# Application of RELAP5-3D© for liquid metal reactor safety

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SAPIENZA
UNIVERSITÀ DI ROMA

Dipartimento di Ingegneria Astronautica, Elettrica ed Energetica (DIAEE)
Nuclear area

Fabio Giannetti
Vincenzo Narcisi
Cristiano Ciurluini
Gianfranco Caruso

# OUTLINE and INTRO

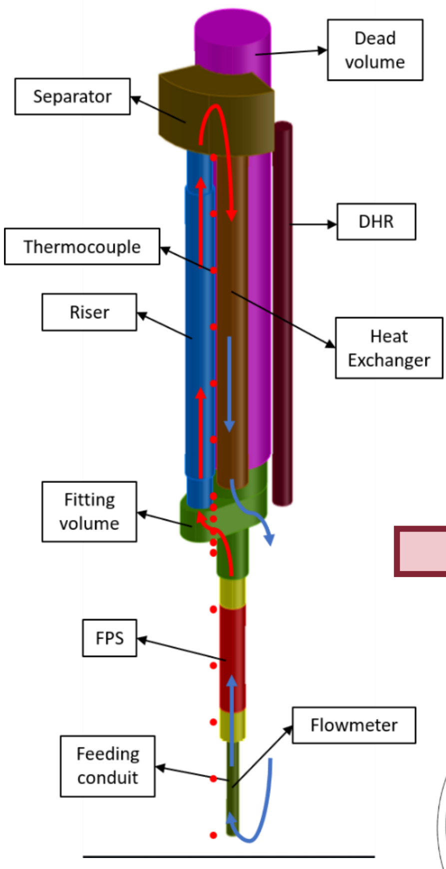
Goal of this activity is to understanding of relevant thermal-hydraulic phenomena that characterize LMFR safety aspects using RELAP5-3D© for these applications:

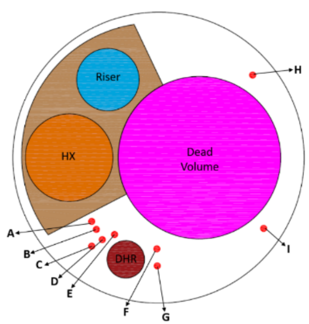
- CIRCE-ICE and CIRCE-HERO LOF experiment for thermal stratification
- NACIE (natural circulation, UQ)
- PHÉNIX EoL Dyssimmetric test (benchmark to evaluate asymmetric effects)
- PERSEO benchmark on passive systems (NEA) (pool boiling and cond.)
- ALFRED with passive-controlled Isolation Condenser (two-phase natural circulation with non-condensable)
- FFTF TH-NK ULOF transient with physical model of GEM

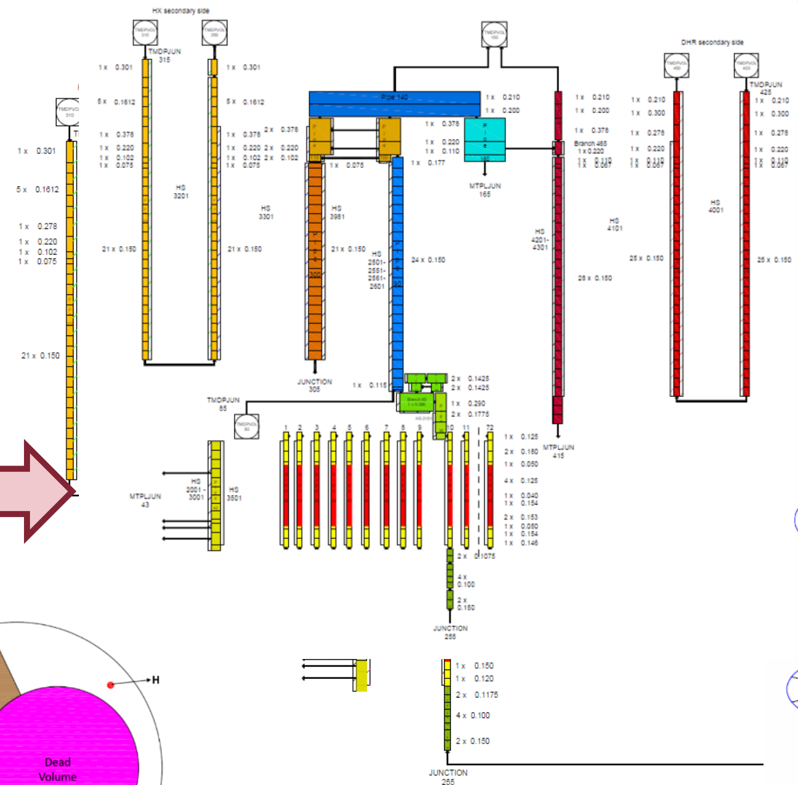
# CIRCE-ICE

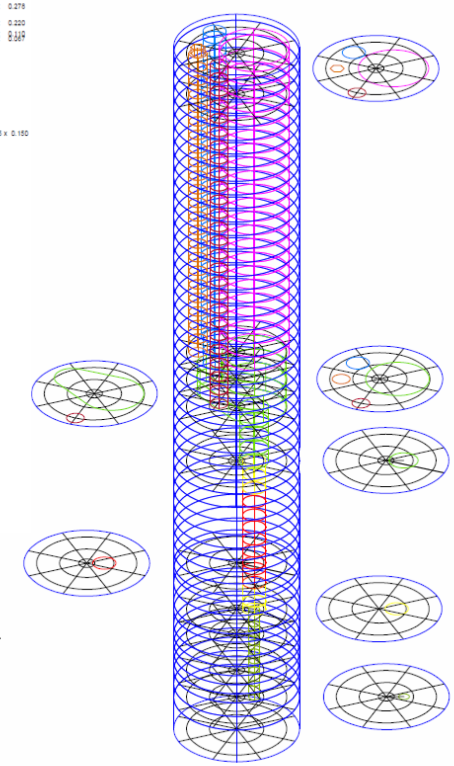
Pool thermal stratification and mixing convection

Gas-enhanced and natural circulation





# CIRCE-ICE – Transient simulation

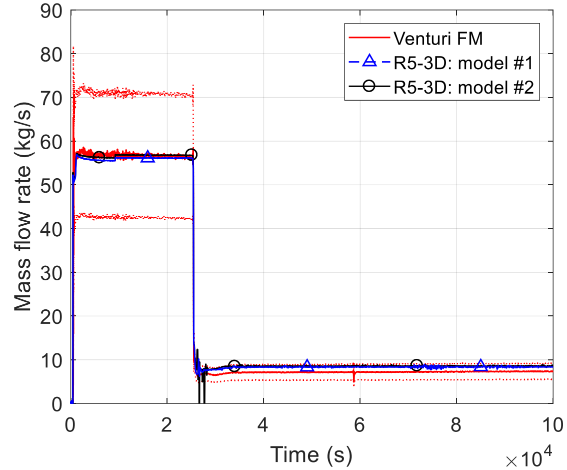
**GEC**

- Good evaluation of **primary MFR**
- Satisfactory prediction of **FPS inlet T** (discrepancies within error band)
- Model #1 provides prediction of the average FPS outlet T
- Model #2 allows more detailed resolution at the FPS outlet
- Good prediction of **heat losses** and of heat exchange through the HX
- Discrepancies in the evaluation of **DHR outlet** T by Model #1

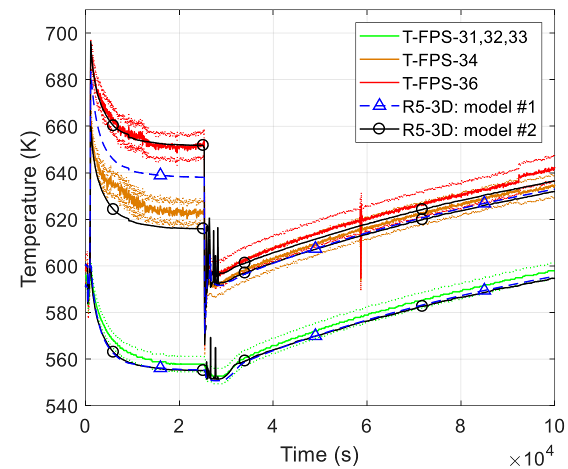
**NC**

- Satisfactory evaluation of the **MFR** after the transition event
- Good prediction of the FPS T drop after transition
- Model #1 slightly underestimates the average FPS outlet T
- Good simulation of the heat losses towards the main pool
- Satisfactory evaluation of the **DHR operation**

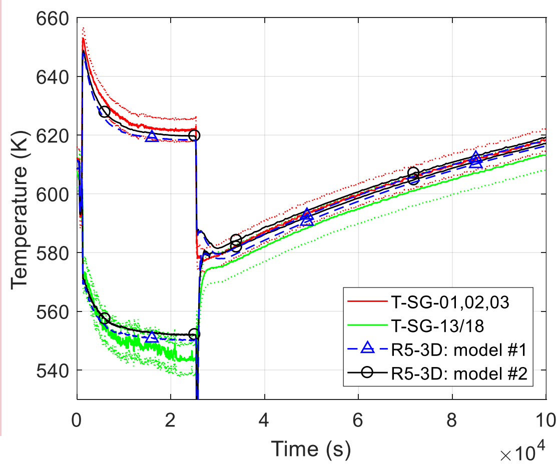
LBE mass flow rate



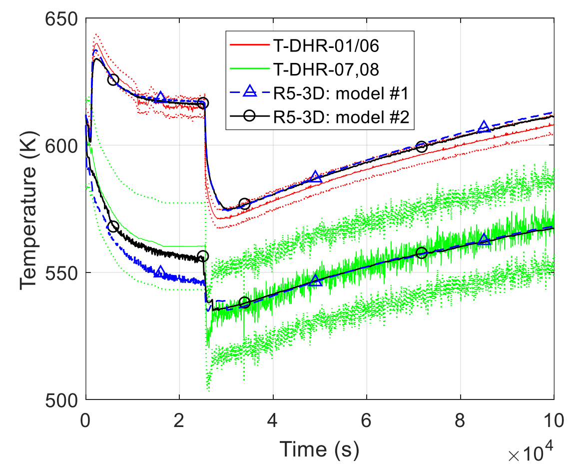

FPS dT



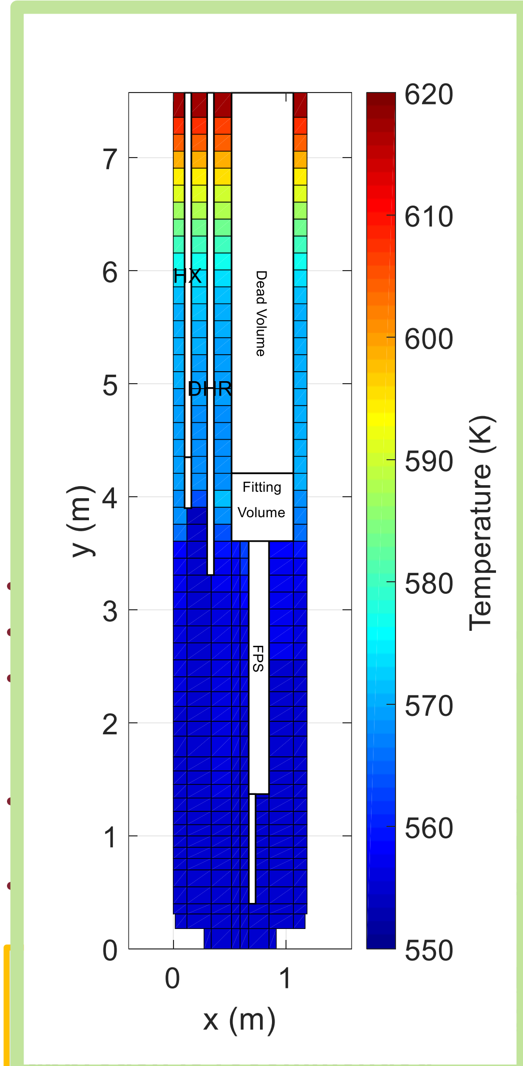

HX dT – LBE side

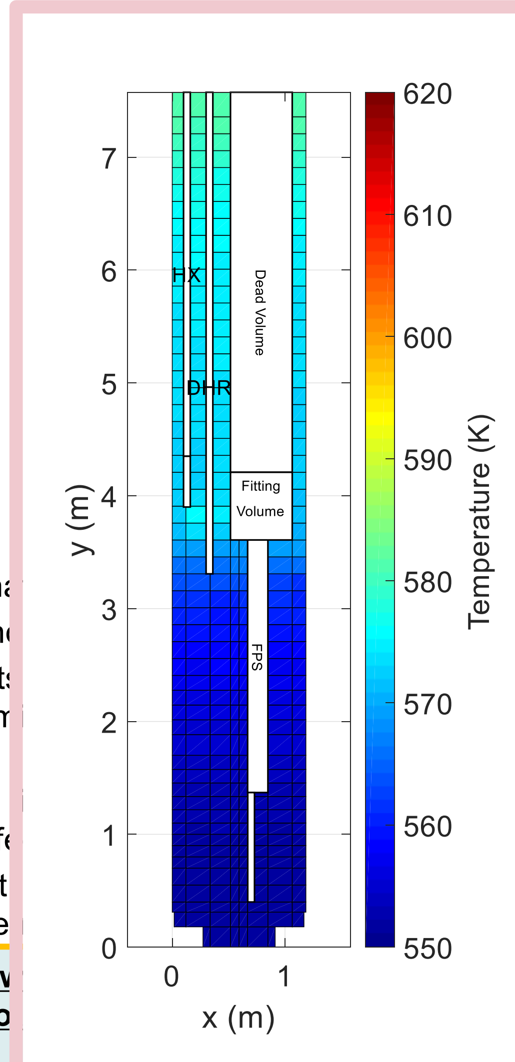



DHR dT – LBE side

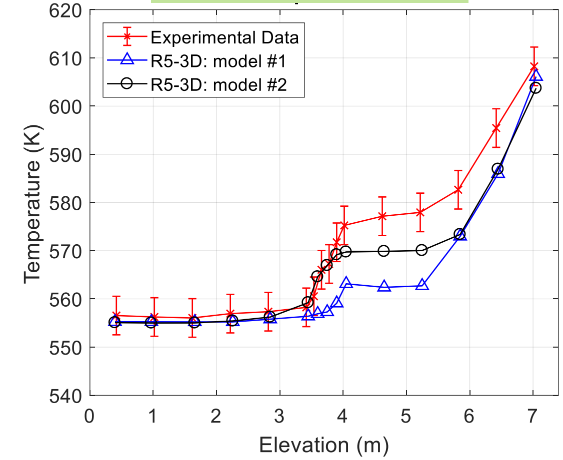


# CIRCE-ICE – Transient simulation




GEC

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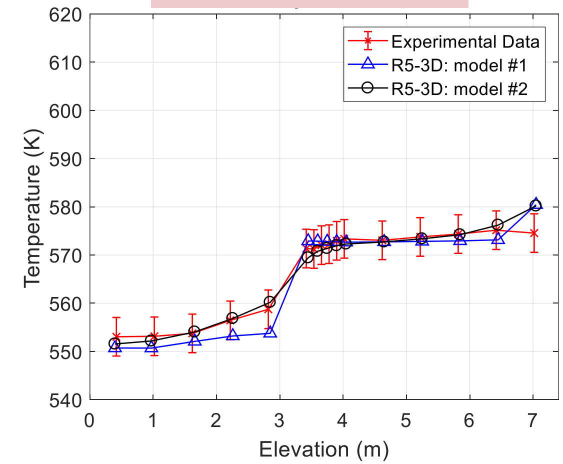
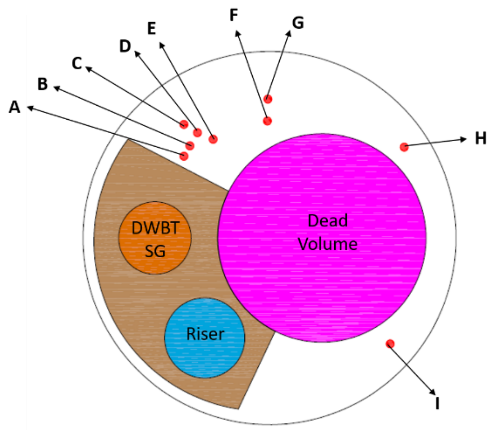
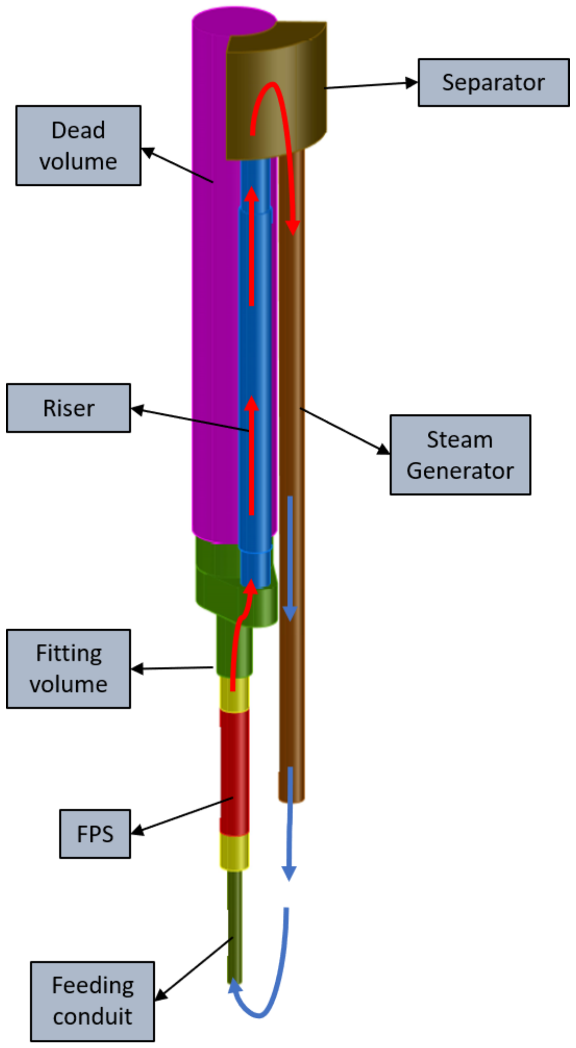


# CIRCE-HERO

**Main differences from ICE**

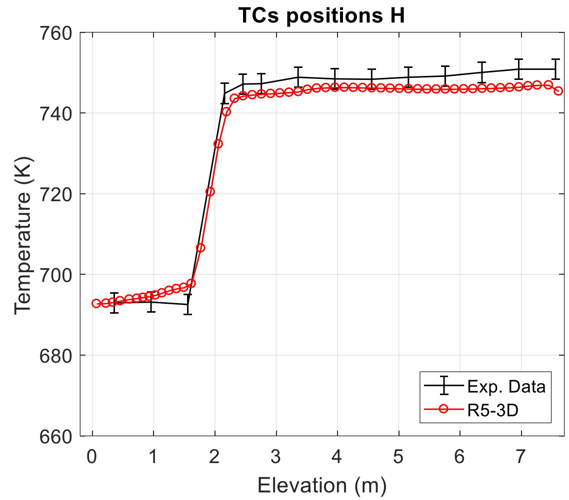
- Double Wall Bayonet Tube Steam Generator (DWBT SG) replaces the HX
- DHR system is removed
- DHR function is accomplished by the DWBT SG, reducing secondary flow rate
- Lager volume of the separator
- FPS thermally insulated with stagnant LBE

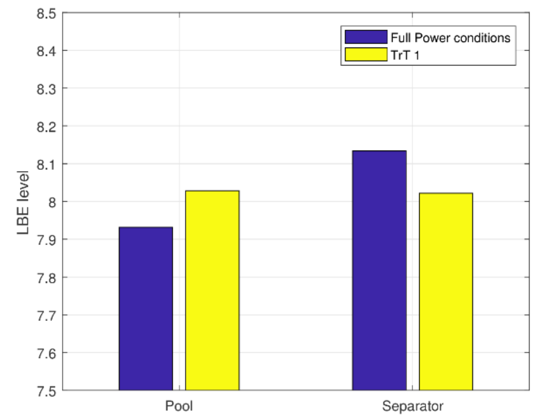


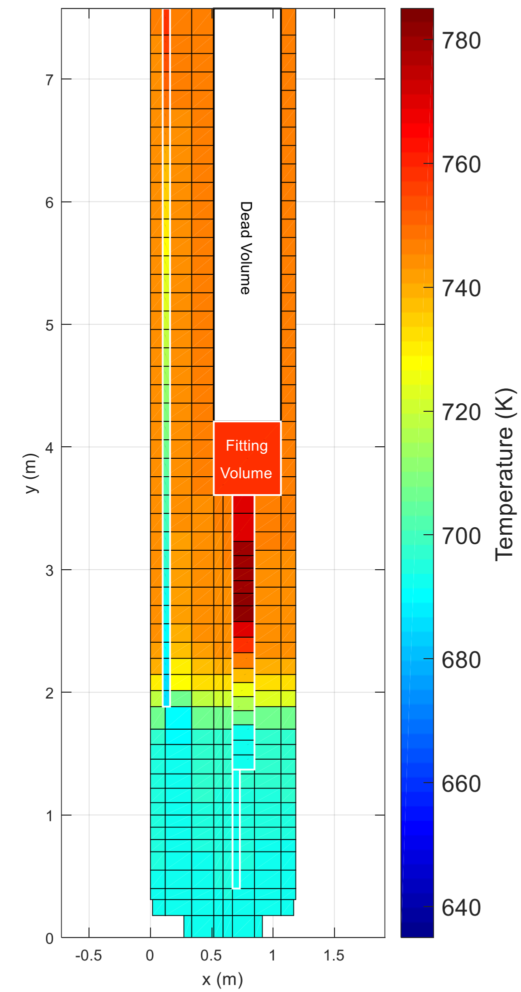



# CIRCE-HERO – Transient simulation

| Parameter | Unit | Exp. | Uncert. | R5-3D | Error |
|---|---|---|---|---|---|
| LBE MFR | kg/s | 34 | 25% | 31.4 | -7.6% |
| Av. FPS inlet T | K | 692.8 | 2.0 | 693.6 | 0.8 |
| Av. FPS outlet T | K | 769.8 | 2.0 | 769.5 | -0.3 |
| Av- SG inlet T | K | 759.9 | 2.0 | 761.3 | 1.4 |
| Av. SG outlet T | K | 674.1 | 12.0 | 687.1 | 13.0 |
| TFM-T0 | kg/s | 0.0372 | 0.0044 | 0.0430 | 0.0058 |
| TFM-T3 | kg/s | 0.0408 | 0.0044 | 0.0479 | 0.0071 |
| TFM-T4 | kg/s | 0.0394 | 0.0044 | 0.0480 | 0.0086 |
| TFM-T5 | kg/s | 0.0372 | 0.0044 | 0.0430 | 0.0058 |
| TC-C0-O70 | K | 647.0 | 2.0 | 644.4 | -2.6 |
| TC-C1-O70 | K | 625.9 | 2.0 | 626.3 | 0.4 |
| TC-C3-O70 | K | 633.9 | 2.0 | 633.9 | 0.0 |
| TC-C4-O70 | K | 633.5 | 2.0 | 633.9 | 0.4 |

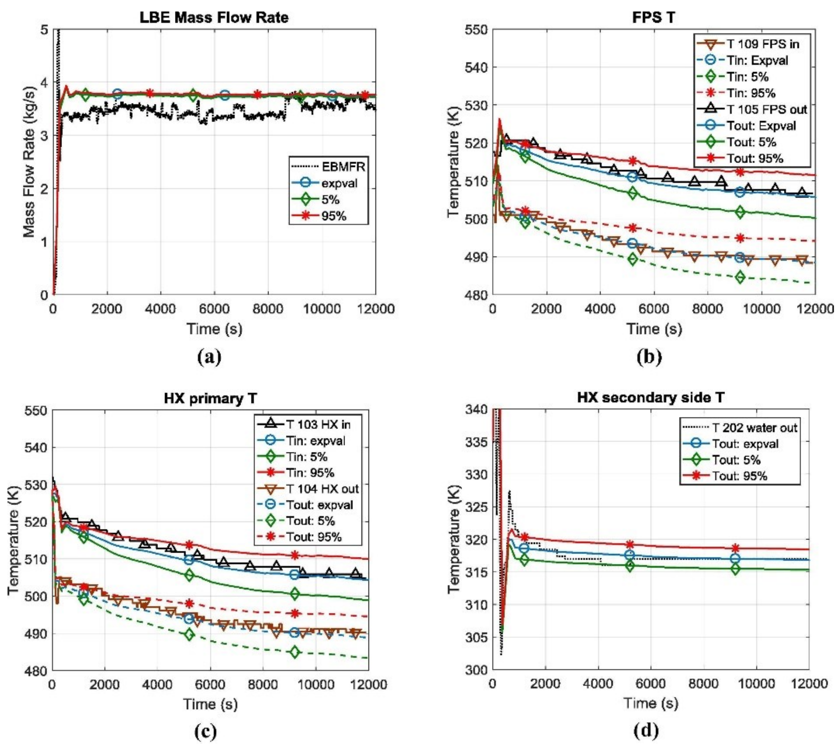


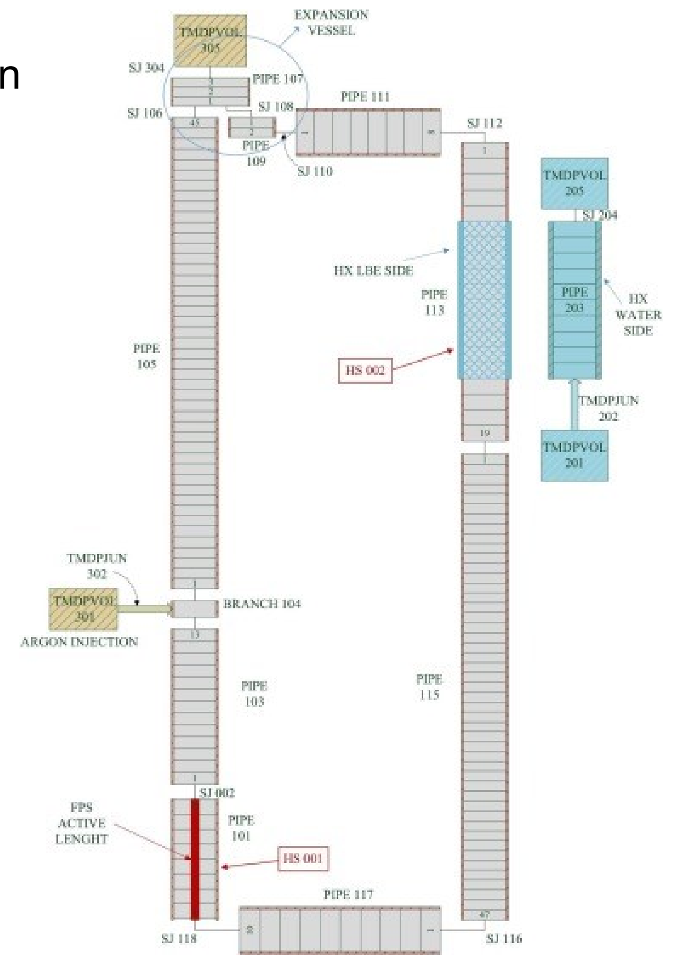



# NACIE facility – test 201 as example for UQ

- NACIE is a loop-type facility cooled by LBE, designed an realized in the ENEA Brasimone Research Centre
- The test 201 was reproduced using R5-3D coupled with RAVEN for the propagation of the uncertainty



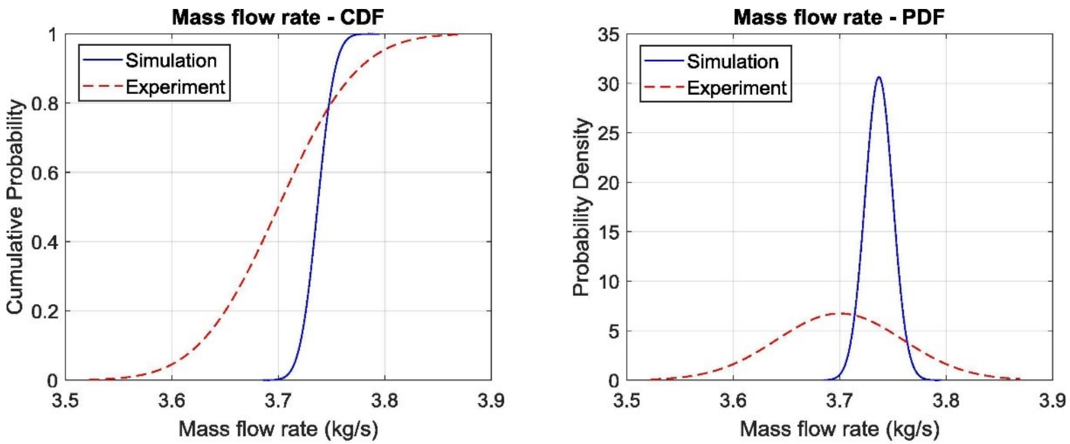
# NACIE facility – test 201 as example for UQ

Samplig parameters: (using normal distrib.)

| $T_{LBE}$ | Power | FW mass flow rate | $T_{FW}$ | Argon injection | Powder Conductivity |
|---|---|---|---|---|---|
| ±1.5 K | ±3% | ±10% | ±1.5 K | – | ±10% |

Perturbation obtained in output (93 run)

| FOM | | Experimental data | | Simulation results | |
|---|---|---|---|---|---|
| | | Mean | $\sigma^2$ | Mean | $\sigma^2$ |
| LBE Mass flow rate | kg/s | 3.7 | 3.50E-03 | 3.7 | 1.70E-04 |
| FPS inlet T | K | 488.6 | 0.25 | 488.5 | 11.43 |
| FPS outlet T | K | 506.7 | 0.25 | 505.7 | 11.85 |
| HX inlet T | K | 504.8 | 0.25 | 504.4 | 11.49 |
| HX outlet T | K | 490.2 | 0.25 | 488.9 | 11.56 |




(a) (b)

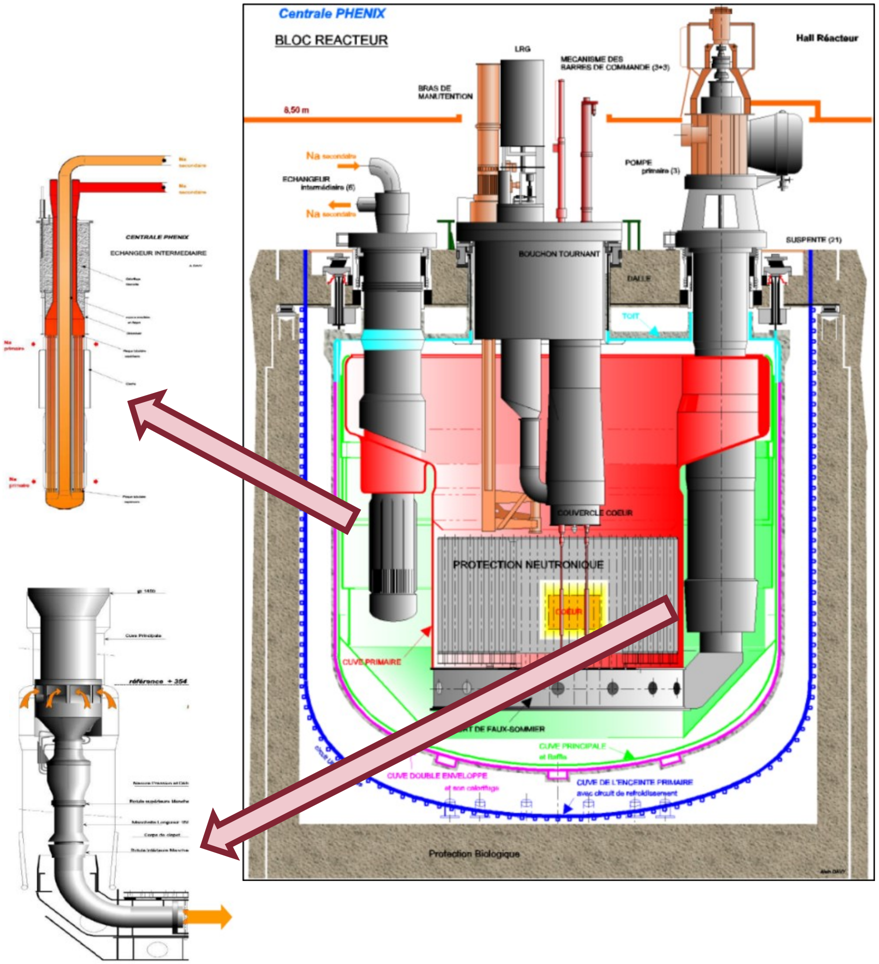
Quantitative comparison beetween experiment and numerical result using CDF area difference and PDF area difference:

- A good agreement is observed for the LBE mass flow rate, where the CDF area difference is lower than 0.5 kg/s
- the average difference between the CDF(sim) and the CDF(exp) for the LBE temperature is 2.5 K.

# PHÉNIX – EoL Dyssimmetric test (H2020 SESAME)

- Pool thermal stratification and mixing convection
- Asymmetric phenomena within large pool
- Asymmetric boundary conditions

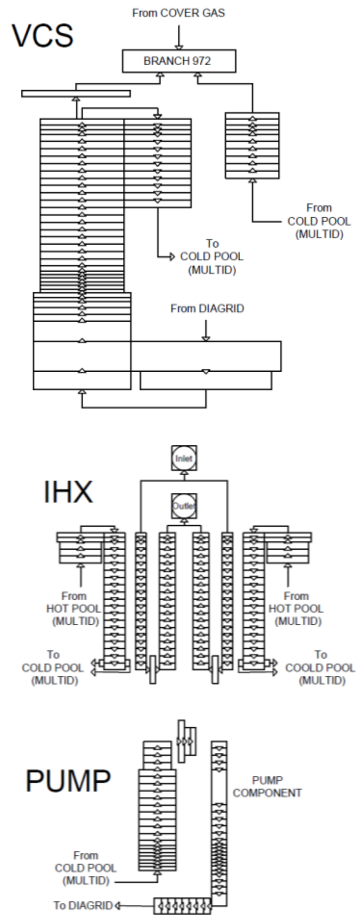
- Main vessel: 11.8 m of diameter containing about 800 ton of Na
- Double-enveloped vessel: it prevents any possible sodium leaks
- Primary containment vessel
- **Reactor pit**: equipped with final emergency system ensuring the decay heat removal in the event of a loss of normal cooling system
- Primary vessel: physical separation between the **hot and cold pools**
- **Strongback**: below the core, it redirects the 10% of the Na mass flow rate to the **vessel cooling system**
- **Diagrid**: it achieves the connection between the pumps and the core
- **Primary pumps (PP)**: 3 PPs ensure the primary coolant circulation
- **Intermediate heat exchanger (IHX)**: 6 IHX guarantee the thermal power removal. From 1993, only 4 IHX was in operation

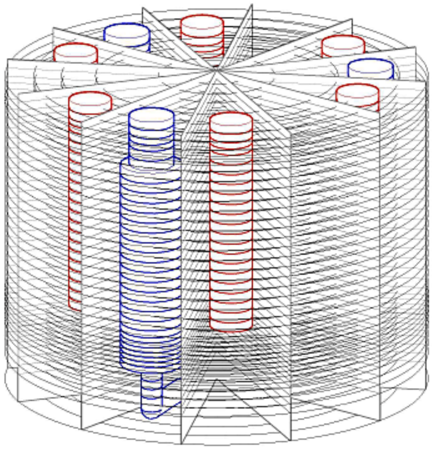


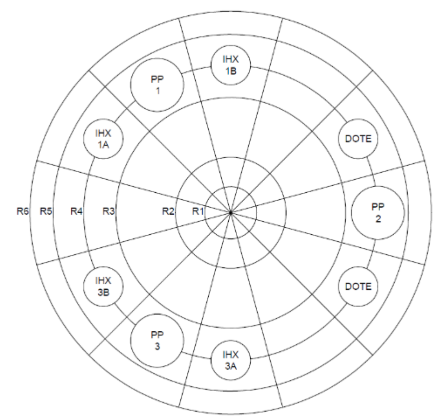
# PHÉNIX – Thermal-hydraulic model

- **MULTID component**: Diagrid, Core bypass, Hot and Cold pool
- **1D model**:
  - Inner and outer core - assembly per assembly
  - Blanket and shielding zones collapsed in 36 and 24 equivalent pipes
  - 3 primary pumps
  - 6 IHXs modelled separately
- **Sliced approach**
- **Relevant elevations** maintained
- **HTC correlations**:
  - Seban-Shimazaki: non-bundle
  - Westinghouse: reactor core
  - Graber-Rieger*: IHXs (through fouling factors)
- Cheng-Todreas correlation for **pressure drop evaluation** in rod bundle

| Parameter | Number of components |
| --- | --- |
| Hydrodynamic volumes | 6940 |
| Hydrodynamic junctions | 11840 |
| Heat structure mesh points | 40170 |
| Lines of code | 22428 |

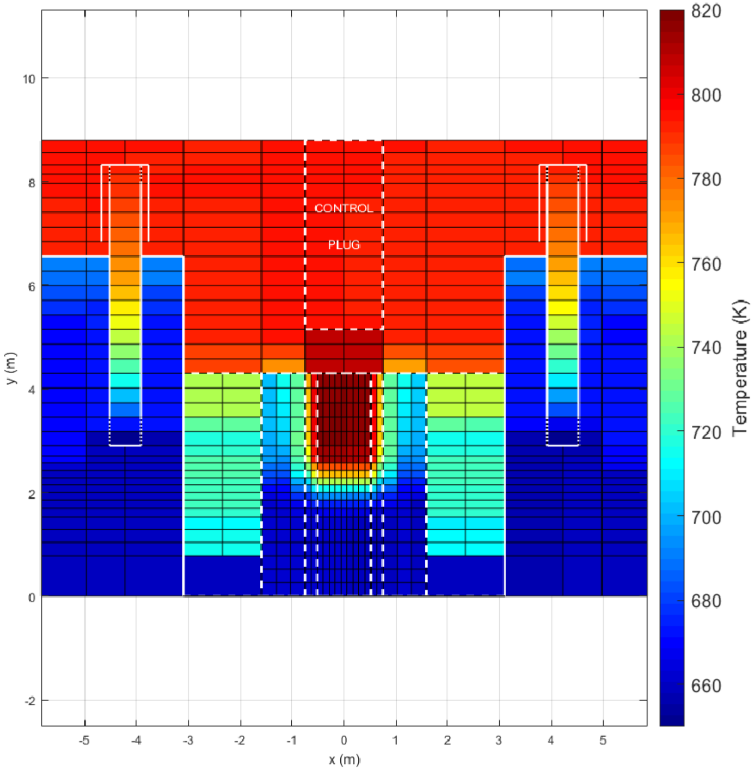




# PHÉNIX – Steady state results

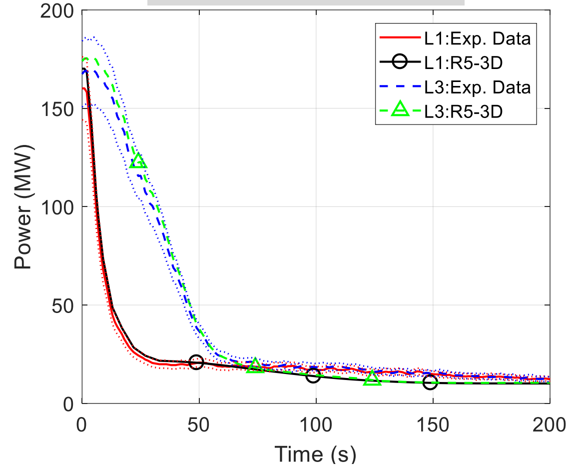
| Quantity | Unit | Experimental data | Simulation result | Error |
|---|---|---|---|---|
| IHX secondary side inlet T | K | 594 | 594 | 0 K |
| IHX secondary side MFR | kg/s | 347 | 347 | 0% |
| PP total MFR | kg/s | 2209 | 2211 | 1% |
| IHX secondary side outlet T | K | 784 | 787 | +3 K |
| Core inlet T | K | 658 | 660 | +2 K |
| Core outlet T | K | 807 | 806 | -1 K |
| IHX primary side inlet T | K | 793 | 792 | -1 K |
| IHX primary side outlet T | K | 658 | 660 | +2 K |
| Core MFR | kg/s | 1988 | 1992 | 0% |
| VCS MFR | kg/s | 221 | 219 | 0% |
| IHX primary side MFR | kg/s | 497 | 498 | -1% |



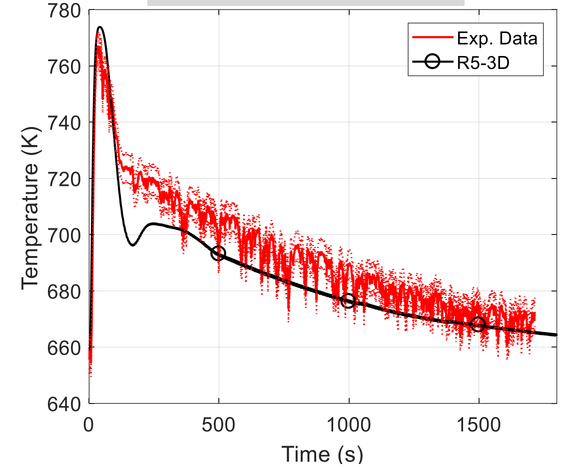
# PHÉNIX – Transient simulation

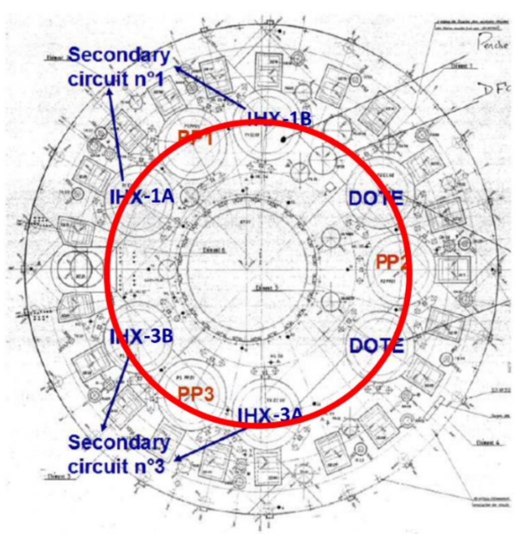
| Time (s) | Action |
|---|---|
| 0 | **Secondary pump trip** (on loop 1): speed reduced from 700 to 100 rpm in about 13 s |
| 5 | **Automatic shutdown**: insertion of the control rods (1.4 mm/s) for 45 s<br>**Turbine trip**<br>**Secondary pump speed reduced** (on loop 3) from 700 to 110 rpm in about 60 s |
| 48 | **SCRAM** |
| 1800 | **End of dissymmetric test** |

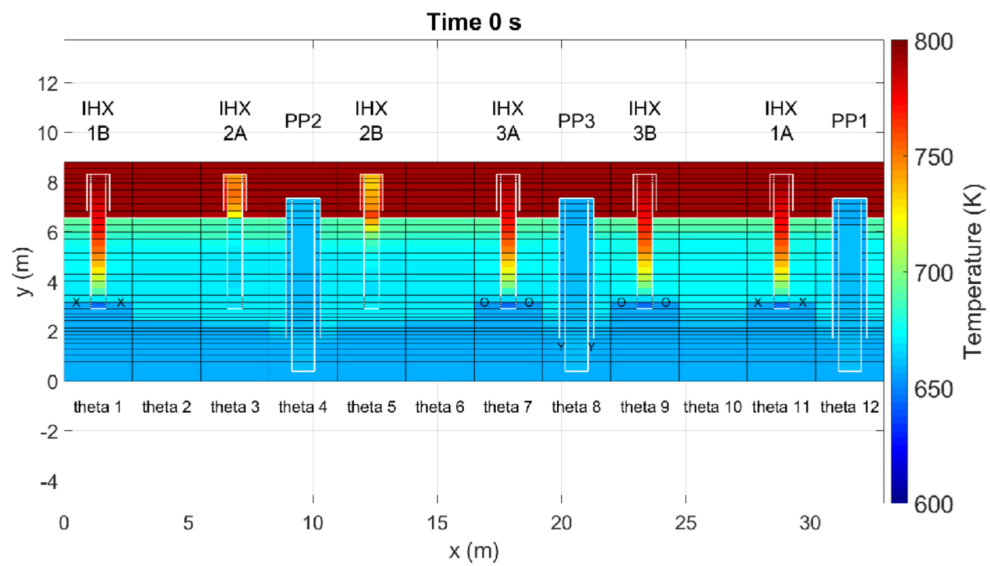
Power removed




IHX-1B outlet T



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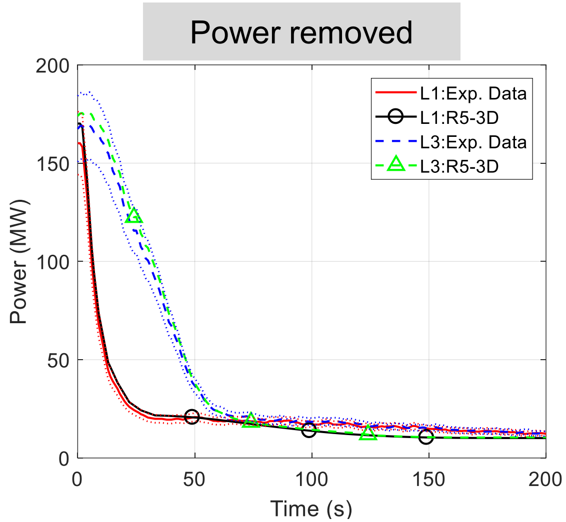
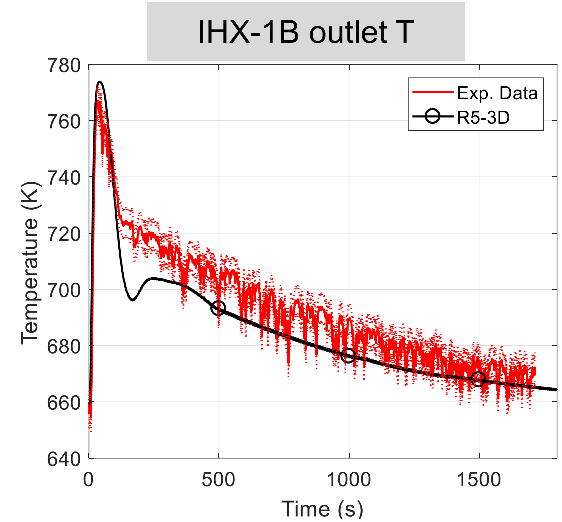
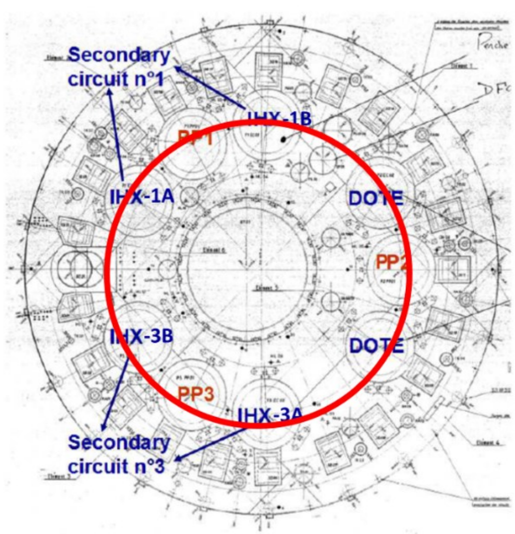
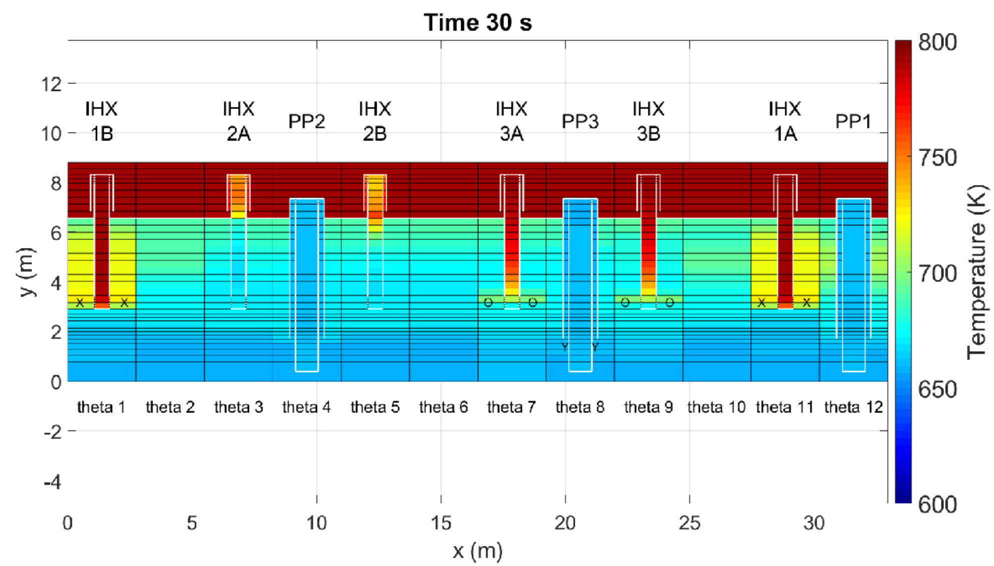


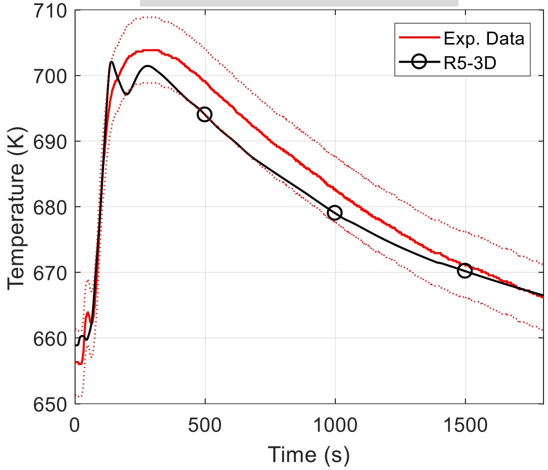



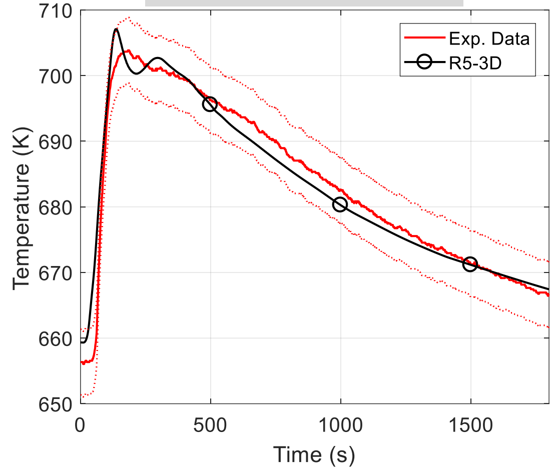



# PHÉNIX – Transient simulation

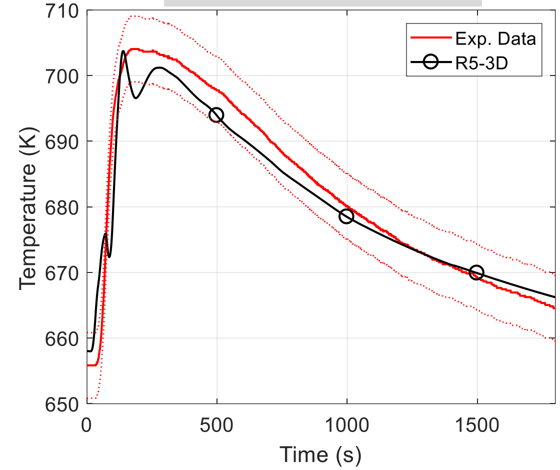
PP1

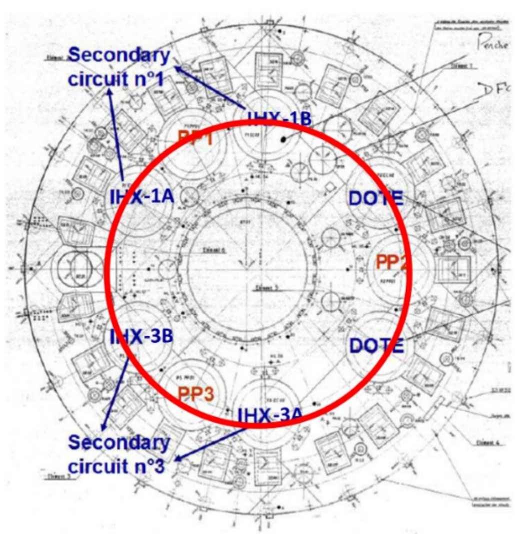


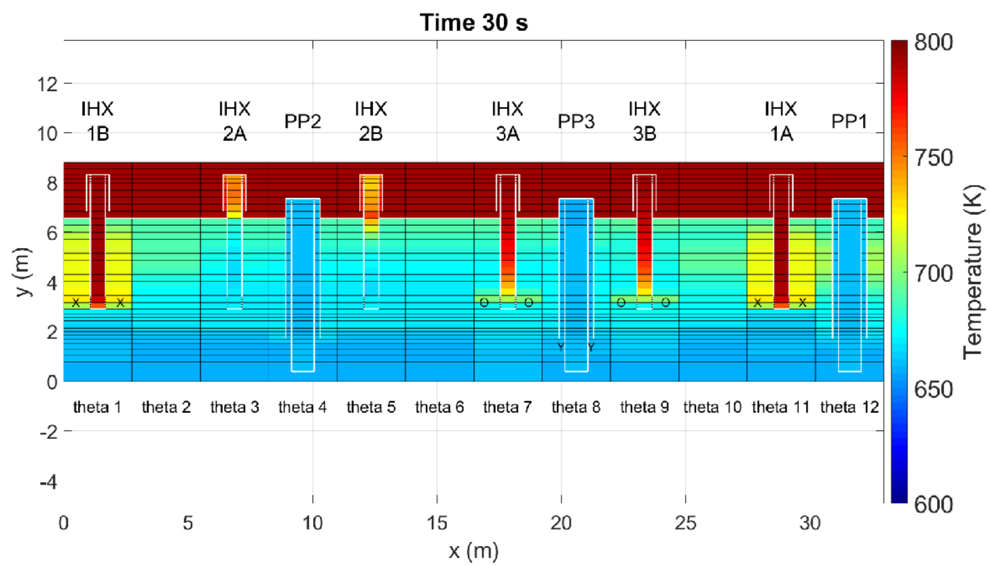

PP2



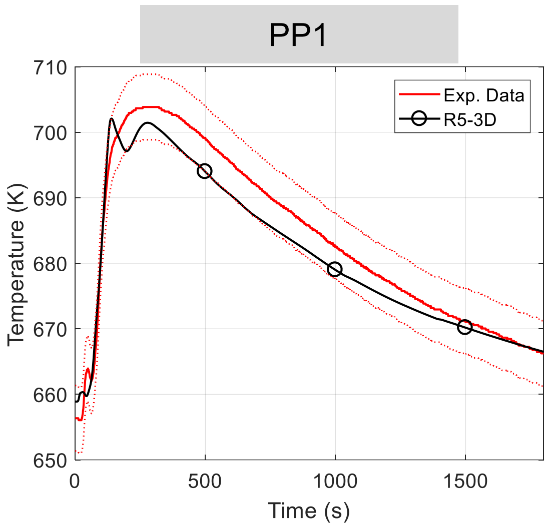

PP3

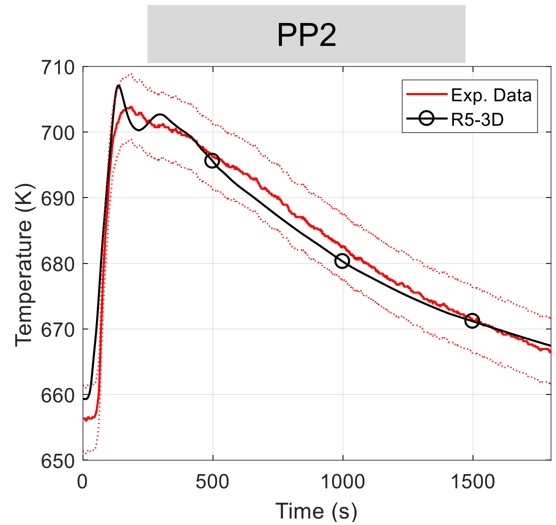


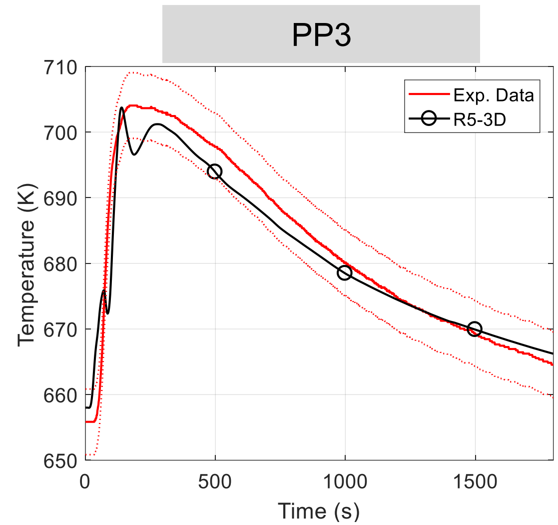



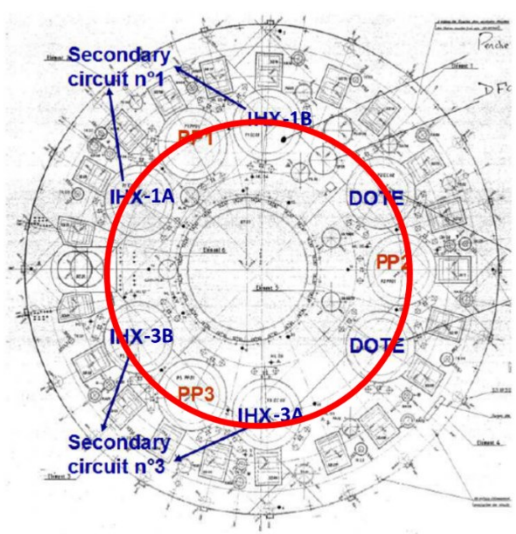



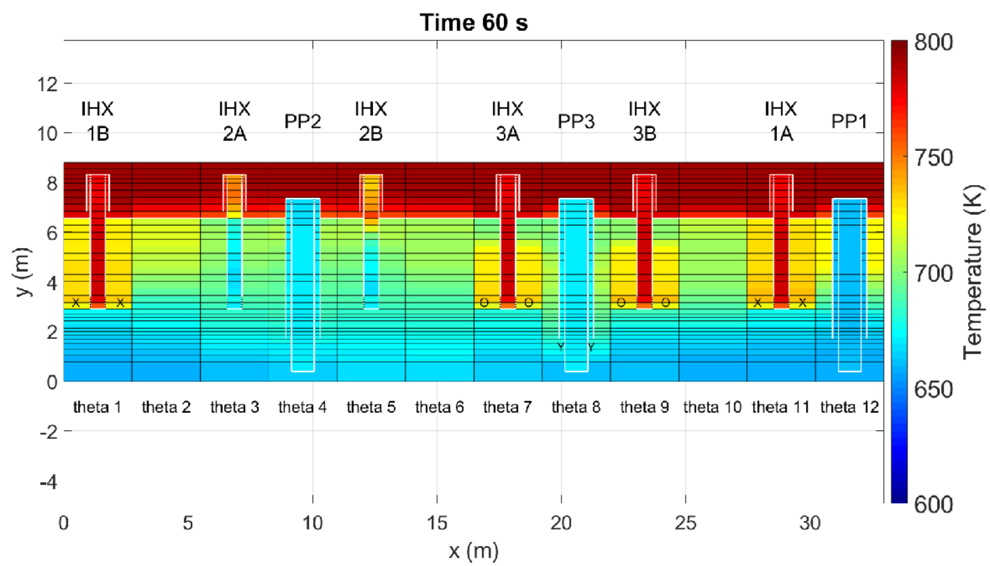
# PHÉNIX – Transient simulation



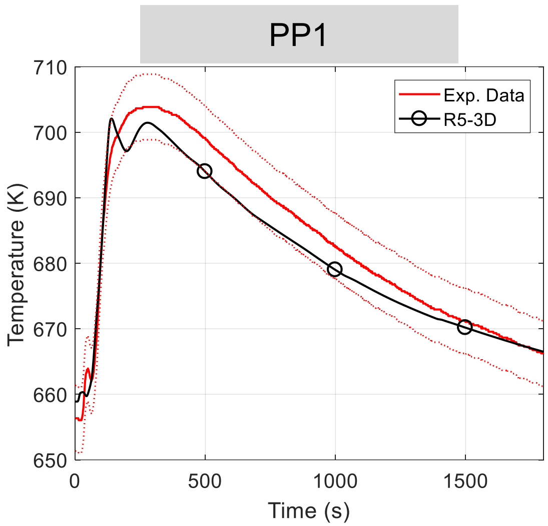



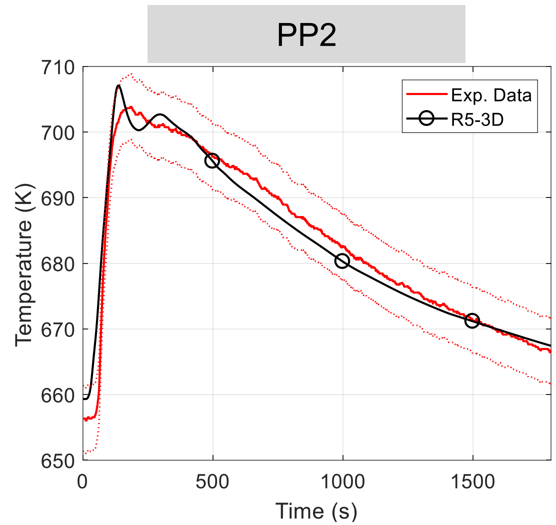



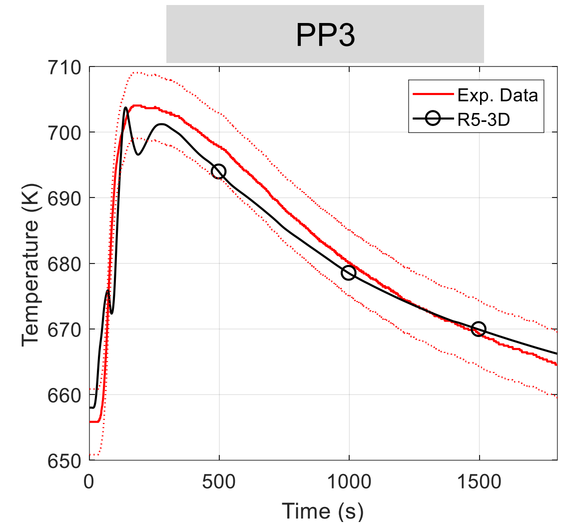



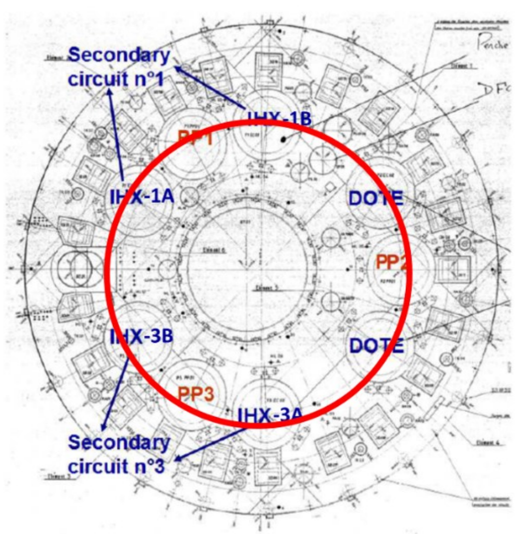



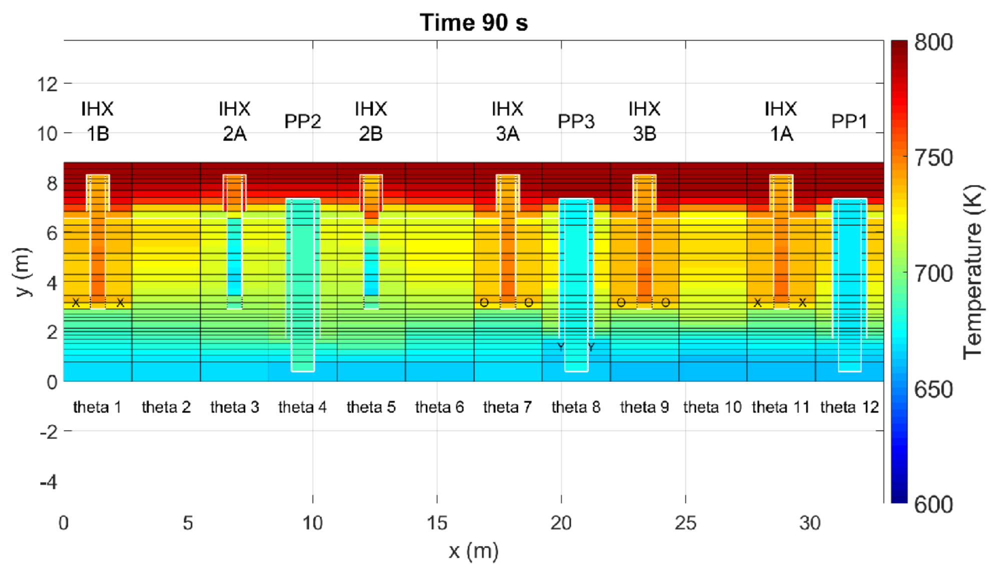
# PHÉNIX – Transient simulation



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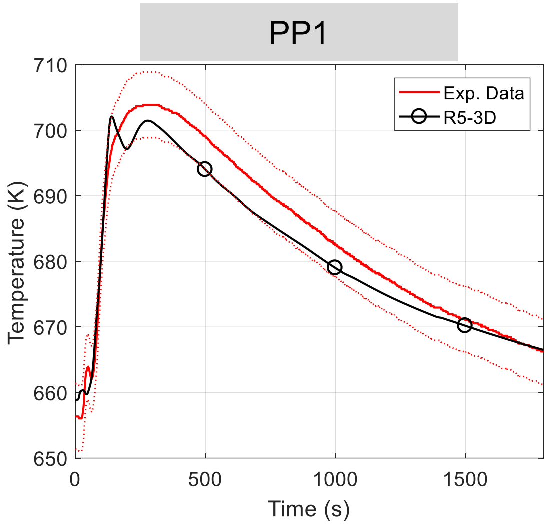
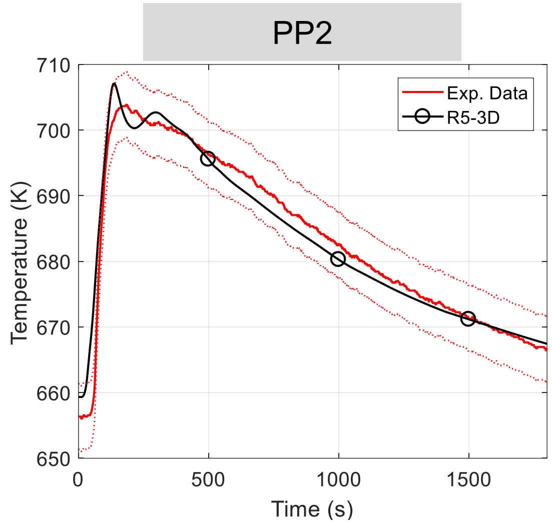
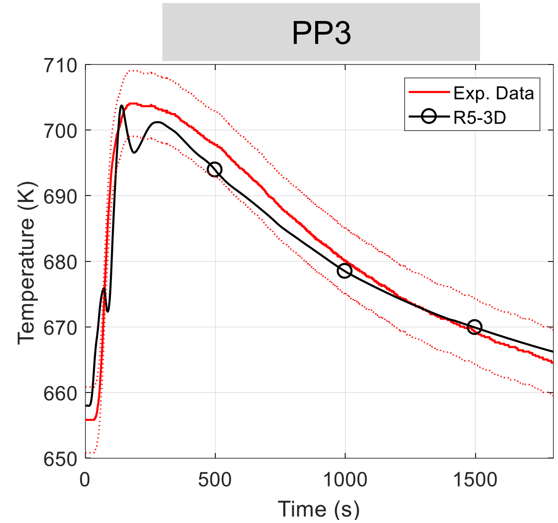
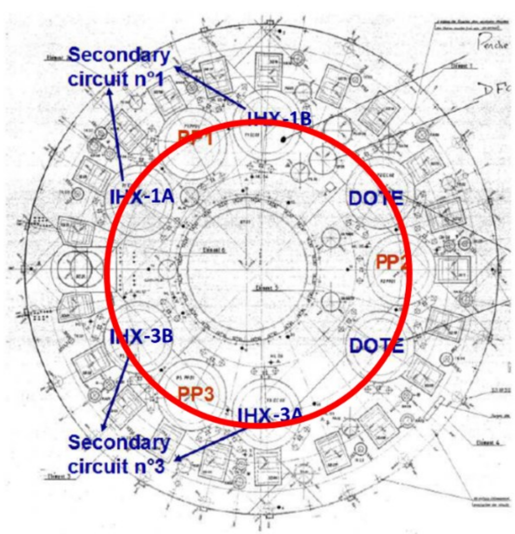
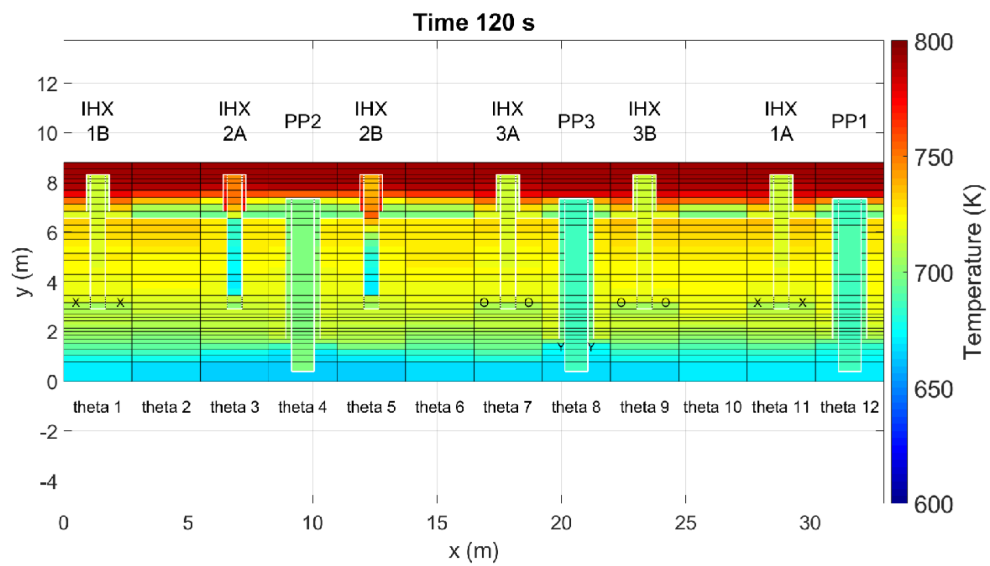


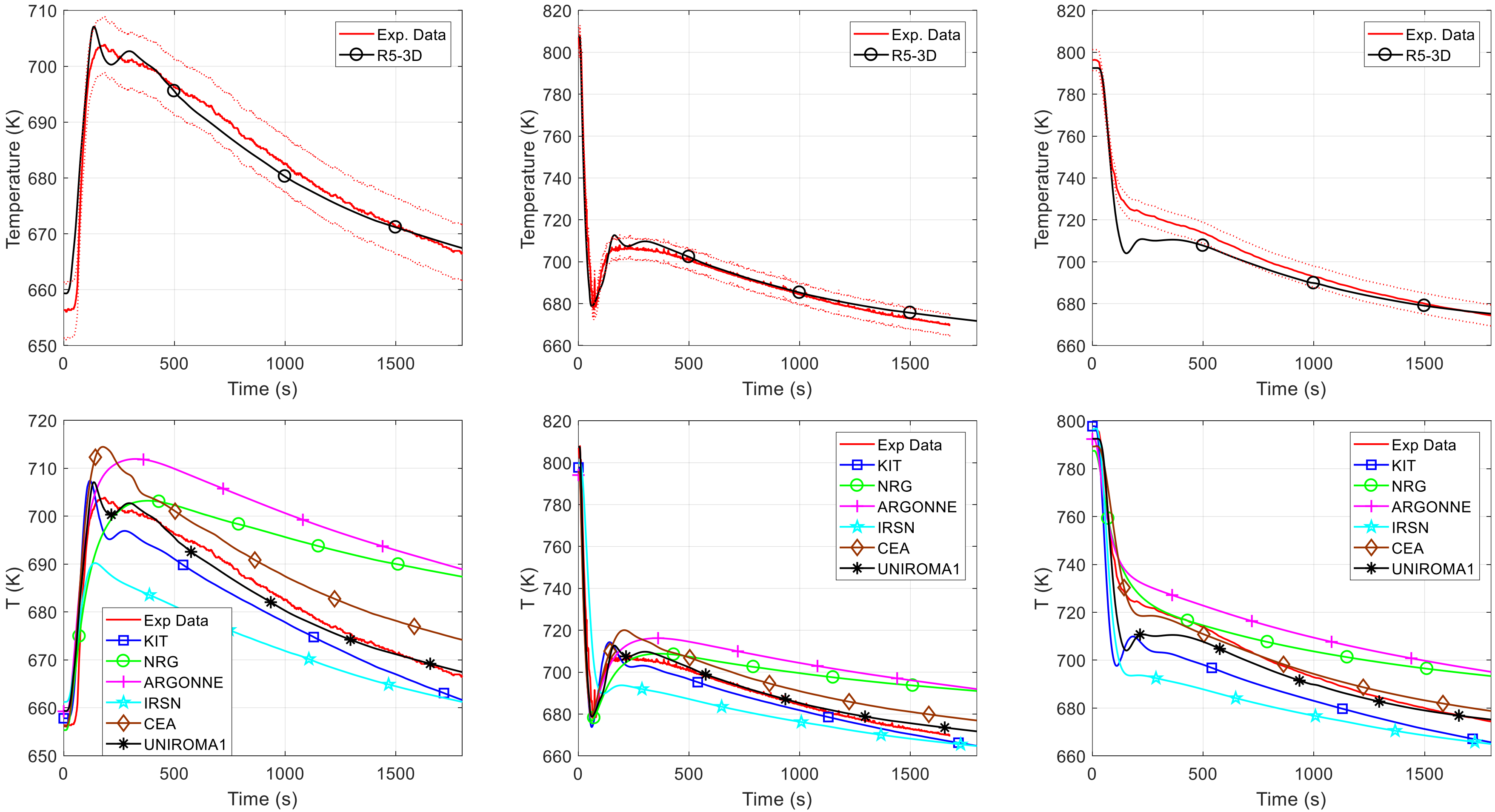



# PHÉNIX – Transient simulation (benchmark)

PP2

Core outlet T

IHX-3A inlet T



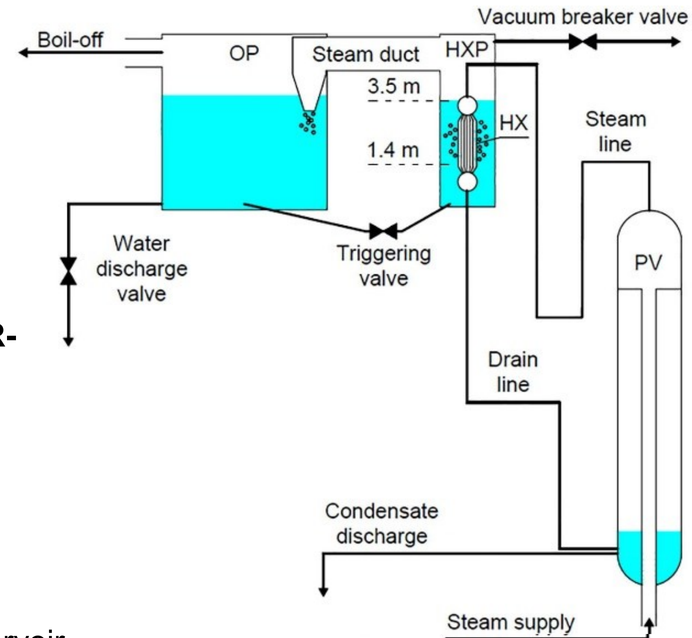
# PERSEO

SIET laboratories in Piacenza (Italy)

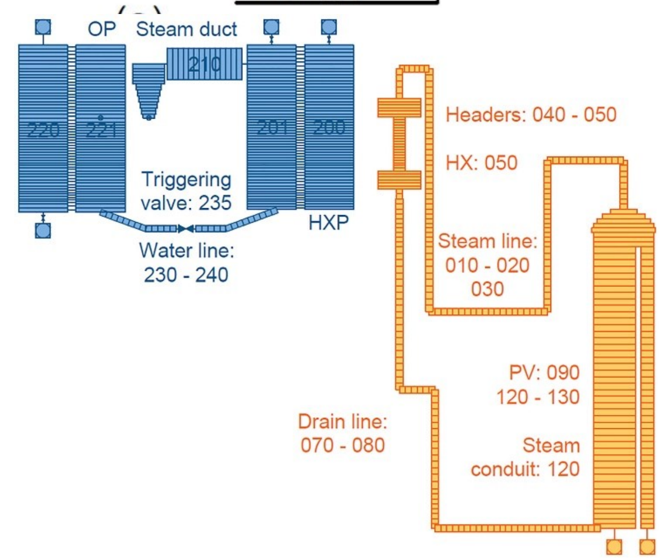
## OECD/NEA/CSNI WGAMA

State of art on reliability of thermal-hydraulic passive systems (**SOAR-RPS**) - **PERSEO** benchmark on passive systems

- Evaluation of the IC performance




- **Pressure Vessel:**
  - it supplies steam at fixed conditions
  - a dedicated valve controlled the level within the component
- **Isolation Condenser:**
  - 120 vertical tubes
- **Pipelines:**
  - connecting the PV and the IC
- **HX Pool:**
  - it contains the isolation condenser
- **Overall Pool:**
  - The water reservoir
- **Steam duct:**
  - It allows the steam flow from the HXP to the OP
- **Triggering valve:**
  - Its opening allows the actuation of the system
- **OP discharge line**
- **OP Boil-off line**

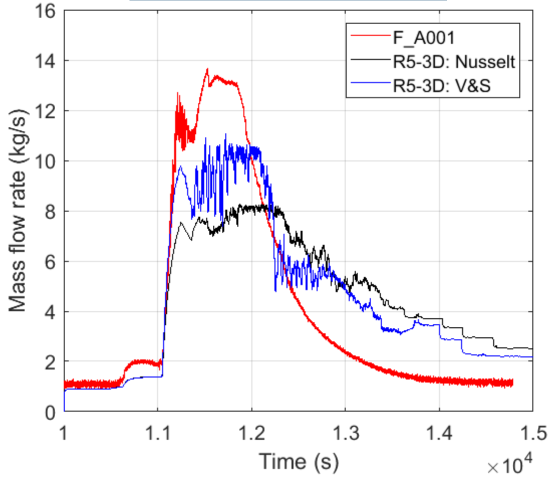


# PERSEO – Transient simulation

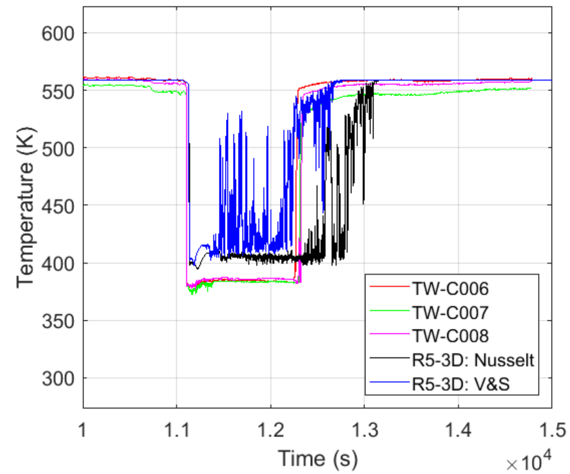
**HTC correlations available in R5-3D**

- Film condensation
  - Default model: Nusselt for laminar, Chato-Shah for turbulent and Colburn-Hougen for diffusion of non-condensable gases
  - Optional model: Vierow-Shrock modification of Nusselt theory
- Boiling:
  - Chen for nucleate and transition boiling, Bromley for film boiling

Primary MFR




IC outside wall T

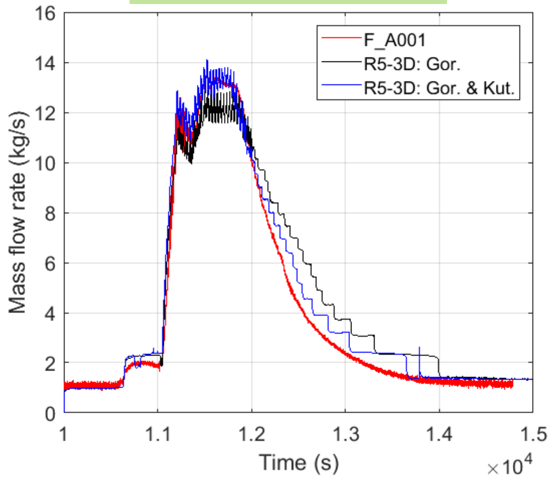



**HTC tuning and implementation in R5**

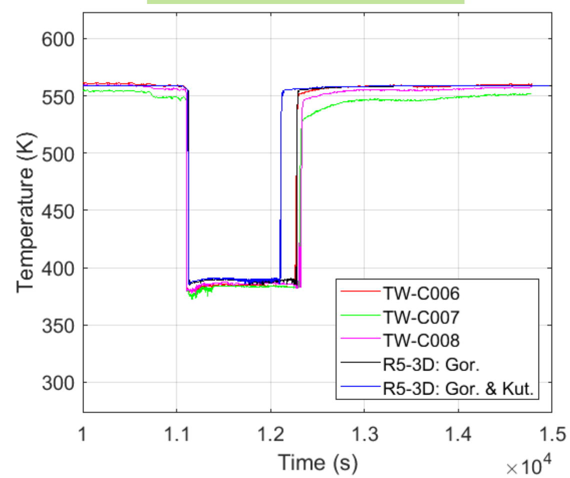
Default models exceed validity ranges

- Multiplicative factor of 1.3 applied for HTC in condensation regime, based on Kutateladze correlation
- Multiplicative factor of 9 applied for HTC in pool boiling regime, based on Gorenflo correlation
- Implementing the right correlation in RELAP5 mod 3.3 we obtain very goof results without tuning

Primary MFR




IC outside wall T



# PERSEO – Transient simulation

**PhW 1 (10000 s → 11260 s)**

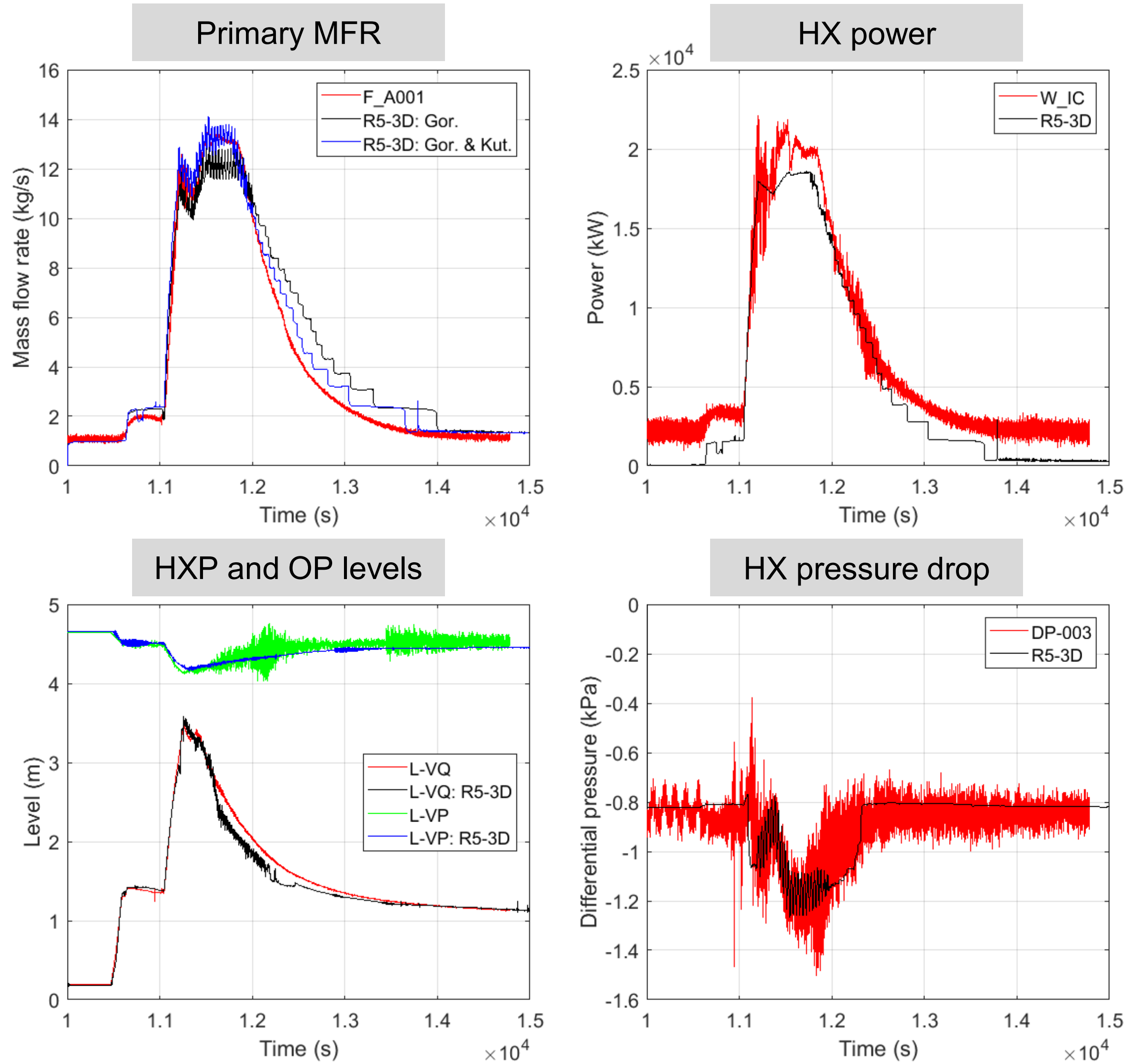
- First activation of the system
- Good evaluation of the primary MFR
- Discrepancy on the HX power
- Good prediction of slow water consumption within HXP
- Satisfactory simulation of maximum values of HXP level and MFR
- Good agreement in the pressure drops

**PhW 2 (11260 s → 11845 s)**

- Quasi-steady operation
- Good evaluation of the MFR
- Underprediction of the HX power

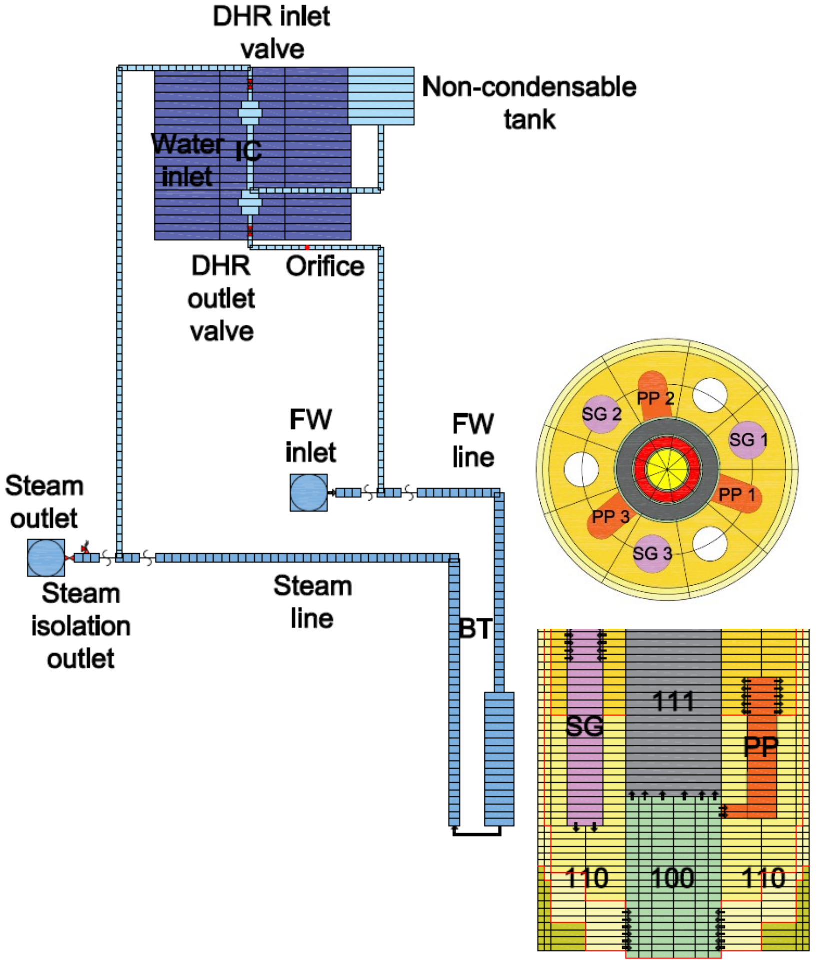
**PhW 3 (11845 s → 14784 s)**

- Boil off in the HXP with a consequent level reduction and power decrease
- Globally agreement between experiment and simulation
- Typical stepwise change in the MFR and power decrease (due to discretization of nodalization scheme)
- Oscillations related to steam condensation instabilities



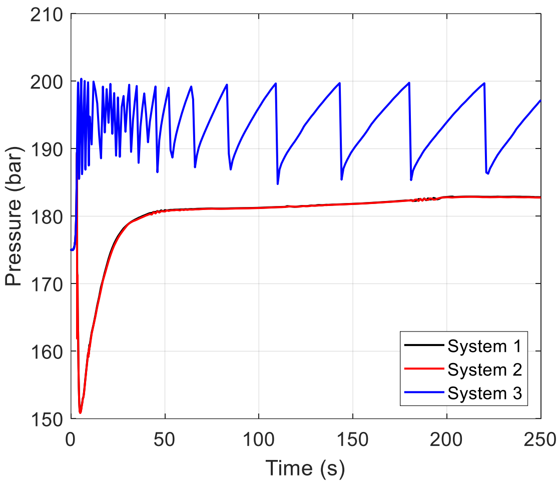
# ALFRED reactor – Isolation Condenser analysis

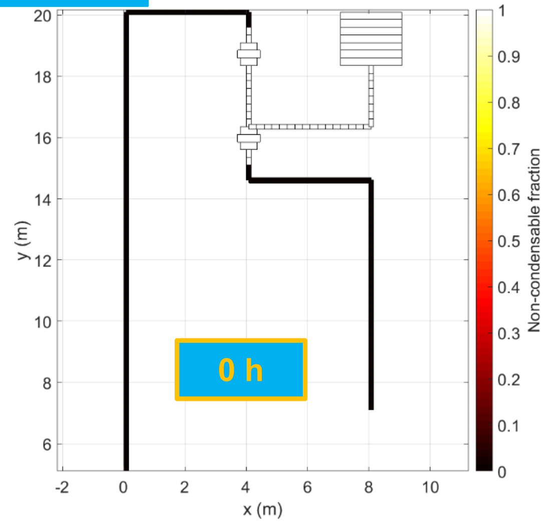
- **Sapienza studied the transient of the system developed by Ansaldo Nucleare**
- **Mono-dimensional region**:
  - Reactor core
  - SG (primary and secondary side): 3 components
  - PP (3 separated PUMP components)
  - Region above the core
  - DHR system: 3 different systems (one per each SG)
  - DHR pool: 3 different pools (each one composed of three vertical PIPE components and multiple cross junctions)
- **Three-dimensional region**:
  - Component #100: core bypass and core inlet region
  - Component #110: RV pools
  - Volume and junction factors reproduces the main features of the RV geometry

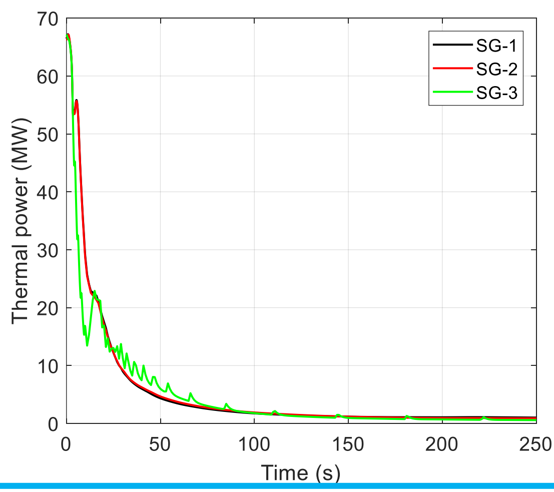


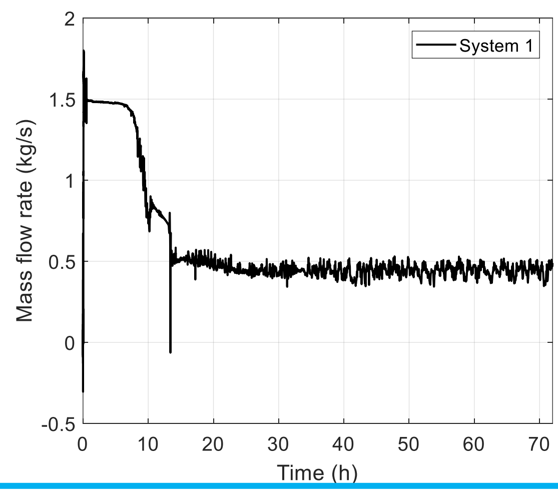
# ALFRED – Transient analysis

## Secondary system

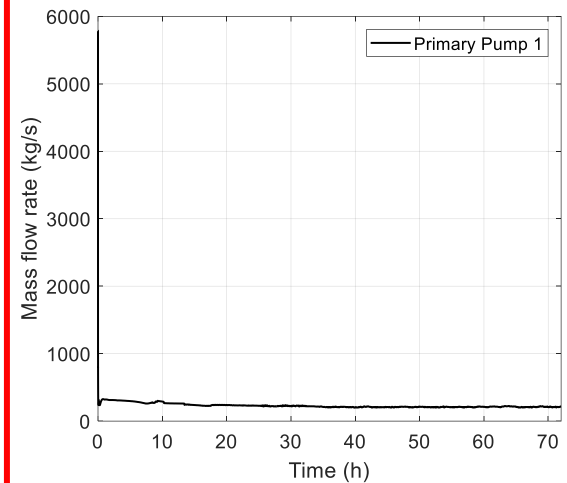


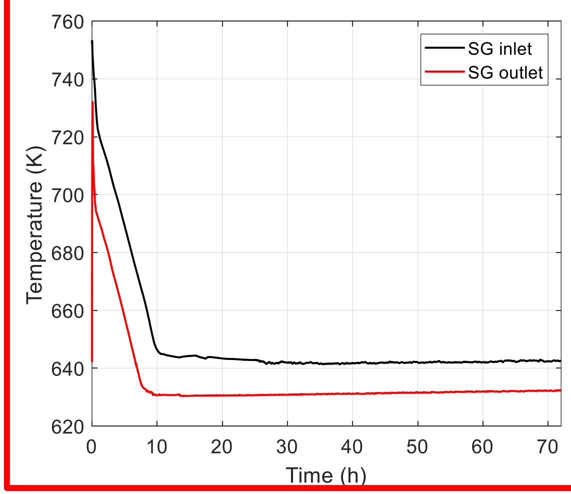



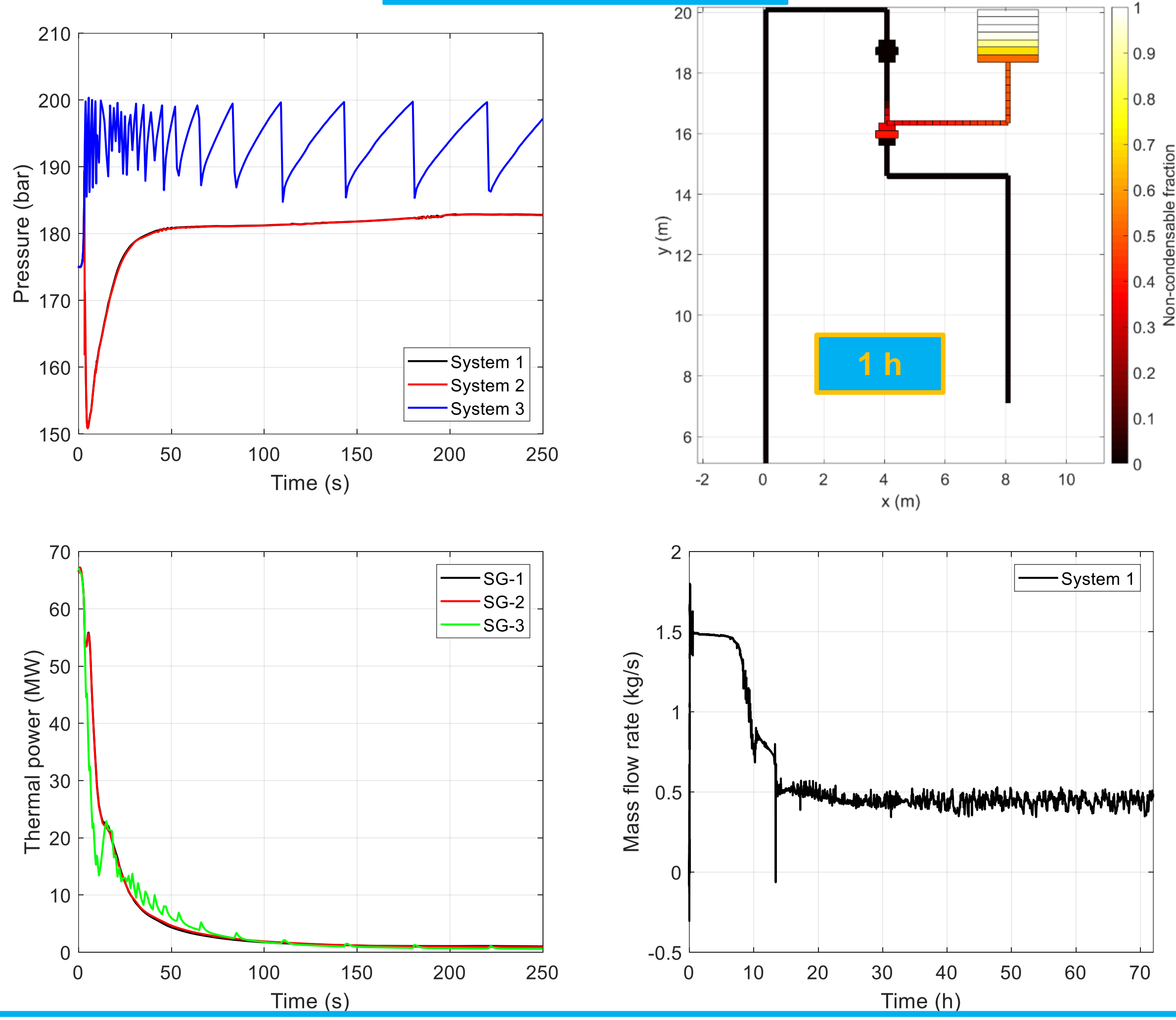

## Primary system



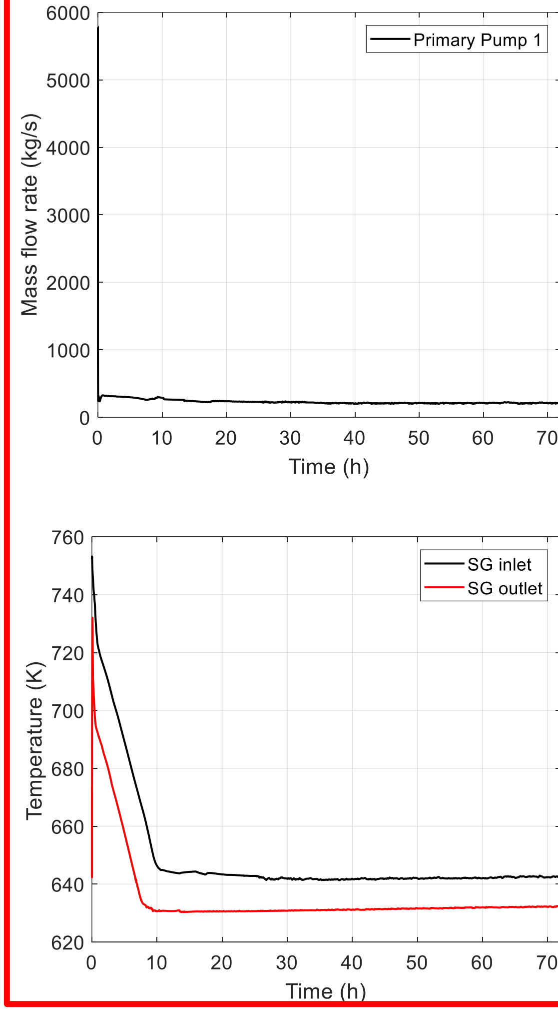



# ALFRED – Transient analysis

## Secondary system

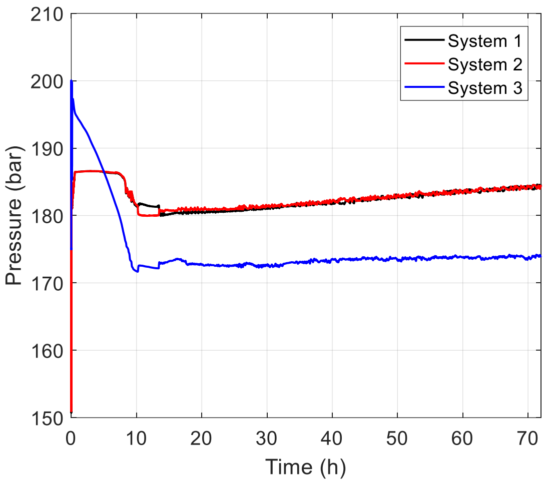


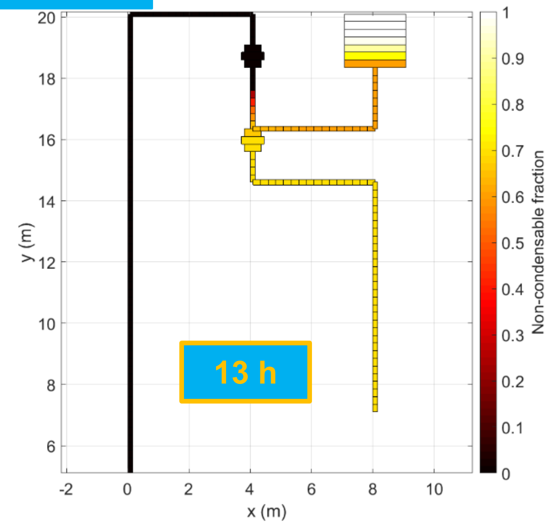

## Primary system

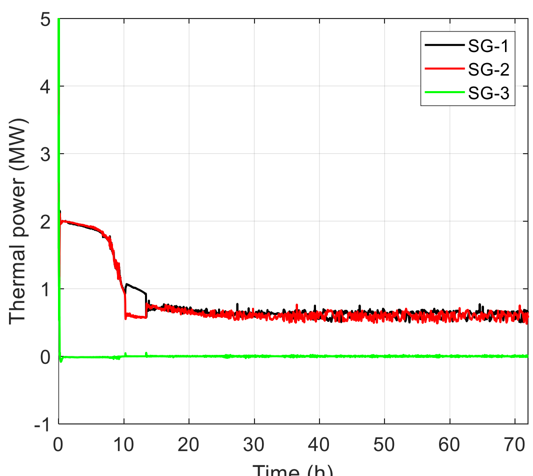


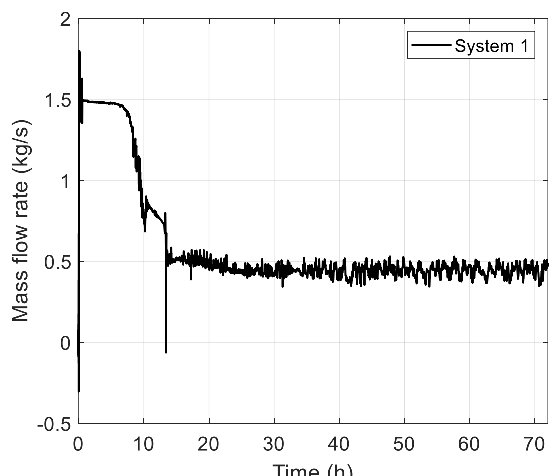
# ALFRED – Transient analysis

## Secondary system

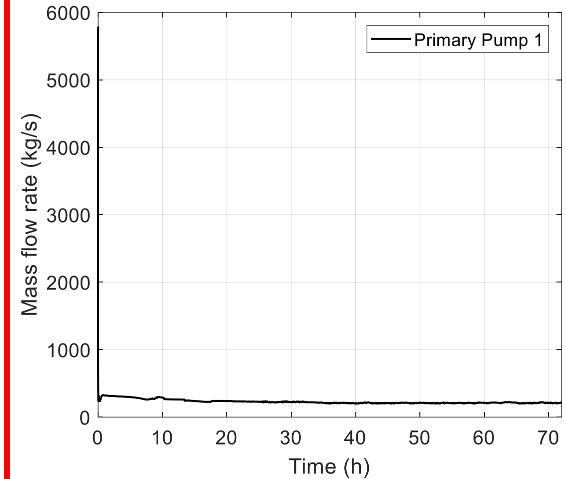


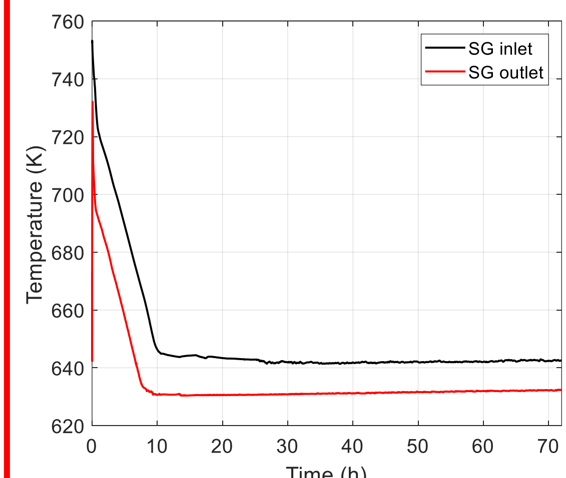



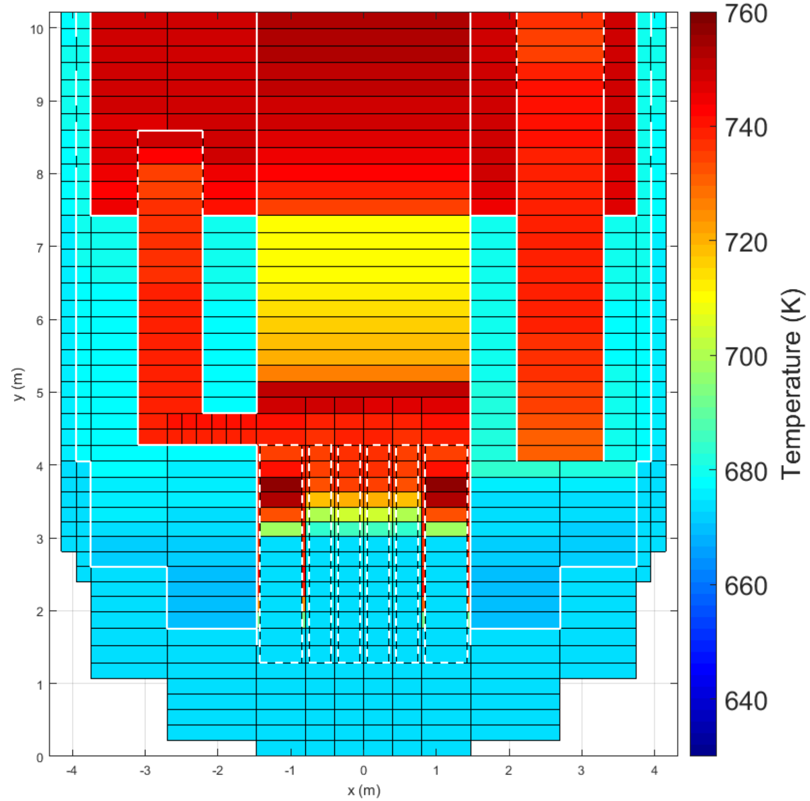

## Primary system



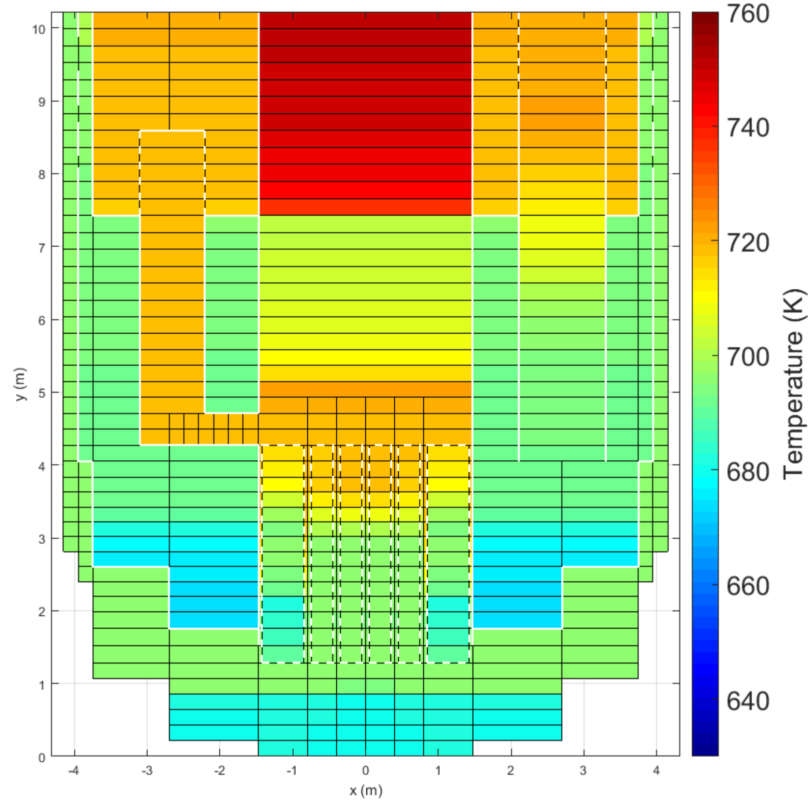



# ALFRED – Transient analysis

0 h

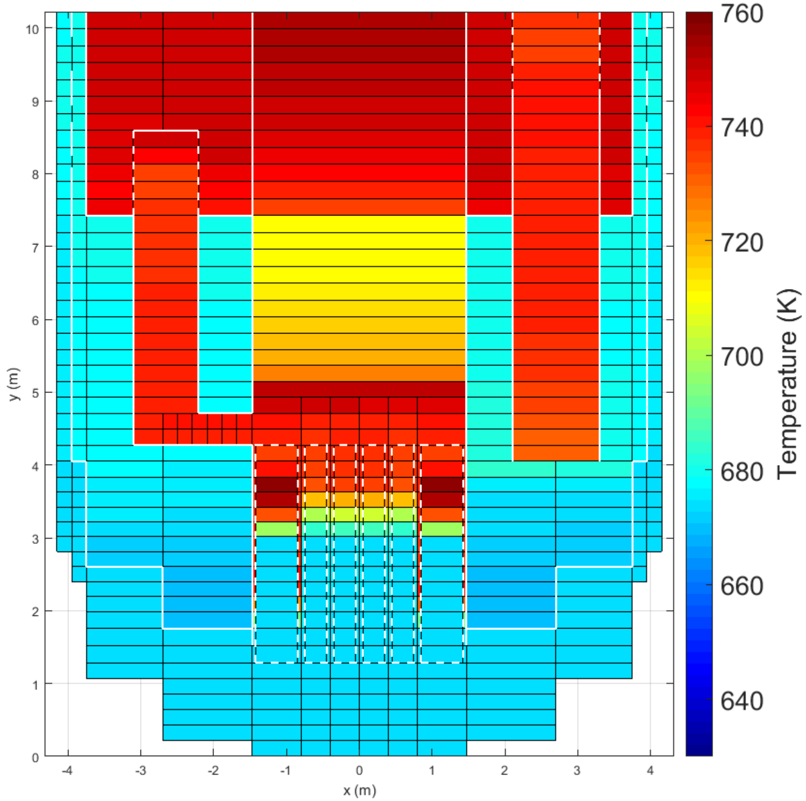



1 h

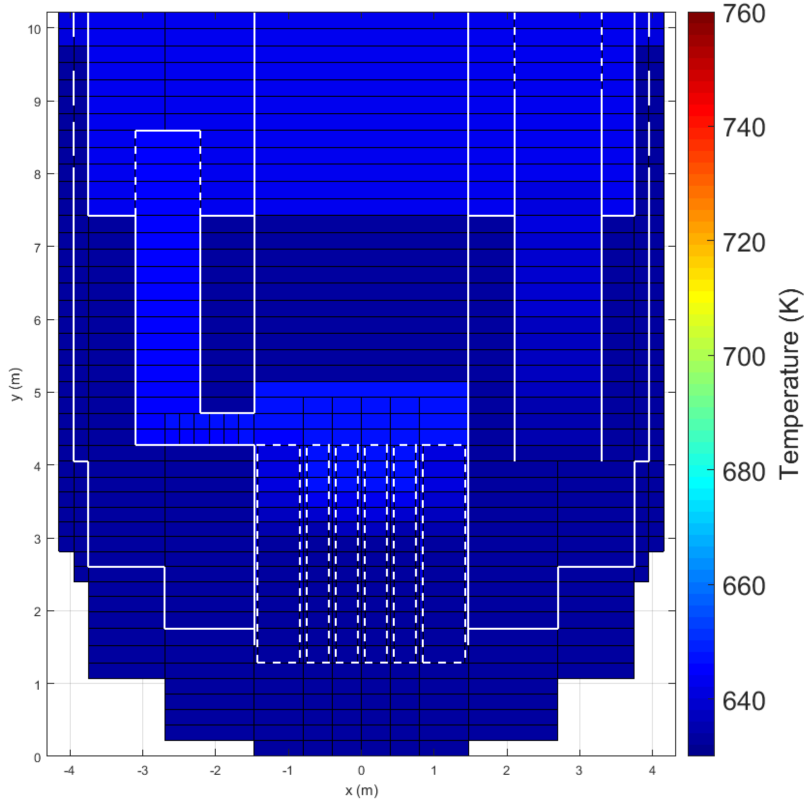


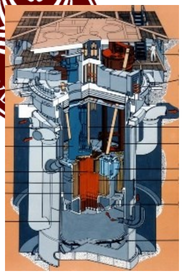
# ALFRED – Transient analysis

0 h



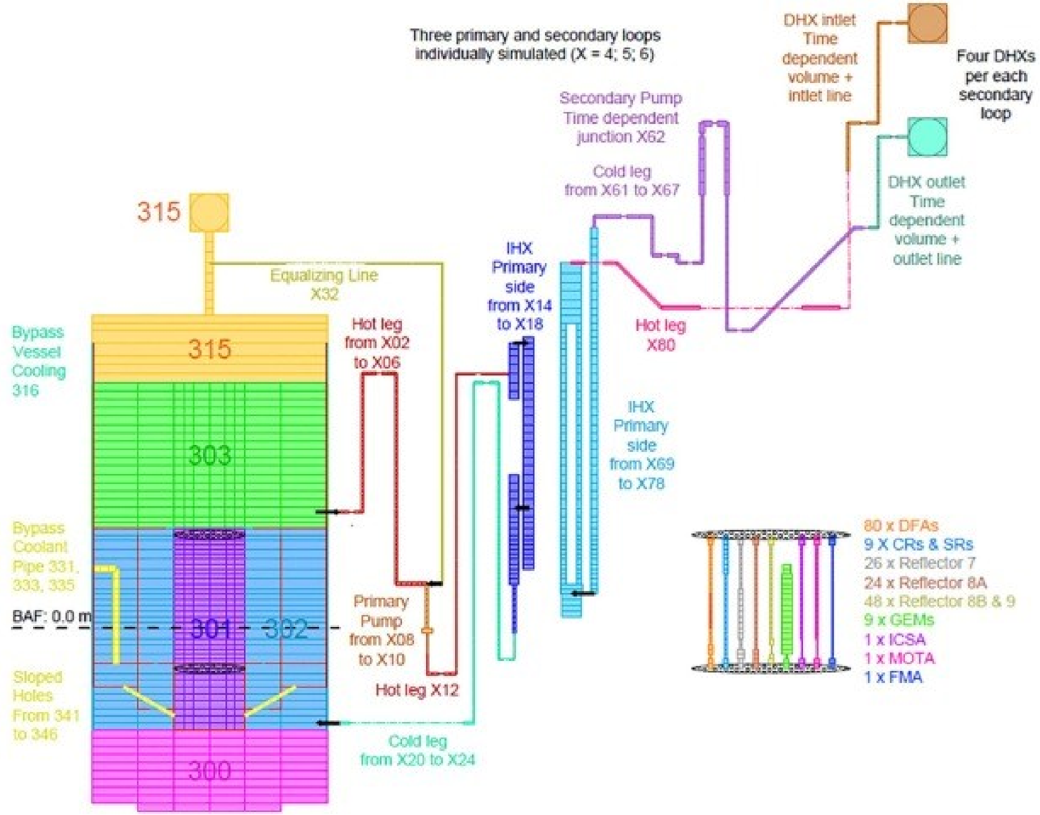

72 h





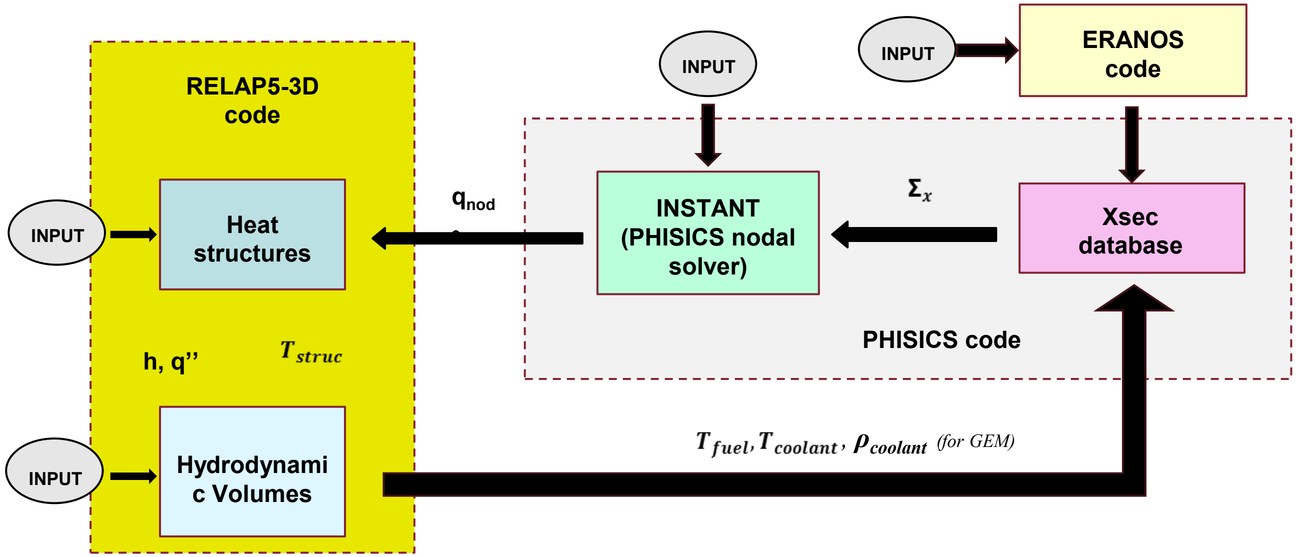
# IAEA CRP Benchmark analysis of FFTF

Sapienza participate to “IAEA CRP Benchmark analysis of FFTF loss of flow without scram test” with a detailed multiphysics modelling based on a NK/TH coupling approach involving RELAP5-3D© and PHISICS codes.



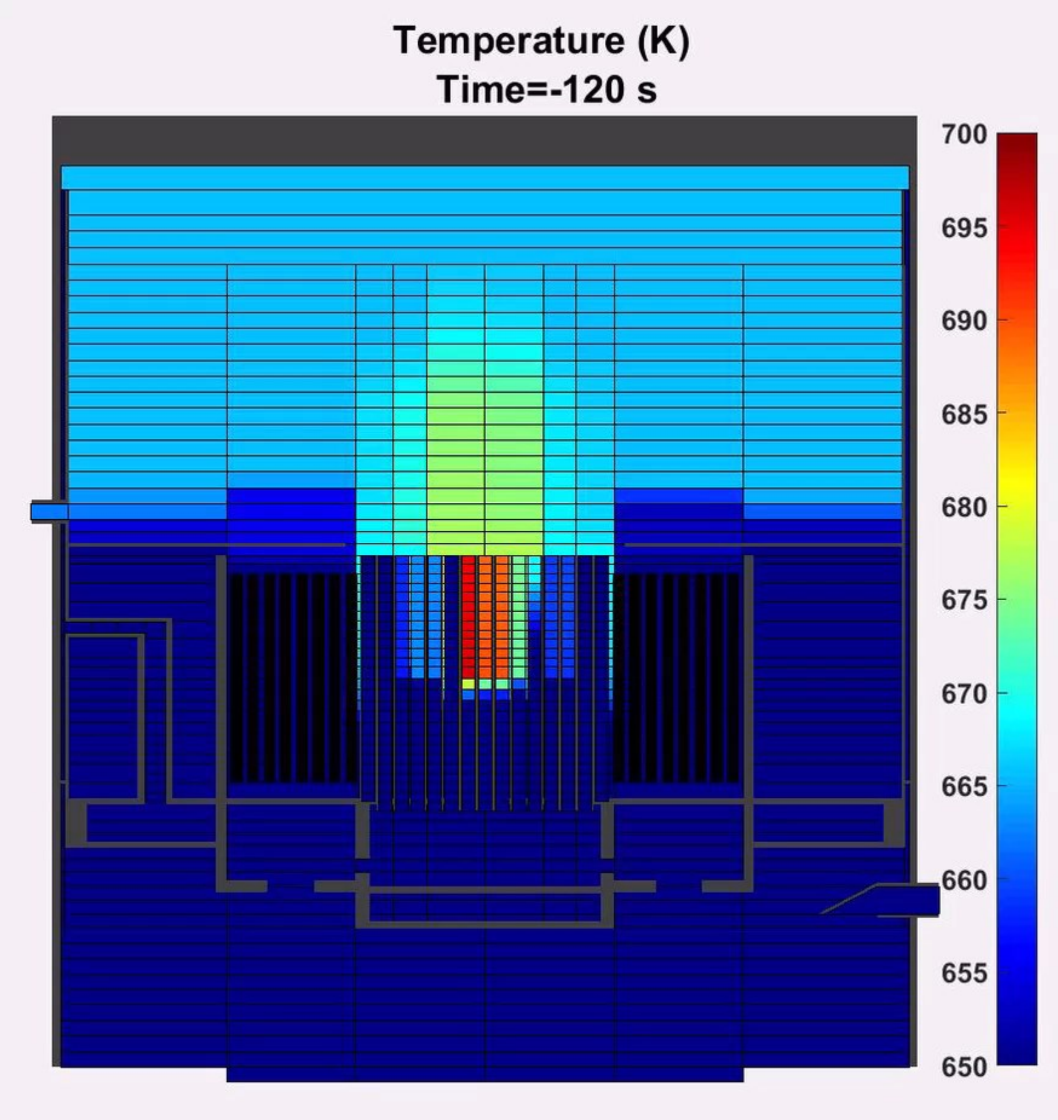
# PHISICS/RELAP5-3D METHODOLOGY USED

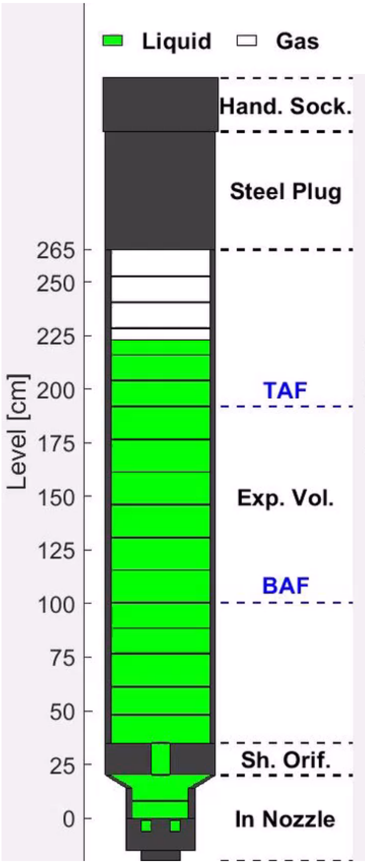
- RELAP5-3D© 4.3.4 for the **thermal-hydraulic domain** (apparently less numerical instability during natural circulation in comparison to 4.4.2 for liquid metals, specific investigation needed)
- PHISICS in order to interpolate the **cross sections (macro)** and to calculate **thermal power distributions (using Xsec set calculated by ERANOS 2.3 – JEFF 3.1.1**)

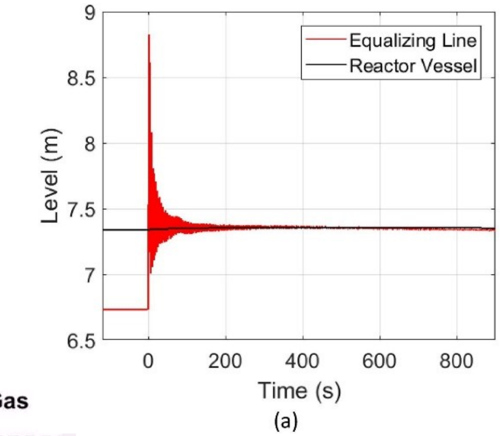



Main focus is on the Gas Expansion Module (GEM) safety system, simulated with the free level of sodium and considered for temperature and density feedback in the NK, to physically evaluate the effect during the transient

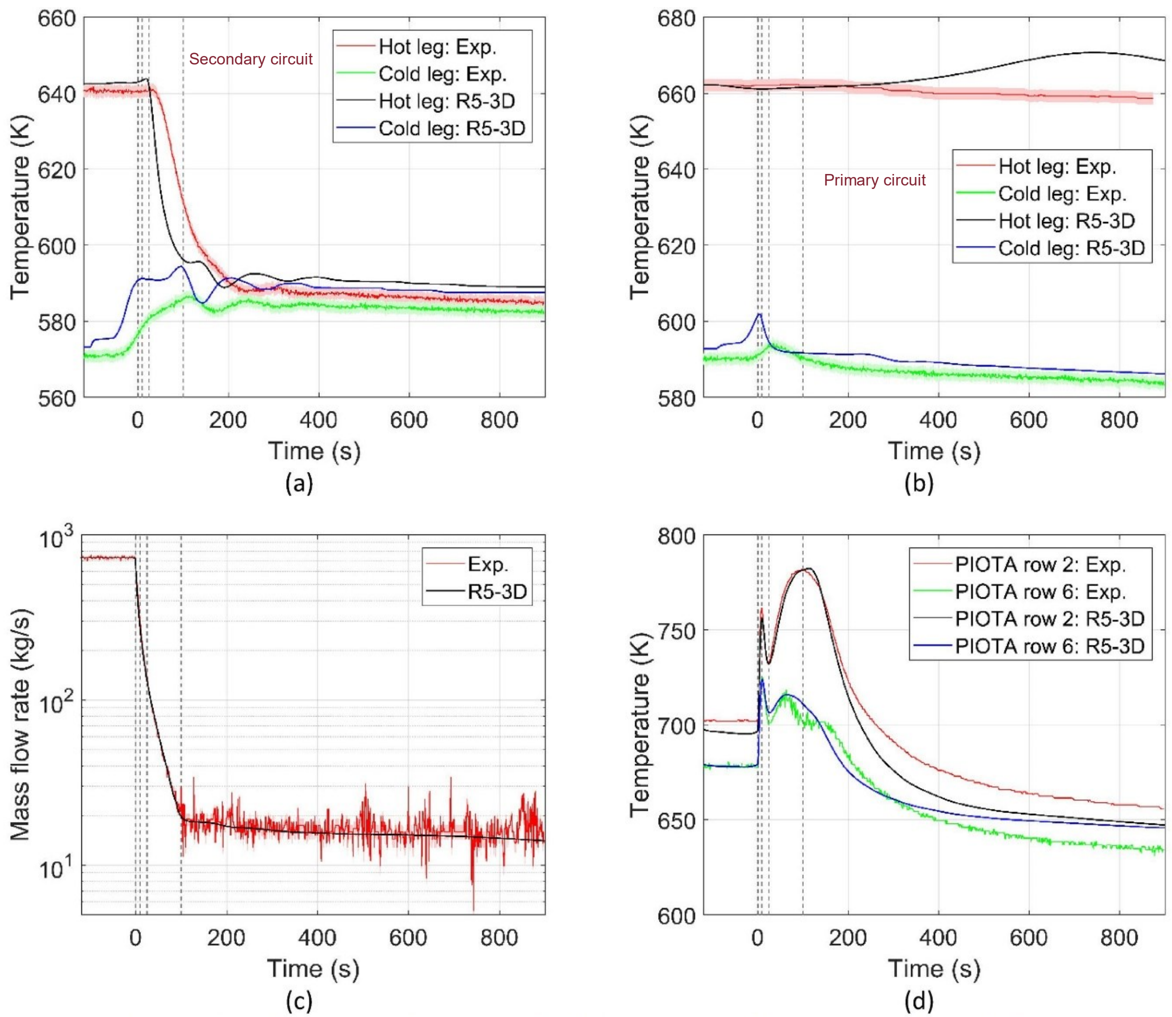
# FFTF ULOF transient results



# FFTF ULOF transient results




- Primary circuit hot leg trend shows possible problems in the upper plenum temperature prediction
- Mass flow rate predicted, but relatively large oscillations are reported
- General agreement for the temperature trend, but local PIOTA temperatures trend show a different behavior after the second peak, that will be investigated during the open phase.

# CONCLUSIONS

- The main goal of the research activity has been to investigate the capabilities of **RELAP5-3D© for LMFR**
- **Pool modelling** has been recognized as relevant issue in the frame of STH code application. R5-3D has highlighted satisfactory capabilities: **MULTID approach is suggested when thermal stratification or asymmetrical effects are expected; otherwise, multiple vertical pipe approach is recommended**. Future works could be dedicated to the implementation of specific nodalization to improve the simulation of natural buoyancy within large plena
- Free level increases obviously the numerical instabilities, but it is possible to simulate also variation of meters and multiple levels with a realistic reproduction of the pressure field
- R5-3D, for **LMFR systems,** has shown good capabilities to reproduce behavior of primary systems under safety-relevant conditions
- The literature reported some criticalities in the prediction of passive safety systems based on IC submerged within water pool, especially related on the evaluation of the heat exchange. The present research activity has confirmed these issues: to improve results it is needed an HTC tuning. Our implementation of specific correlation in RELAP5 mod. 3.3 shows the possibility to solve the problem, obtaining very good results
- TH-NK analysis are in good agreement with experimental results, simulating directly free levels and void effects

# THANKS FOR YOUR ATTENTION