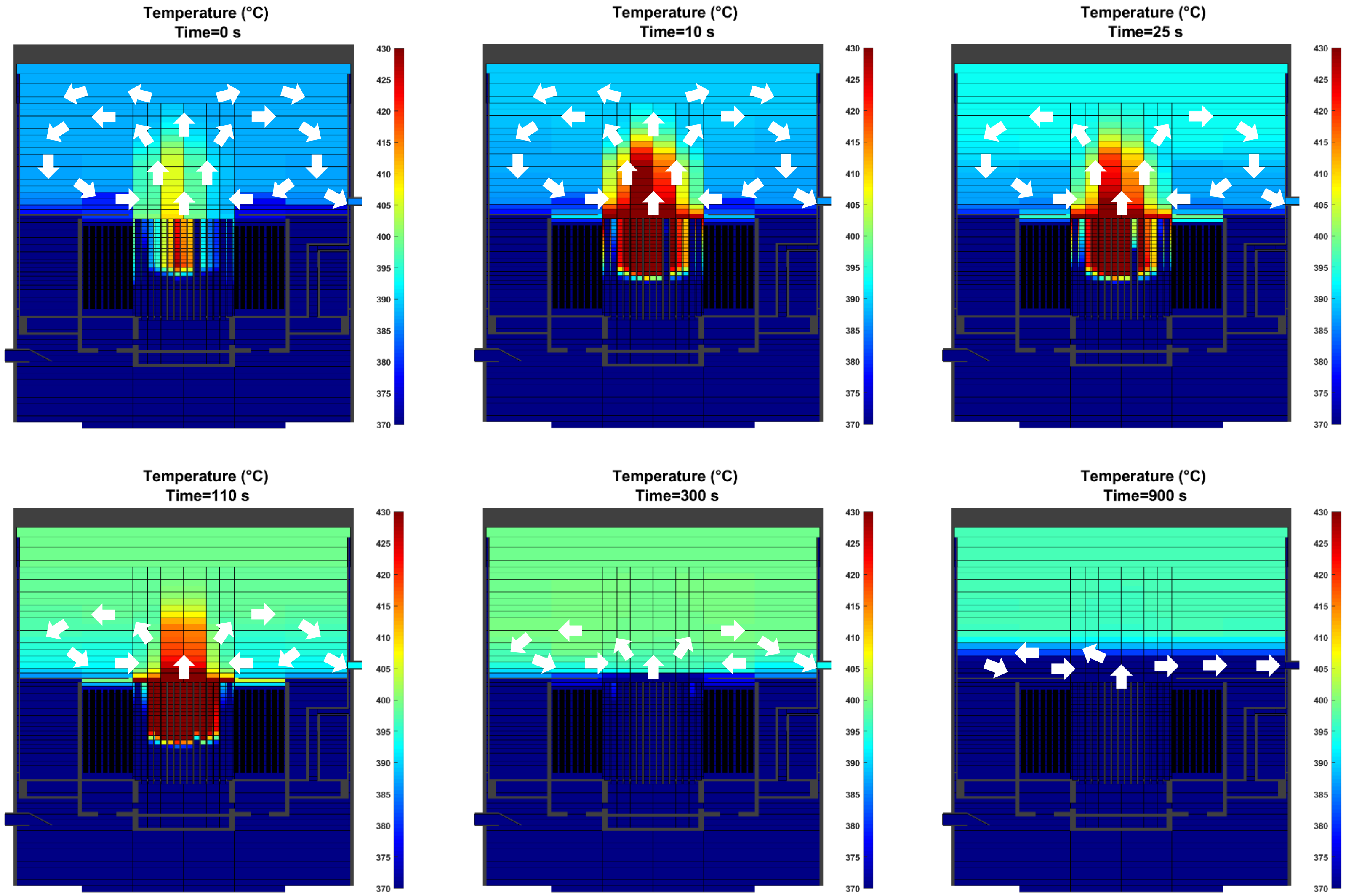
Primary loop 1 HL



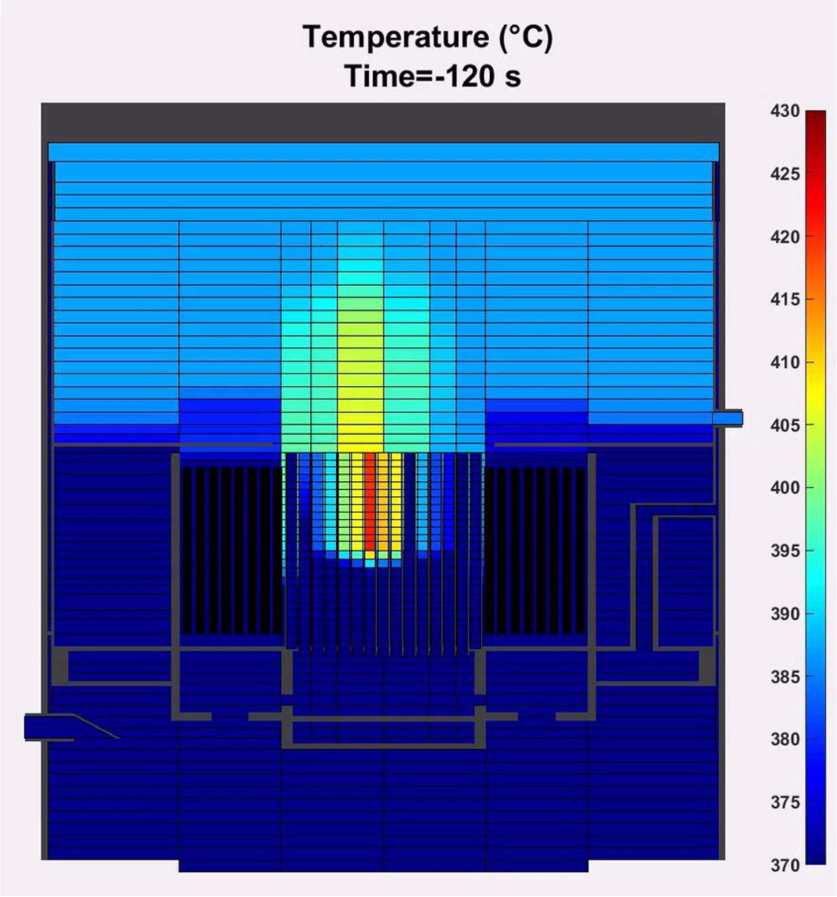
- <u>Possible explanation</u>: thermal stratification experienced in the horizontal pipeline at the RV outlet during 1982 pre-operational tests, [Stover]. Something similar probably occurs during LOFWOS Test #13. After forced flow is lost, RV outlet plenum is warm-up and hotter sodium enters the primary HL, probably causing thermal stratification and influencing TC measurement (due to instrument vertical position within the pipeline). R5-3D models the horizontal pipeline with 1D component, not allowing the simulation of such phenomena.

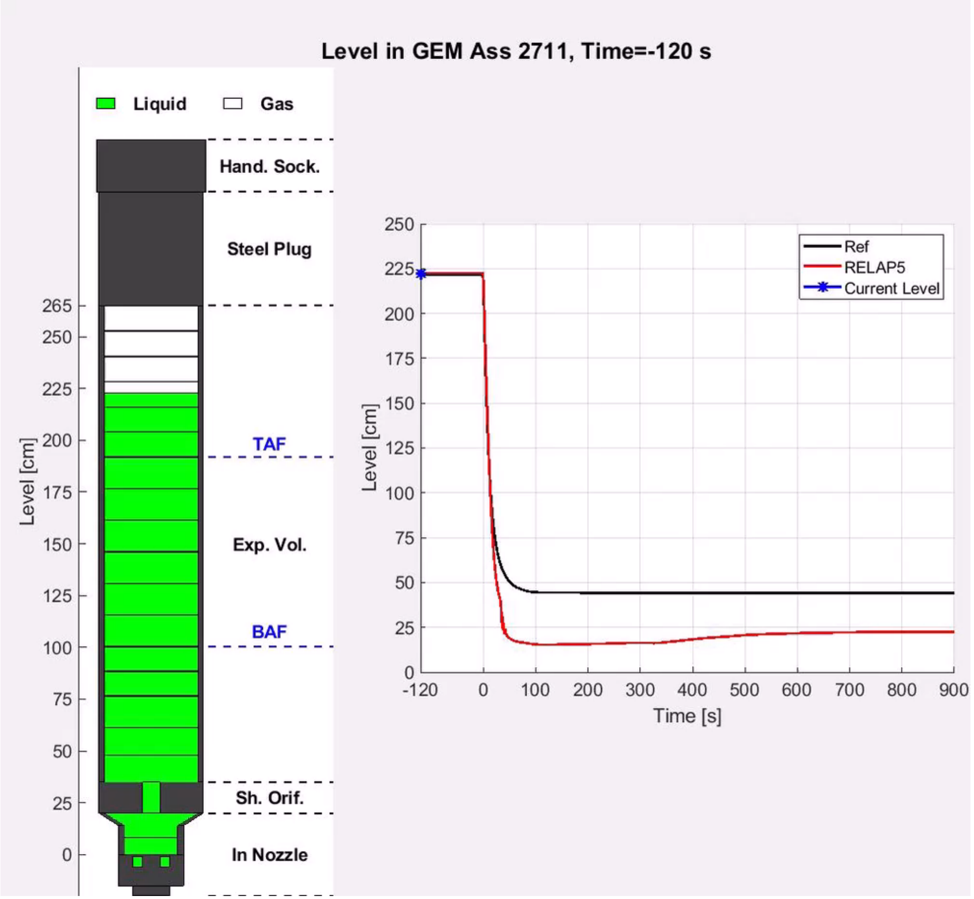
FFTTF LOFWOS TEST #13: POOL STRATIFICATION AND FLUID MOTION

- After the SoT a heating of the central region of the outlet plenum enhances the sodium mixing at the beginning of the test
- It leads to the heating of the upper region of the RV and the formation of a slight thermal front, as shown at 25s.
- As the upper region warms, the thermal front moves downward, reaching the bottom of the outlet plenum around 300 s after the SoT. At this time, core temperature becomes colder than the outlet plenum and the sodium flow path involves only the bottom region of the plenum.



FFTTF LOFWOS Test #13 TH transient analysis: RV 2D Temperature Map and GEM free level





CONCLUSIONS AND FUTURE WORK

- The PHISICS/RELAP5-3D© coupled simulations demonstrated to be able to well reproduce the FFTF LOFWOS Test #13 transient.

- The main quantitative discrepancies are due to the following aspects:

    1. The **assembly to bypass heat transfer**, taking place within the core and strongly influencing the PIOTA temperature trends, mainly the one of the row 6 component (addressed in the only-TH model but not actually applied to the coupled calculation).
    2. The eventual presence of **temperature transducers thermal inertia affecting the secondary loop** TH behavior (explaining the differences observed between calculation outcomes and experimental data in the correspondent cold and hot leg temperatures).
    3. The eventual occurrence of **primary loop hot leg pipe thermal stratification**, explaining the correspondent temperature increase predicted by the code and not measured by the correspondent TCs.
    4. The **reactivity feedbacks** correlated to the core thermomechanical deformations not well considered in our NK model, such as diagrid, fuel and CR expansion (only a linear and radial fuel dilatation is actually considered);

- All these aspects will be furtherly investigated in the future developments of the activity, in order to improve the coupled codes modelling capabilities with respect to liquid metal fast reactors applications.

THANKS FOR YOUR ATTENTION