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Simulation challenges of the Molten Salt Fast Reactor

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On behalf of the SAMOFAR consortium

It’s nuclear

But it's nuclear 2.0

The Molten Salt (Fast) Reactor is a huge step forwards in the field of

- Safety of nuclear energy
- Sustainability of nuclear energy
- Societal acceptance of nuclear energy

SAMOFAR is the EC funded project focussing on the Safety Assessment of the Molten Salt Fast Reactor (11 partners and 6 observers)

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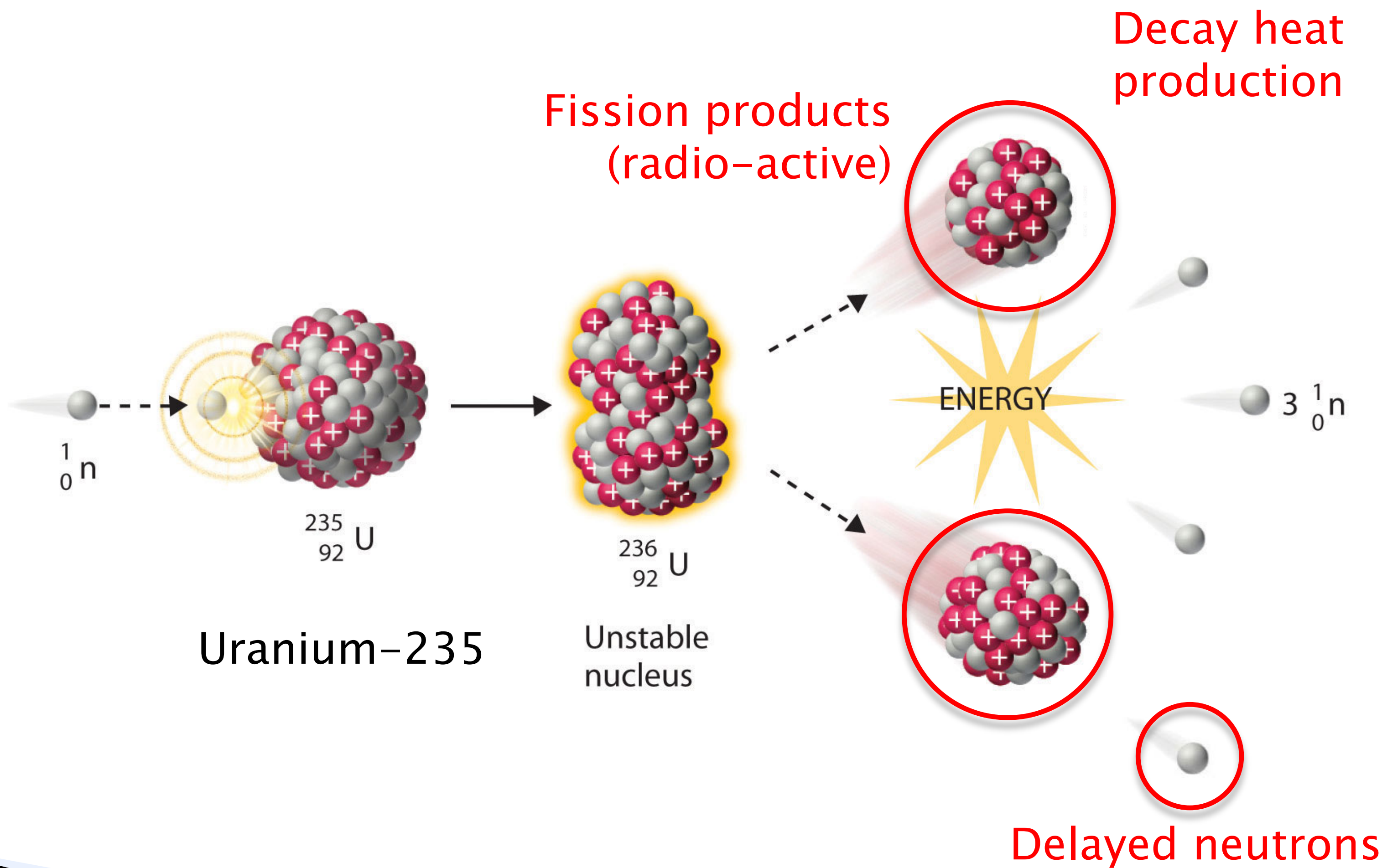
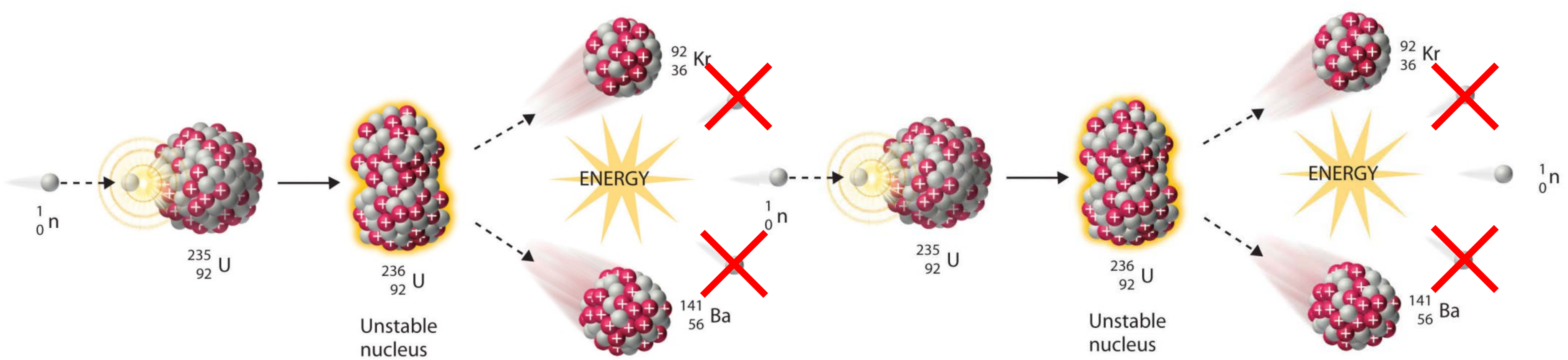
Nuclear fission process



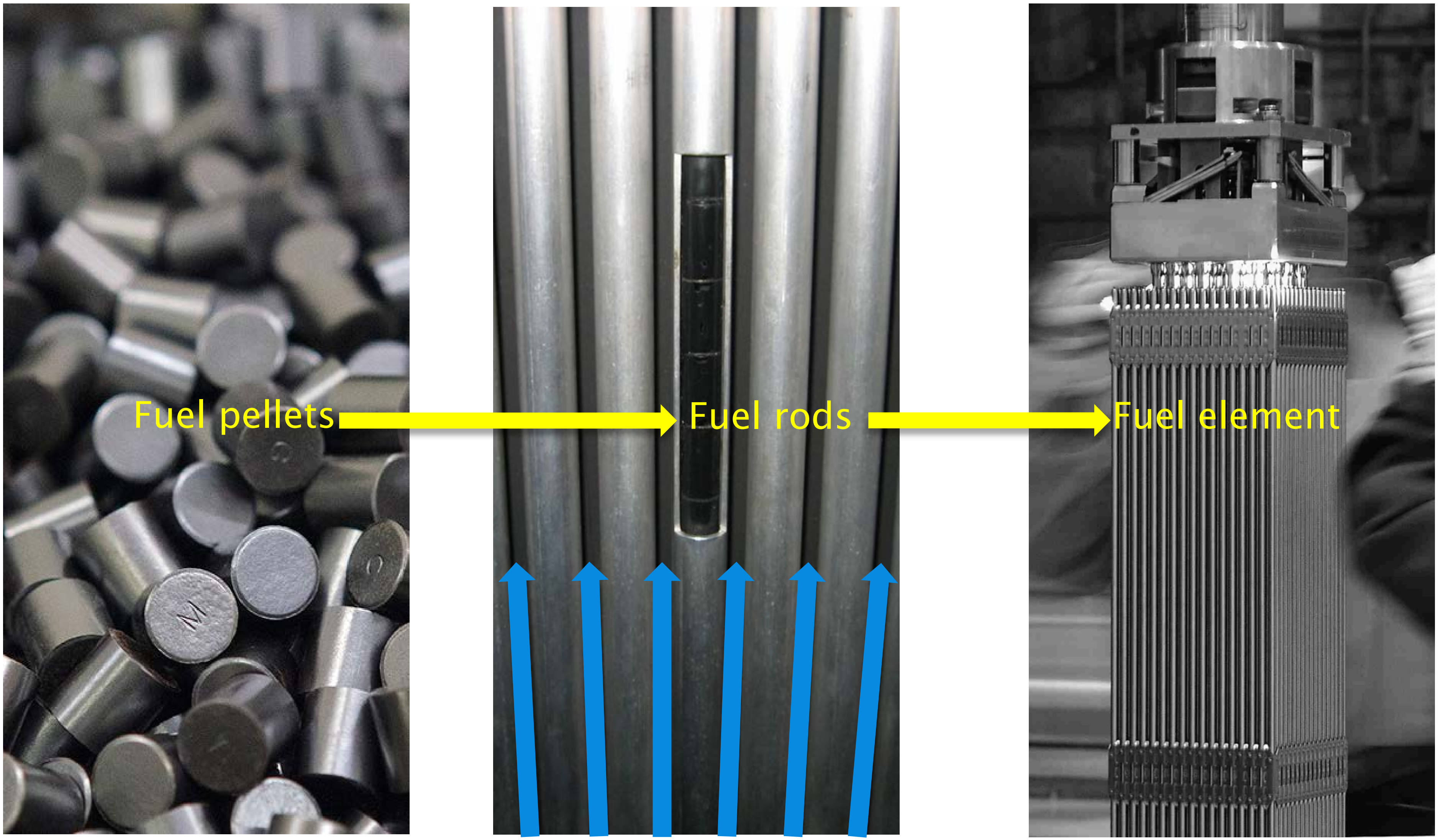
Chemwiki, CCPL

Nuclear chain reaction



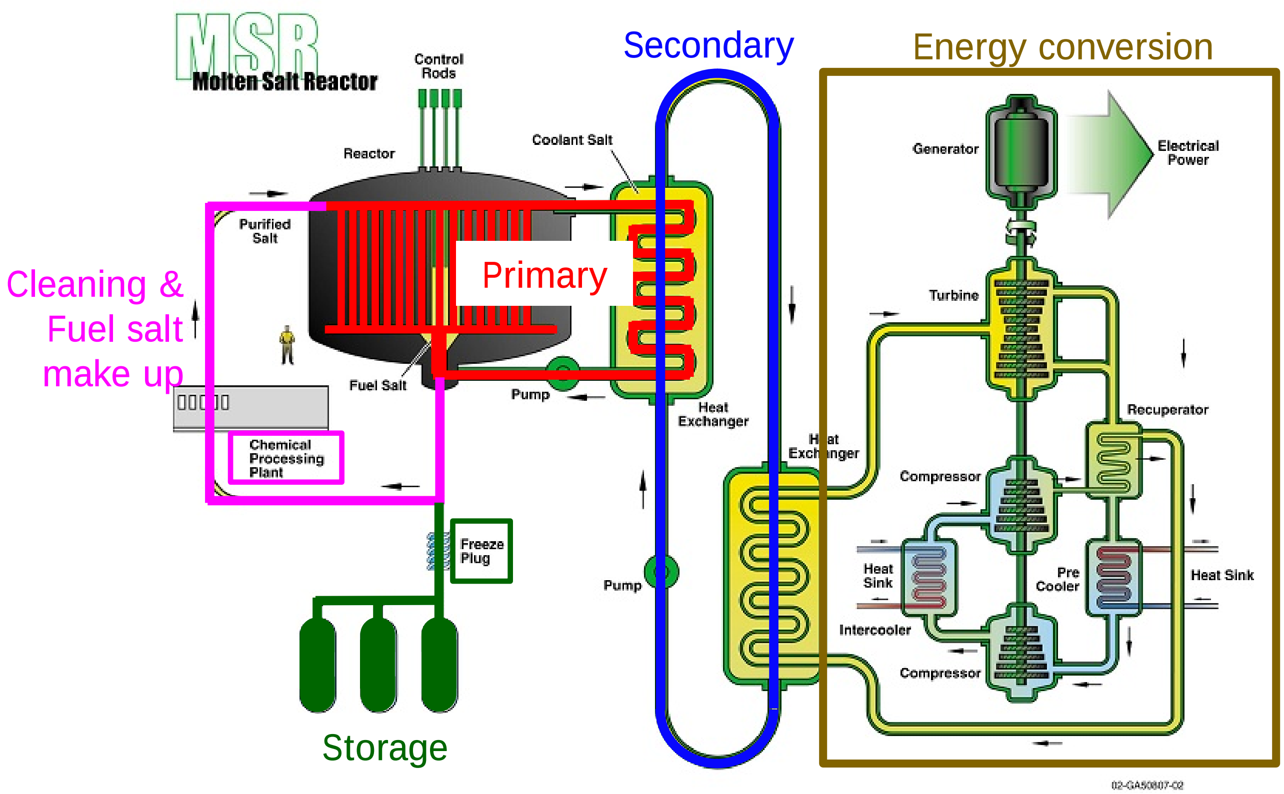
Chemwiki, CCPL

Traditional nuclear energy

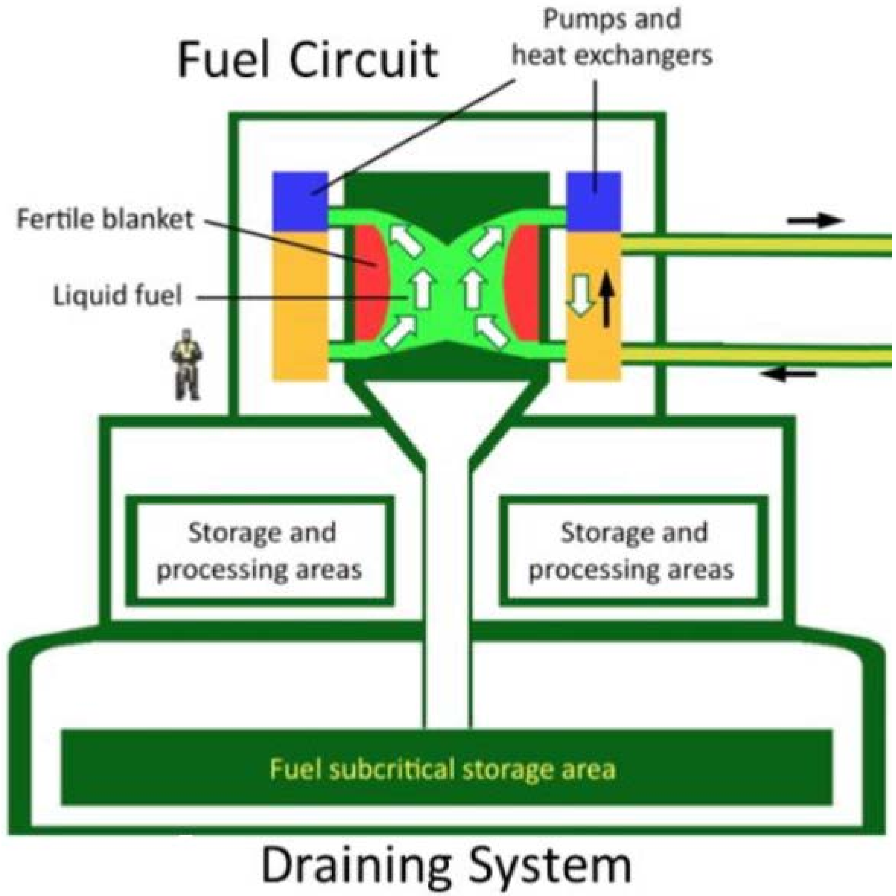



TVO, Olkiluoto, Finland

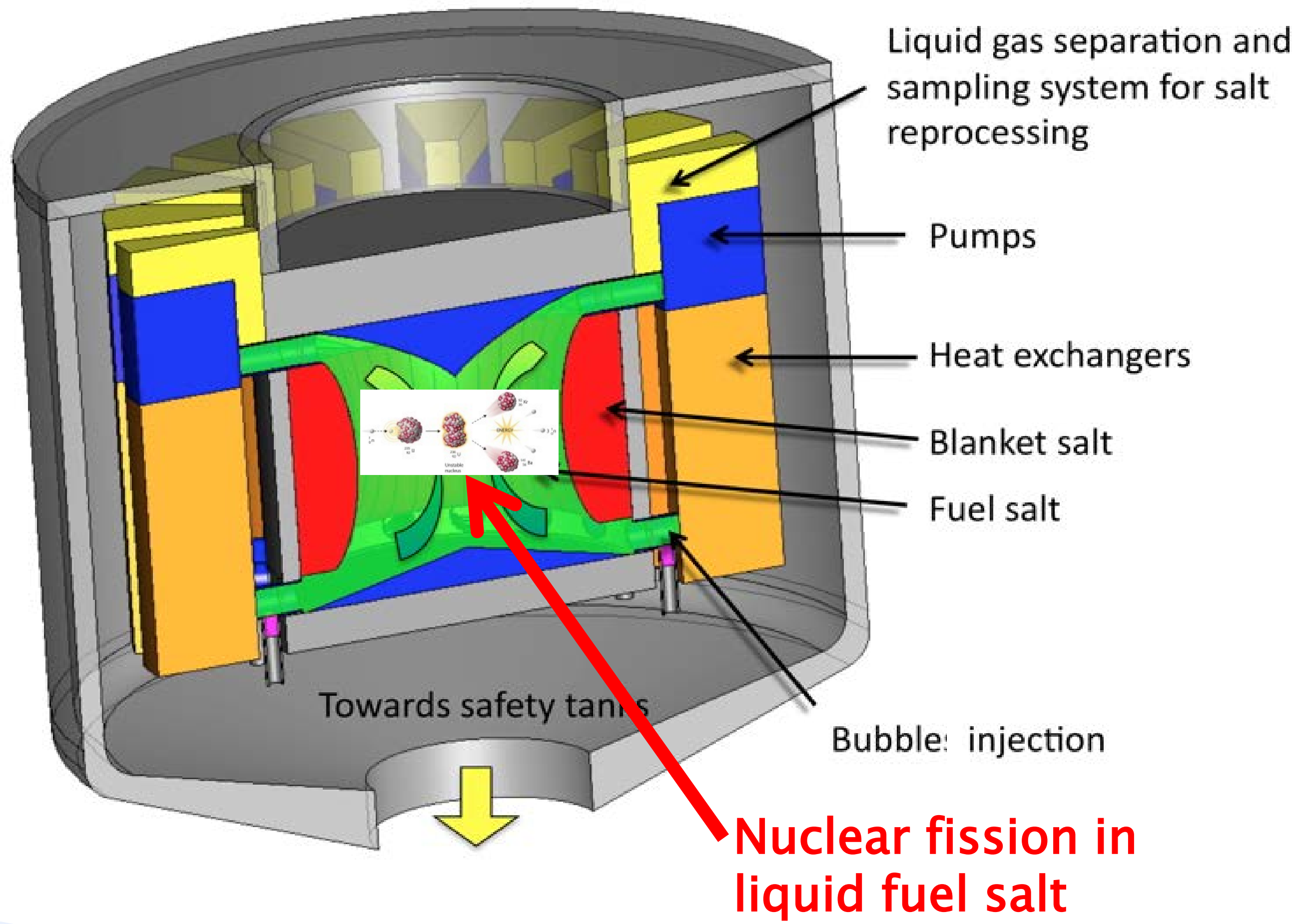
Loop-type Molten Salt Reactor



Pool-type Molten Salt Fast Reactor



MSFR primary circuit



MSFR characteristics

Parameter	Value
Thermal/electric power	3000 MWth / 1300 MWe
Fuel salt temperature rise in the core (°C)	100
Fuel molten salt - Initial composition	LiF-ThF_4-$^{233}UF_4$ or LiF-ThF_4-$^{enr}UF_4$-(Pu-MA)F_3 with 77.5 mol% LiF
Fuel salt melting point (°C)	585
Mean fuel salt temperature (°C)	725
Fuel salt density (g/cm^3)	4.1
Fuel salt dilation coefficient (g.cm^{-3}/°C)	8.82 10^{-4}
Fertile blanket salt - Initial composition (mol%)	LiF-ThF_4 (77.5%-22.5%)
Breeding ratio (steady-state)	1.1
Total feedback coefficient (pcm/°C)	-8
Core dimensions (m)	Radius: 1.06 to 1.41 Height: 1.6 to 2.26
Fuel salt volume (m^3)	18 (1/2 in the core)
Total fuel salt cycle in the fuel circuit	3.9 s

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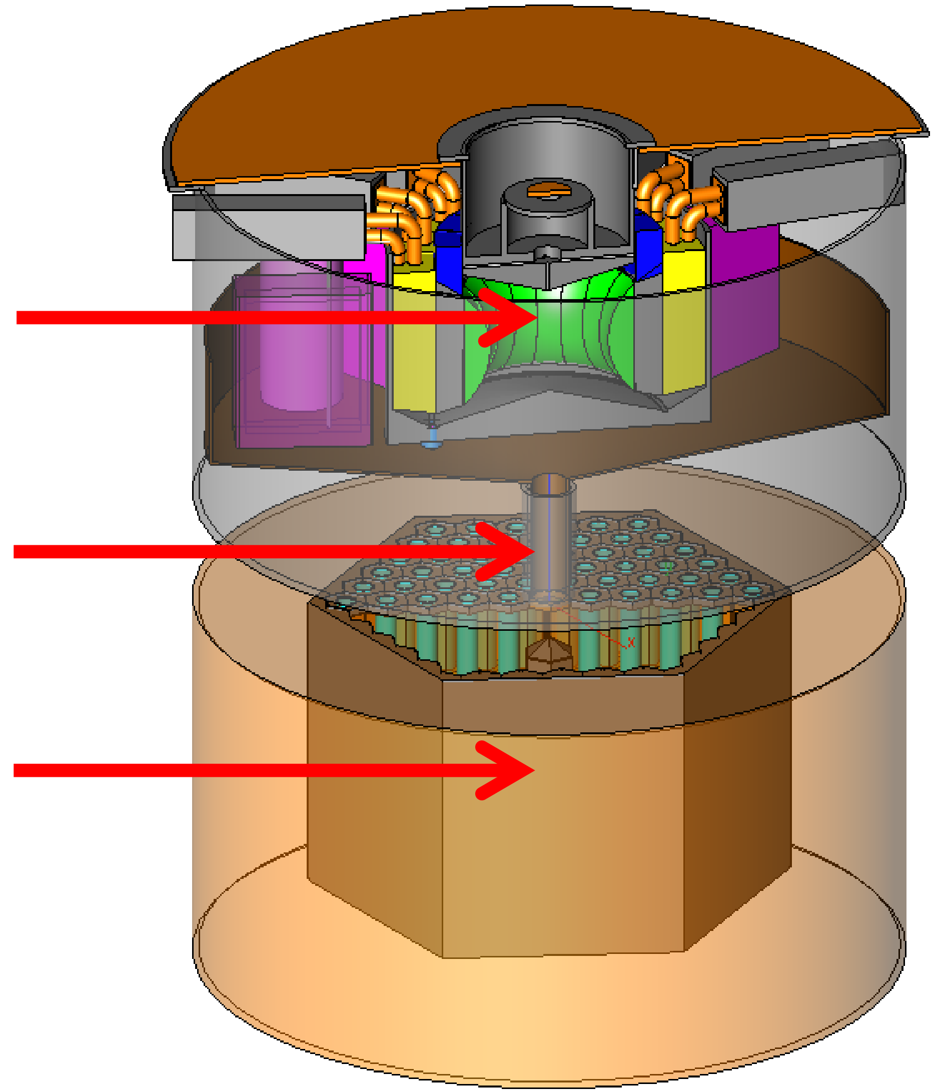
Simulation challenges

- Fuel flow and heat production in the
  - Reactor core
  - Fuel pumps
  - Heat exchangers
- Melting freeze plug and draining of salt
- Decay heat removal from drain tanks



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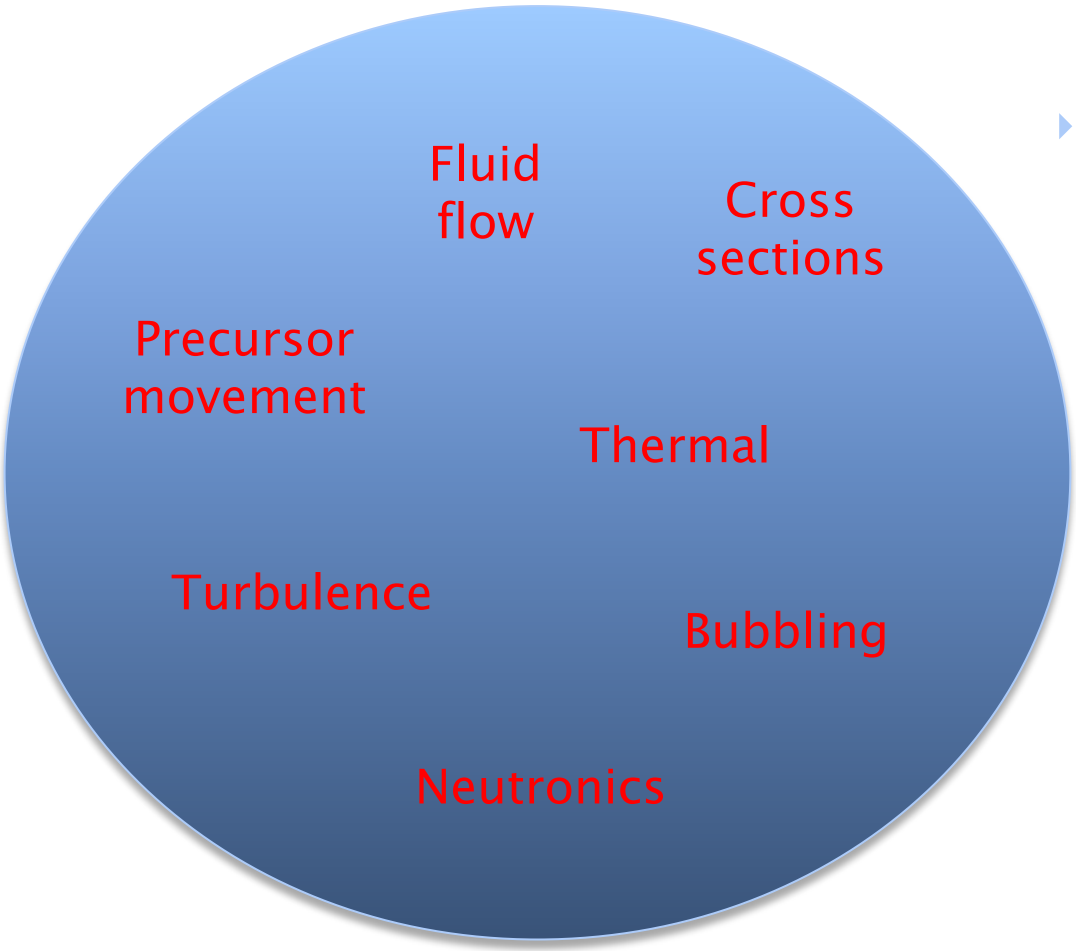
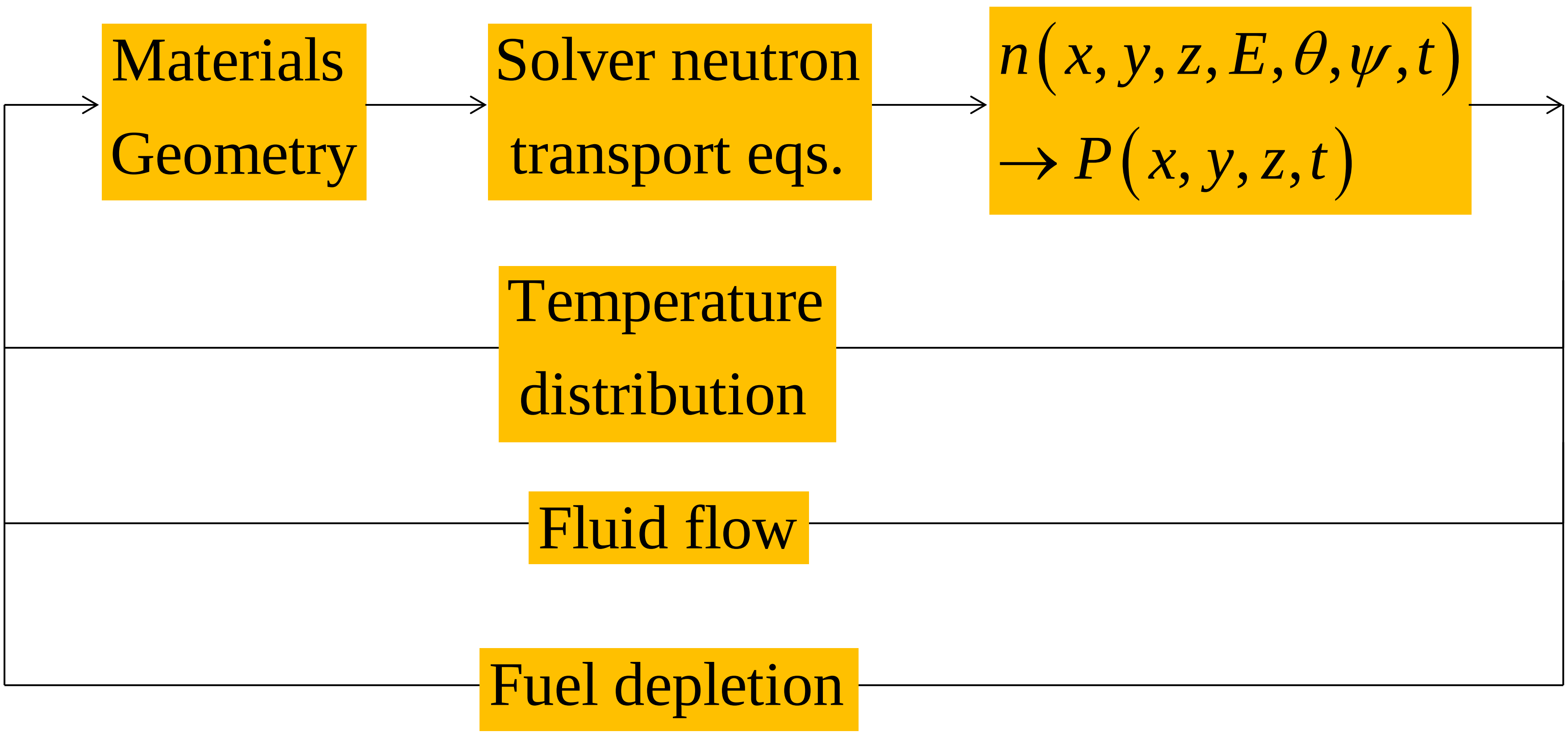
Multiphysics in the MS(F)R



- Capabilities needed
  - Moving fuel -> moving precursors
  - Complex geometry
  - Three-dimensionality
  - Heat transfer, (two-phase) fluid flow, stress analysis, neutronics
  - Temperature feedback effects on cross sections
  - Voidage feedback from bubbling and on effect flow structure

Multiphysics simulation codes



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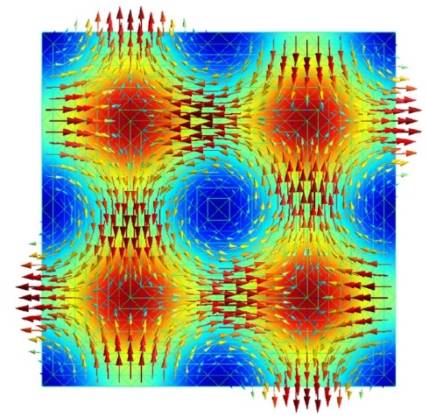
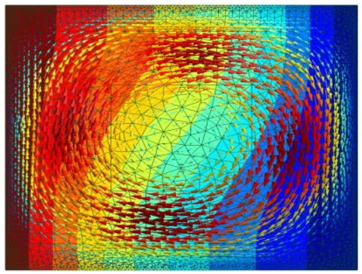
Multiphysics simulation codes

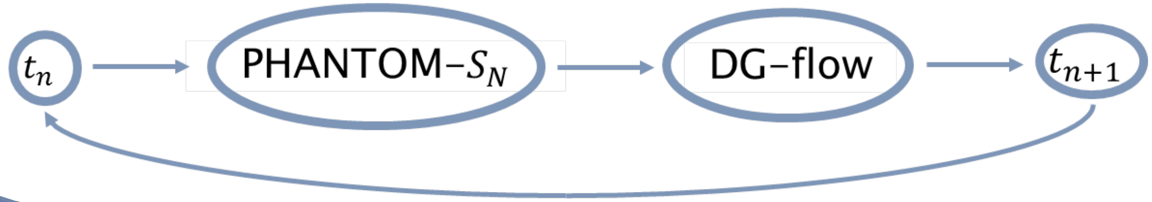
- CFD and neutronics solvers DG-FEM
- RANS turbulence models (k-ω, k-ε)
- Energy state and equations of state
- Energy equation on solid domains (CHT)
- Generalized perturbation analysis neutronics
- Loose coupling→JFNK coupling
- Uncertainty propagation coupled codes (PCE)
- Include other multiphysics phenomena



2D Taylor vortex benchmarking



Buoyancy-driven cavity benchmark



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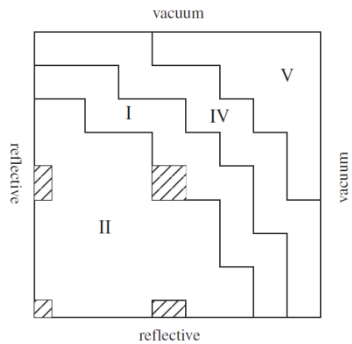
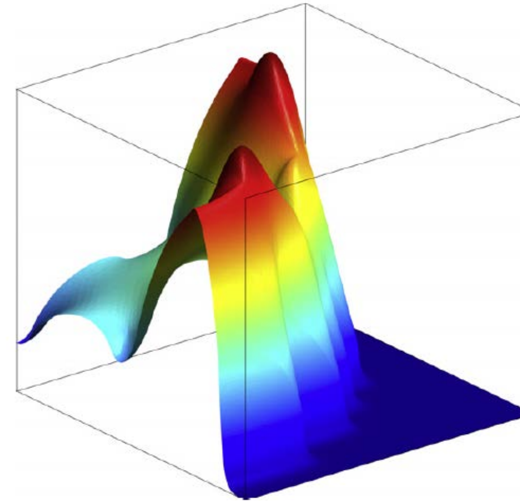
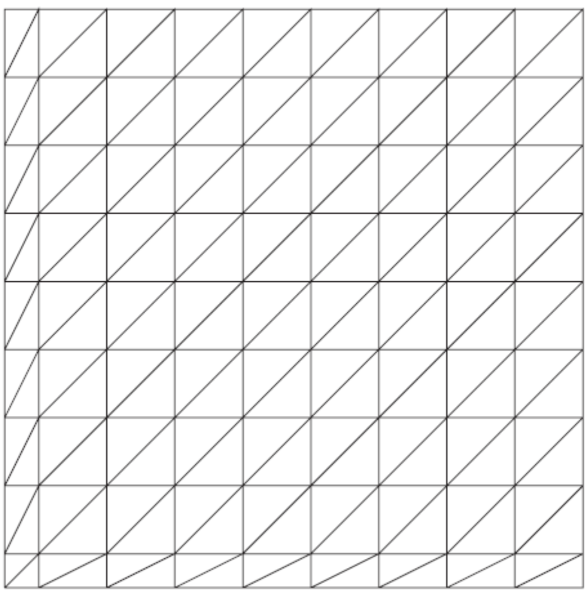
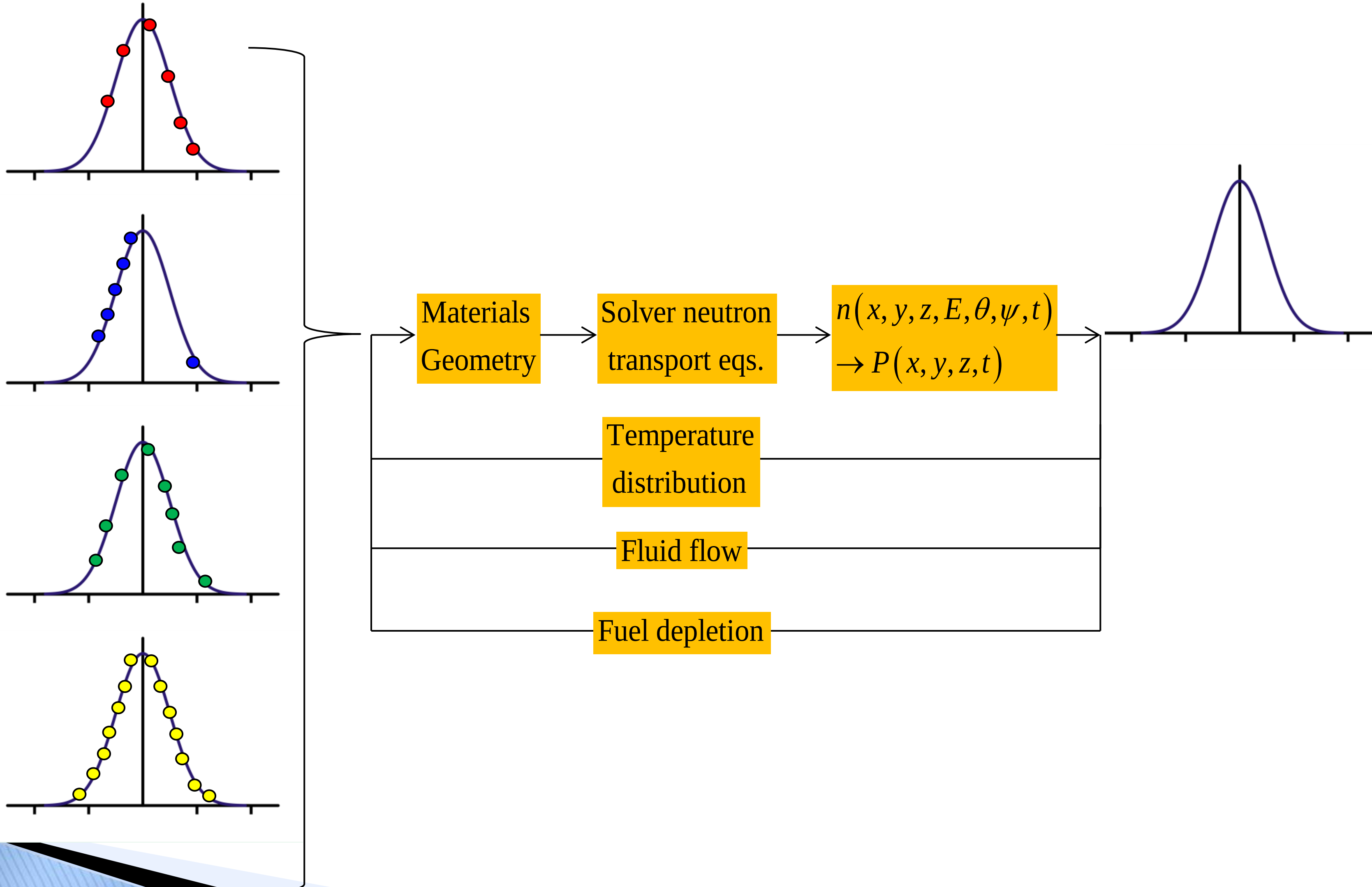
Adaptive refinement







Uncertainty analysis



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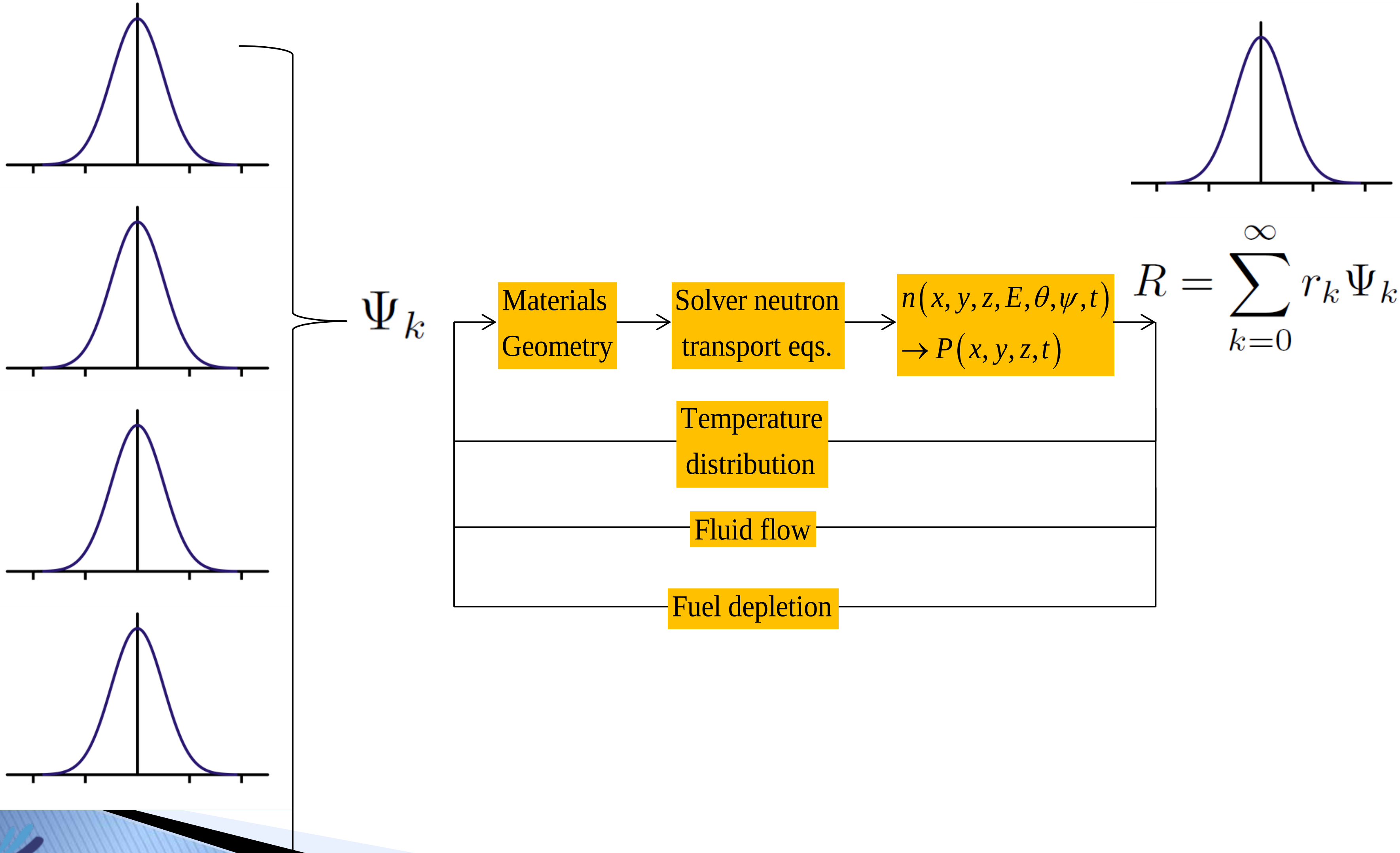
Uncertainty analysis



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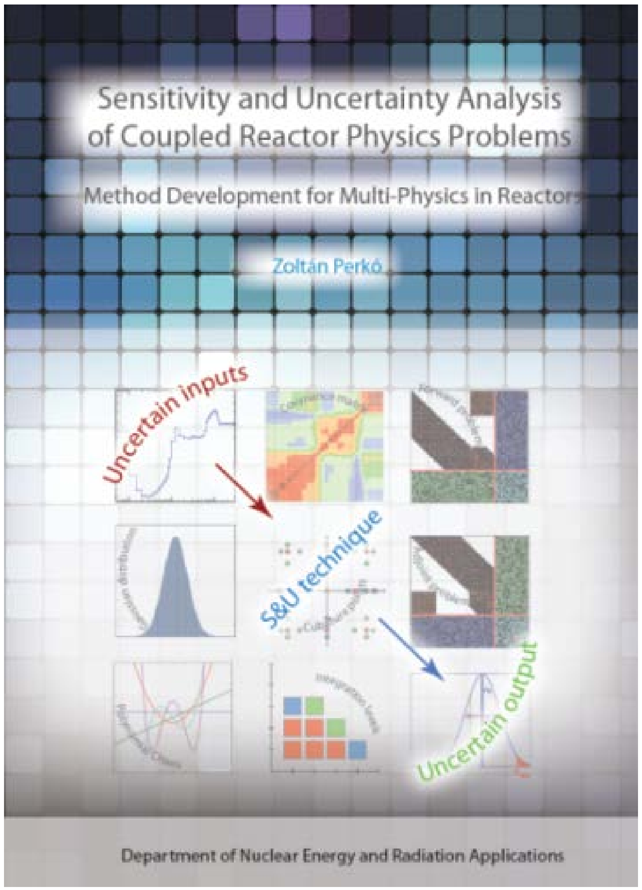
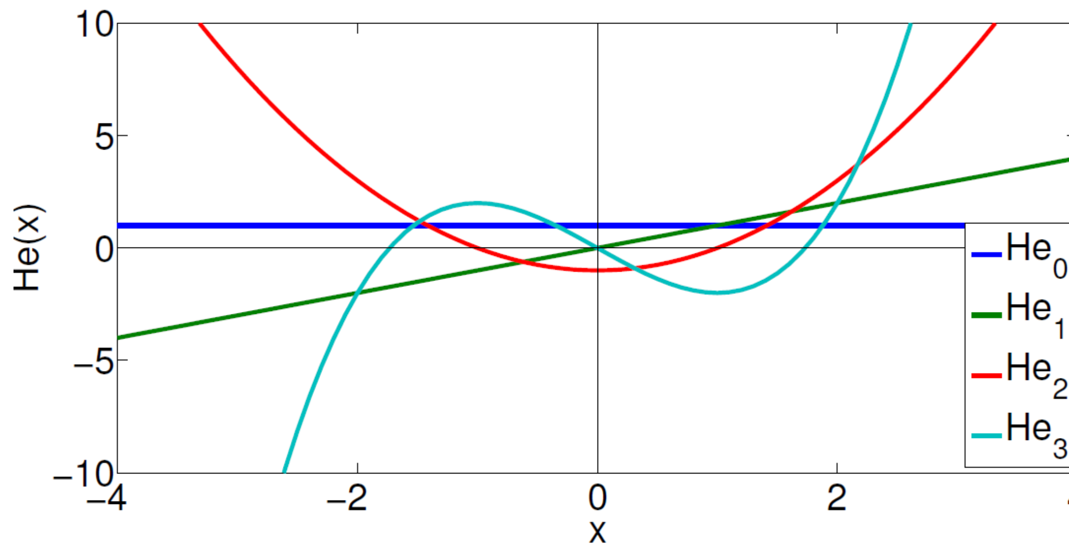
Polynomial chaos expansion: FANISP



$$R = \sum_{k=0}^{\infty} r_k \Psi_k$$



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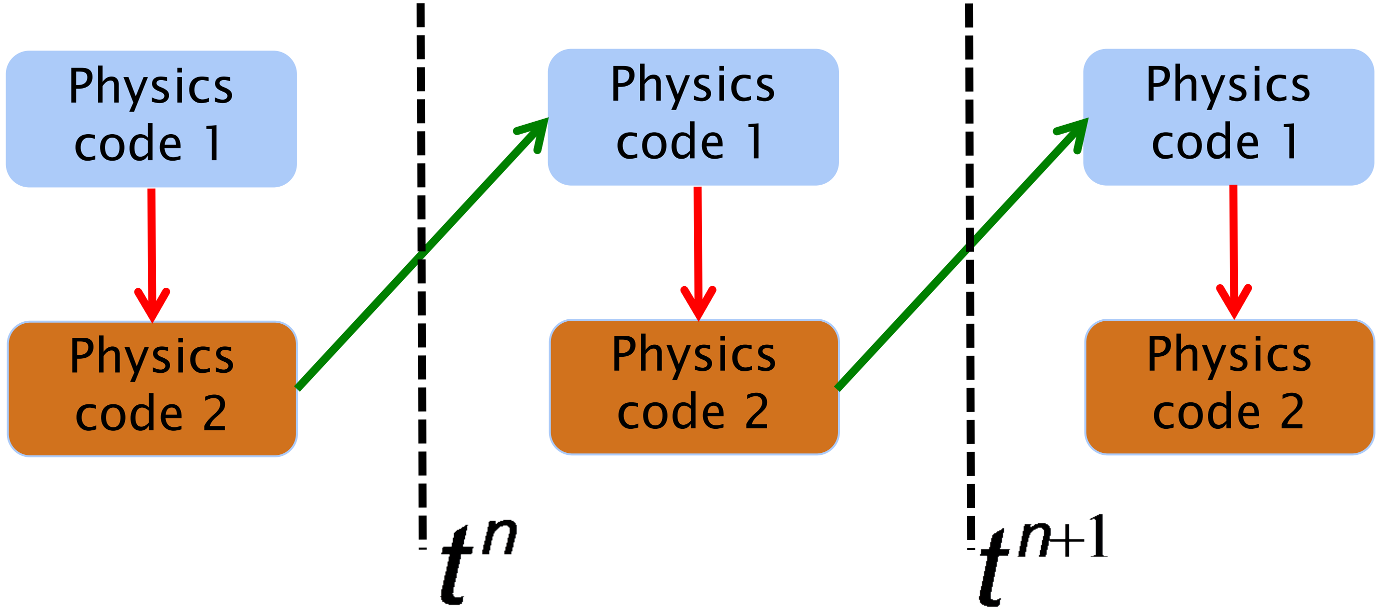
Conventional (loose) coupling

Splitting schemes



- Easy to implement using existing (black-box) codes
- Cheap on a time step basis
- At most first-order time accuracy
- Stability may be issue; though difficult to analyse
- Data exchange depends on physics and time scales

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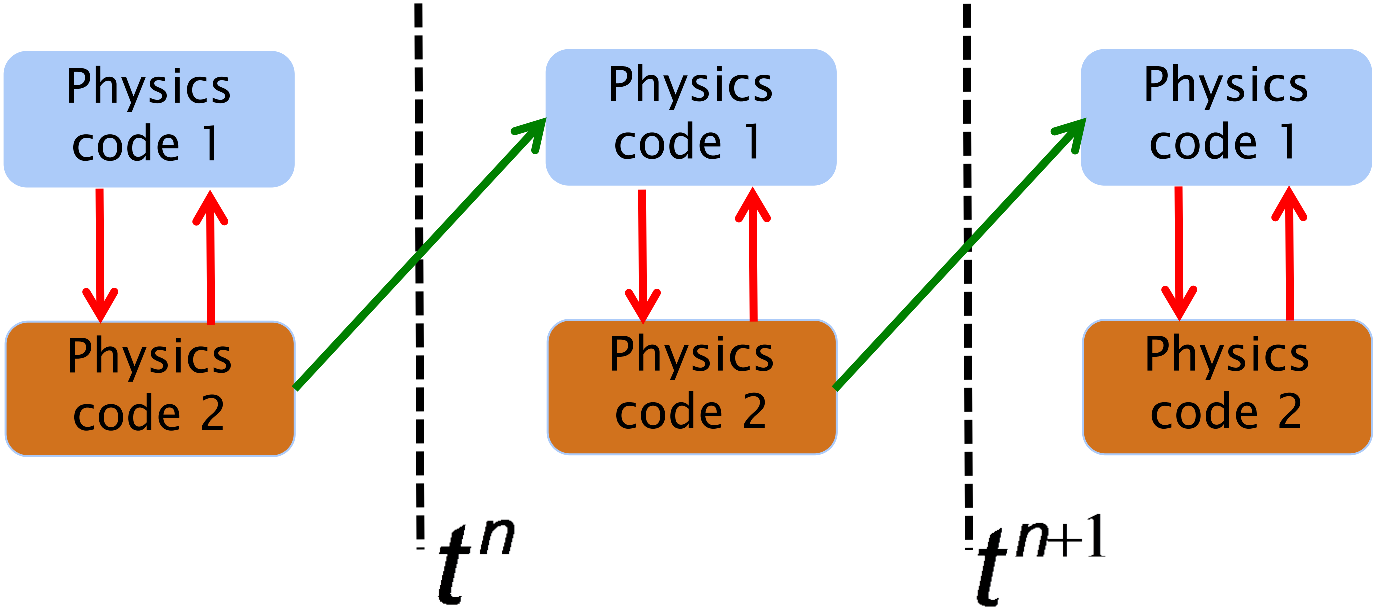
Tight coupling scheme

Iteration per time step



- Still easy to implement using existing codes
- Iteration may be expensive
- Time accuracy dictated by that of the individual codes (full potential can be achieved)
- Coupling no longer dominates stability

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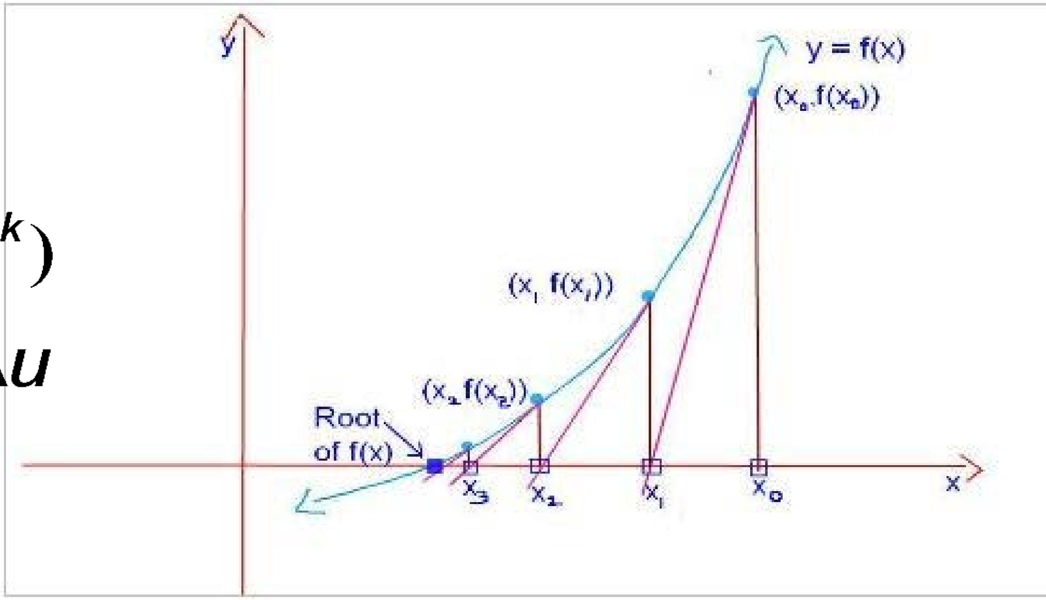
Newton's method

$$F(u)=0 \rightarrow \begin{cases} J\Delta u = -F(u^k) \\ u^{k+1} = u^k + \Delta u \end{cases}$$



- Quadratic convergence close to solution
- Requires *Jacobian* (intrusive!, mostly unavailable)
- Large linear system in each Newton iteration
- Combine with Krylov methods (Knoll&Keyes, Journal of computational physics **193** (2004):357-397).

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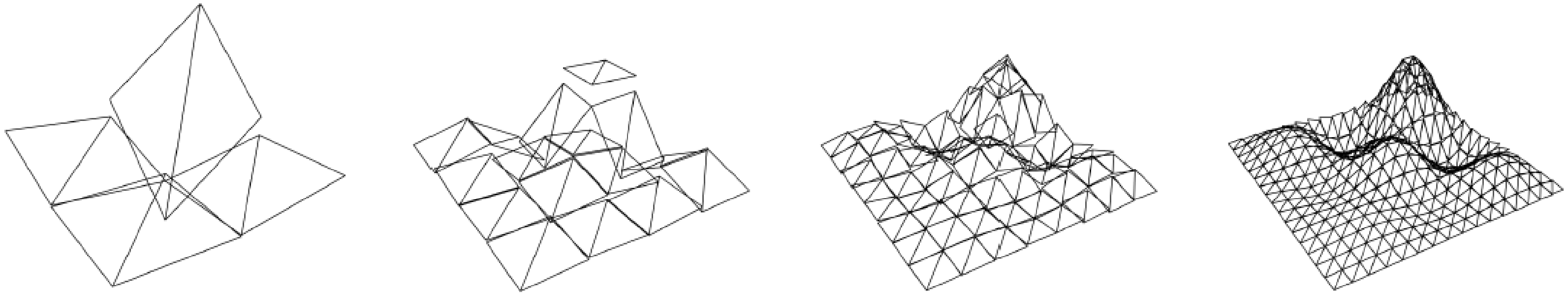
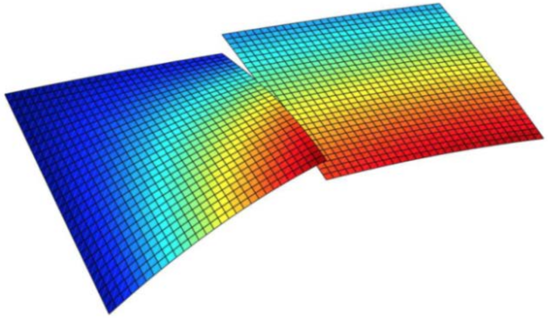
Why Discontinuous Galerkin?



Several advantages:

- **Arbitrary order** of accuracy on each element
- **High flexibility** regarding **meshes** (structured/unstructured)



- Local ***hp*-refinement** possible
- **Compatibility** between CFD and radiation code

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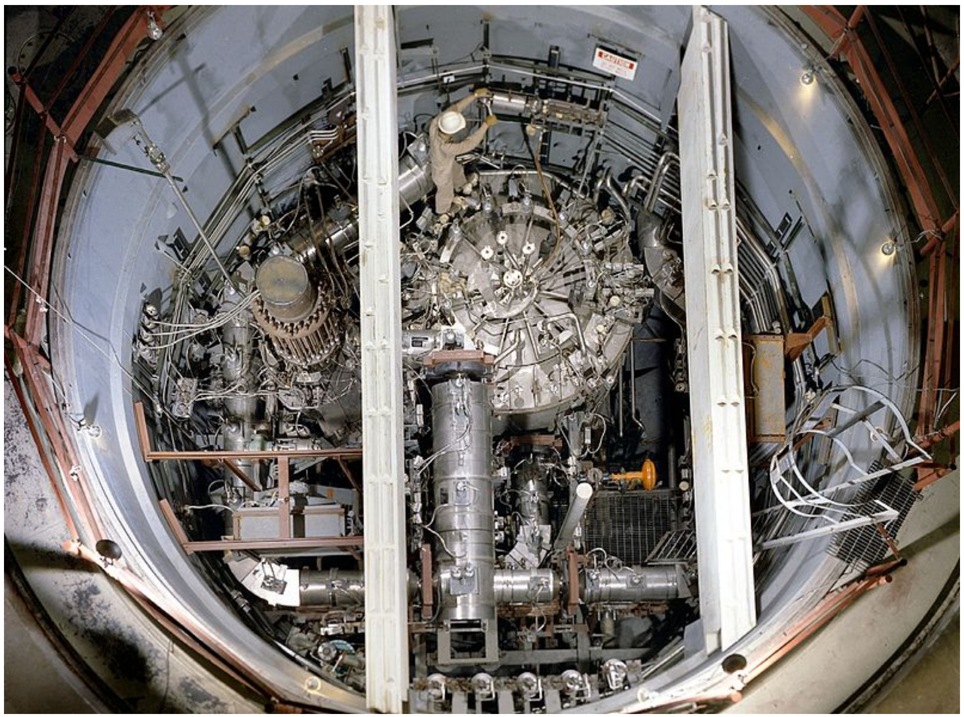
Molten Salt Reactor Experiment (MSRE 1965-1969)



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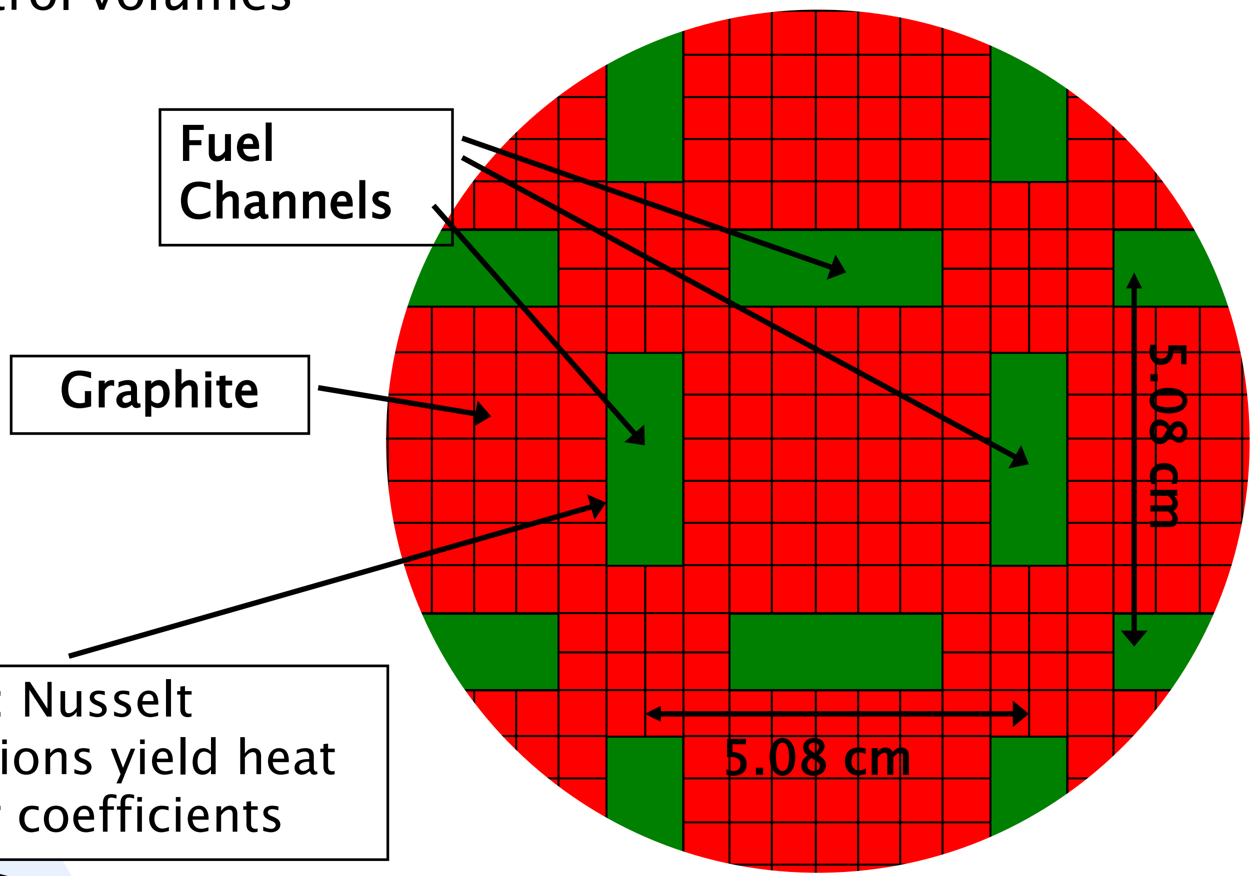
MSRE: 3D model

- Fuel: Heat convection (vertical)
- Moderator: Heat conduction (3D)
- Individually calculating each fuel channel (1150 channels)
- Bulk temperatures for fuel channels
- ~1.5 million control volumes



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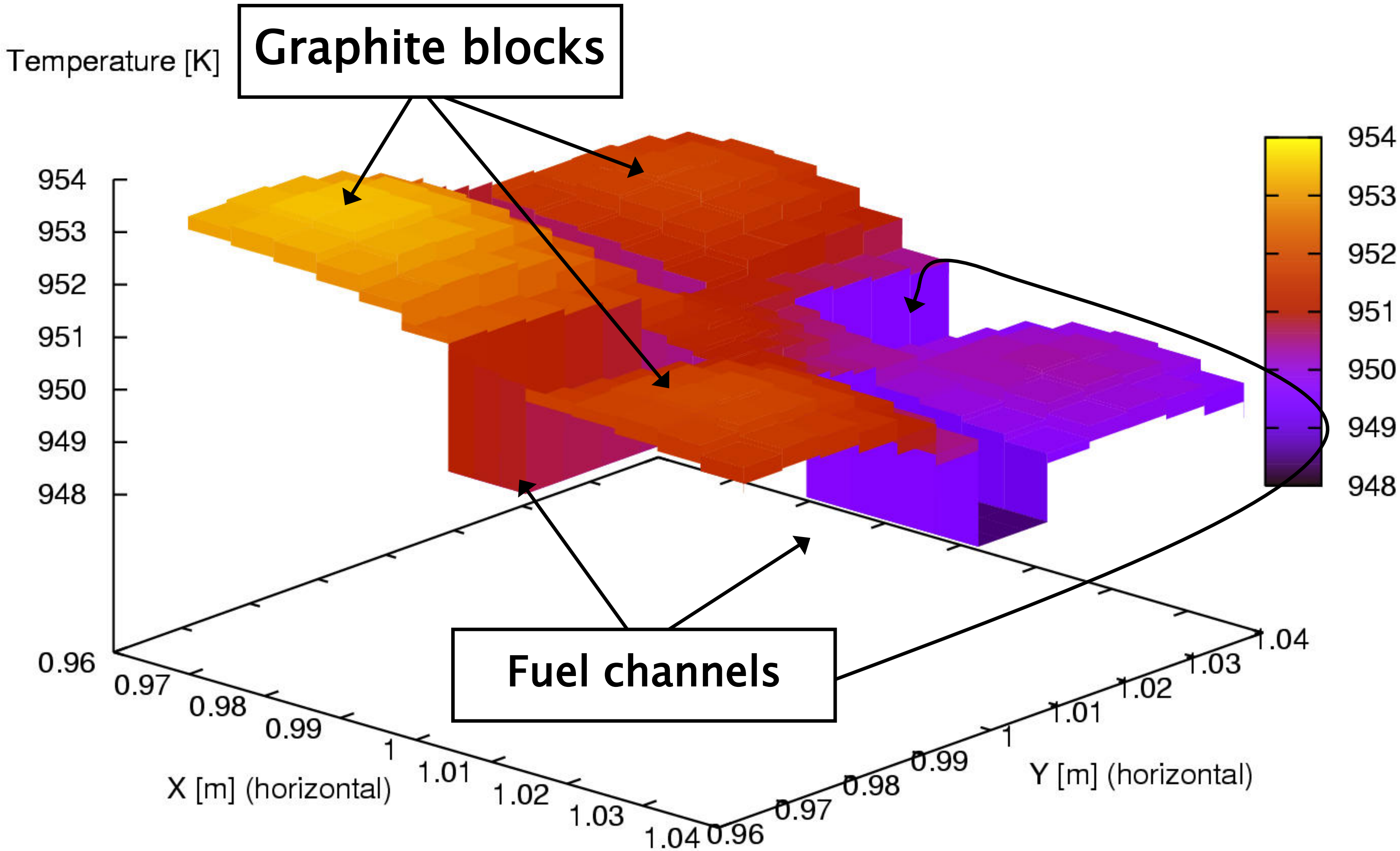
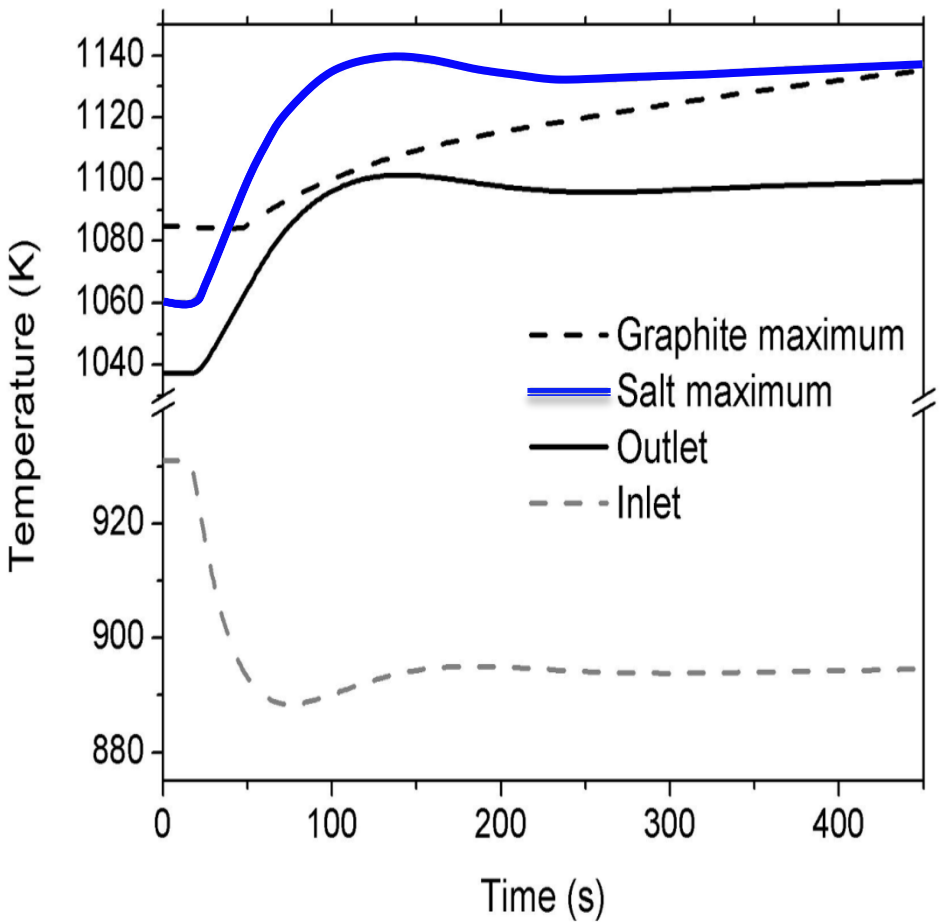
MSRE: Temperature field close-up

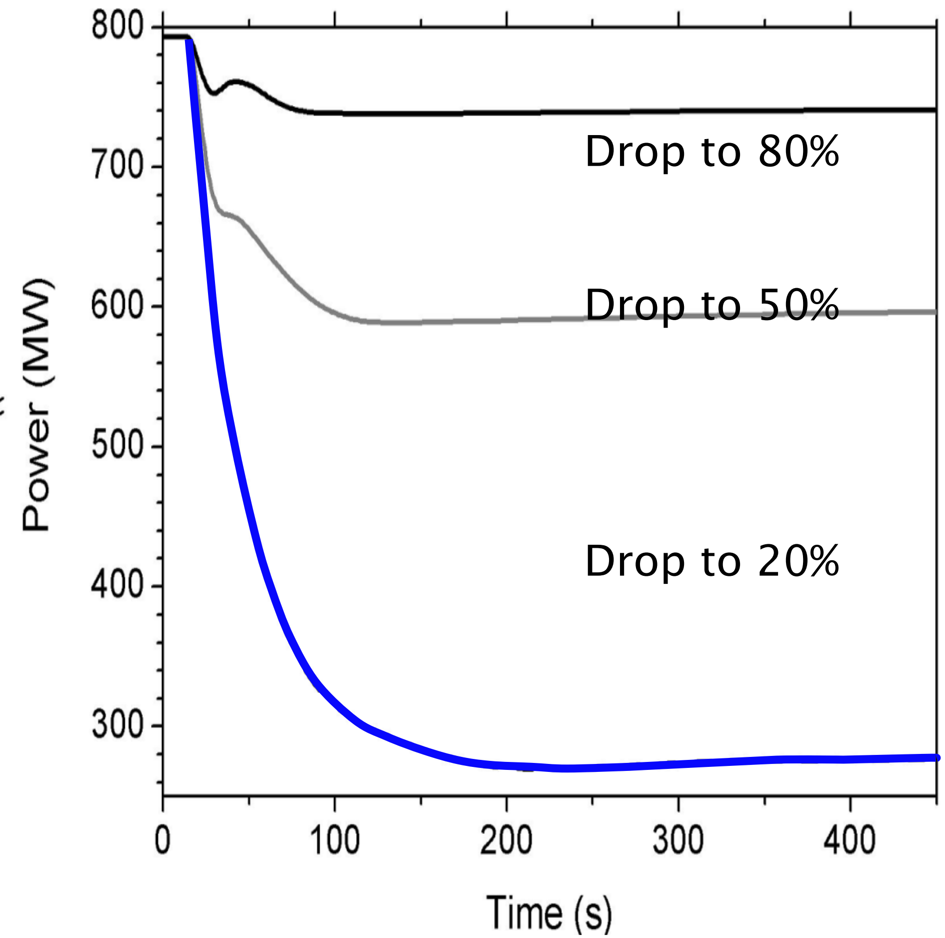
High resolution calculation to determine the surface temperature of the graphite and the heat transfer



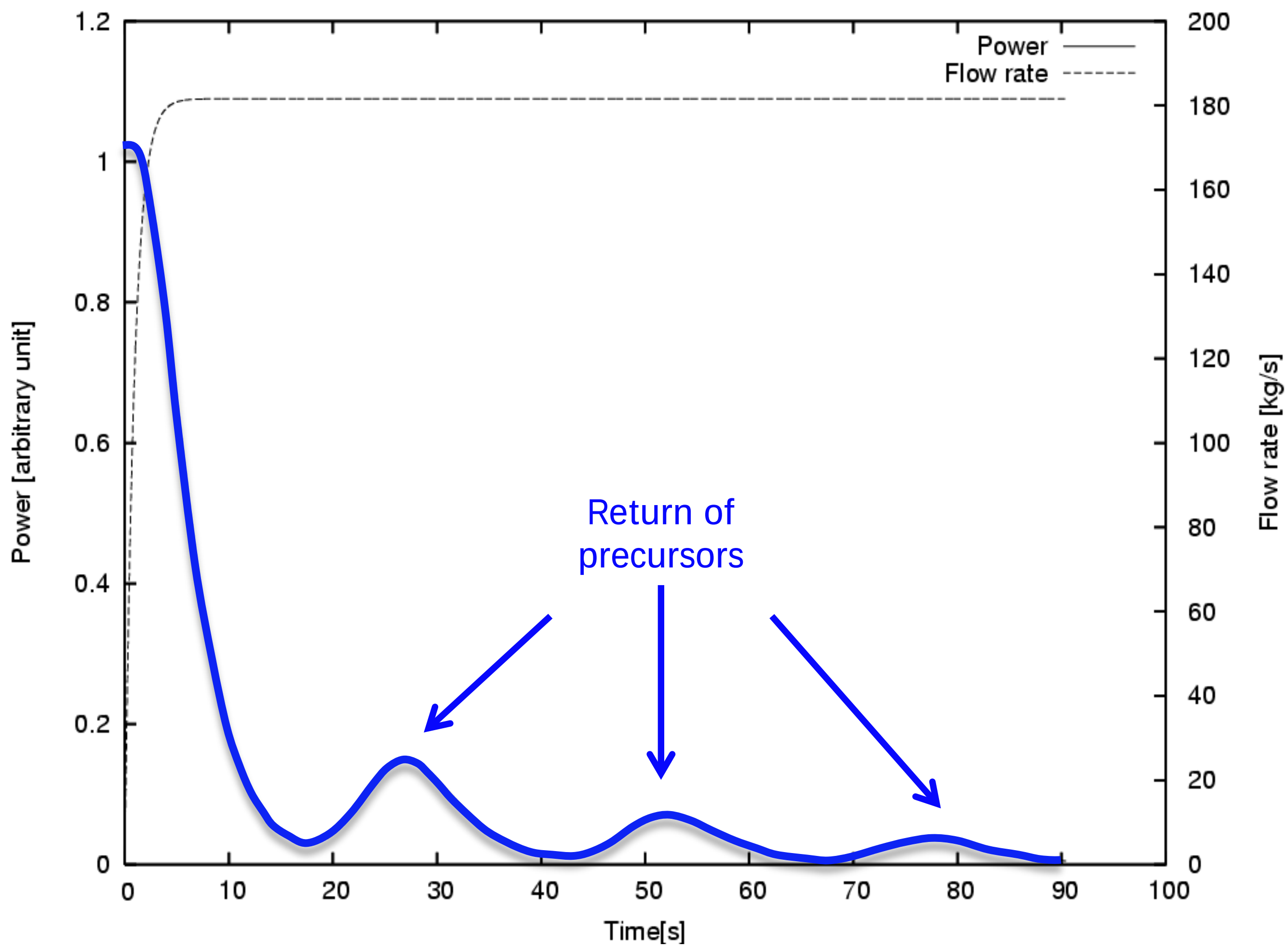
MSRE: Pump failure

Pump coast-down to 20%





MSRE: Pump start-up



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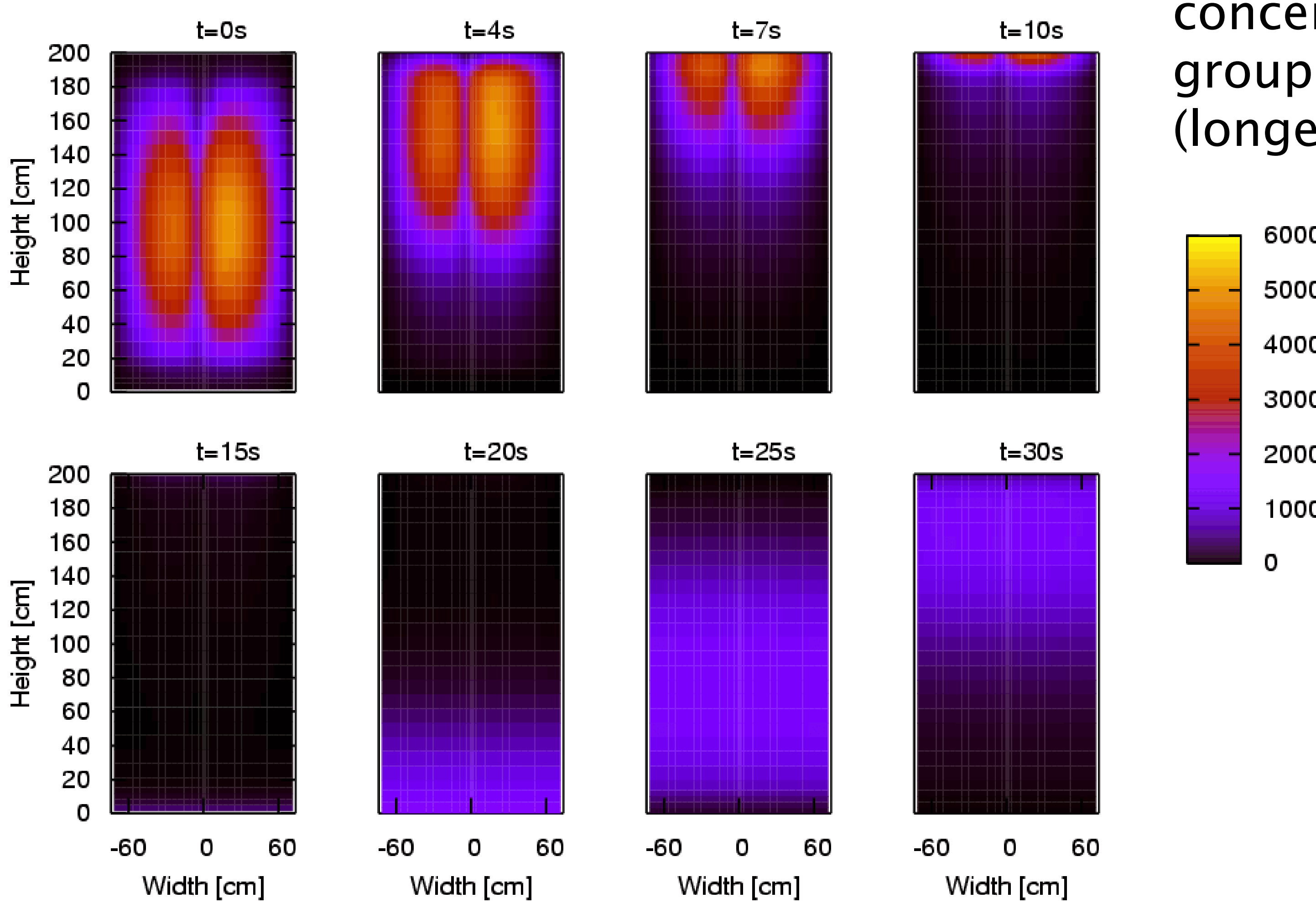
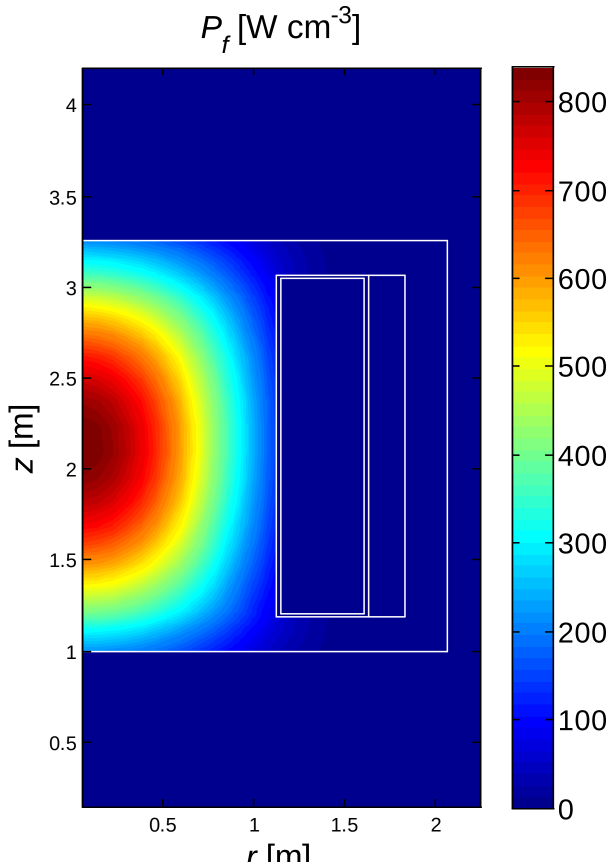
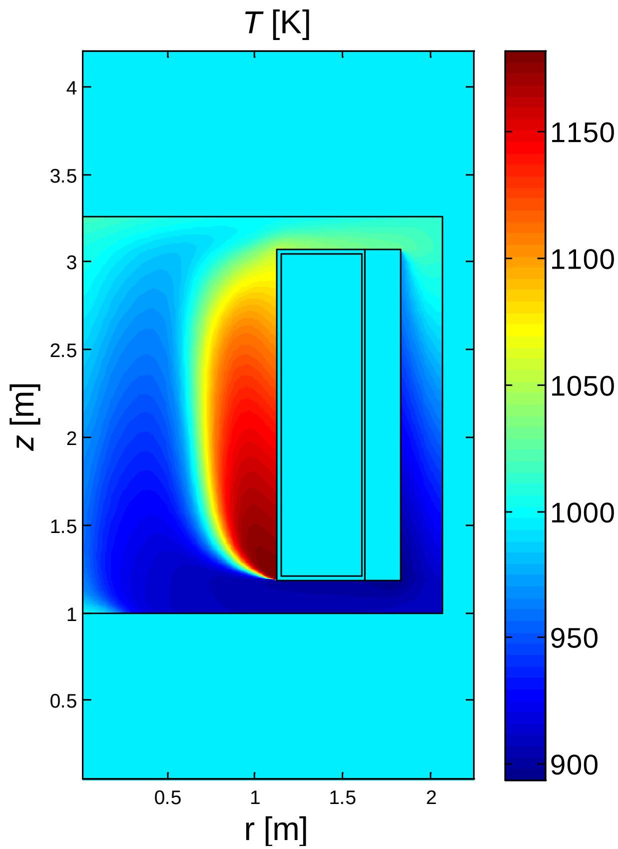
MSRE: Pump start-up

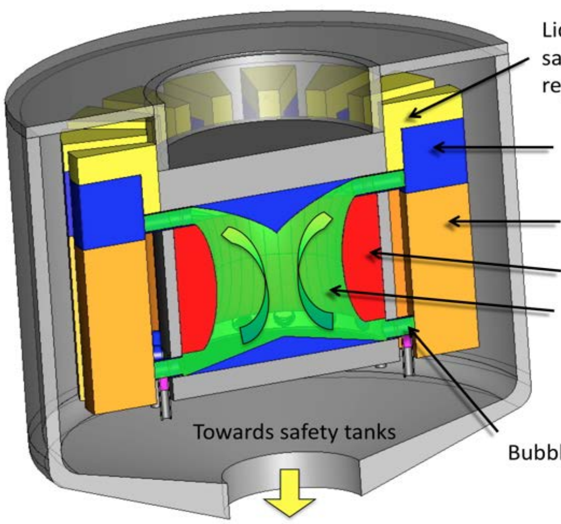


Precursor concentration group 6 (longest $T_{1/2}$)

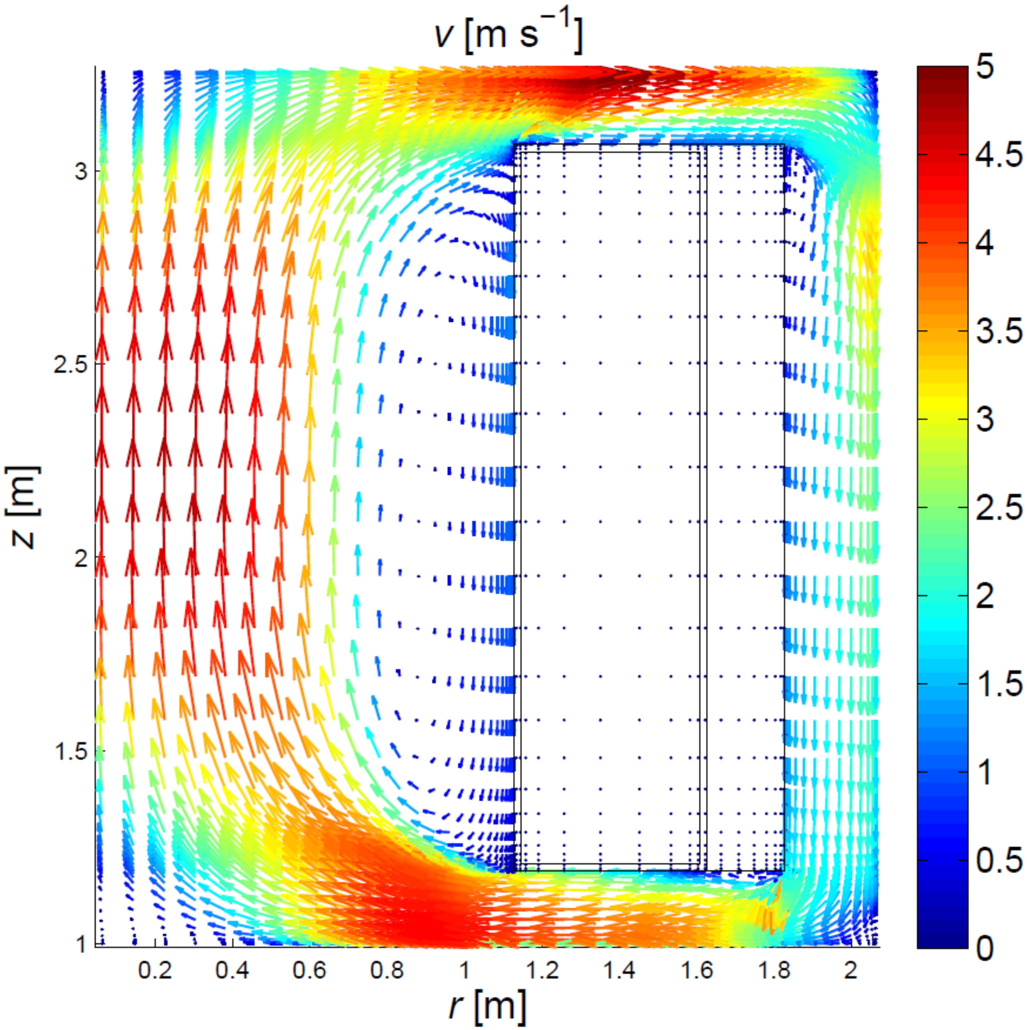
MSFR: Steady state power–temp





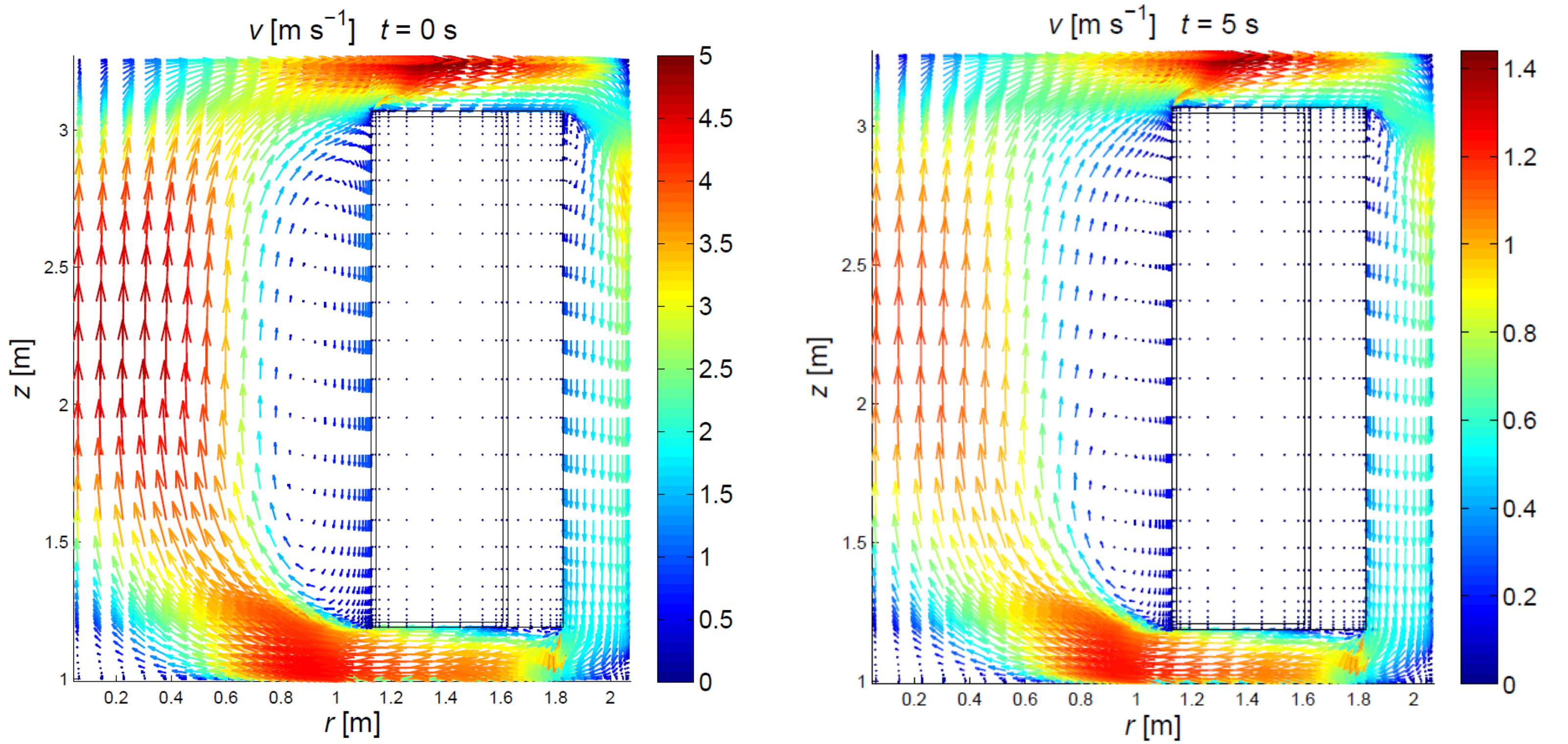


MSFR: Steady state flow



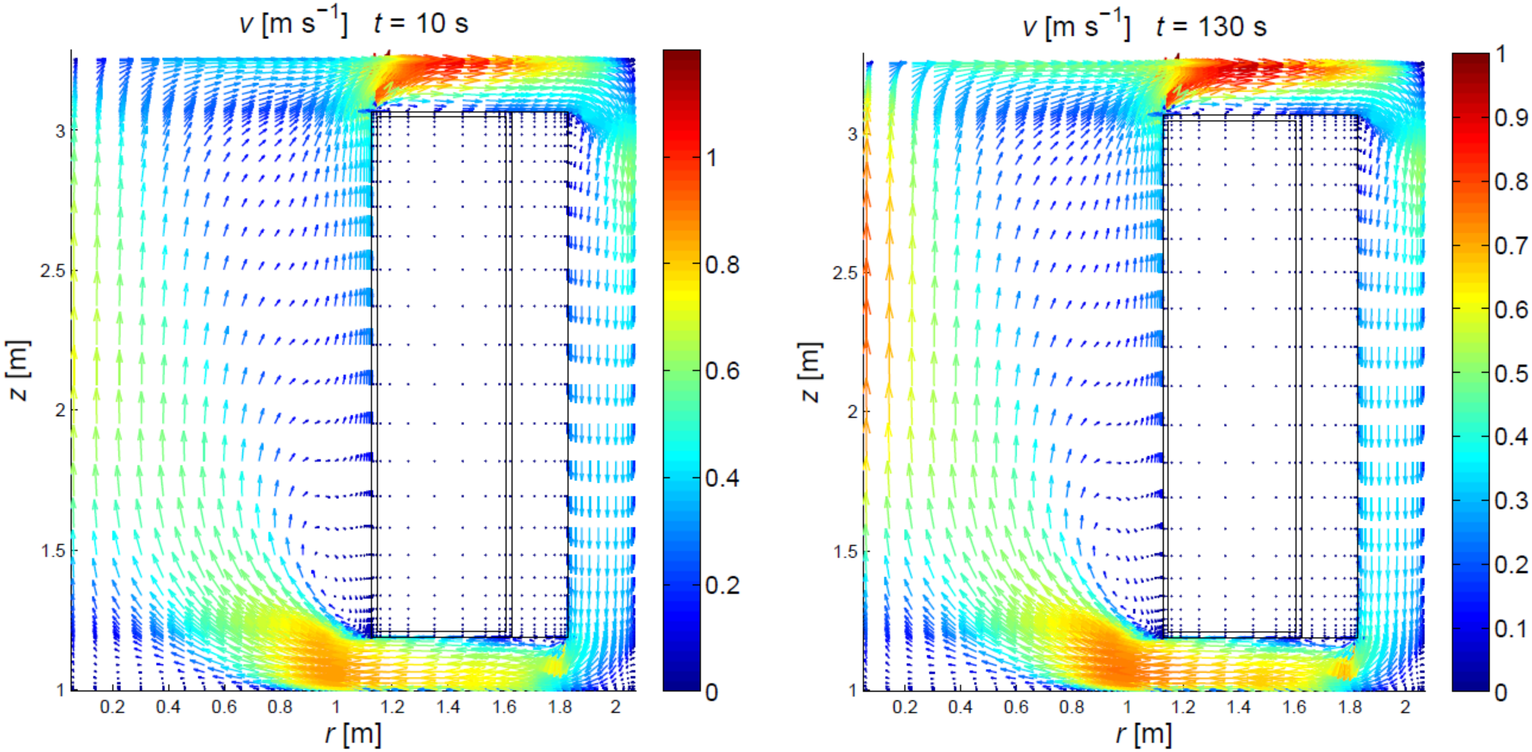
- Main recirculation loop: disadvantage for temperature field
- Small secondary flow in corner regions

MSFR: Pump failure



- Rapid initial decay of flow rate within first 5 seconds

MSFR: Pump failure



- Flow almost steady state after 130 seconds
- Flow rate decreased by factor 6 compared to steady-state
- Natural convection with different structure of recirculation zone
- Complex interplay between flow and buoyancy

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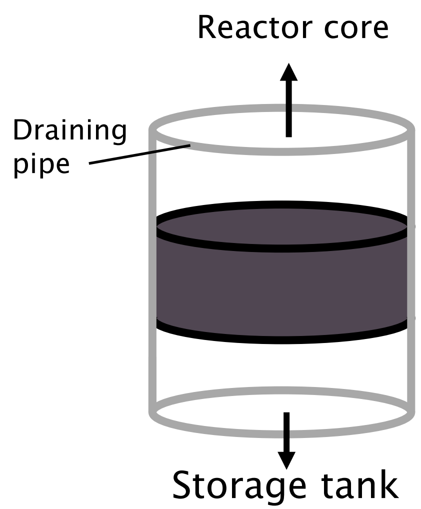
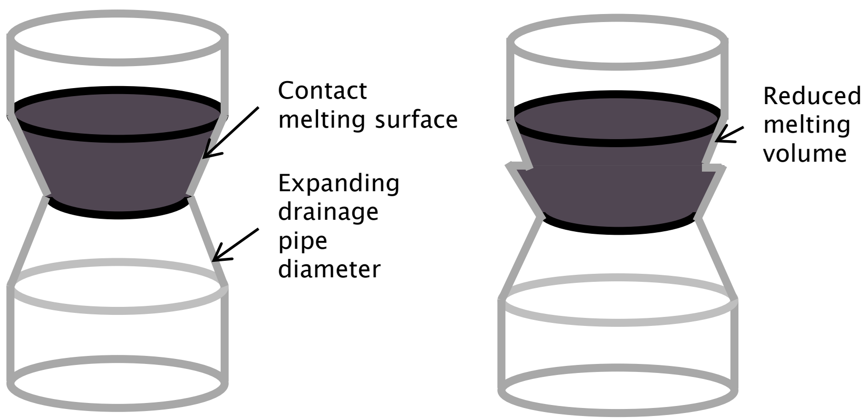
Freeze plug melting

Cylindrical Plug



Wedge Plug



Challenges

- **Vertical plug walls:** unknown friction
- **Uniform draining pipe width**: Potential jamming

Advantages

- **Wedge shape:** Stability during transient operation & accelerated contact melting
- **Expanding draining pipe**: No jamming

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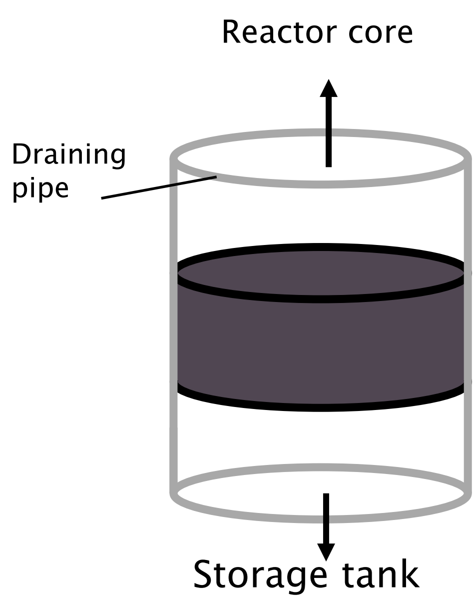
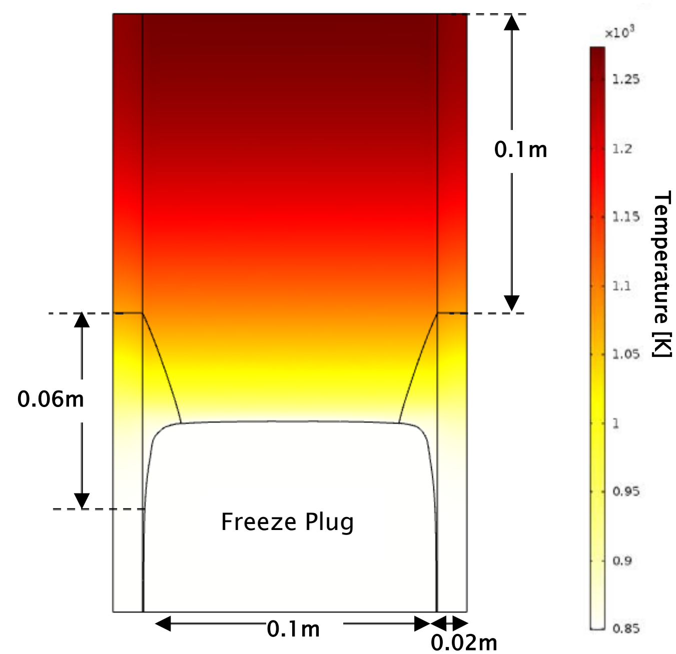
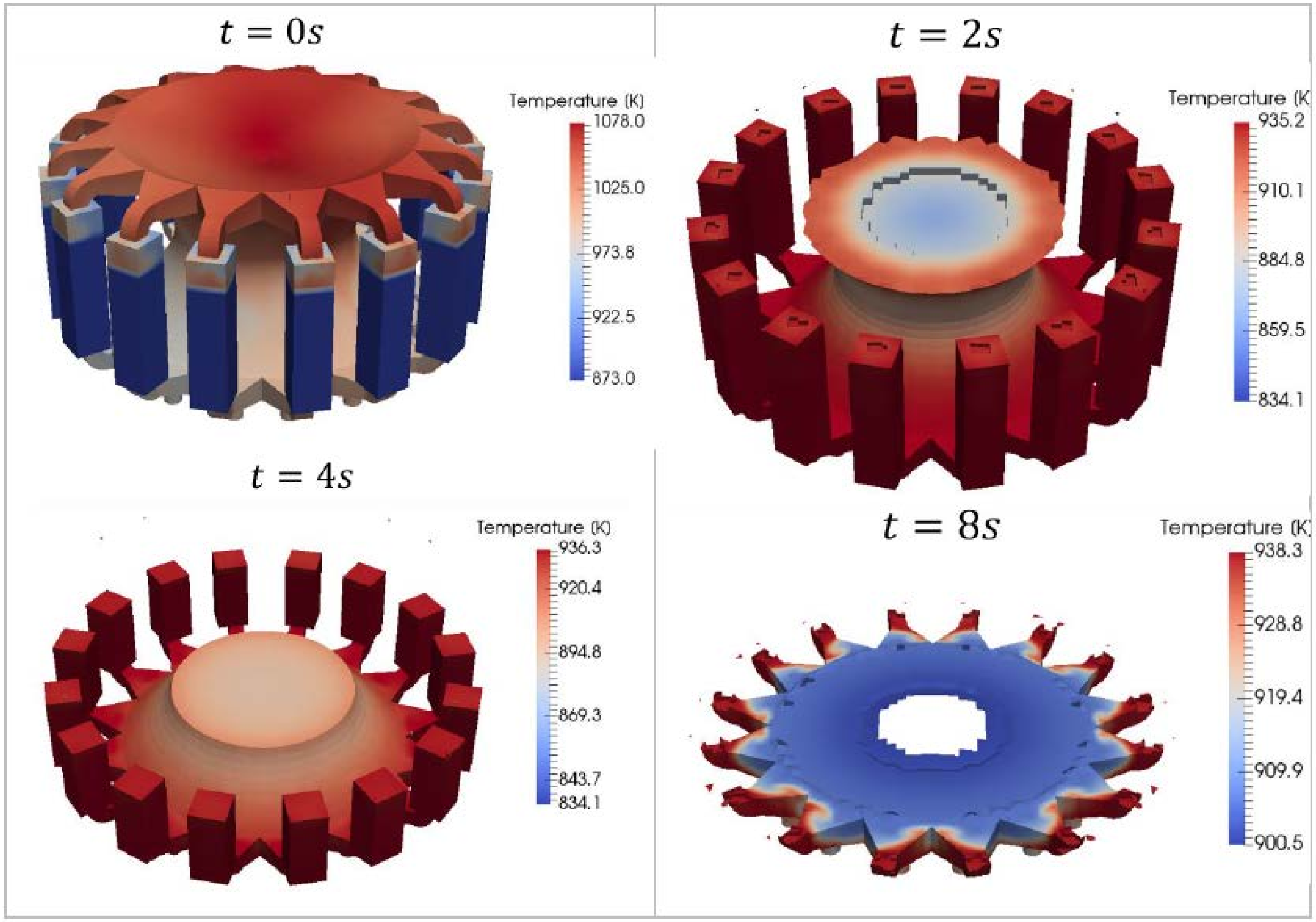
Freeze plug melting

- Assumptions:
  - No subcooling
  - No cavity flow
  - Decay heat source of 100MW in core
  - Drainage pipe thickness of 0.02m
  - FliNaK
- Approx. 6cm of melting observed after 300





Draining of the fuel circuit



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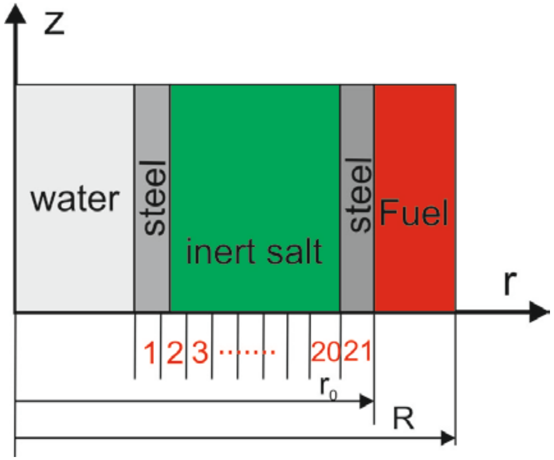
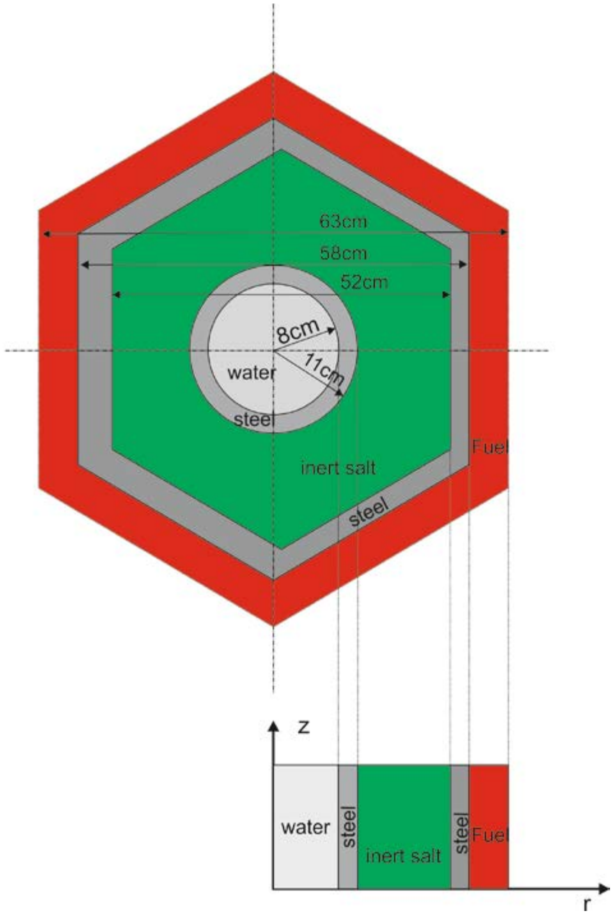
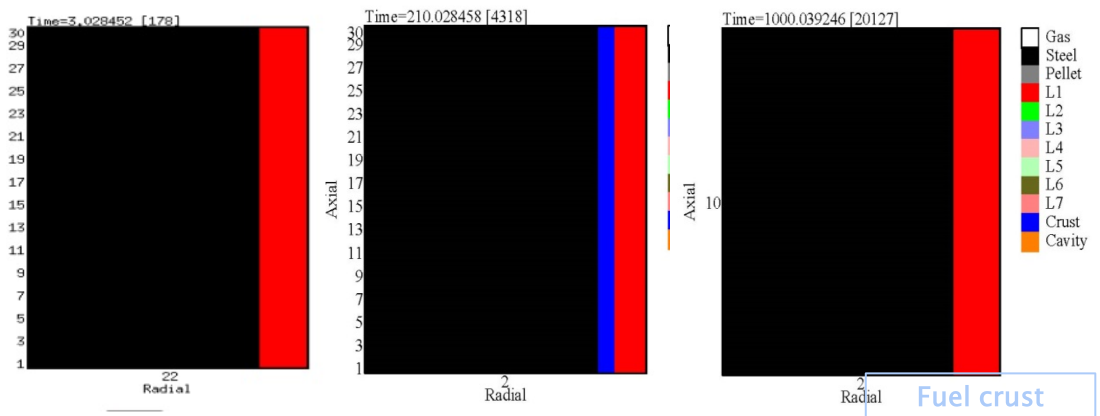
Draining tanks heat removal

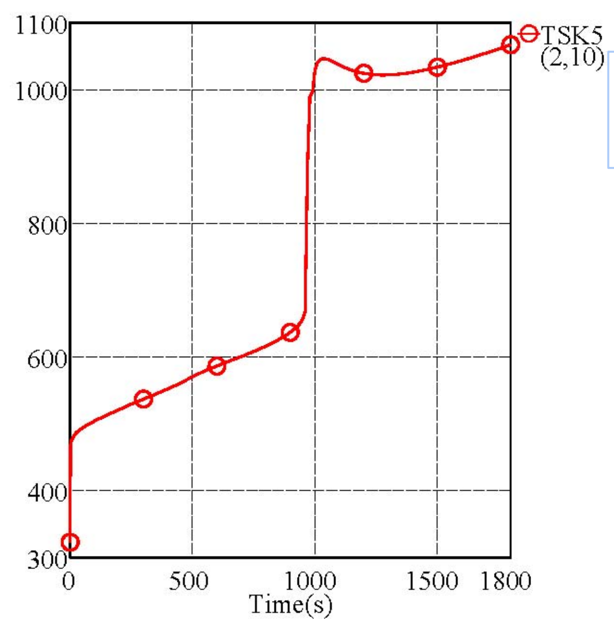
- Homogeneous power production in fuel salt
- Solidification phenomena

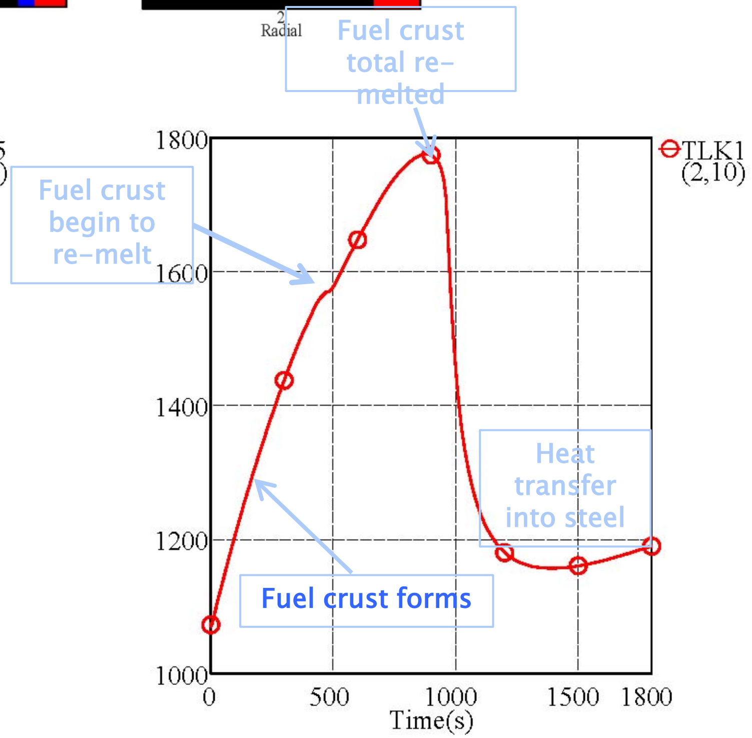




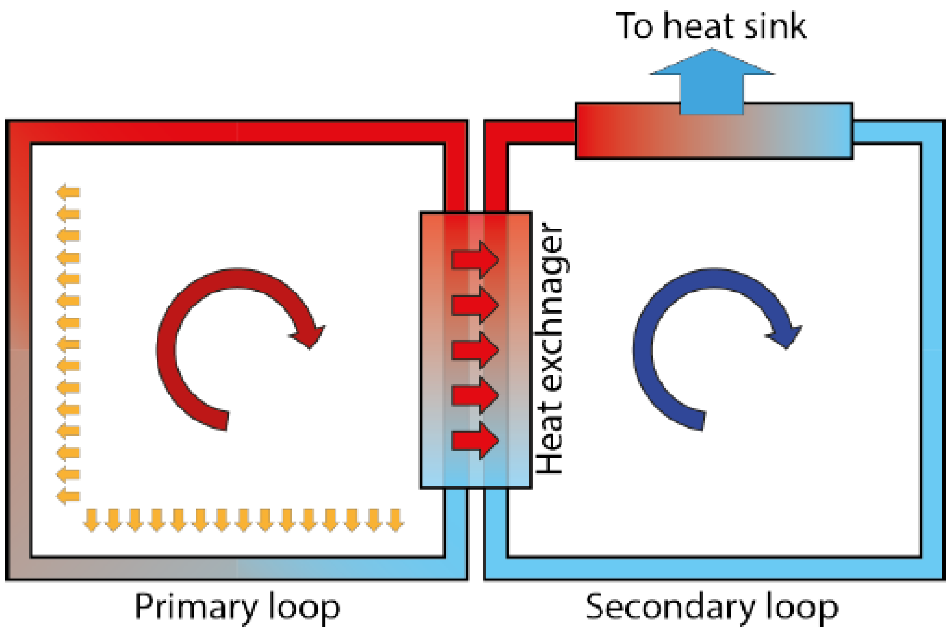
Draining tanks heat removal







Experimental validation: DYNASTY



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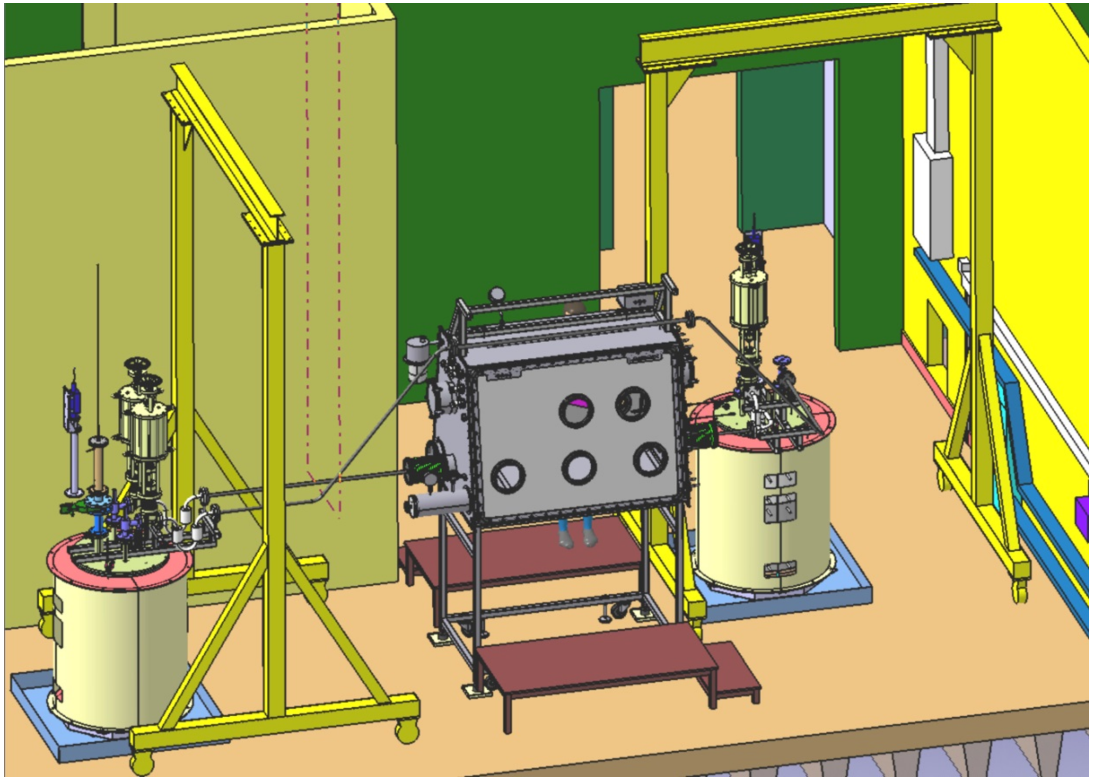
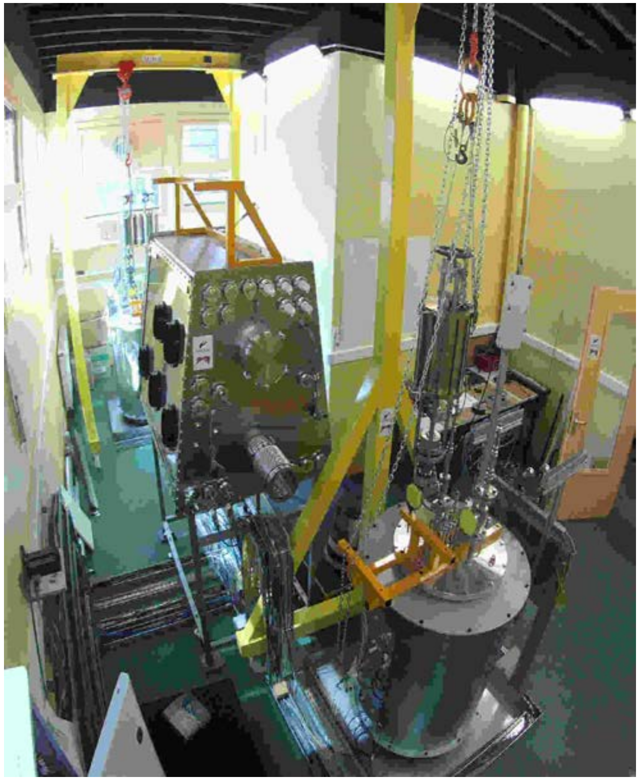
Experimental validation: SWATH





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Conclusions

- Simulation of the Molten Salt Reactors is challenging and requires rigourous multiphysics codes and methods
- Challenges especially in
  - Primary fuel circuit (core, pumps, heat exchanger, …)
  - Freeze plug design and
  - Decay heat removal (passive cooling, solidification, …)
- Participation of industry very much appreciated

- Website: www.SAMOFAR.eu
- Contact: J.L.Kloosterman@tudelft.nl

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