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From tool development to transient analysis

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Final meeting, 4 July 2019

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TU Delft

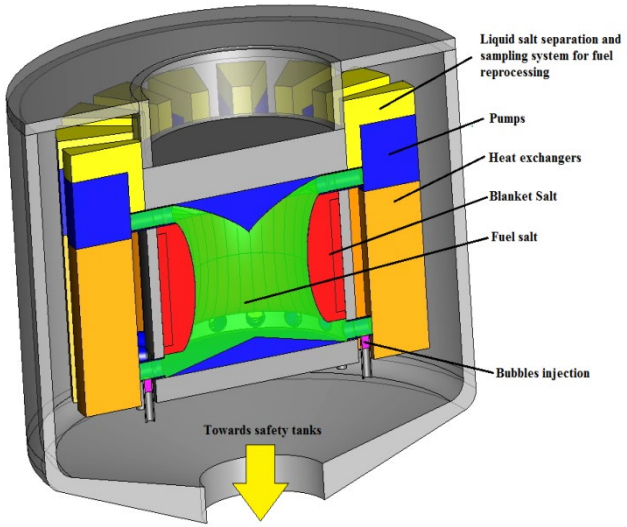
PAUL SCHERRER INSTITUT PSI

KIT Karlsruher Institut für Technologie

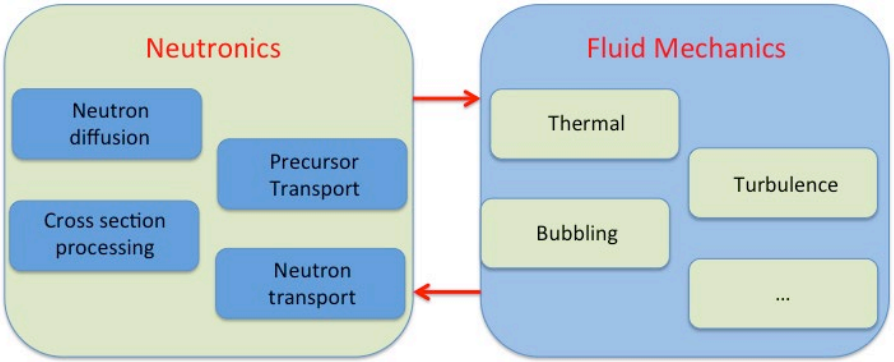
EDF

The Molten Salt Fast Reactor

Modelling needs



- The MSFR is a **circulating fuel** reactor, => the **precursors are transported** by the liquid fuel => **stronger coupling** between neutronics and fluid-dynamics.
- A **helium bubbling** system is foreseen for a more efficient removal of the gaseous fission products, and as a possible option for the reactivity control.
- The **compressibility** of the mixture may have an important effect on dynamics behavior of the MSFR, expecially in fast, super-prompt-critical transients.



A **multi-physics modelling** approach is required

Need to develop/extend and benchmark code systems

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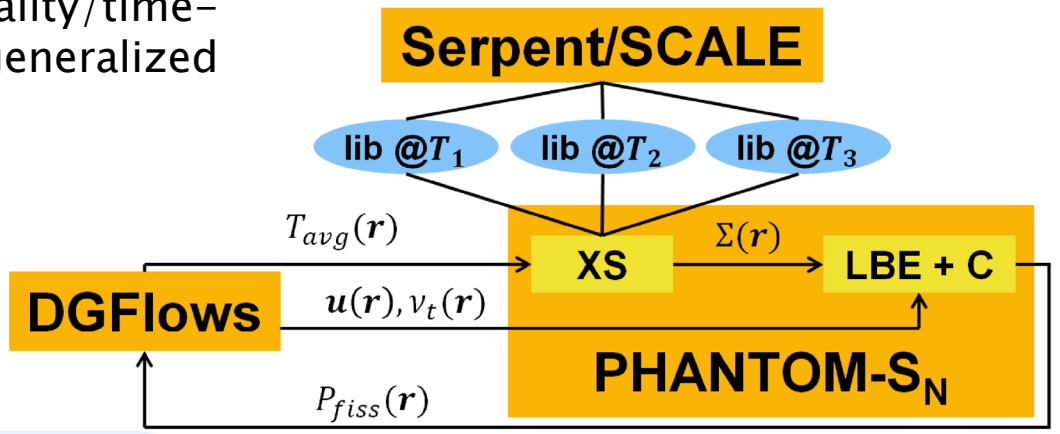
TUD multi-physics tool

- **S_N radiation transport code** (PHANTOM-SN) coupled to **RANS solver** (DGFlows), both in house tools
- **Discontinuous Galerkin FEM** for space discretization. Can handle structured/unstructured meshes, and support local refinement
- **2nd order BDF schemes** for time discretization.
- DGFlows: solves low-Ma RANS equations, with pressure-correction. Can handle properties fully variable with temperature
- PHANTOM-SN: solves the multi-group Boltzmann transport equation coupled to delayed neutron precursors equations.

Extensive capabilities: principal and multimodal calculations of criticality/time-eigenvalues; both regular and generalized perturbation analysis



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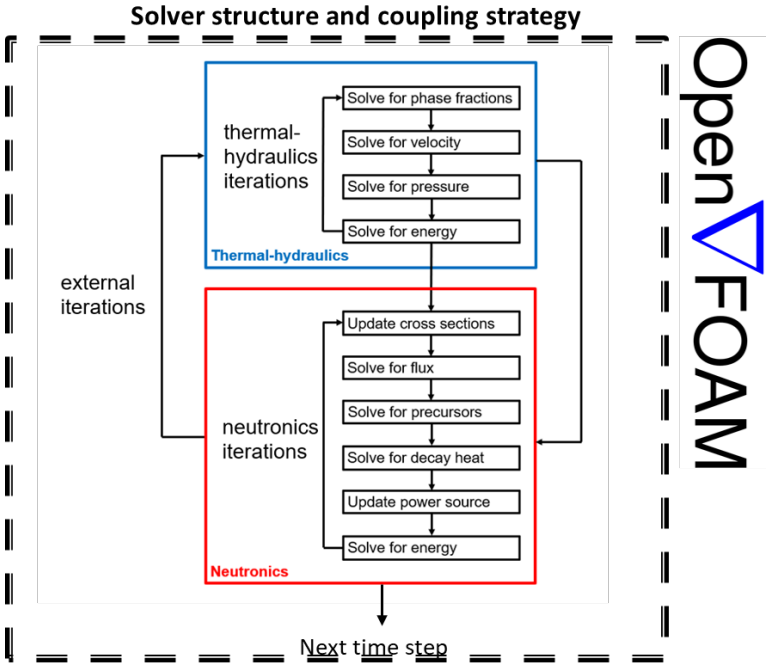
PoliMI multi-physics tool

A multiphysics model has been developed, including:

- Multi-group neutron diffusion equations;
- Multi-group SP3 neutron transport equations;
- A two-phase, compressible thermal-hydraulics model, based on a ''two-fluids'' (or Euler-Euler) approach;
- Transport equations for the moving precursors.

This model has been implemented into an OpenFOAM solver **to study the accidental transients of the MSFR, the impact of the helium bubbling system and the fuel compressibility effects.**



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PSI multi-physics tool

- Based on the OpenFOAM C++ library

- Cross-section
- Spatial kinetics
- Fission products
- Correlations
- Sub-grid scale
- Solvers
- Applications

1. Diffusion
2. SP3 (on going)
3. Advecting SP3
4. DHP (on going)

Extensive use of Run Time Selection mechanism!

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PSI multi-physics tool

Freezing model

- Homogeneous enthalpy-porosity
  - Energy source models phase indicator α
  - Momentum source models flow resistance
  - Iteration in order to search for freezing front

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) - \nabla \cdot (\tau) = -\nabla p - Cu * \frac{(1-\alpha)^2}{(\alpha + q)^3}$$

$$\frac{\partial \rho h}{\partial t} + \nabla \cdot (\mathbf{u} h) - \nabla \cdot (k \nabla T) = -L \frac{\partial \rho \alpha}{\partial t}$$

$$\alpha = \alpha^{-1} + r * \frac{c_p}{L} * (T - T_m)$$

KIT and EdF tools

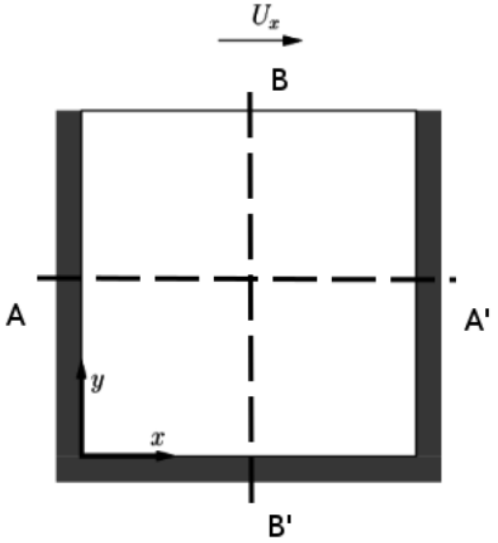
- SIMMER code: review and modification of salt properties (to match MSFR thermal conductivity)

- Analytical models to simulate draining

Code2code benchmarking

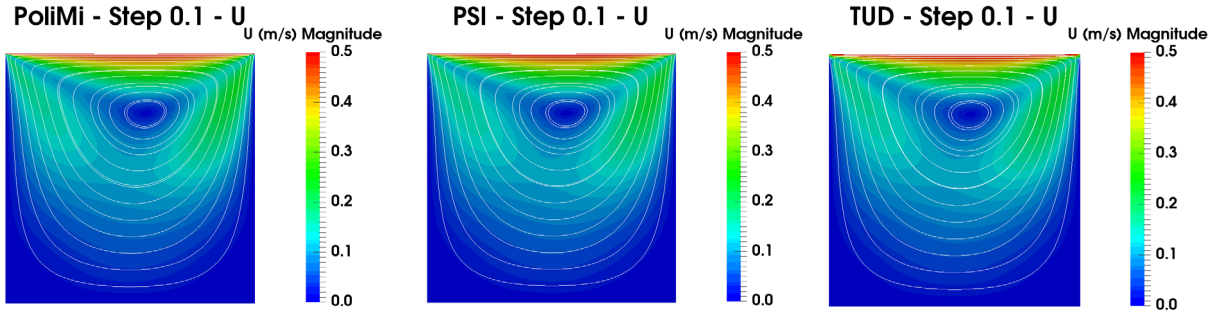
The CNRS benchmark

- **Simplified benchmark for multiphysics codes**, still representative of MSFR. Developed at **CNRS** by M. Aufiero, A. Laureau, P. Rubiolo.
- Goal: **easily test the capabilities of multi-physics codes** with respect to the characteristics of MSR systems (fuel motion and strong multiphysics coupling).
- **Step-by-step approach**, three phases: (0) single physics, (1) code coupling with increasing complexity and (2) transient analysis
- Main characteristics:
  - Prescribed nuclear data (condensed into 6 groups)
  - No Doppler feedback, only density
  - Laminar flow, Boussinesq approximation
  - Simple 2D geometry
  - Constant thermodynamic properties

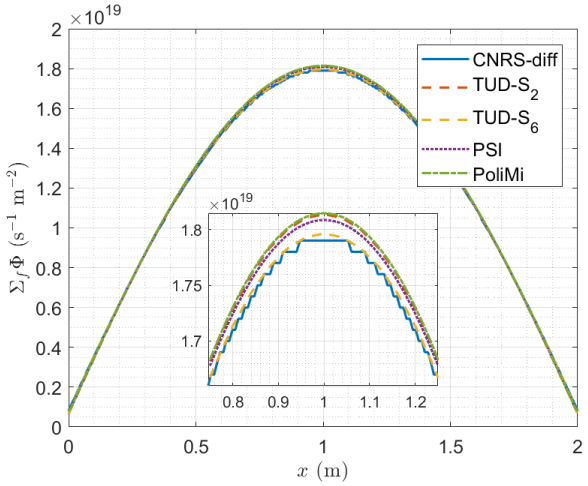


CNRS benchmark– Phase 0

- Step 01 – Velocity

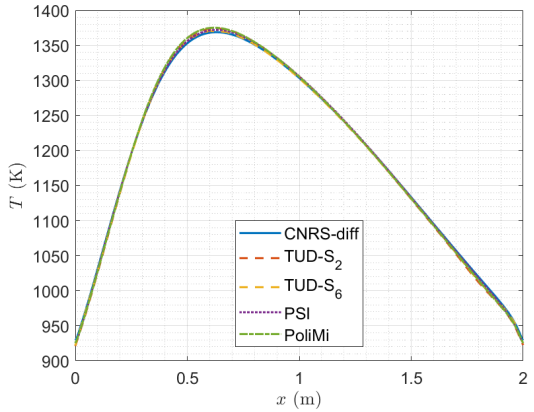


- Step 02 – Neutronics

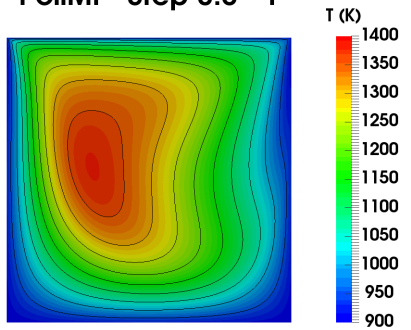


	ρ_{stat} (pcm)
PoliMi	421.2
PSI	411.7
TUD-S_2-P_1	482.6
TUD-S_6-P_3	578.1

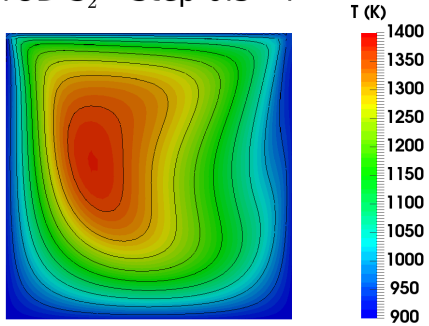
- Step 03 – Temperature



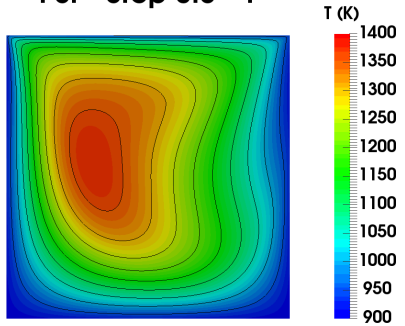
PoliMi - Step 0.3 - T



TUD-S_2 - Step 0.3 - T



PSI - Step 0.3 - T

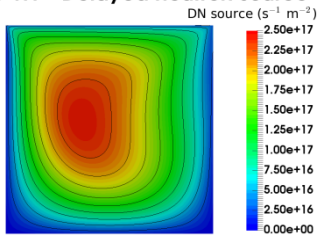


CNRS benchmark – Phase 1

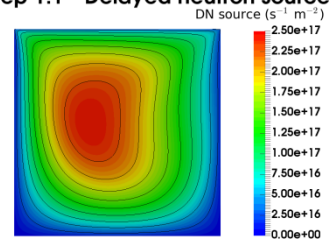
- Step 11 – Velocity coupling

	$\rho - \rho_{stat}$ (pcm)
PoliMi	– 62.0
PSI	– 63.0
TUD-S_2-P_1	– 62.0
TUD-S_6-P_3	– 60.7

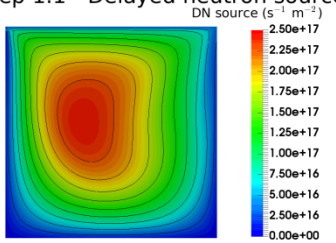
PSI - Step 1.1 - Delayed neutron source



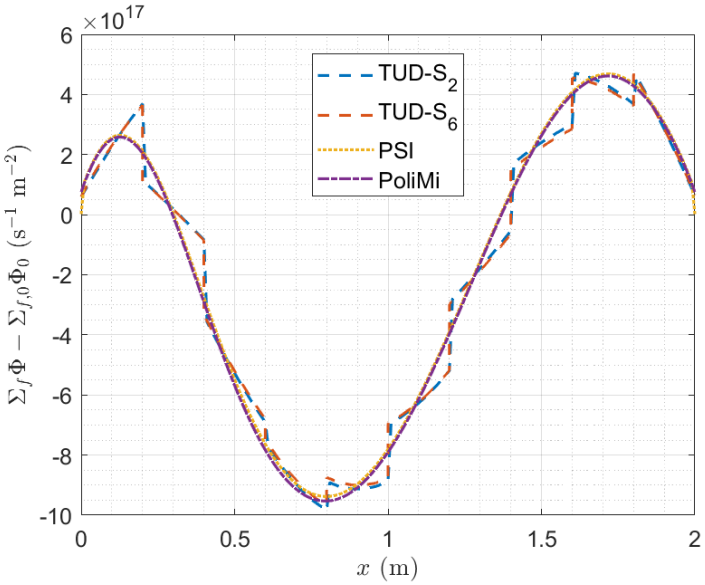
PoliMi - Step 1.1 - Delayed neutron source



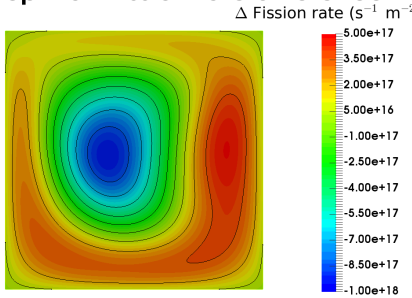
TUD-S_6 - Step 1.1 - Delayed neutron source



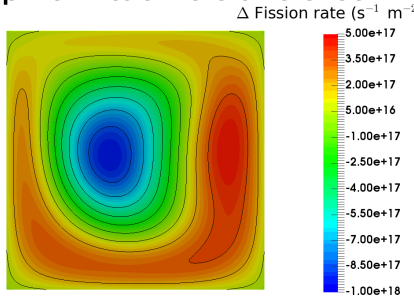
- Step 12 – Power coupling



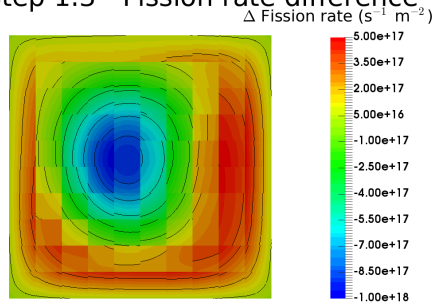
PoliMi - Step 1.3 - Fission rate difference



PSI - Step 1.3 - Fission rate difference



TUD-S_2 - Step 1.3 - Fission rate difference



Zoning used in TUD results explains observed differences

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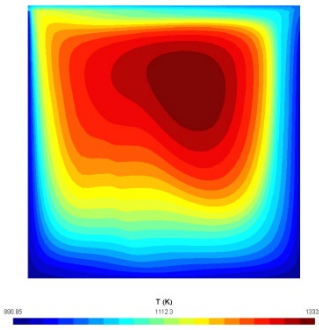
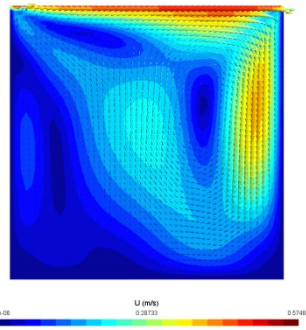
CNRS benchmark– Phase 2

From steady-state with $U_{lid} = 0.5\text{ms}^{-1}$ and $P = 1$ GW, vary heat transfer coefficient according to a sine wave (amplitude 10%, variable frequency)

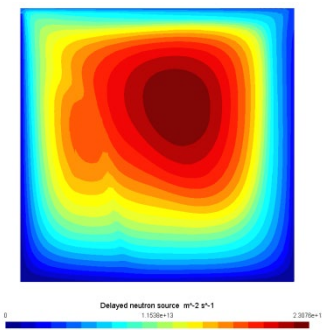
Temperature

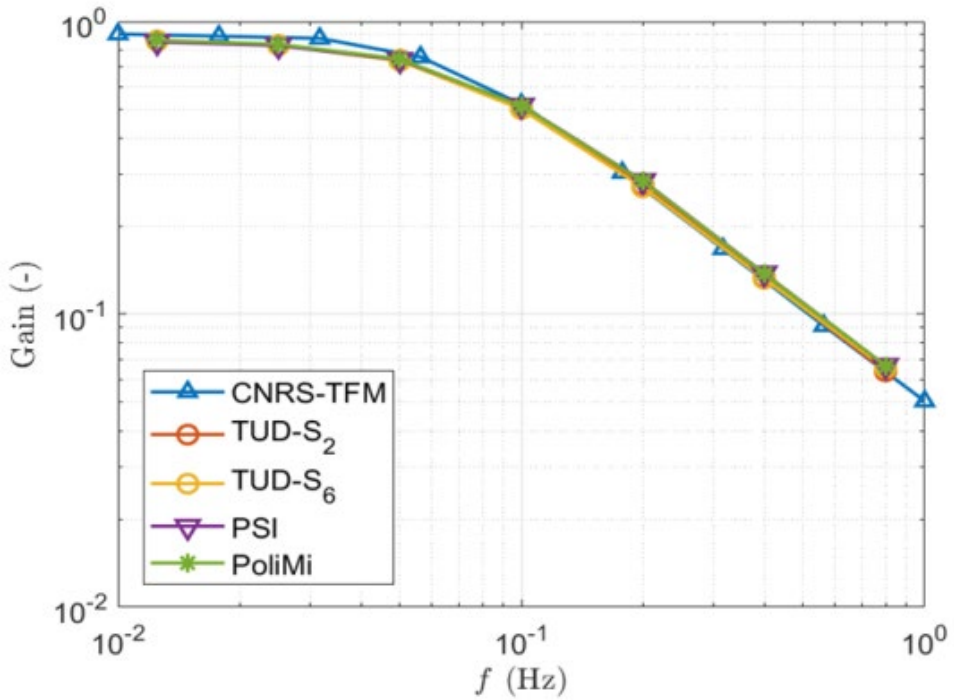


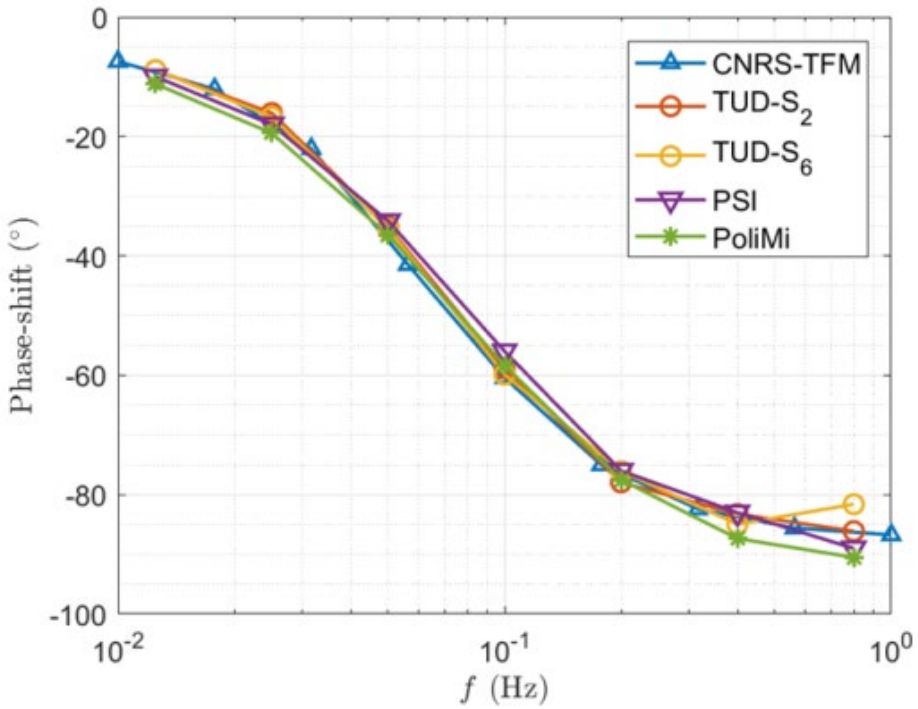
Velocity



Delayed neutron source







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Code2code benchmarking

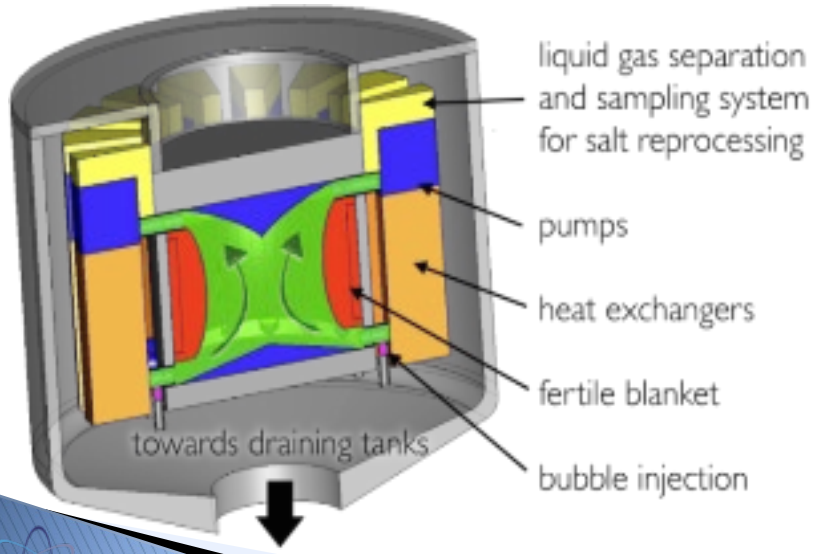
Conclusions

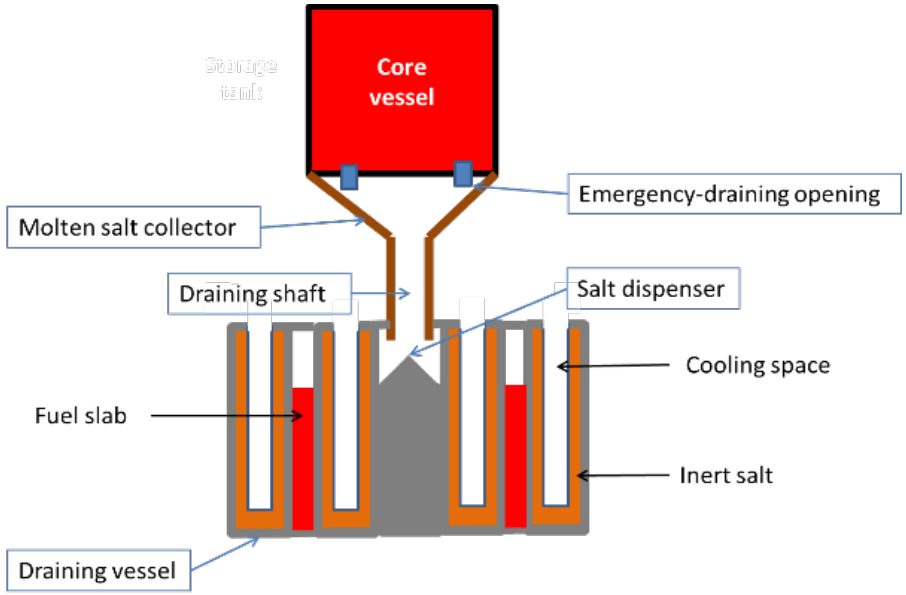
- Benchmark served its purpose
- Results of participants in good agreement. Between a 0.1 and a few percent max
- Whenever there is a difference these can be explained:
  - Meshing and order of approximation
  - Physics model used (diffusion vs transport, S_2 vs S_6)

Codes proved to be suitable to simulate MSFR behavior

MSFR transients

- Two types of transients have been selected
  - **Fuel circuit** transients
  - Transients involving the **emergency draining tank**





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Fuel circuit transients

- **ULOFF**: The mass flow reduction is simulated with an exponential decay of the pump head with a time constant of 5 s

- **ULOHS – 1** (very conservative): step reduction of heat transfer coefficient (HTC) to zero
- **ULOHS – 2** (more realistic): vary HTC and secondary average T in time, to mimic reduction of mass flow rate of intermediate circuit and ECS (to 20%). Again, exponential trends with 5s time constant

Fuel circuit transients

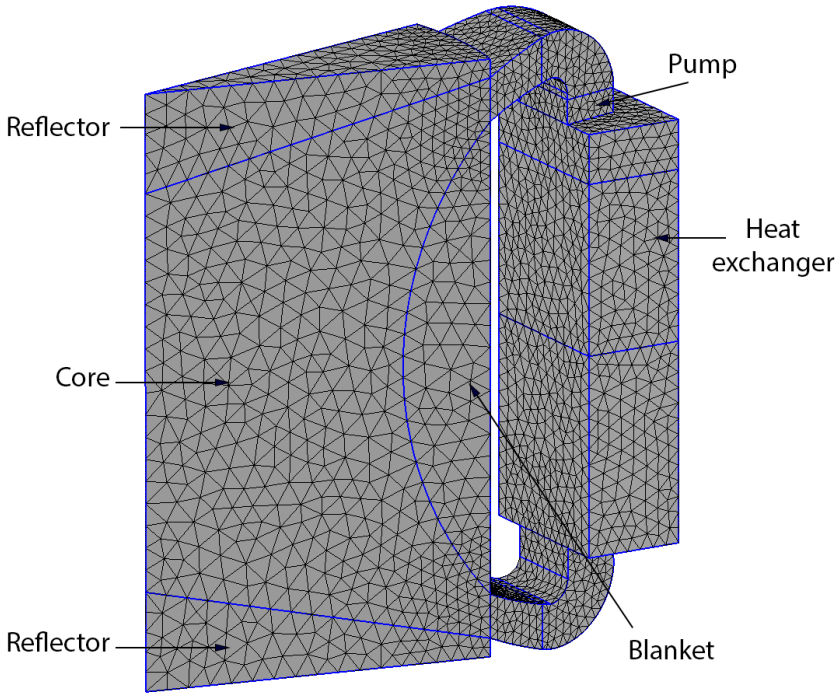
- **TLOP**: Combination of ULOFF and ULOHS (quick reduction to zero of heat removal)
- **RAA**: Step insertion of reactivity: 1.2$ (super-prompt critical) and 0.5$
- **OVC**: Same approach as for ULOHS, but opposite: vary HTC and secondary average T to simulate fast increase in extracted power

EDS transients

- **Draining of salt**, after melting of freeze-valves.
- **Salt cooling** in the draining tank

Steady-state conditions

- Steady-state conditions simulated using the 3D reactor geometry (1/16 wedge).
- Blanket and reflectors included in TUD model, because of SN transport code. PoliMI and PSI diffusion codes impose albedo boundary conditions.
- Thermal exchange with reflectors and blanket neglected (adiabatic bc)
- TUD: tetrahedral mesh, locally (hierarchically) refined near walls for CFD calculations. Shared master mesh, exchange of data through Galerkin projection
- PoliMI/PSI: hexahedral mesh



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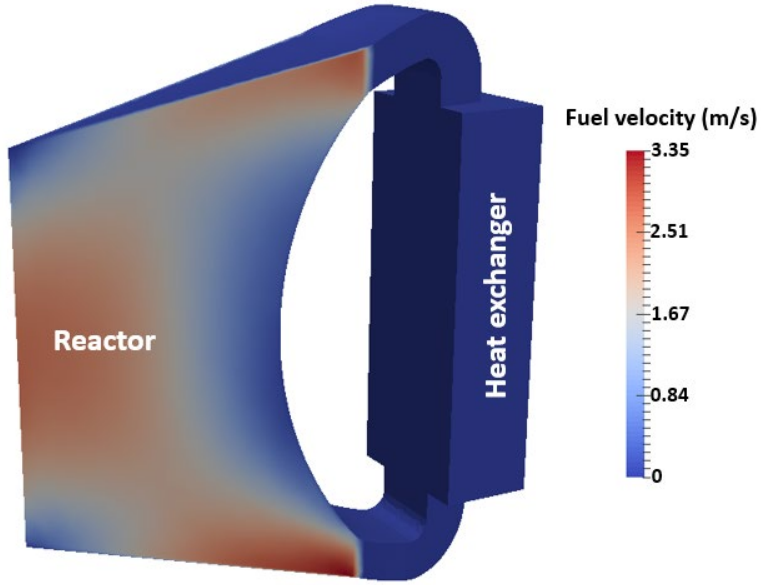
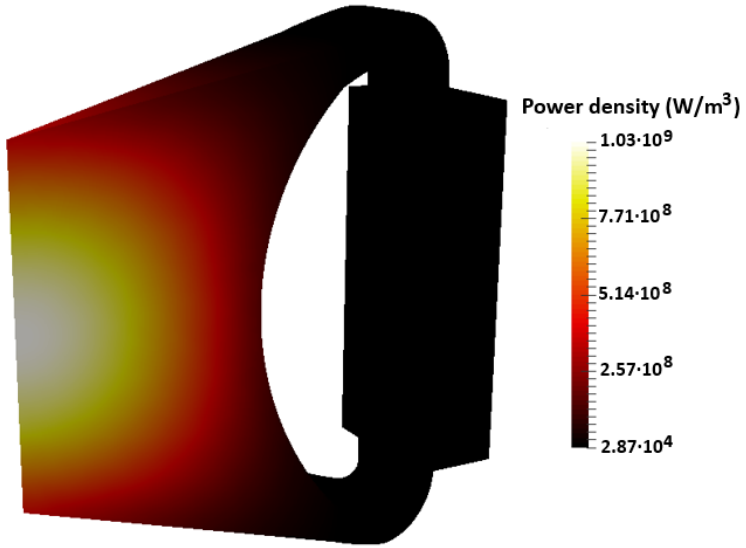
Steady-state conditions

Nominal power	3000 MW
Nominal flow rate	4.5 m^3/s
Fuel cold leg temperature	923 K
Fuel hot leg temperature	1023 K
HX pressure drop	4.5 bar
Intermediate coolant temperature	908 K
Fuel composition (% mol.)	LiF (77.5) ThF (6.6) UF_4 (12.3) TRU-F_3 (3.6)





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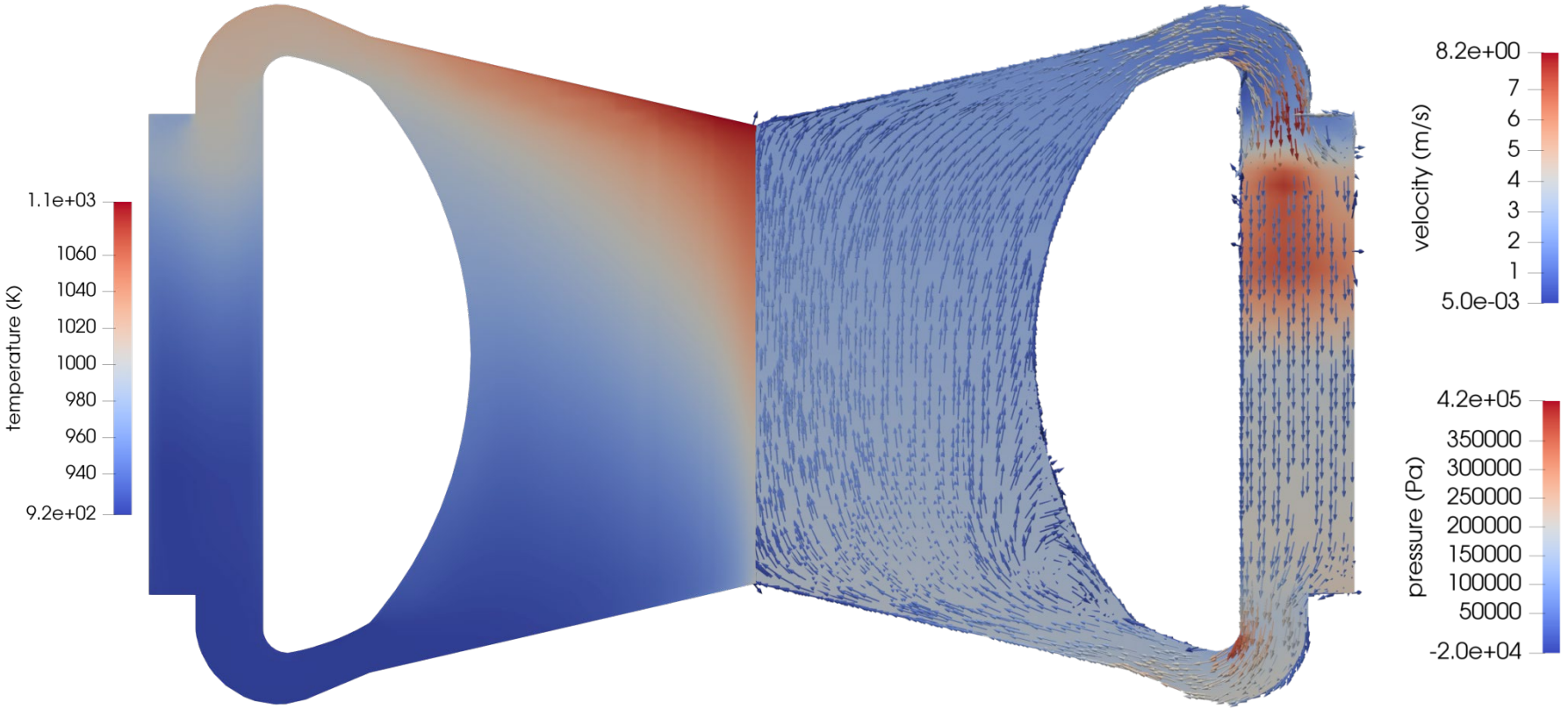
Pressure, velocity, and temperature



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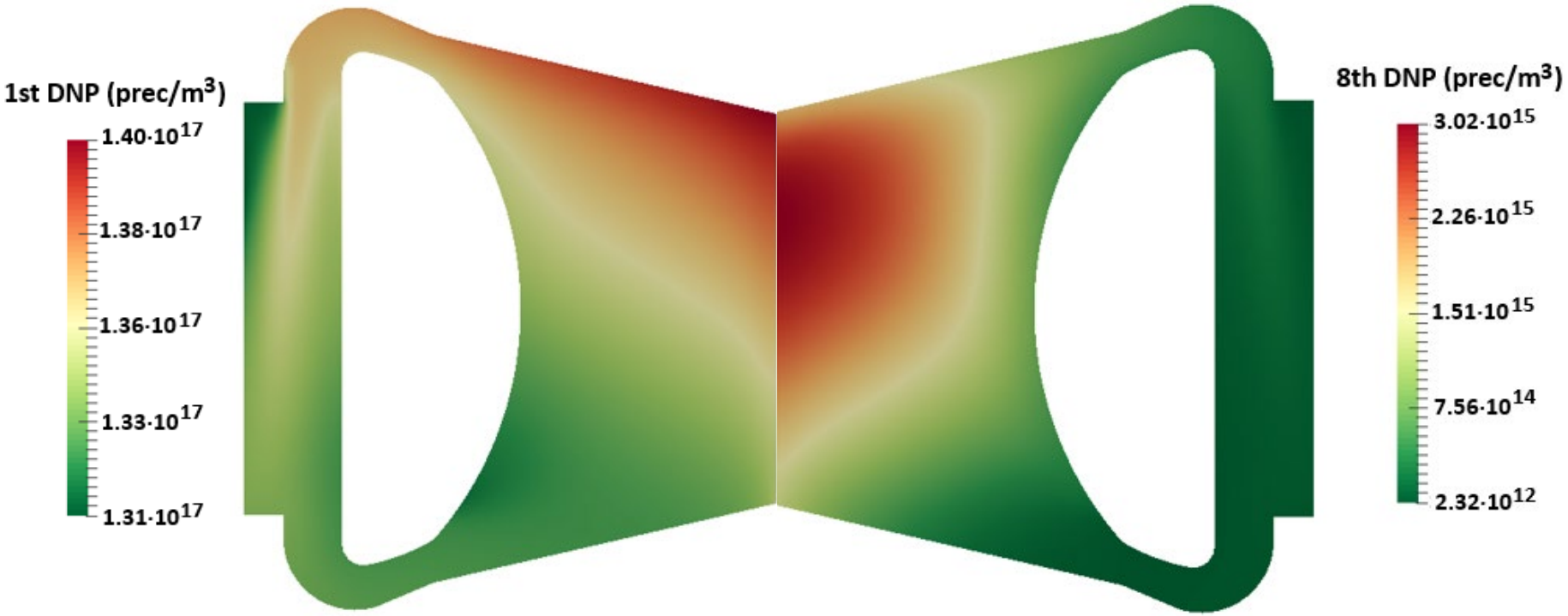
Delayed neutron precursors



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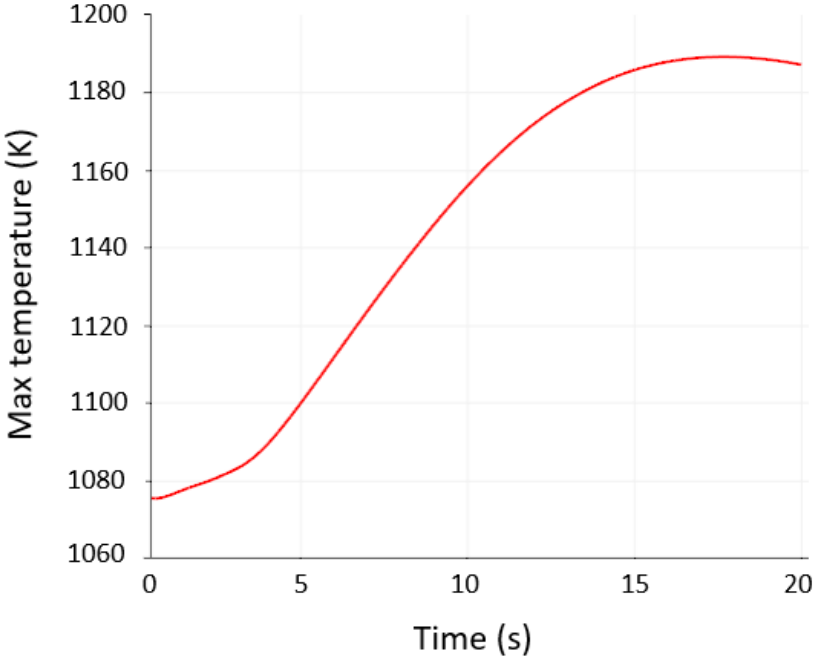
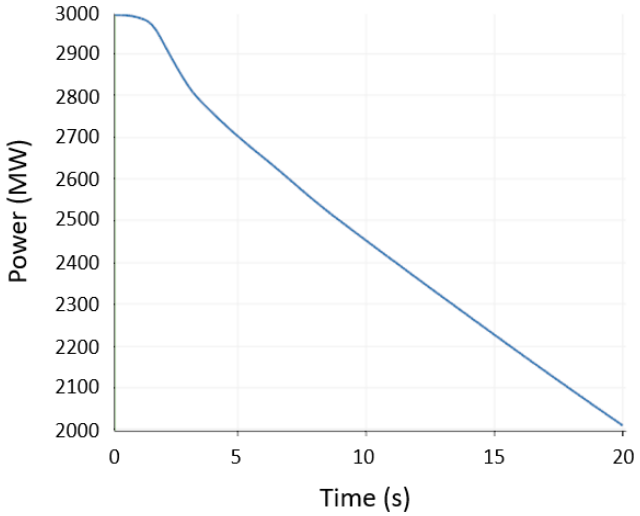
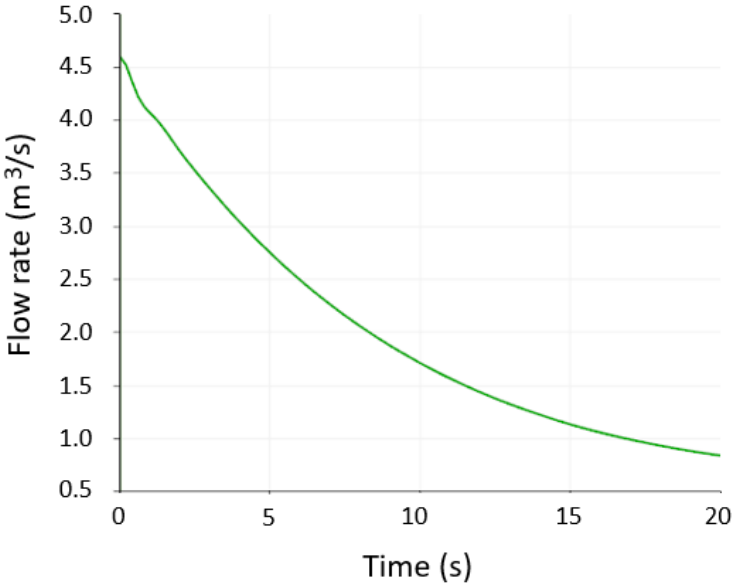
ULOF transient

Exponential reduction to zero of the pump head, with $\tau = 5s$







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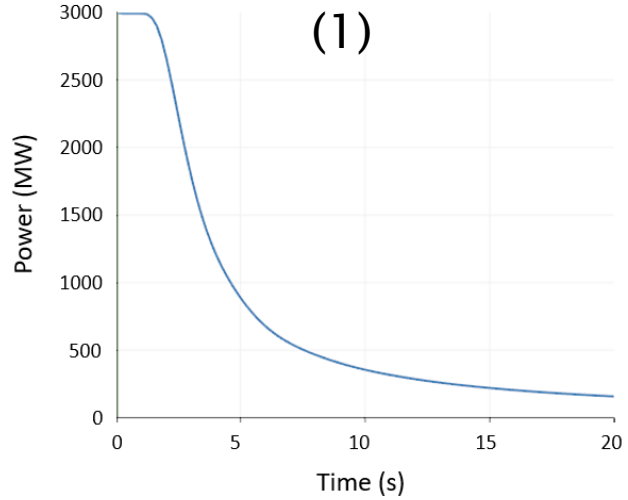
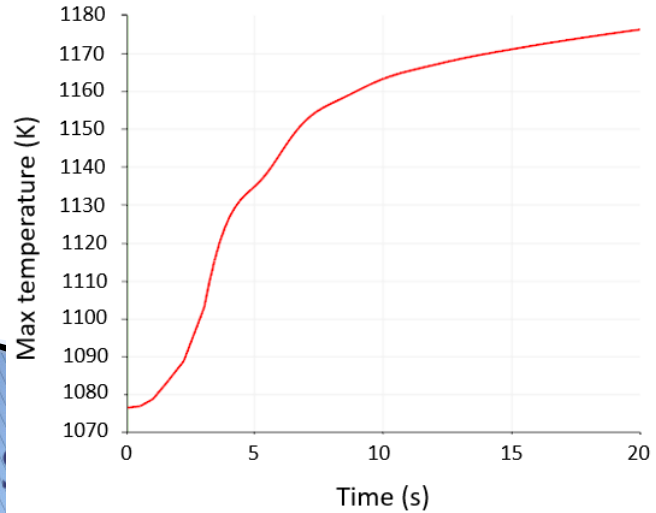
ULOHS transients (1 and 2)

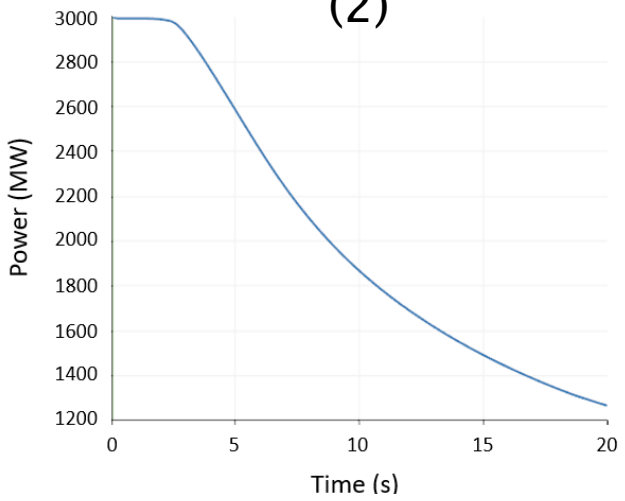
1) Stepwise reduction to zero of the HX heat transfer coefficient
2) Exp. reduction to 20% of interm. and ECS mass flow rate, with $\tau = 5s$

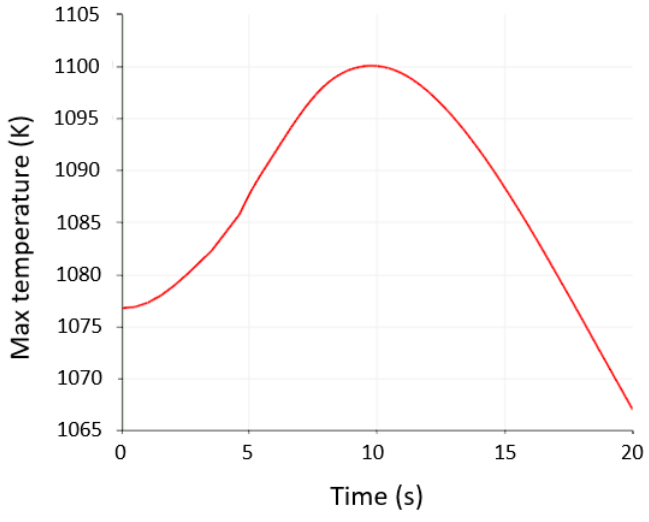
(1)





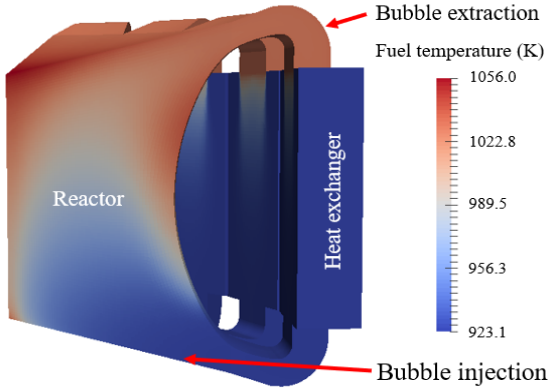
(2)





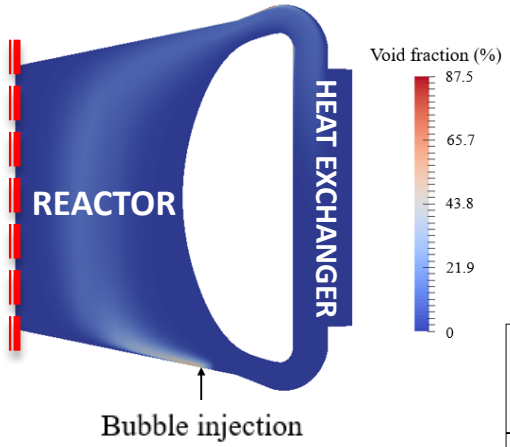
Analysis of the He bubbling

Evaluation of the void reactivity coefficient



The void reactivity coefficient of the bubbles has been evaluated. Two approaches can be used:

- Assuming a uniform bubble distribution (green);
- Calculating the bubble distribution with the multiphysics solver (blue).



Visible differences arise between the two approaches. Spatial and neutron importance effects have a strong impact on the void reactivity feedback.

Core average void fraction (%)	Multiplication factor		α_v (pcm/%)	
	Uniform bubble distribution	*Real bubble distribution*	*Uniform bubble distribution*	*Calculated bubble distribution*
0	0.96581	0.96581	-	-
0.437	0.96511	0.96444	-171.8	-336.6
0.876	0.96434	0.96308	-180.2	-335.0
1.308	0.96360	0.96179	-181.5	-330.9

(evaluated with the SP3 neutronics model)

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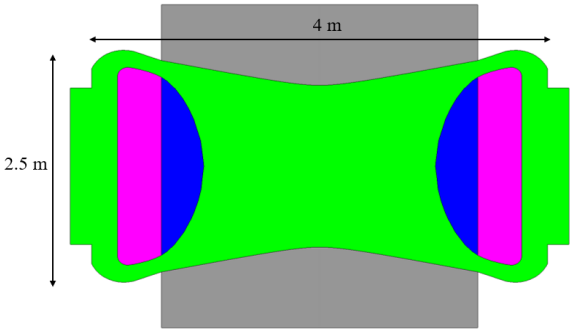
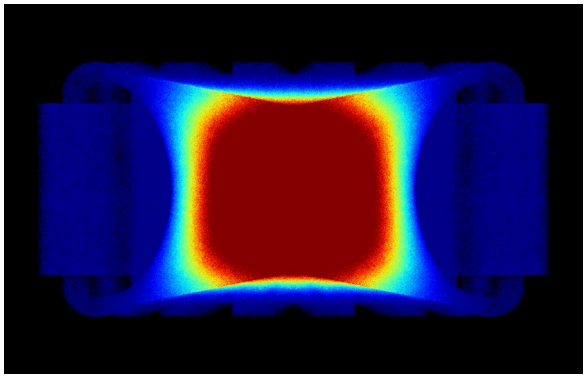
Analysis of the He bubbling

Monte Carlo comparison



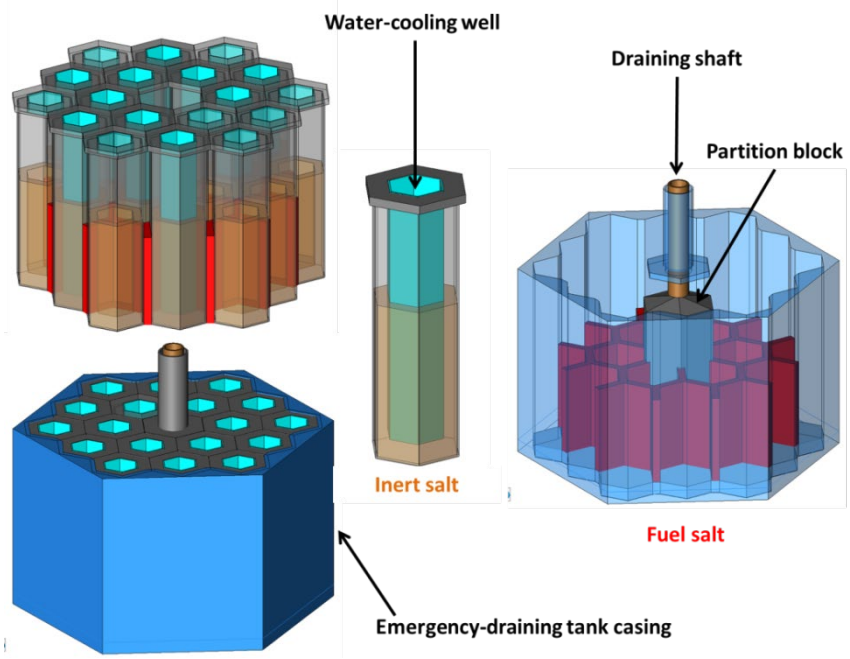


For comparison, a Montecarlo model of the same 3D geometry has been realized with Serpent 2, importing the bubble spatial distribution calculated by the OpenFOAM solver.

Core average void fraction (%)	Multiplication factor		α_v (pcm/%)	
	Uniform bubble distribution	*Real bubble distribution*	*Uniform bubble distribution*	*Calculated bubble distribution*
0	0.97110 ± 0.00005	0.97110 ± 0.00005	-	-
0.437	0.97042 ± 0.00005	0.96980 ± 0.00005	-165.1 ± 17.2	-315.9 ± 17.2
0.876	0.96970 ± 0.00005	0.96855 ± 0.00005	-169.7 ± 8.6	-309.5 ± 8.6
1.308	0.96904 ± 0.00005	0.96731 ± 0.00005	-167.4 ± 5.8	-308.5 ± 5.8

- Good agreement is obtained with the OpenFOAM calculations (differences $< 9\%$).
- Again, the void reactivity feedback depends on the bubble distribution.
- This consideration is not affected by the method we choose to model neutronics.

EDS transients

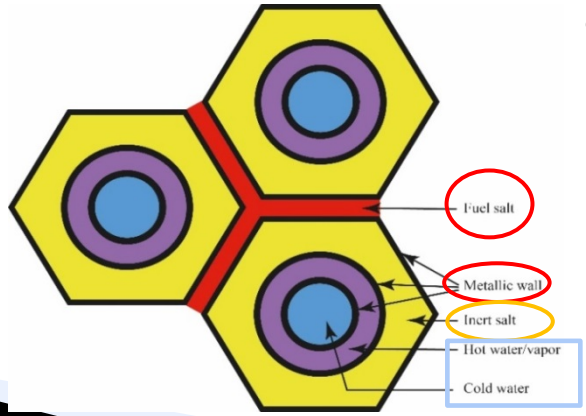


Tasks:

1. drainage of the fuel salt into an emergency draining system (EDS).
2. Decay heat remove in EDS.

Input from WP1:

1. Detailed design of core+EDS.
2. Thermophysical properties of Salt, structure mateials, etc. (solid, liquid and vapor phase).

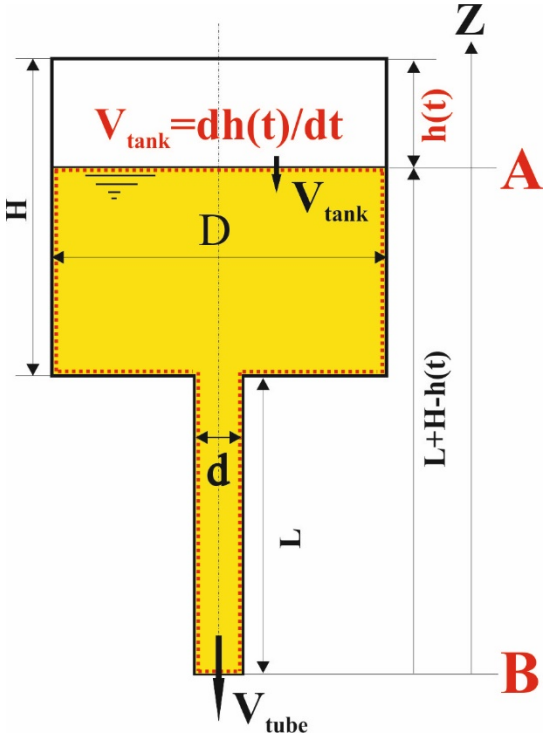


SAMOFAR

Reactor draining

Analytical KIT model

- **Analytical model** developed at KIT to compute draining time
- Draining time: after which no salt remains in the core and the tube that connects the core to EDT
- **Simplified geometry** employed for analytic calculations
- Analytical model based on mass and energy conservation equations + correlations for friction factors
- Assumption: freeze-plug fully melted (otherwise, **dramatic increase** of draining time)
- Particular functions considered:
  - draining time vs draining tube diameter;
  - draining time vs draining tube length;
  - draining time vs damage degree of freeze plug



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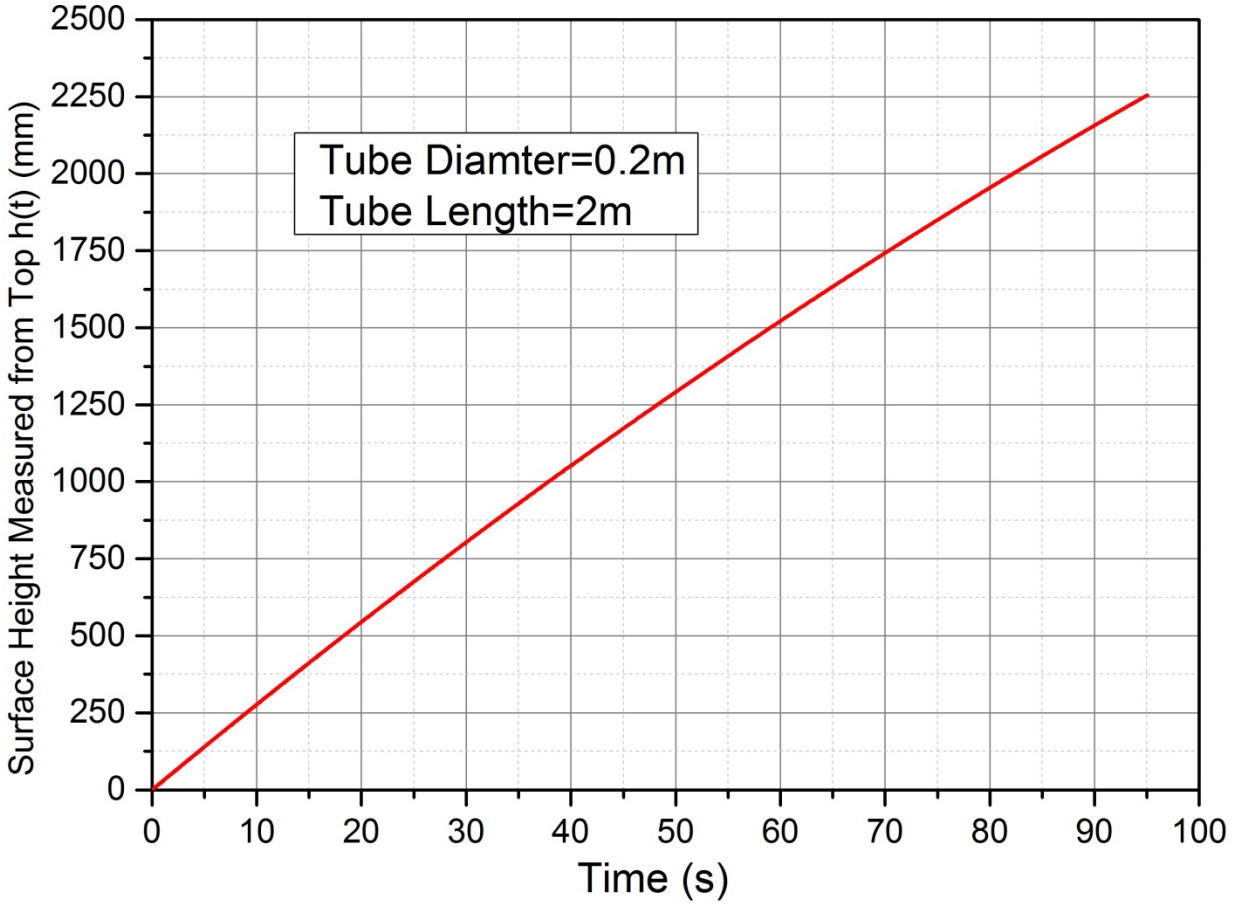
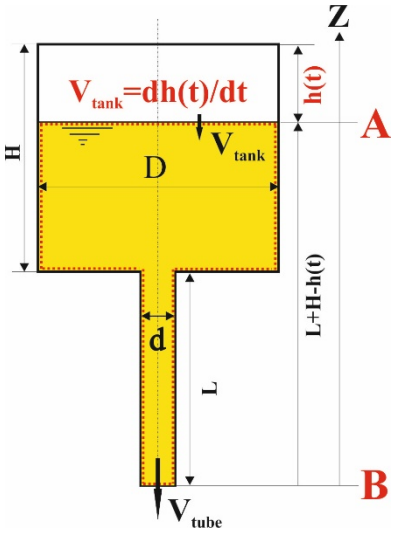
Reactor draining

Analytical KIT model

Drainage Time VS Surface Height Measured from the Core Top





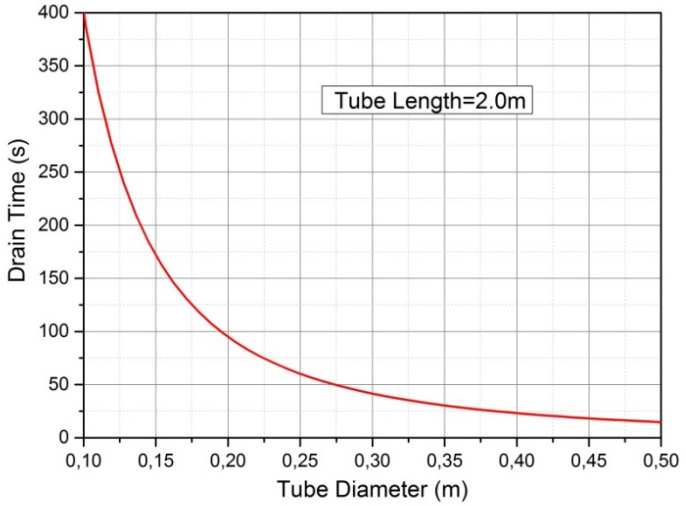
Draining Time: ca. 95s

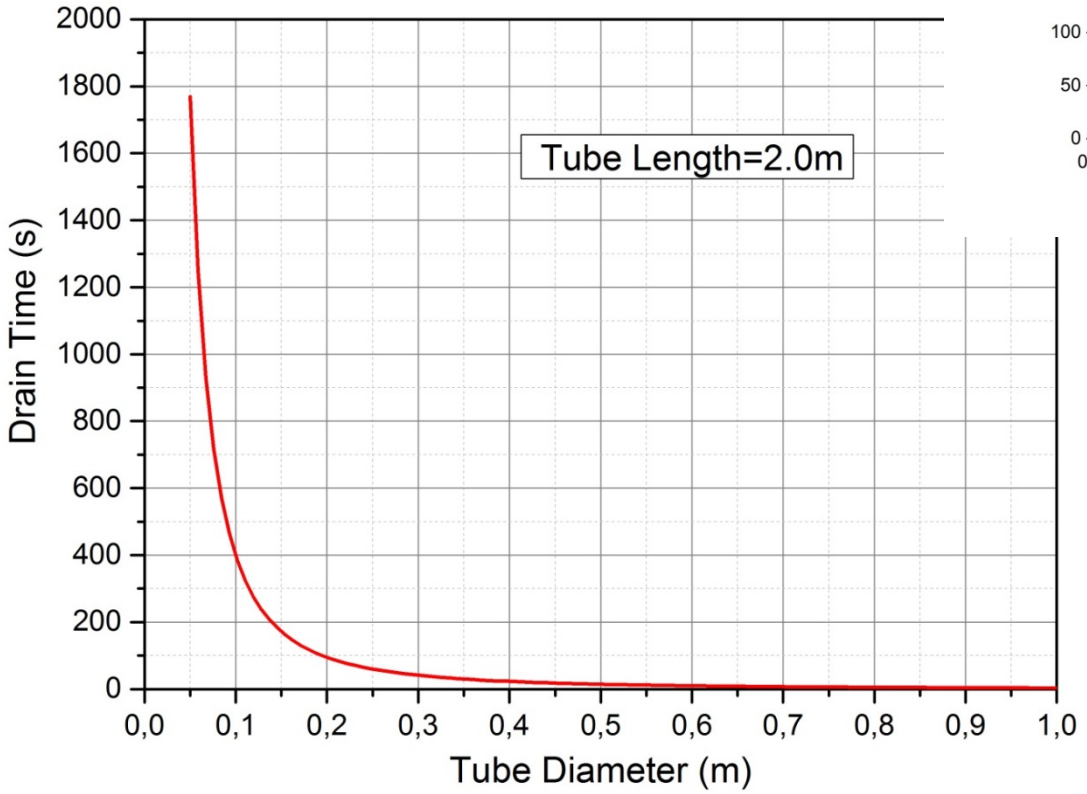
Reactor draining

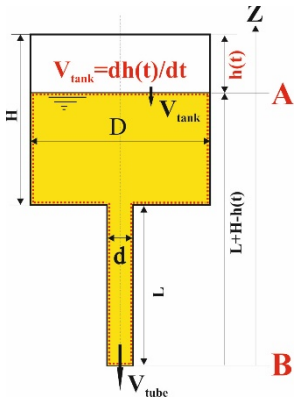
Analytical KIT model

Drain Tube Diameter & Drain Time

Huge increase for small diameter values (less than Dtube=0.2m)



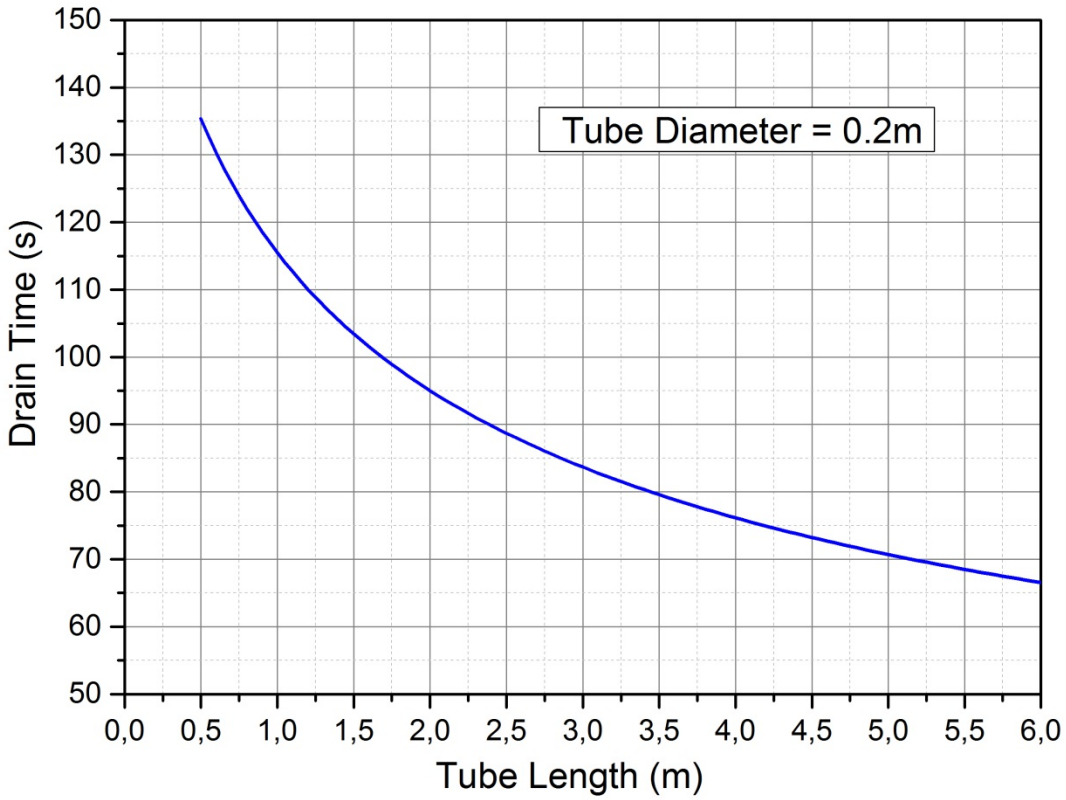


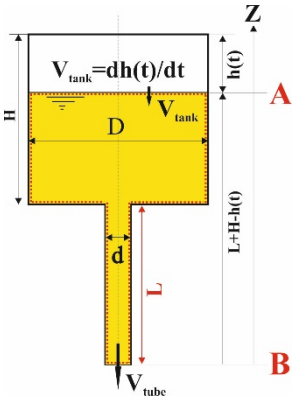


Reactor draining

Analytical KIT model

Drain Tube Length & Drain Time





though the wall friction is higher for longer tube, the draining time is smaller

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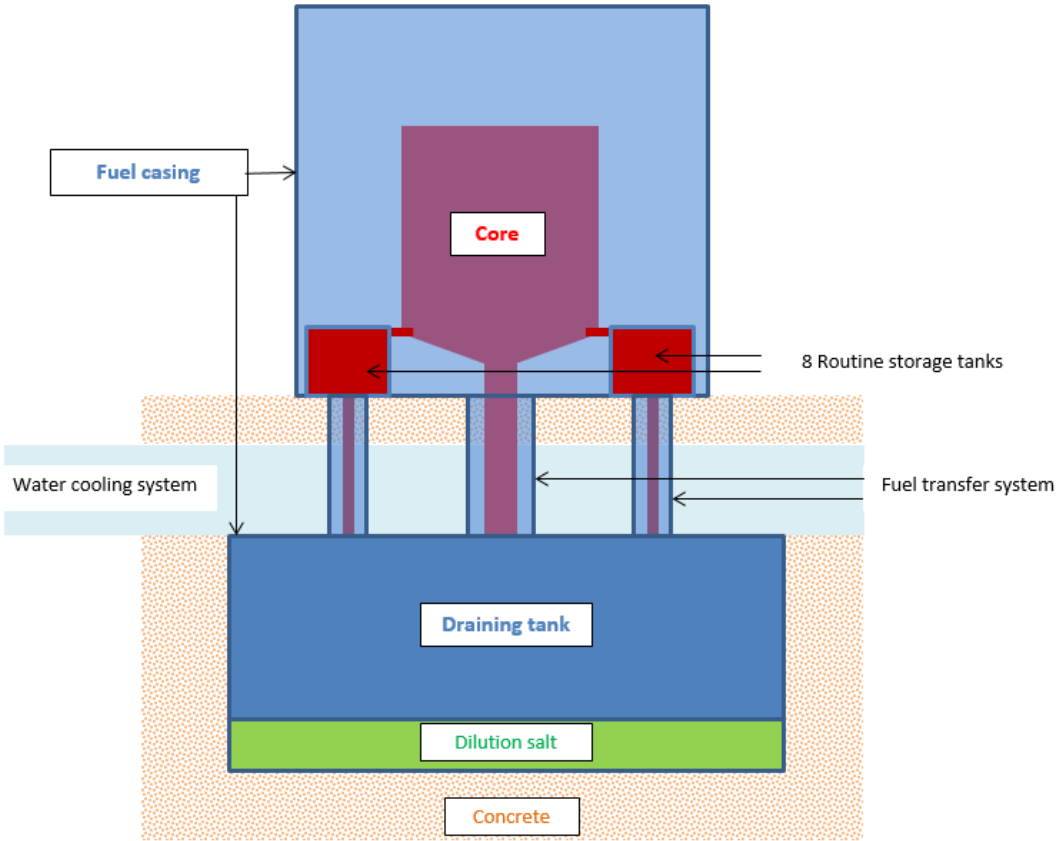
Reactor draining

- Goal = model of the draining of the tank through 1 or 16 orifices (over 16 orifices)



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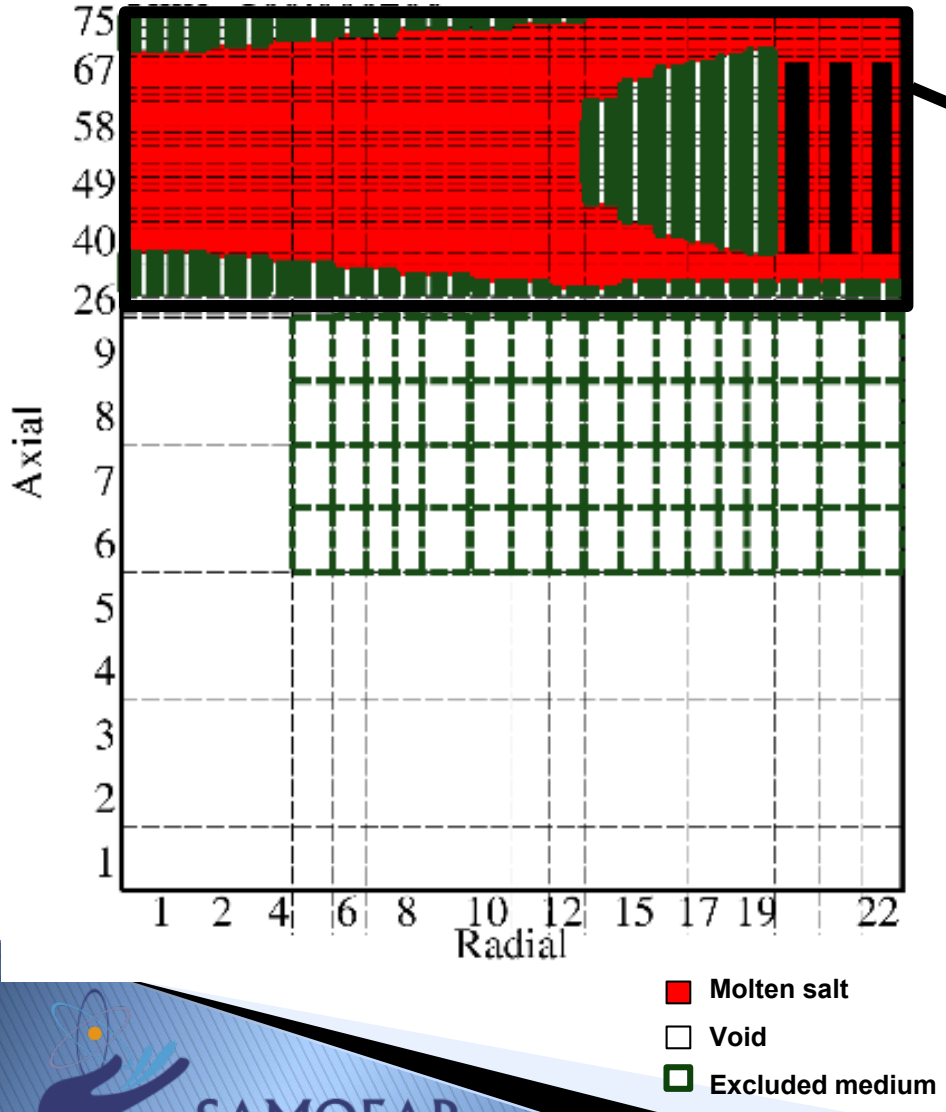
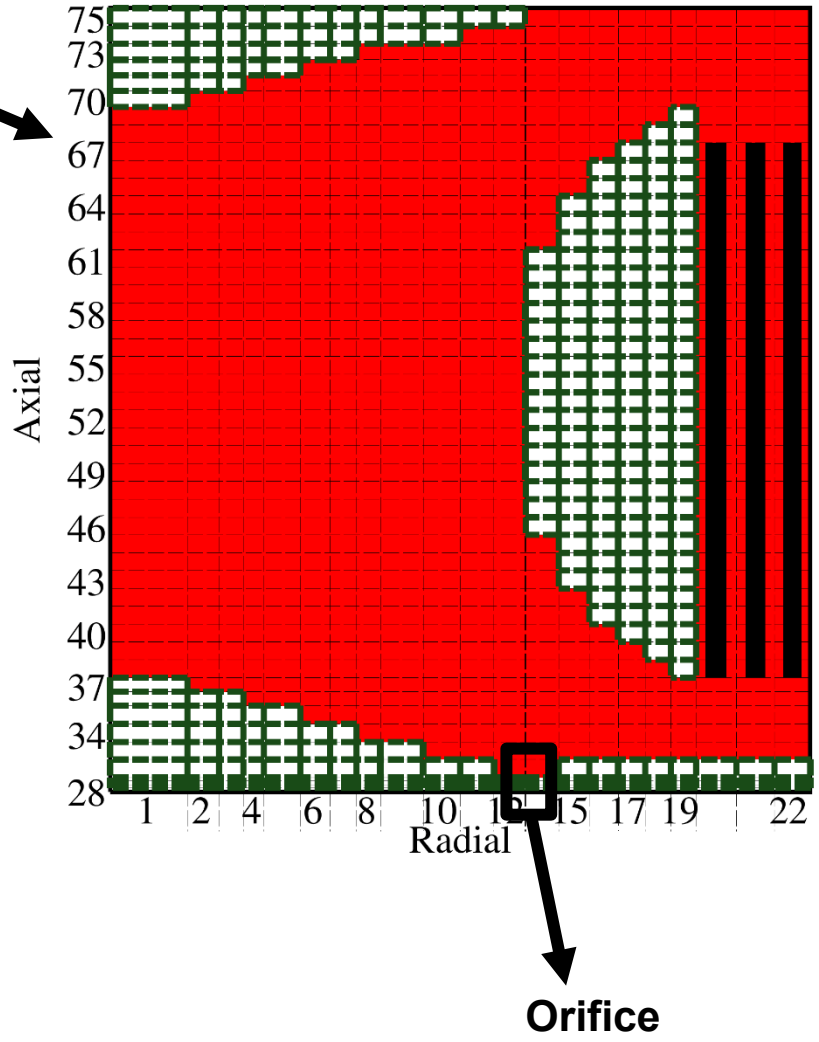
Reactor draining





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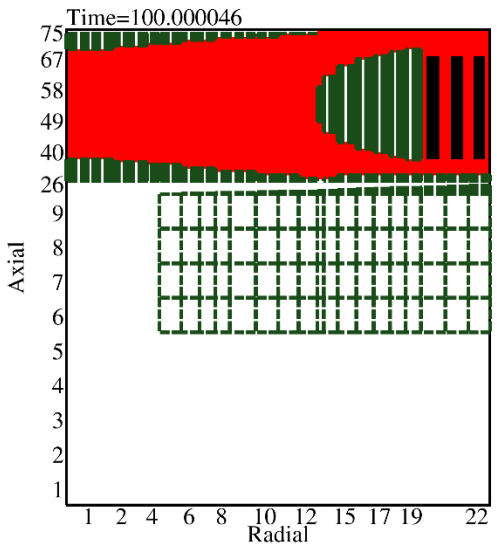
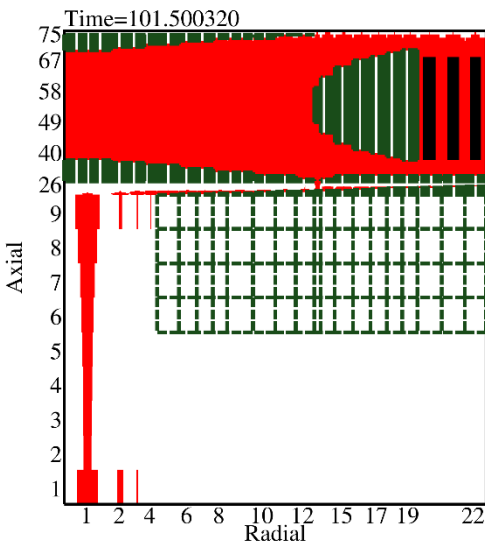
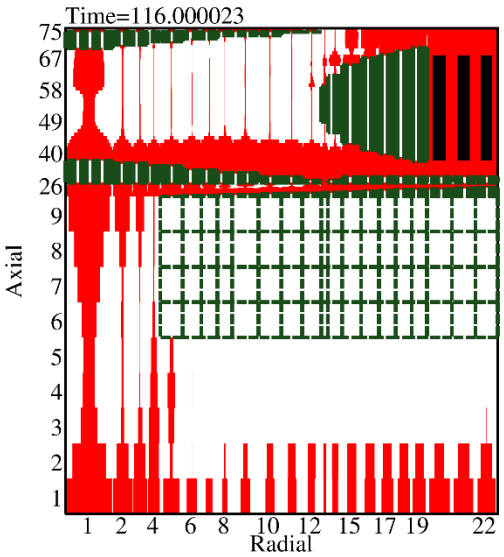
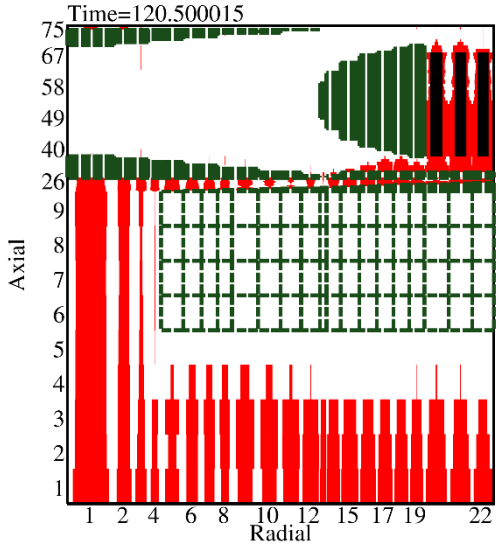
Reactor draining

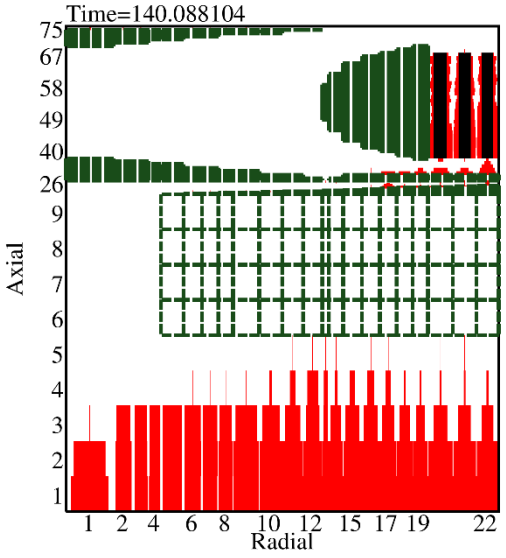
- From steady state: instantaneous stop of pumps and 16 opened orifices

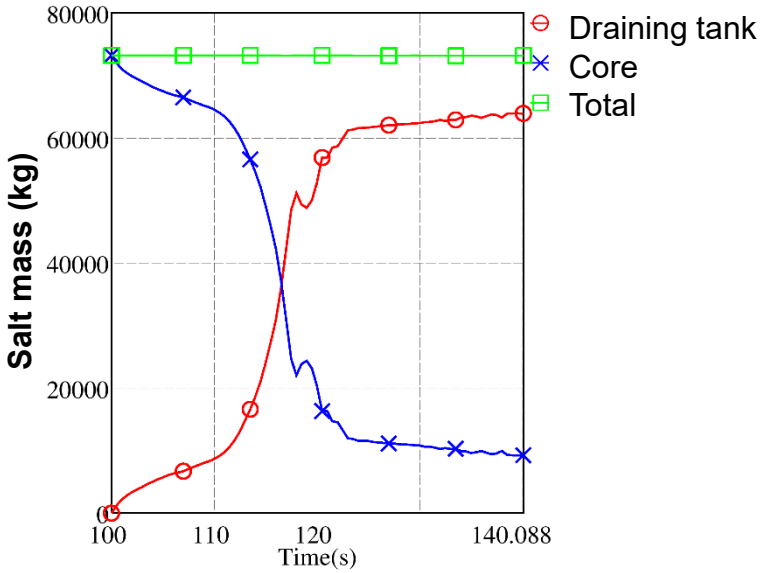






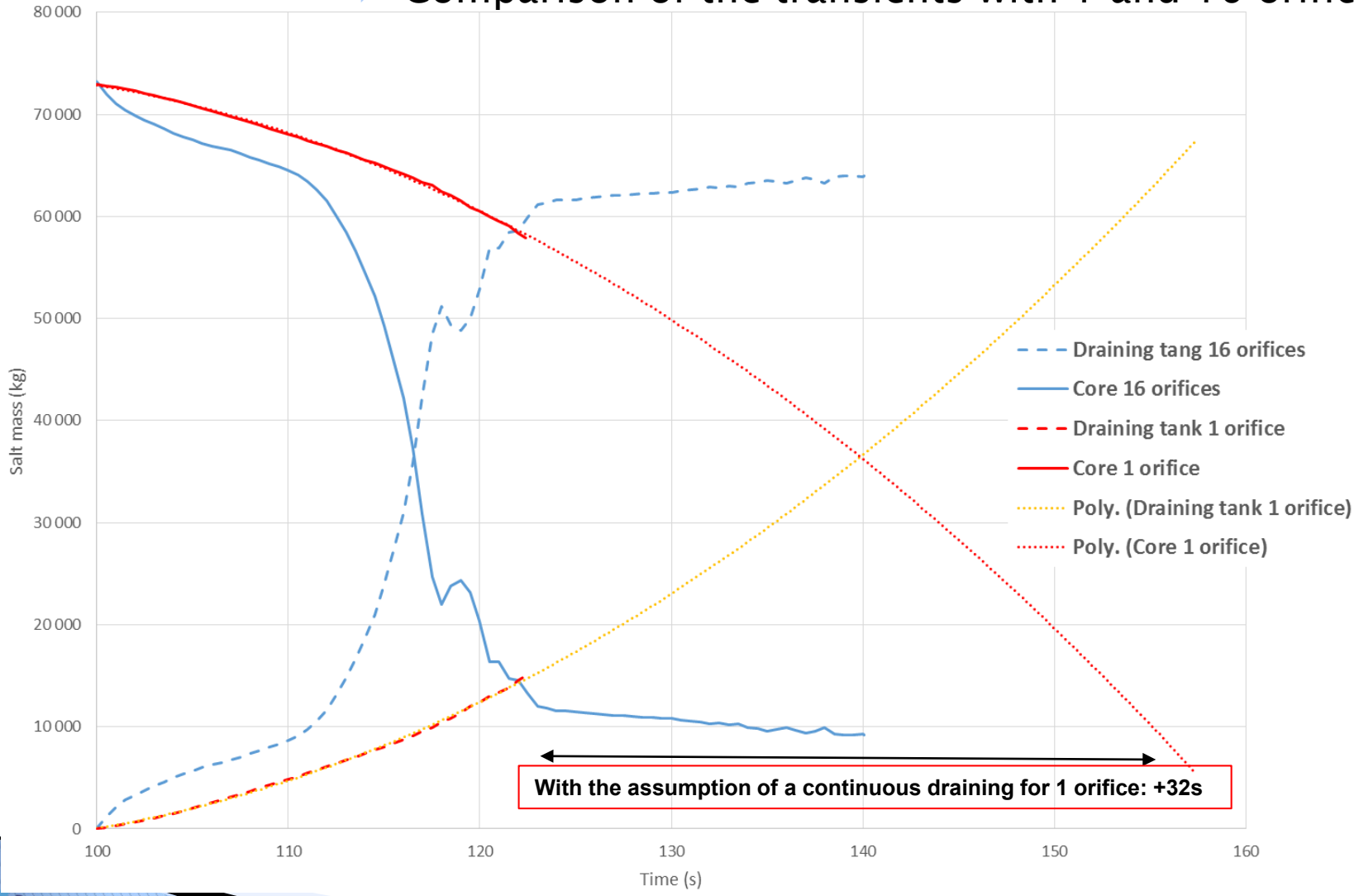






Reactor draining

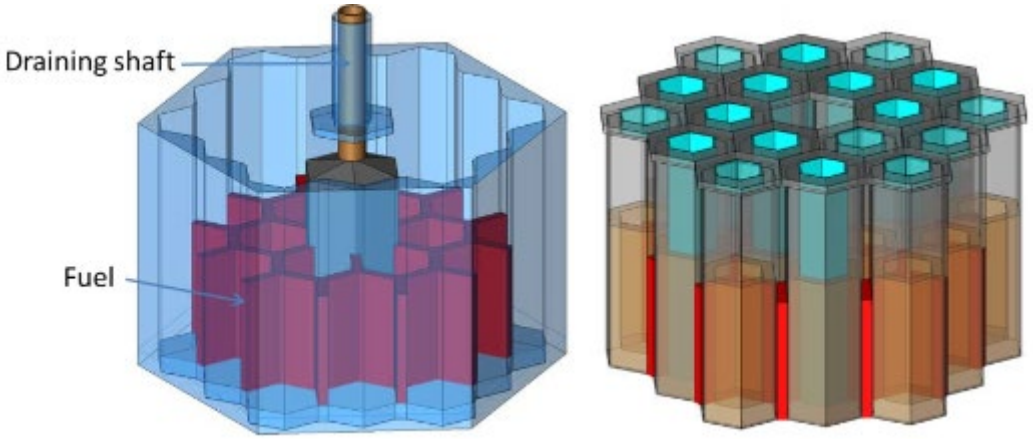
- Comparison of the transients with 1 and 16 orifices:

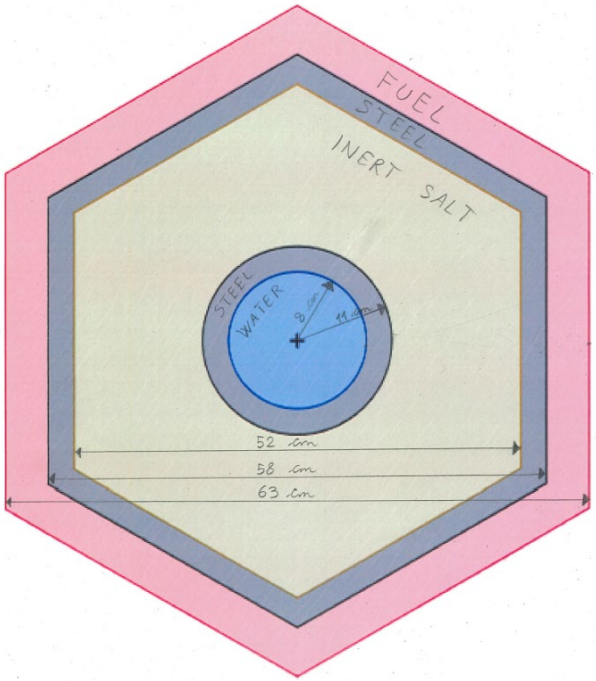


Salt behavior in draining tank

Numerical and analytical calculations of salt cooling in EDT

- EDT design: based on the concept described in the project
- Hexagonal cooling rods surrounded by the fuel to be cooled



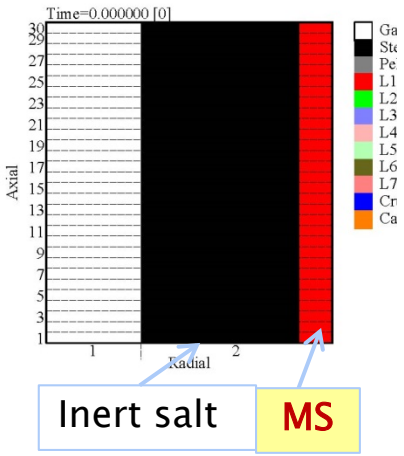


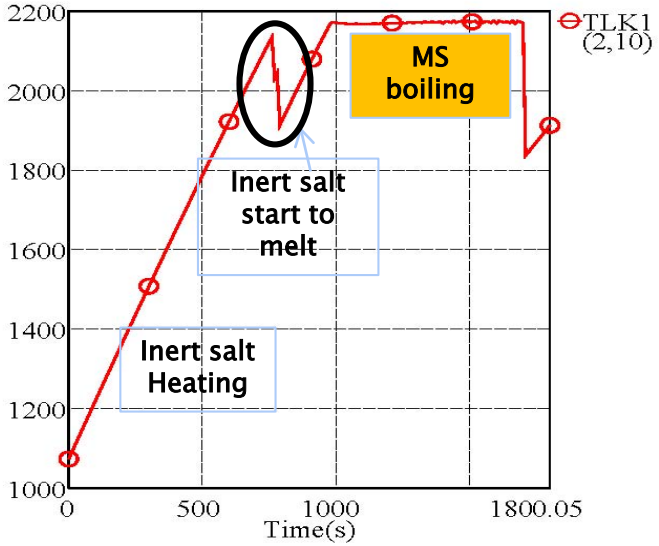
- **The inert salt provides additional grace time**
  - Melting latent heat
- Volume of the tank: 36 m^3
- Double of the amount of fuel to be relocated
- A simplified geometry for a EDT “cell” is considered in the following

Salt behavior in draining tank

Numerical analyses with SIMMER

- Transient analyses with SIMMER on salt behavior in the draining tank: **design modifications are needed**.





- The thermal conductivity of inert salt is too small (~1 W/K/m),
- Therefore the Decay Heat is not effectively transferred to the inert salt
- Therefore the liquid fuel temperature increases steadily.

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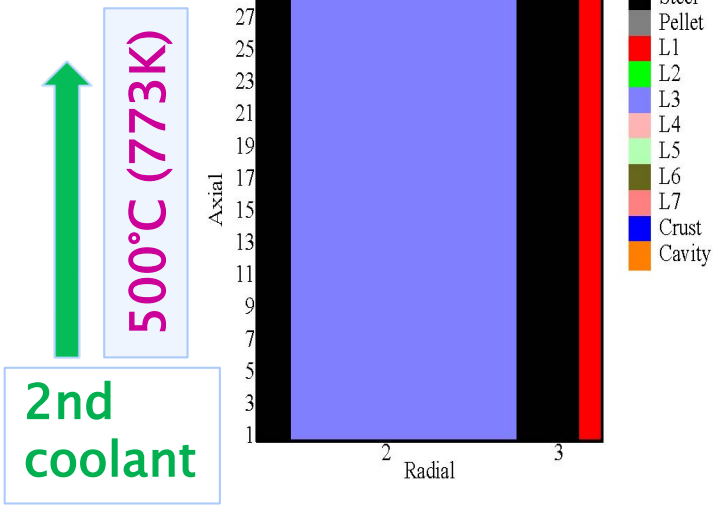
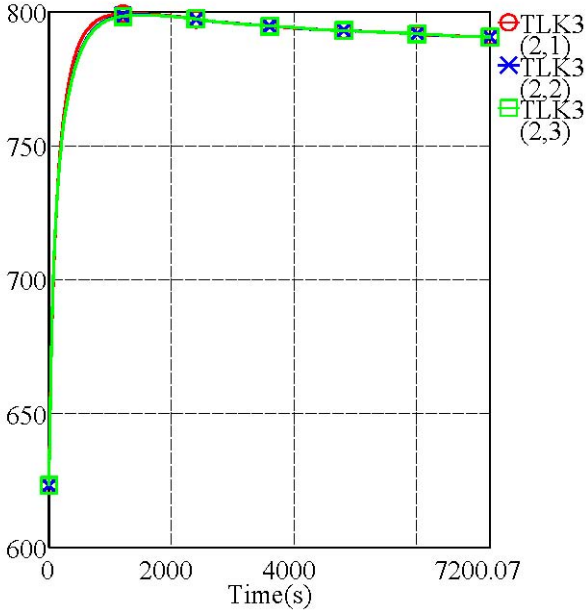
Salt behavior in draining tank

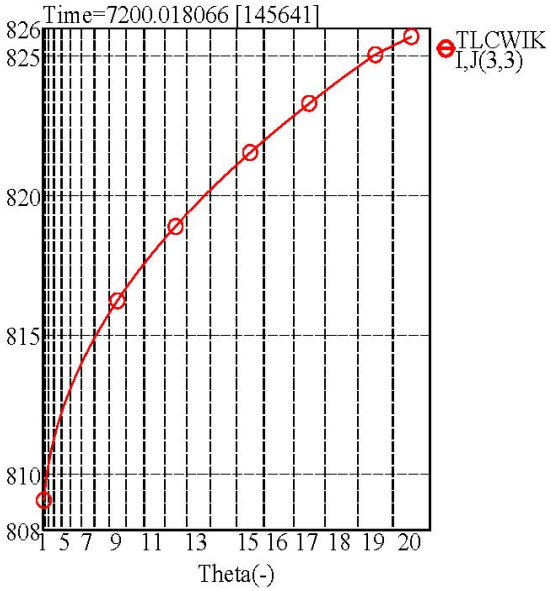
Numerical analyses with SIMMER

- **Alternative coolants** such as **Pb** can be used instead of inert salt.





Pb Temp.



SteelTemp.

Buffer coolant (Pb) + 2nd coolant (water):
Long term safety can be insured.

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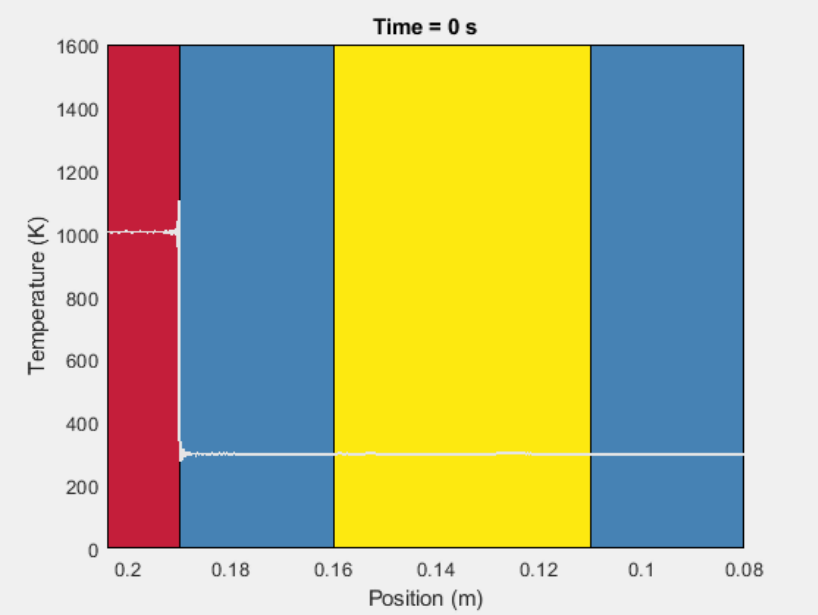
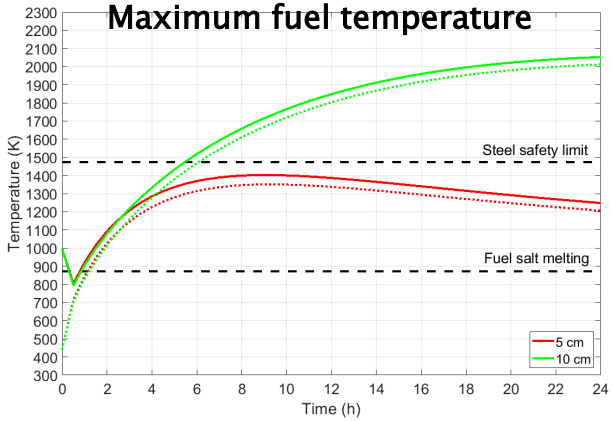
Salt behavior in draining tank

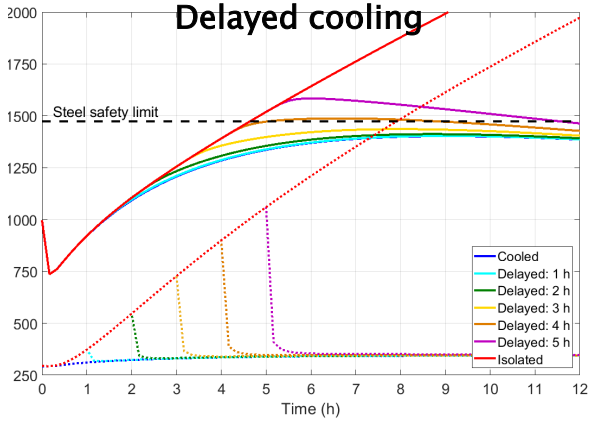
New Analytical model

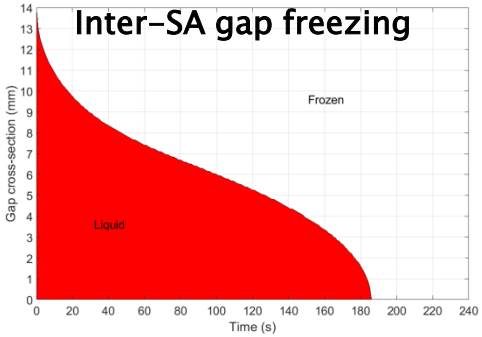
A new **analytical model** was developed that shows possible dimensions for EDT cells

- EDT geometry
  - Analytical model
  - Suggested different dimensions
  - Fuel salt inter-assemblies gap: 2.8 cm
  - Inert salt thickness: 5 cm
- Transient 1D calculations
  - **Estimated grace time: >3 h**
  - **Draining is reversible**
  - **Steel safety limit never exceeded**









Conclusions

- New codes have been developed or extended
- Code-to-code benchmarking proved the tools are able to reproduce accurately the characteristics of the MSFR
- Steady state and transient conditions have been simulated
- Both analytical models and numerical tools have been exploited to simulate reactor draining and salt cooling in the EDS

THANK YOU
FOR YOUR KIND ATTENTION!

SAMOFAR