HIGH TEMPERATURE THERMAL HYDRAULICS MODELING OF A MOLTEN SALT: APPLICATION TO A MOLTEN SALT FAST REACTOR (MSFR)

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CNRS/IN2P3/LPSC - Grenoble

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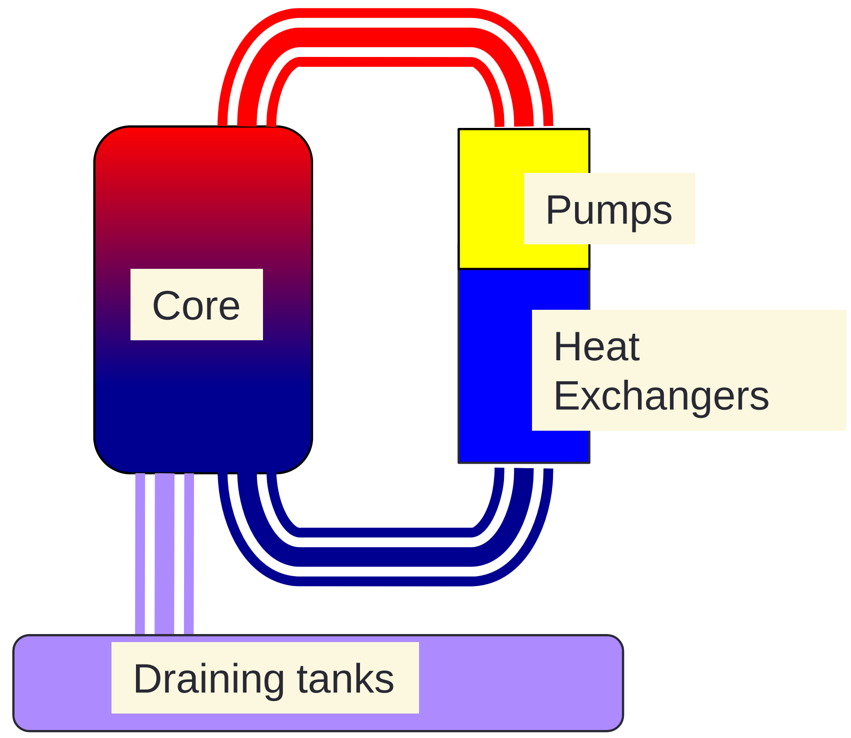
Outline

1. The Molten Salt Fast Reactor (MSFR)
2. Toward a multi-physics model of the MSFR
3. Current MSFR Thermal Hydraulics Model
4. Open issues related to the modeling of a molten salt
5. Ongoing experimental and modeling developpments

THE MOLTEN SALT FAST REACTOR (MSFR)

- Why using a liquid fuel?
- Main characteristics of the MSFR
- Fuel draining system

Why using a liquid fuel?



If needed adequate criticality and fuel cooling margins can be obtained by passively changing the geometry of the fuel salt

Main advantages:

- Possibility to reconfigure passively the fuel geometry outside the core cavity:
  - *Uncouple optimization of design and safety*
  - *New passive safety systems*
- Possibility of on-line fuel loading and reprocessing

and some of the new challenges:

- New methodology is needed to perform the safety evaluation (Severe accident?)
- A single breach in the first barrier could hypothetically lead to the leak of a significant amount of the fuel inventory

The MSFR Concept

❑ What is a MSFR ?

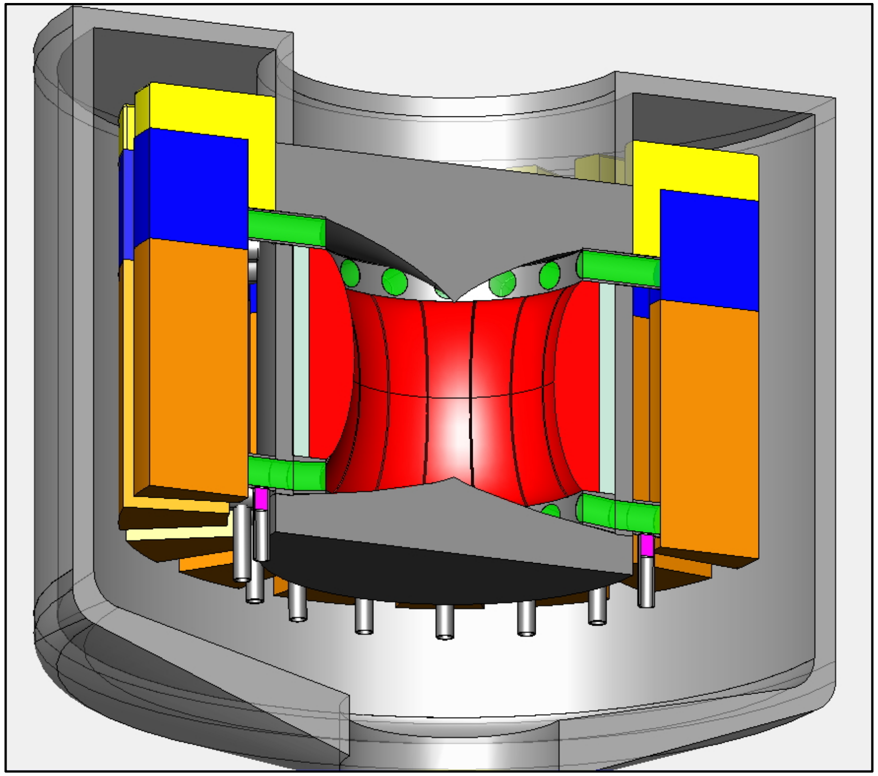
- Liquid fuel reactor using a molten salt as fuel matrix and coolant (LiF)

$77{,}5\%\ \mathrm{LiF} + 18{,}7\%\ \mathrm{ThF_4} + 3{,}8\%\ \mathrm{UF_4}$

- Based on a Thorium fuel cycle (^{232}Th / ^{233}U)
- No solid moderator in the core to obtain a fast neutron spectrum
- No core internal structures
- Online refueling and reprocessing

❑ Three reactor loops

- Fuel salt loop
- Intermediate loop
- Thermal conversion loop



❑ Fuel loop operating conditions

- High temperatures (~750°C)
- Low pressures (~1 bar)
- Fuel salt recirculation time ~4 s

Design Aspects Impacting Reactor Safety

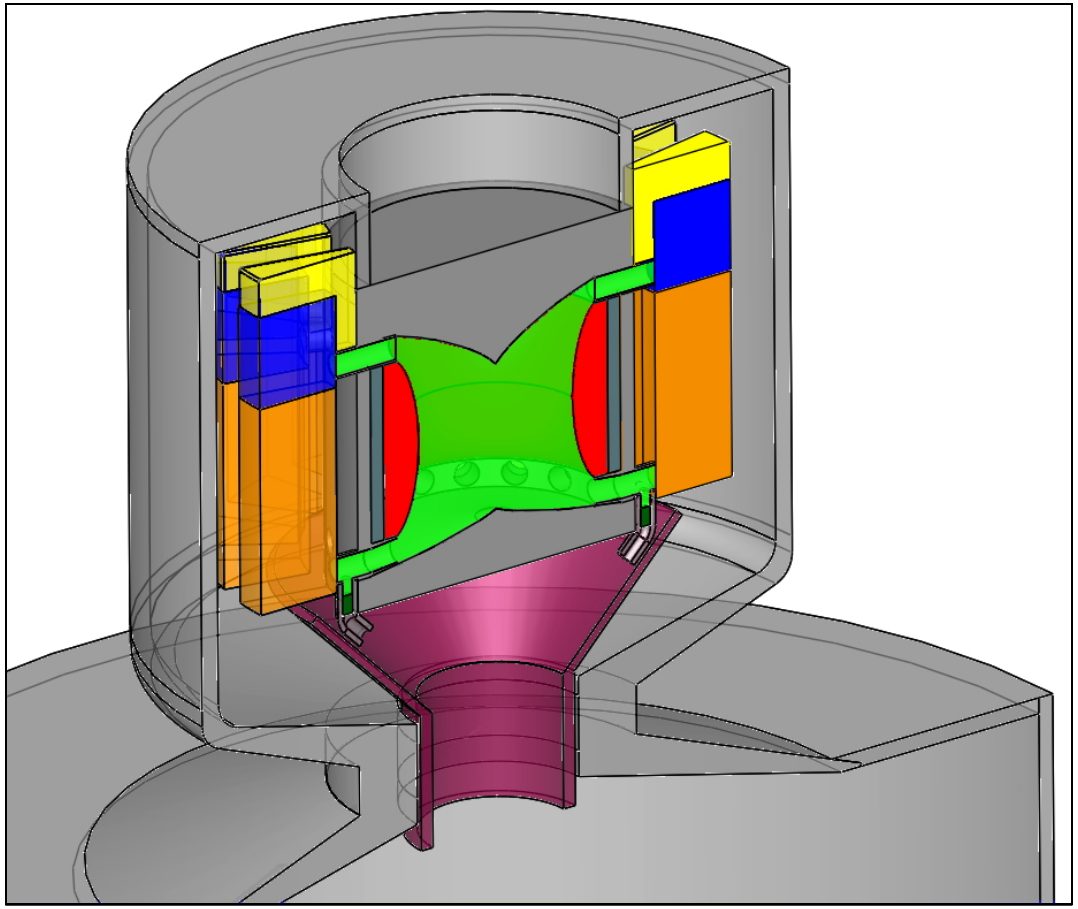
- Liquid fuel
  - ❑ Molten salt acts as nuclear fuel and coolant
  - ❑ Relative uniform fuel irradiation (no loading plan)
  - ❑ A significant part of the fissile inventory is outside the core

- No control rods in the core
  - ❑ Small fuel temperature gradient and core reactivity excess (nominal conditions)
  - ❑ Reactivity can be controlled by the heat transfer rate in the HX and the fuel salt feedback coefficients, continuous fissile loading and the geometry of fuel salt mass
  - ❑ No requirement for controlling the neutron flux shape (no DNB, uniform fuel irradiation, etc.)

- Fuel salt draining system
  - ❑ Cold shutdown is obtained by draining the molten salt from the fuel circuit
  - ❑ Changing the fuel geometry allows for adequate shutdown margin and cooling
  - ❑ Fuel draining can be done passively or by operator action

A Novel Reactor Shutdown System

Fuel salt draining system = Shutdown system



- ❑ It has keys factors that can improve reactor resistance against Fuskushima-like events
- ❑ Performs two of three safety functions
- ❑ Need to demonstrate that it relies on physically sounded mechanisms:
  - Safety vane reliability
  - Molten salt conditions during draining

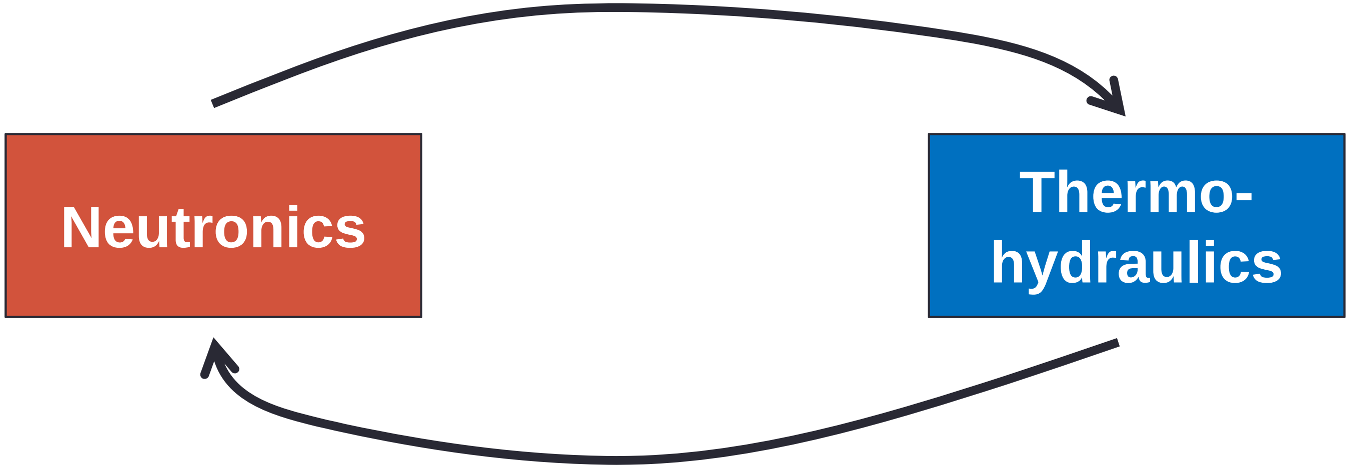
Critical point: having a detailed understanding of the phenomena taking place in a high temperature molten salt flow

TOWARD A MULTI-PHYSICS MODEL OF THE MSFR

- Neutronics and thermo-hydraulics coupled model
- Feedbacks effects and delayed neutron precursors

Neutronics and Thermo-hydraulics Coupling

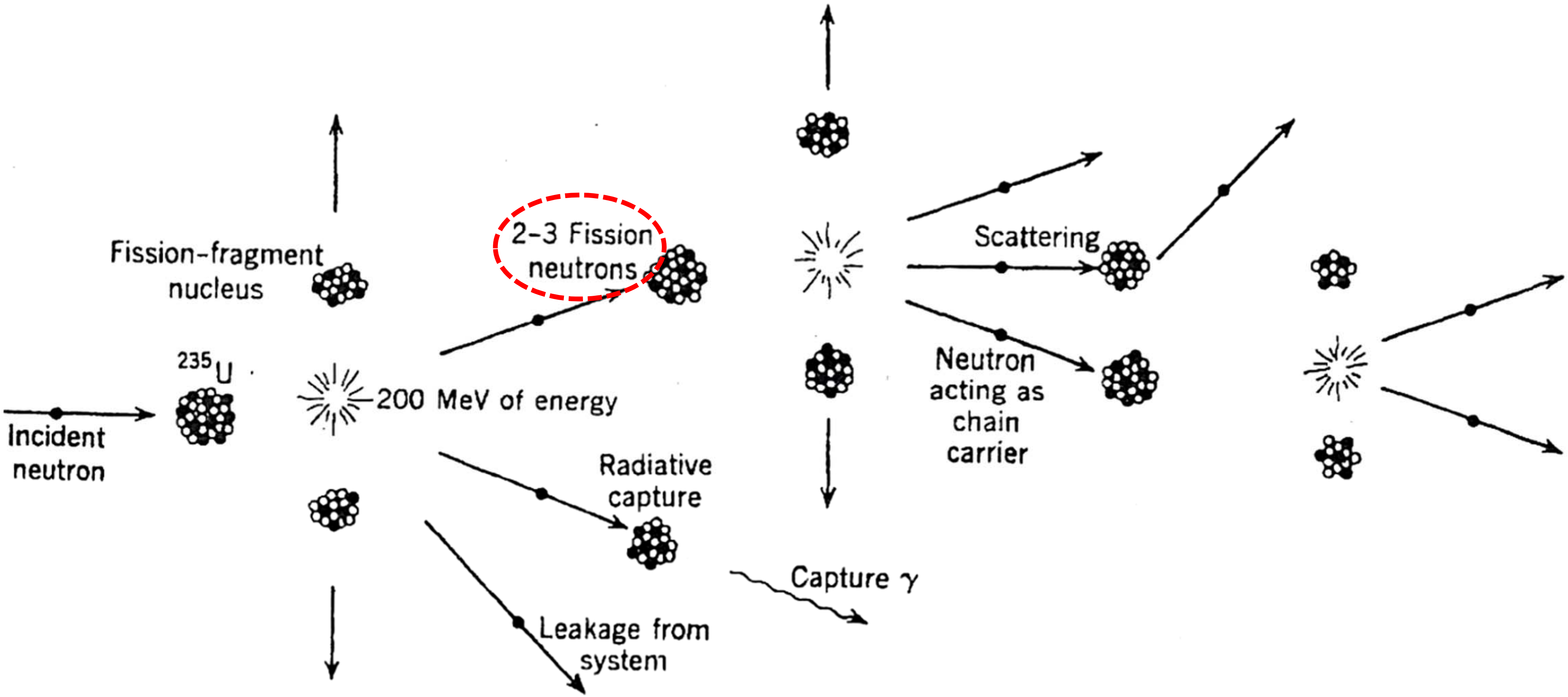
- A strong coupling between fuel power generation and fuel thermal-hydraulics (T&H) exist in the MSFR:
  - ☐ Fission power distribution determines the temperature profiles in the fuel salt
  - ☐ Feedback effects: the fuel salt temperatures, densities and velocities modify the nuclear properties and thus nuclear reaction rates
  - ☐ Delayed neutrons: emitted by some of the fission products transported by the fuel salt
- Numerical resolution requires a coupled resolution of the reactor neutronics and thermo-hydraulic equations



Neutronics

Thermo-hydraulics

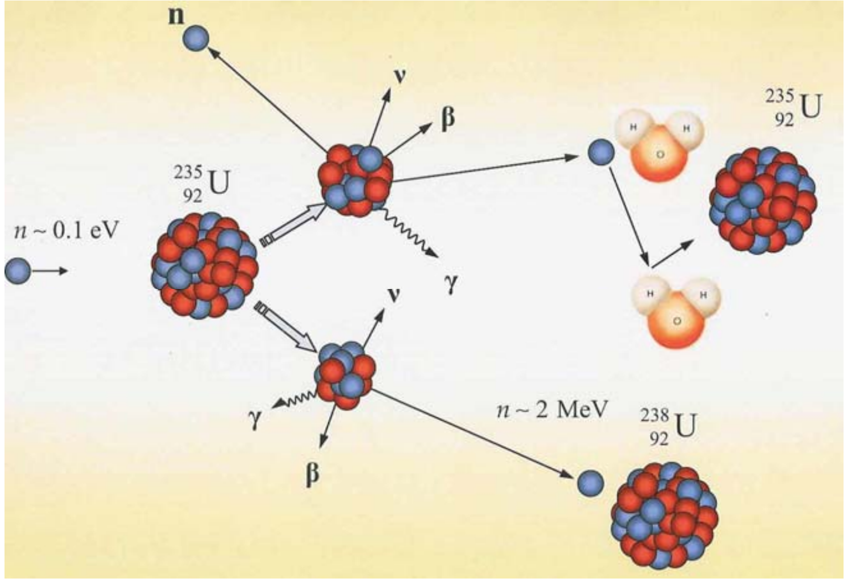
A Simple Schematic of a Fission Chain Reaction



What is the equilibrium condition?

- Exactly “one” neutron per fission should be kept in average to induce a new fission

Reactor Multiplication Factor "k"



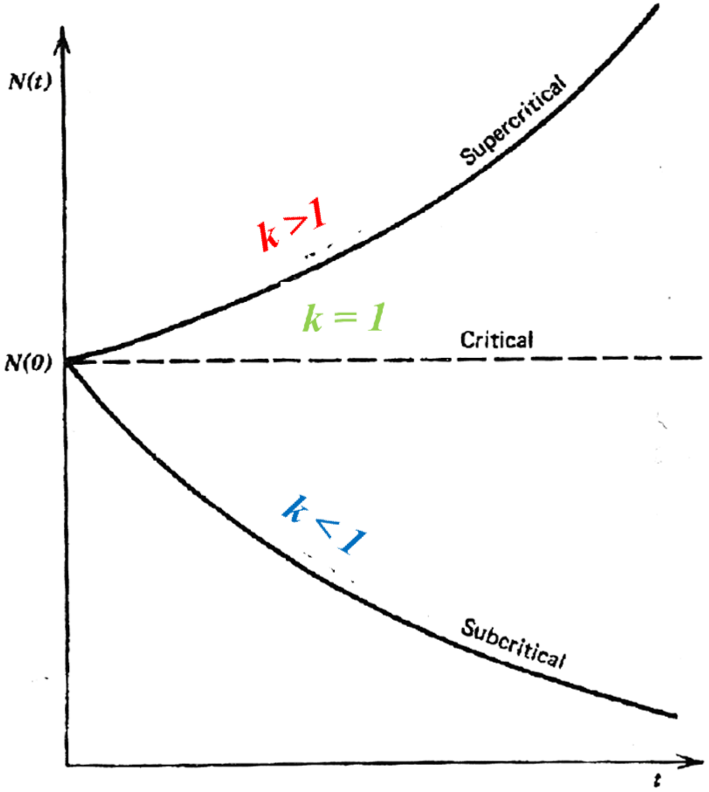
The reactor multiplication can be defined as:

$$\boxed{k = \frac{Neutrons\ number\ at\ the\ \mathbf{Generation\ i+1}}{Neutrons\ neutron\ at\ the\ \mathbf{Generation\ i}}}$$

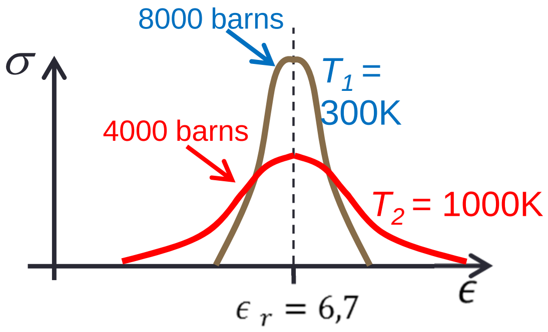
An alternatively definition but a more practical for computing k is:

$$\boxed{k = \frac{Productions}{Absorptions + Leaks}}$$

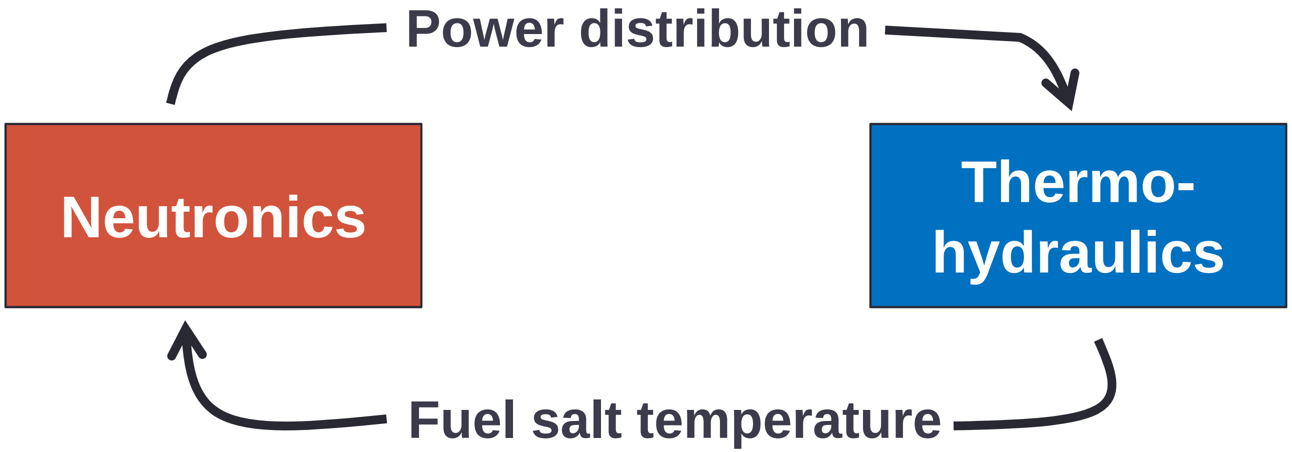
Reactor control is about keeping k = 1 !



Neutronics feedback effects



- Neutronics feedback effects
  - ❑ Two effects: Doppler and salt density feedbacks
  - ❑ In the MSFR both feedbacks are strongly negative: $\left(\frac{\partial k}{\partial T} < 0 \text{ and } \frac{\partial k}{\partial \rho} < 0\right)$


Power distribution

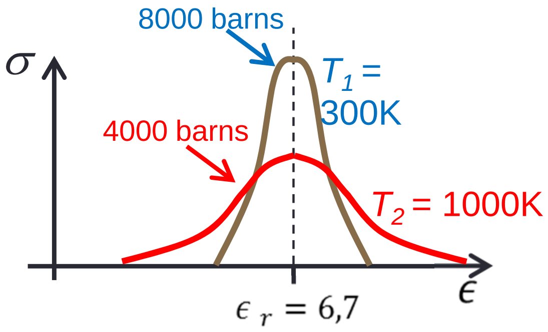
Neutronics

Thermo-hydraulics

Fuel salt temperature

- Both feedbacks contribute to stabilize the chain reaction
- Need to accurately compute the fuel salt temperature to estimate them

Neutronics feedback effects



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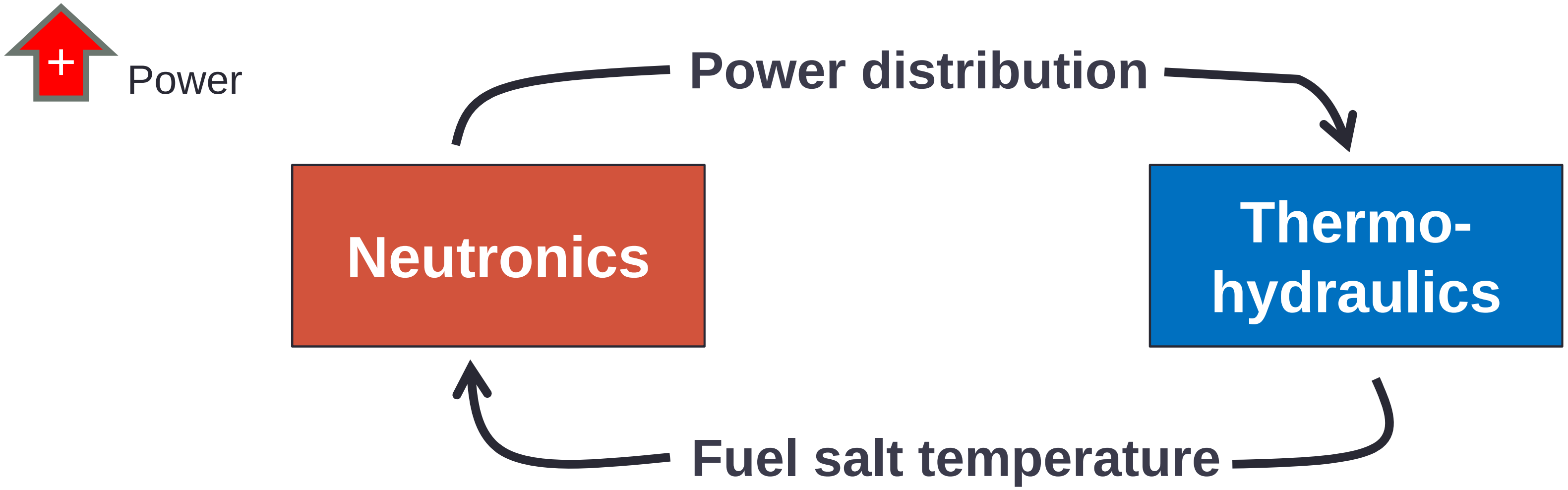

Power

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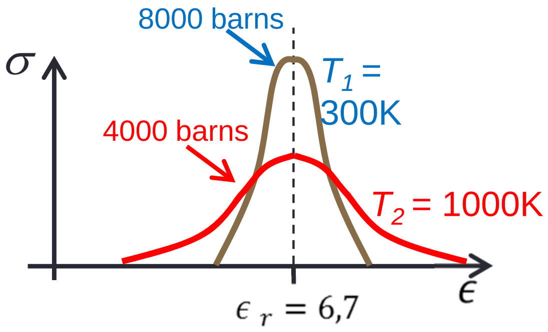

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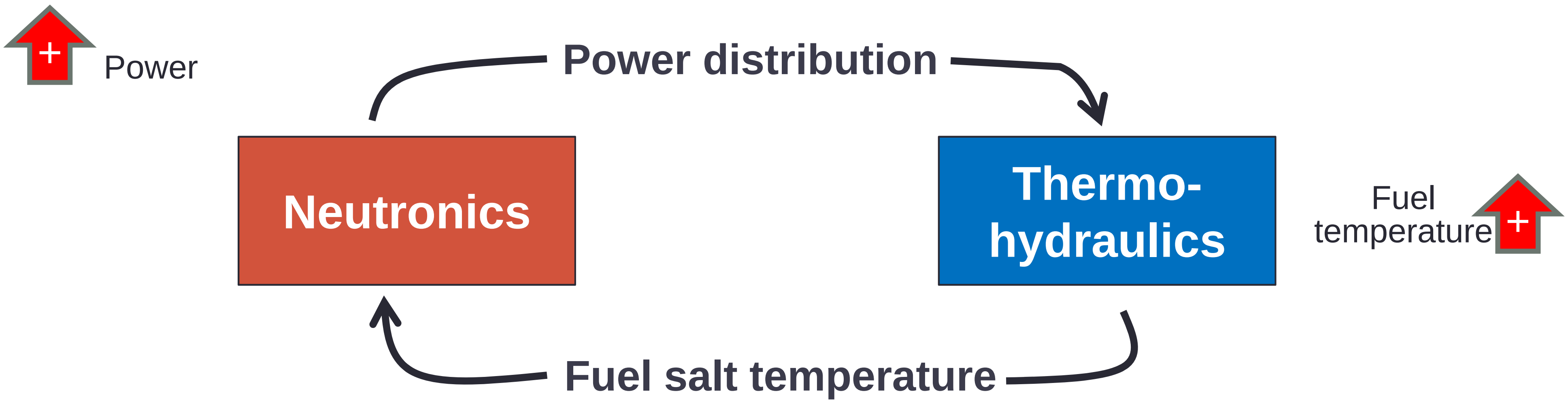

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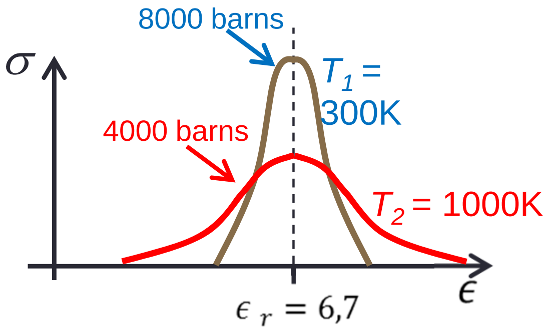

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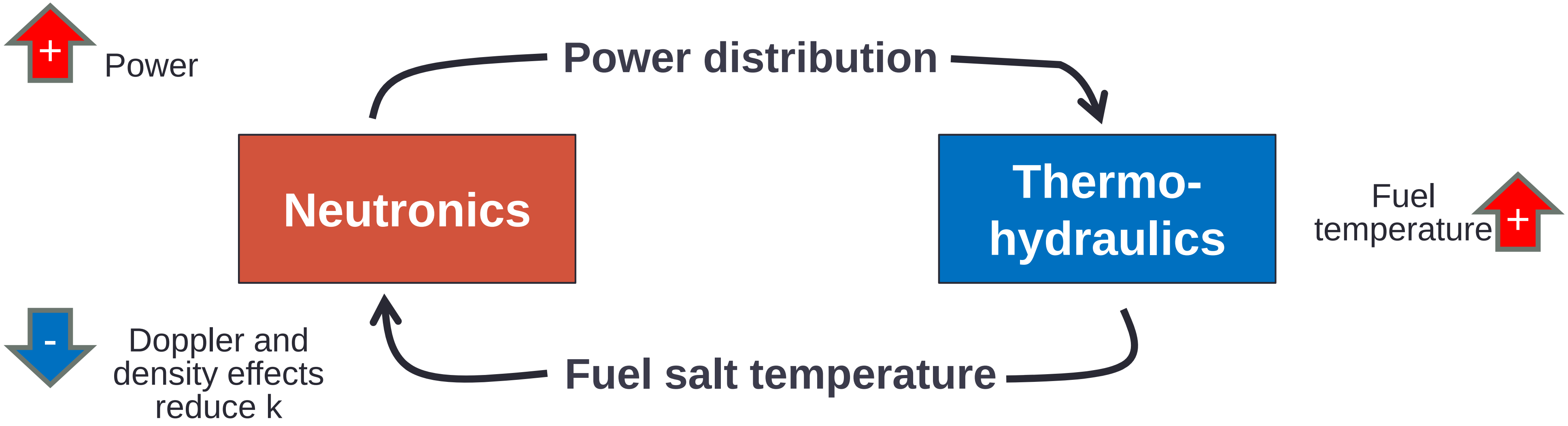

Power

Power distribution

Neutronics

Thermo-hydraulics

Fuel temperature

Doppler and density effects reduce k

Fuel salt temperature

- Both feedbacks contribute to stabilize the chain reaction

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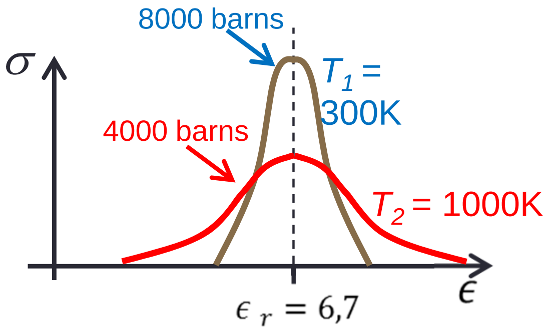
Neutronics feedback effects



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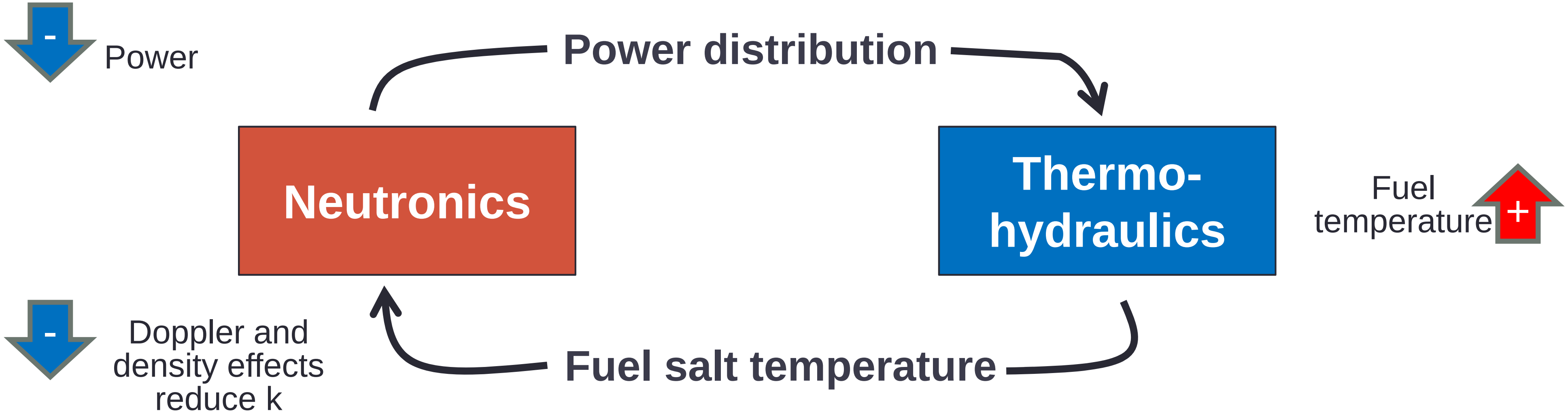

- Power

Power distribution

Neutronics

Thermo-hydraulics

Fuel temperature +

- Doppler and density effects reduce k

Fuel salt temperature

- Both feedbacks contribute to stabilize the chain reaction
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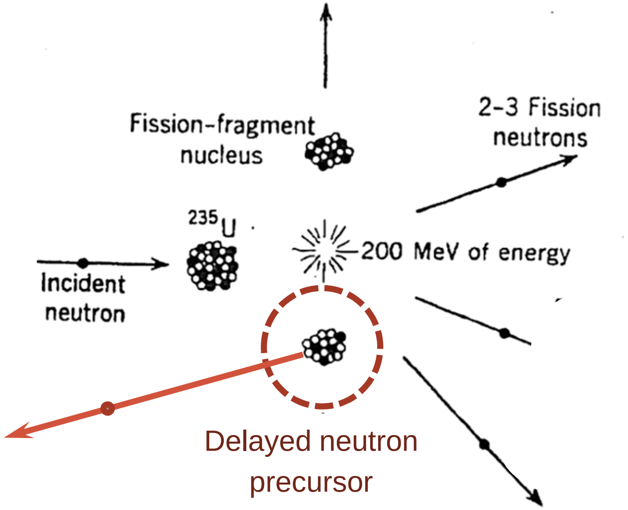
Production of delayed neutrons

- Some fission products (called neutron precursors) decay by emitting a delayed neutron
- The delayed neutrons represent small fraction of total neutrons (<1%)



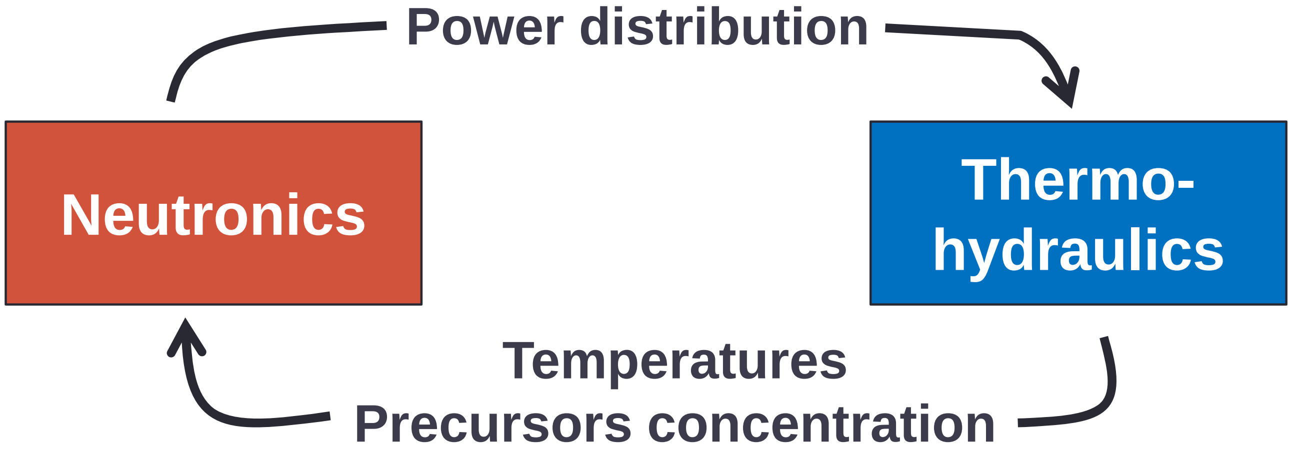
- The decay time of delayed neutrons (~sec) is much longer than the typical neutron lifetime (~ μsec)

– They introduce a significant inertia and slowdown the reactor response

– Need to accurately track their position since the fuel is flowing in the core cavity

MSFR Reactor Core Model

- Coupled neutronics and T&H numerical simulations are performed:
  - ☐ Steady-state conditions
  - ☐ Transient conditions
- Salt velocities and temperatures, and concentration of neutron precursors estimated with the CFD code *OpenFOAM*
- Power distribution calculated with a Monte Carlo neutronics code (*MCNP* or *SERPENT*), a neutron diffusion model or an hybrid model (Fission Transient Matrices), etc.



Power distribution

Neutronics

Thermo-hydraulics

Temperatures
Precursors concentration

CURRENT MSFR THERMAL HYDRAULICS MODEL

- Why using a CFD approach ?
- Flow governing equations
- Example of steady-state calculations using a coupled neutronics thermo-hydraulics model

Why using a CFD approach ?

- Some important flow phenomena inherent to this reactor are:
  - ❑ Circulation of delayed neutron precursors (e.g. effective delayed neutron fraction depends on the flow field)
  - ❑ Complex fuel salt flow patterns such as flow recirculations have a significant impact on the core wall temperature distribution
  - ❑ Flow distribution also impacts the reactor feedback coefficients
  - ❑ Large core cavity with significant 3D and turbulence effects

- Adequate T&H modeling of the MSFR requires thus
  - ❑ Numerical resolution of the Navier-stokes equation for turbulent flow (classical approaches such as sub-channel models are not well suited)
  - ❑ Coupled neutronics and T&H numerical simulations are necessary

CFD Common Approaches

- **Reynolds-averaged Navier–Stokes equations (RANS)**: this approache uses the time-averaged equations of motion for fluid flow (continuity, NS, energy). Time averaging is on a large scale so turbulence is filtered out
- **Direct numerical simulation (DNS)**: computational fluid dynamics simulation in which the Navier–Stokes equations are numerically solved without any turbulence model. Computational mesh should allow to resolve all significant scale of turbulence
- **Large eddy simulation (LES)**: family of method that compromise between RANS and DNS. Large-scale eddies are resolved in the flow equation solution while the effects from the small-scale eddies are obtained from dedicated models (low-pass filtering)
- **Detached eddy simulation (DES):** further compromise between RANS and LES, to capture key physical phenomena in the lowest possible amount of computer time. Consist in a modified RANS model which switches to a subgrid scale formulation in regions where a LES calculations is needed.

MSFR Thermal Hydraulics Model

- Solved Reynolds Averaged Navier Stokes (RANS) equations with the Realizable k-epsilon turbulence model (Re ~ 500,000)
- Incompressible flow with Boussinesq approximation (= buoyancy term)
- Temperature stratification effects are expected to be small
- Use turbulence models developed for water flows (similar Re and Pr)
- Single phase fluid (no salt solidification)
- Fuel pumps as imposed pressure rise in the circuit
- Simplified model for the HXs
- Precursors concentration estimated as a chemical species
- Energy source: fission power (viscous dissipation is neglected)
- Transient simulations with steady state boundary conditions

MSFR RANS Equations

Averaged mass conservation equation

$$\boxed{\frac{\partial \bar{u}_j}{\partial x_j} = 0}$$

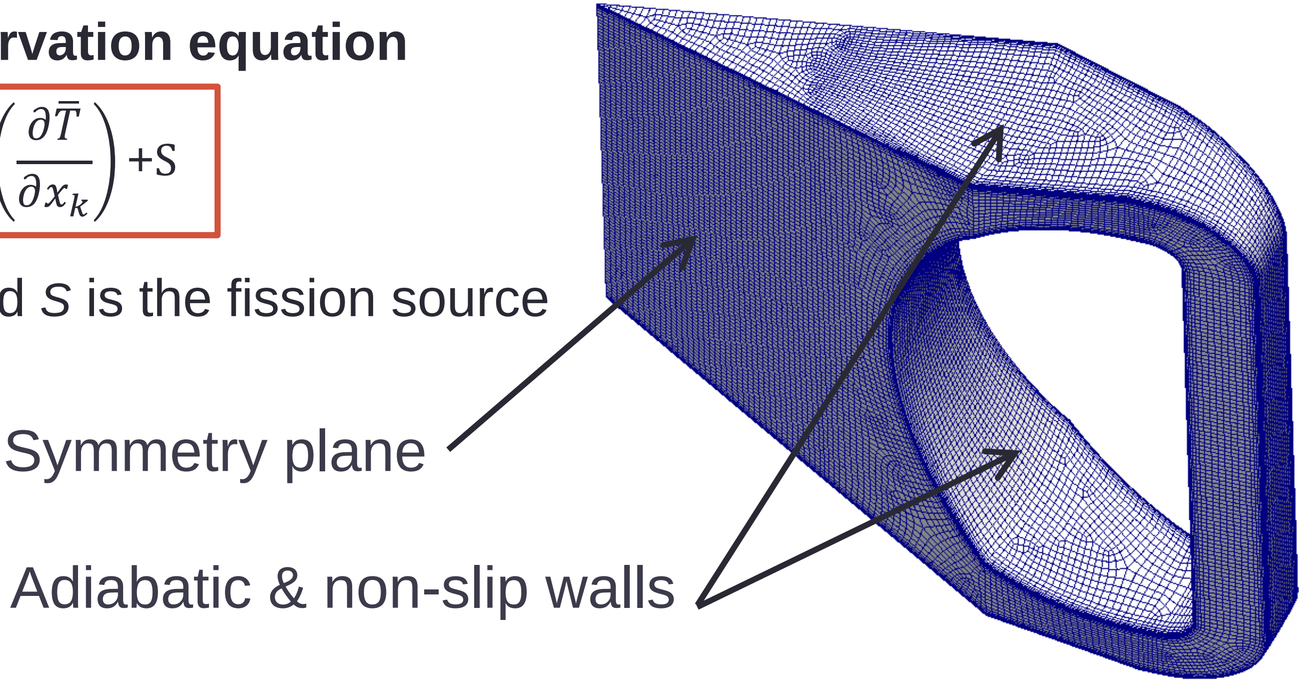
Momentum conservation equations

$$\boxed{\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{u}_j\,\bar{u}_i\right) = -\frac{\partial}{\partial x_i}\left(\frac{\bar{p}}{\rho_o} + \frac{2}{3}\,k\right) + \frac{\partial}{\partial x_j}\left\{(\upsilon + \upsilon_t)\left[\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \frac{2}{3}\left(\frac{\partial \bar{u}_k}{\partial x_k}\right)\delta_{ij}\right]\right\} + g_i\left[1 - \beta(\bar{T} - T_o)\right]}$$

Fuel salt energy conservation equation

$$\boxed{\frac{\partial \bar{T}}{\partial t} + \frac{\partial\left(\bar{u}_j\,\bar{T}\right)}{\partial x_j} = k_{eff}\,\frac{\partial}{\partial x_k}\left(\frac{\partial \bar{T}}{\partial x_k}\right) + S}$$

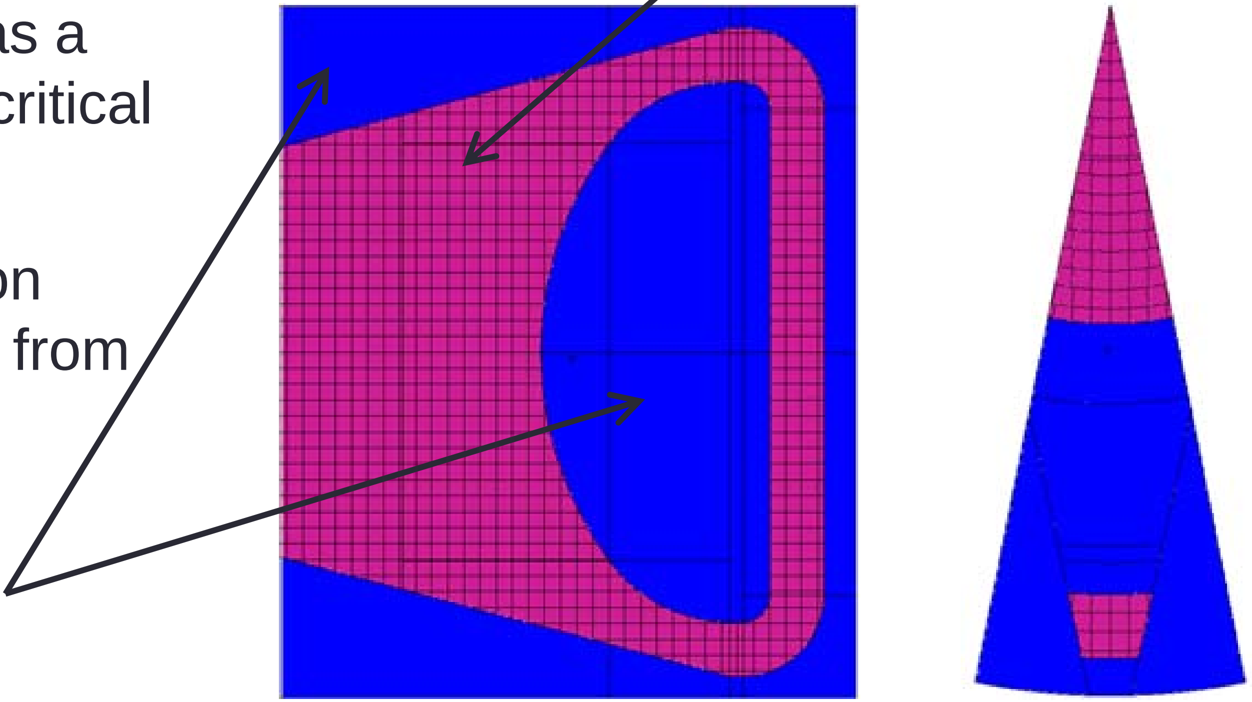
where $k_{eff} = \frac{\upsilon_t}{Pr_t} + \frac{\upsilon}{Pr}$ and S is the fission source



CFD geometry (1/16 core) = 300,000 cells

Power Source: Neutronics Model

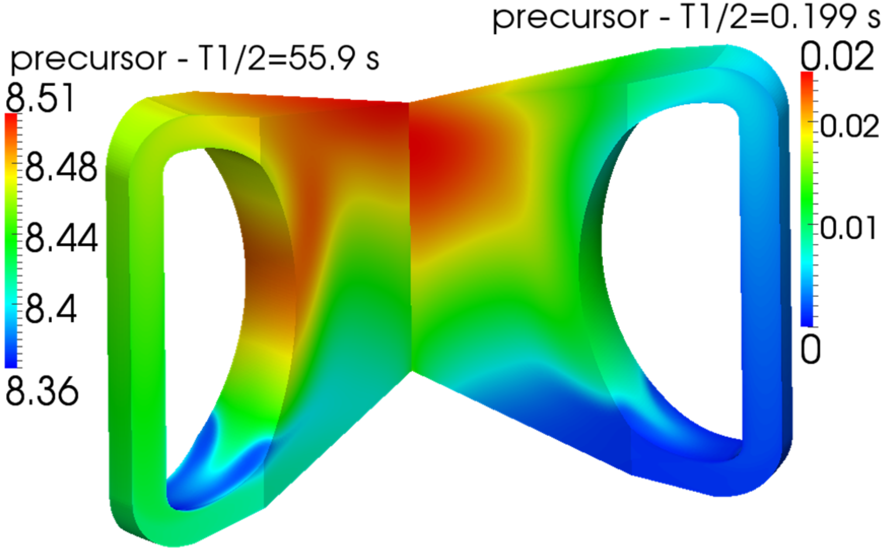
- Same domain as that of the CFD model
- Elementary cell = brick with curved surfaces
- Total number of volumes = 5,000
- Precursors considered as a neutron source in a subcritical prompt reactor
- Density and cross section (ENDF-B7) recalculated from CFD temperature fields



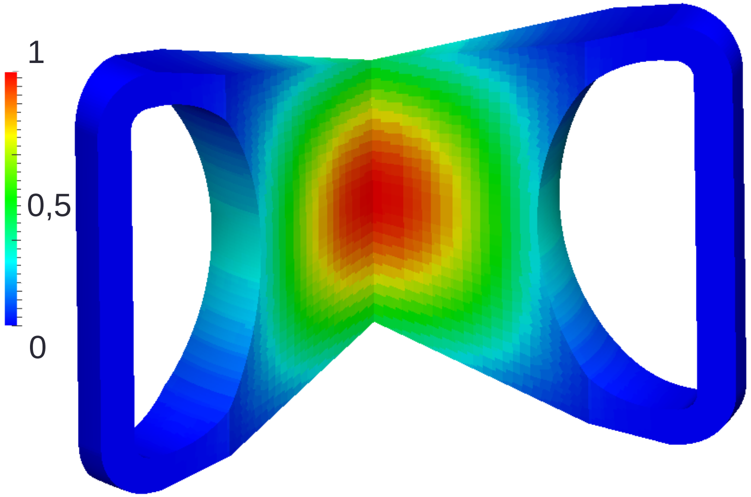
MCNP geometry (1/16 core) = 5000 volumes

Example of steady-state calculations Power Shape and Precursors Circulation

- Numerical simulations performed in the framework of the PhD thesis of A. Laureau
- Weak impact of the shape of the temperature distribution on the neutron flux shape
- Concentration is more uniform for delayed neutron precursors with longer decay periods
- Effective delayed neutron fraction ≅163 pcm



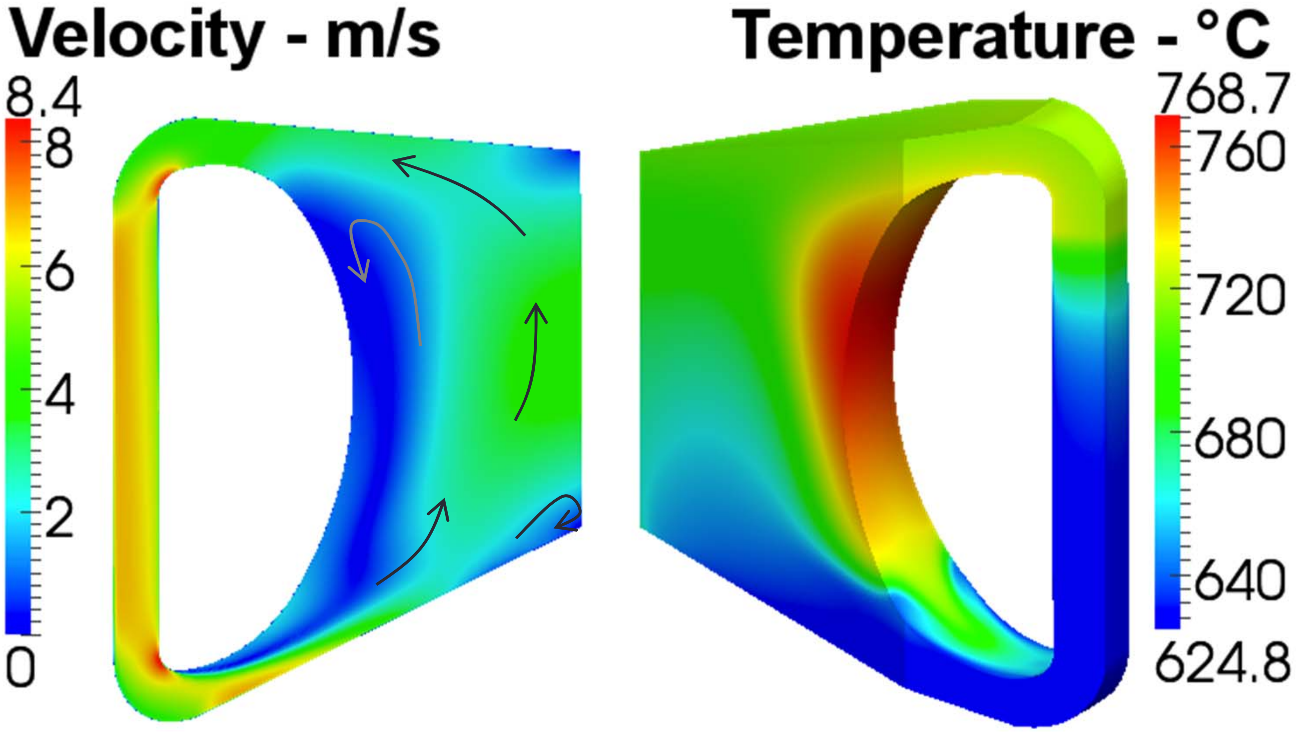
Precursors concentration



Normalized power shape

Fuel salt velocity and temperature fields

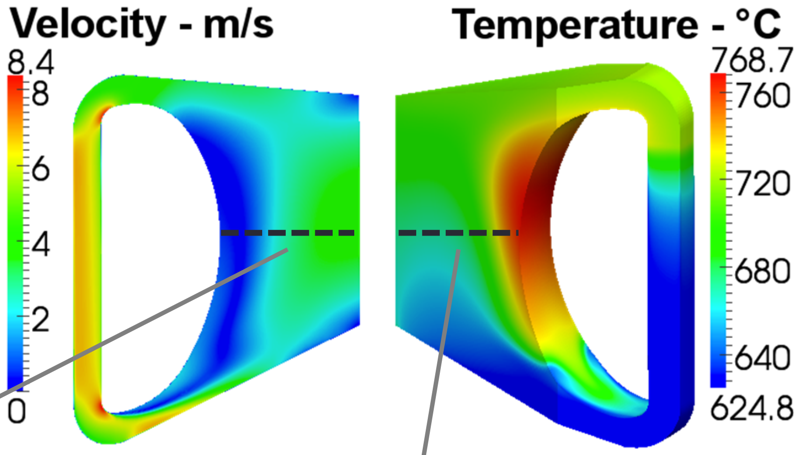
- Three recirculation zones: bottom and top reflectors, radial blanket
- The HX geometry has an important effect on the inlet cavity jet
- The overall direction of the flow rotation in the recirculation zones is not compatible with a thermal convection (i.e. temperature stratification effects seem to be small)

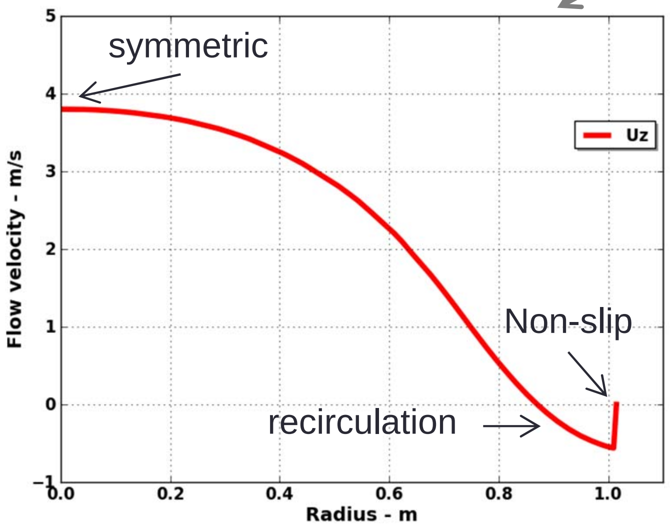


Velocity and temperature fields

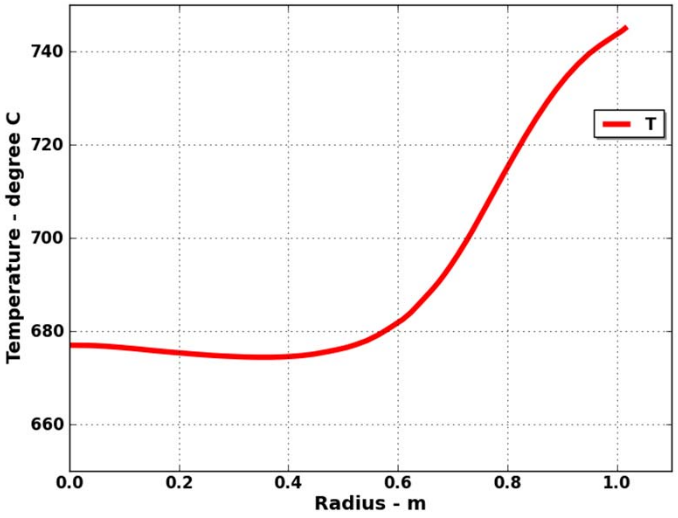
Fuel salt hot Spot

- Hotspot: near the radial blanket and due to a flow recirculation
- Maximum temperature is well below the maximum allowed temperature for the fuel salt (1100°C)





Velocity (half elevation)



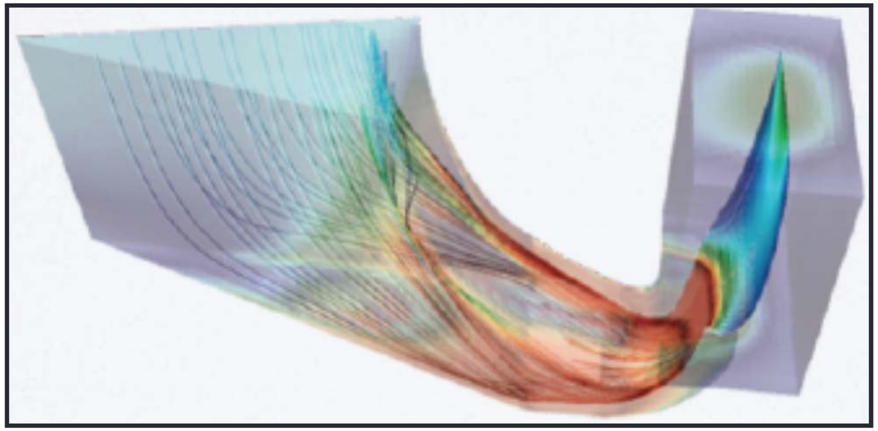
Temperature (half elevation)

CURRENT CHALLENGES RELATED TO THE MODELING OF A MOLTEN SALT

- Physical phenomena inherent to a molten salt
- Experimental techniques
- Numerical modeling

Physical Phenomena Inherent to a Molten Salt

- Complex heat transfer : conduction, convection, radiative and phase change
- Salt optical properties are not well known and depend on the elements dissolved in the fluid
- Volumetric heat source: nuclear fissions and decay heat



Flow streamlines in the core cavity inlet (PhD Thesis A. Laureau)

- 3D flow patterns and turbulence regime (core cavity / reactor components)
- Possible presence of recirculation zones impacting the temperature distributions
- Natural convection may be established under some specific situations

Physical Phenomena Inherent to a Molten Salt

- Neutronics feedback coefficients depend on the fuel salt flow characteristics
- Effects associated to the circulation of the effective delayed neutron precursors
- Possibility of undesirable fuel salt solidification in the fuel loop

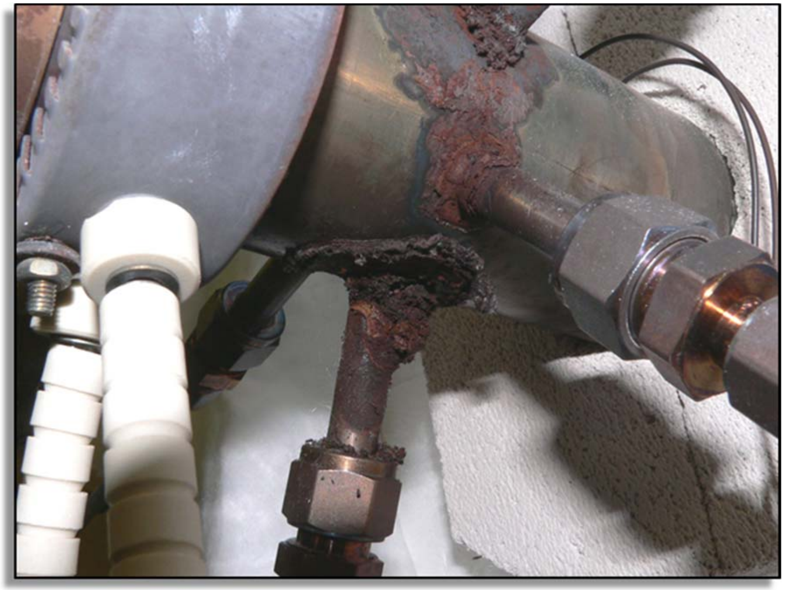
FFFER Loop pipe

Salt ingot obtained after rapid solidification

- Complex solid phase morphology
- Coupling of the T&H with some thermomechanical phenomena during fast transients (pressure waves)

Experimental Techniques

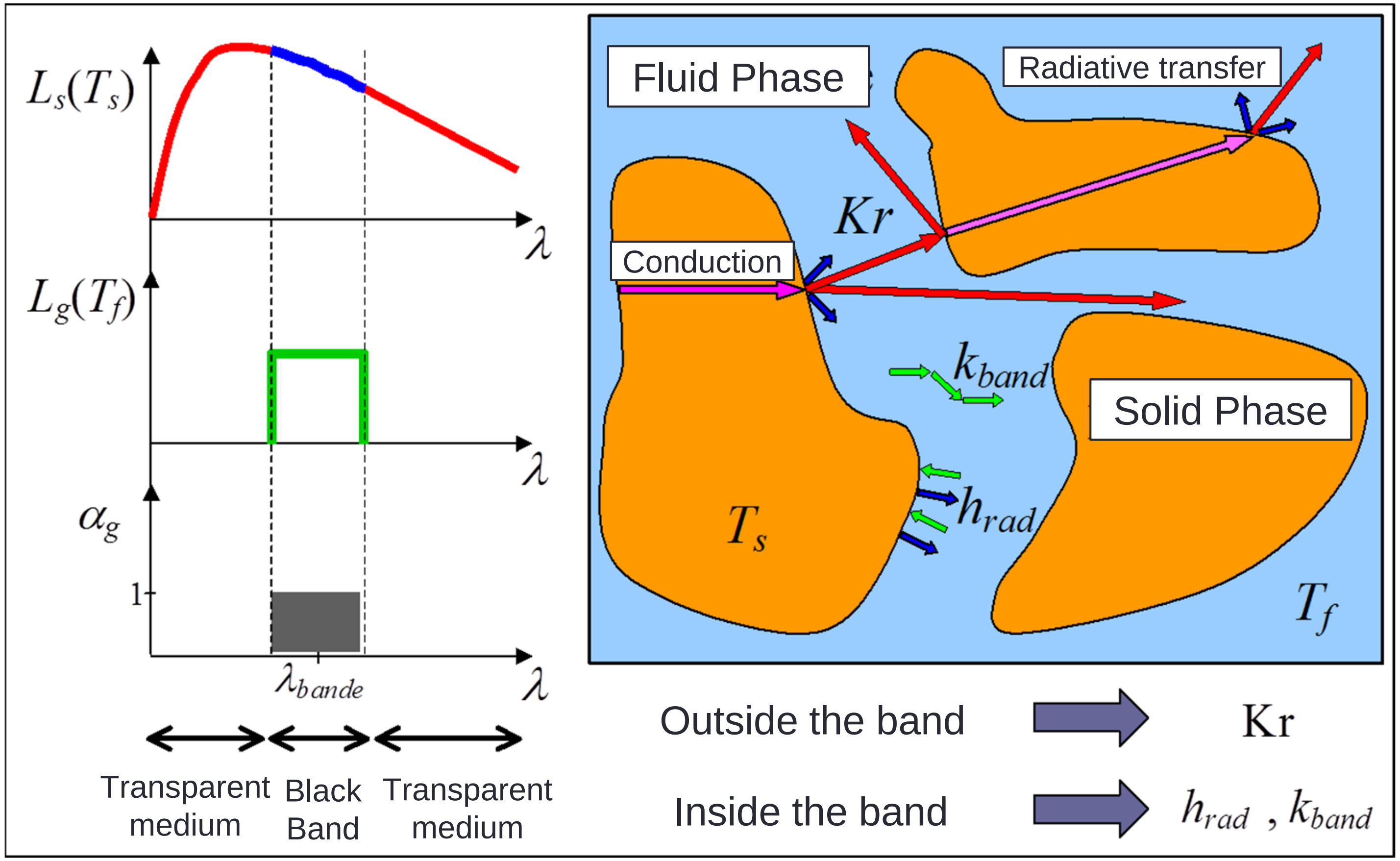
- Fluorides require working with high temperature
  - ❑ Use of electric heating systems
  - ❑ Use of adapted thermal insulation
- Reactivity to water
  - ❑ Require use of inert atmosphere
  - ❑ A small leak could lead to very fast corrosion



- Adapted instrumentation
  - ❑ Implementation of flow visualization techniques is not practical
  - ❑ Flow and level measurements are challenging
- Design of meaningful experiments (repeatability / sensitivity)

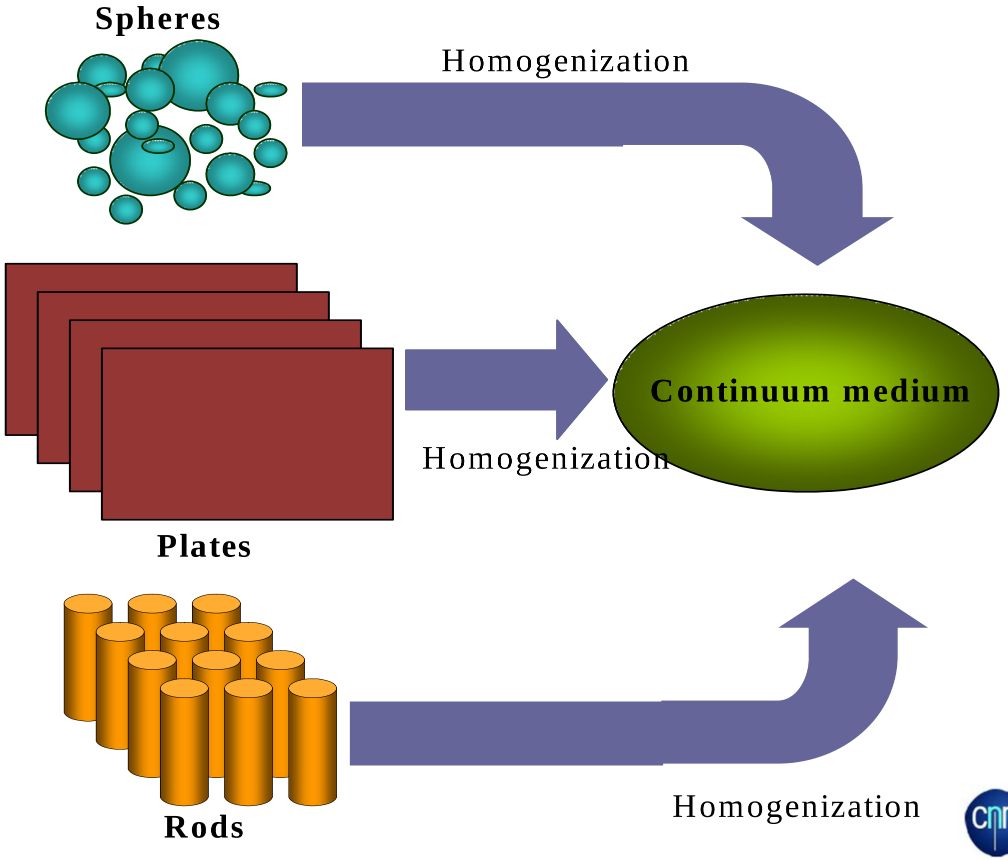
Numerical Modeling

- Triple coupling (Neutronics, Thermo-hydraulics and Thermomechanics)
- Coupled heat transfer mechanisms in various phases (solid, liquid and gas)
- Complex thermal radiation heat transfer



Numerical Modeling

- Adapted RANS turbulence models
- Accuracy cloture equations and wall functions for a molten salt
- Modeling of interfaces during melting/solidification
- Uncertainties on the materials properties
- Use of porous medium approach where the microscopic information is not necessary
    - ❑ MSFR Heat Exchangers
    - ❑ Determination of a space averaged equations
    - ❑ Example: Darcy equations



ONGOING EXPERIMENTAL AND MODELING DEVELOPMENTS

- FFER experiment
- SWATH experiment
- Development of more accurate numeric models

FFFER Forced Convection Loop (Ghetta & Giraud)

- FFFER = Forced Fluoride Flow for Experimental Research (Flinak salt)
- Main Objectives were:
  - ❑ Study the bubbles separation in the salt
  - ❑ Acquire technical experience designing and operating a high temperature salt experiments

- Significant experience has been gained in FFFER in areas such as molten salt instrumentation, flow control, heating and isolation design, vanes, salt circulator, etc. and will be key for the success of the future SWATH facility

Salt at WAll : Thermal ExcHanges

SWATH includes both experiments and numerical simulations

☐ Objectives

- Confirm/improve knowledge on the main assumptions of salt models
- Define the optimal experimental conditions that ensures good experimental data and adequate compatibility with the numerical models

☐ Challenges

- Accidental configurations are not well known thus the study focus rather on the underlying principles
- Developing new correlation is not the main goal of the experiments

Selection of the salt and the experimental domain

Selection of the facility and the experimental working strategy

Selection of an Adequate Salt Model

LiF-ThF$_4$				
Temperature [°C]	**Density** [kg/m^3]	**Heat capacity** [KJ/(m^3.K)]	**Thermal conductivity** [W/(m.K)]	**Viscosity** [Pa.s]
900	3948	8489	≈ 1,03	≈ 5.10^{-3}

Excellent coolant for heat storage … but far less good thermal conductivity that liquid metals

- → **The heat transport mechanism by convection become relatively more important and require a good precision in the T&H models**
- → **It is therefore important that the coolant used as “model” in the experiments is a salt type**
- → **Extensive experience with Flinak from FFFER loop**

SWATH Similitude with the Reactor Salt Flow

- Flow regime (laminar or turbulent) depends on the Reynolds (***Re***) number

$$Re = \frac{\rho L}{\mu} U$$

- Heat convection transfer depends on the Prandtl (***Pr***) number

$$Pr = \frac{\mu C_p}{\lambda}$$

The Pr numbers depends only on the fluid intrinsic characteristics which in our applications are function of the temperature

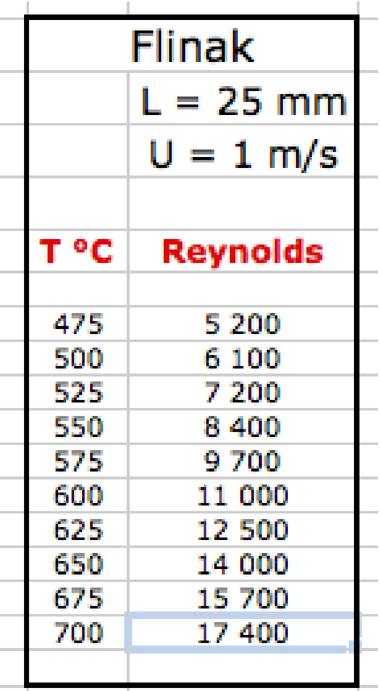
- The natural convection depends on the Grashof (***Gr***) number

$$Gr = \beta \, \Delta T \; g \, L^3 \left(\frac{\rho}{\mu}\right)^2$$

Reynolds **(*Re*)** and Grashof **(*Gr*)** dimensionless numbers can be adjusted to obtain reasonable similitude by changing the experimental setup characteristic length L, the flow velocity U for the ***Re*** and the temperature difference ΔT pour ***Gr***

SWATH Similitude with the Reactor Salt Flow

- **Flow regime (Reynolds number) :**
  The likely normal and accidental fuel salt flow Re ranges can be adequately covered by Flinak. In the example:
  - Experiment temperatures ranging from 475°C to 700°C
  - Experiment characteristic length L = 25 mm
  - Flow velocity U = 1 m/s



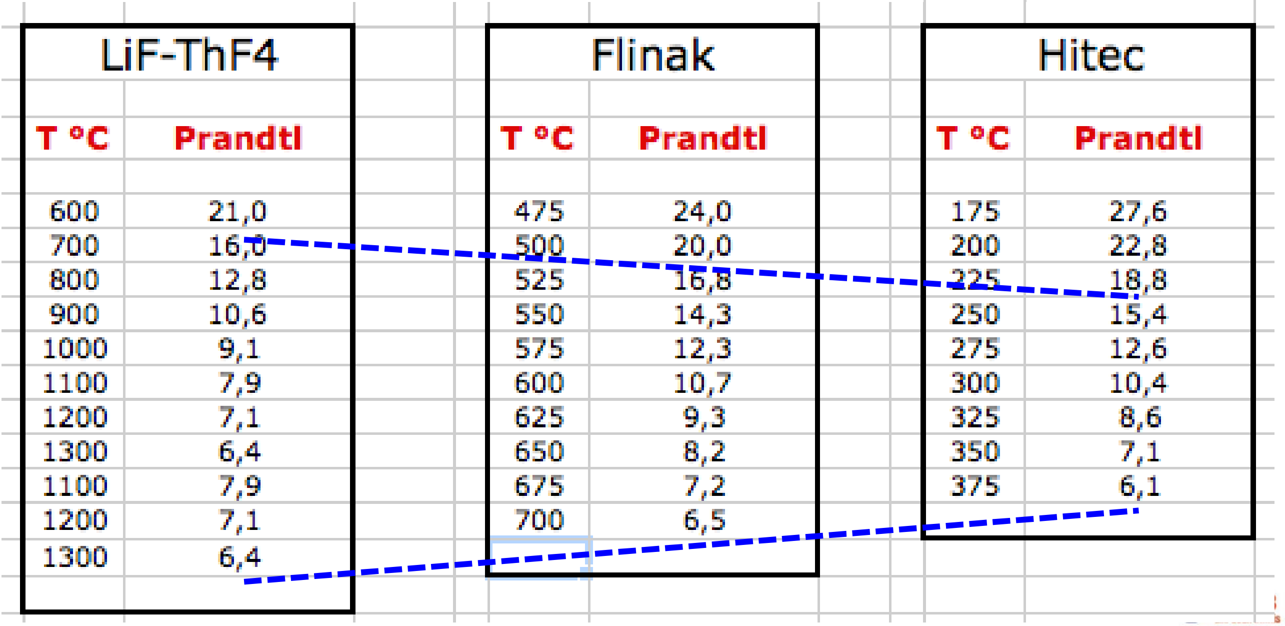
Flinak

L = 25 mm

U = 1 m/s

T °C	Reynolds
475	5 200
500	6 100
525	7 200
550	8 400
575	9 700
600	11 000
625	12 500
650	14 000
675	15 700
700	17 400

- **Heat convection transfer (Prandtl number) :**
  The most likely normal and accidental Prandtl ranges are covered by Flinak and HITEC



LiF-ThF4

T °C	Prandtl
600	21,0
700	16,0
800	12,8
900	10,6
1000	9,1
1100	7,9
1200	7,1
1300	6,4
1100	7,9
1200	7,1
1300	6,4

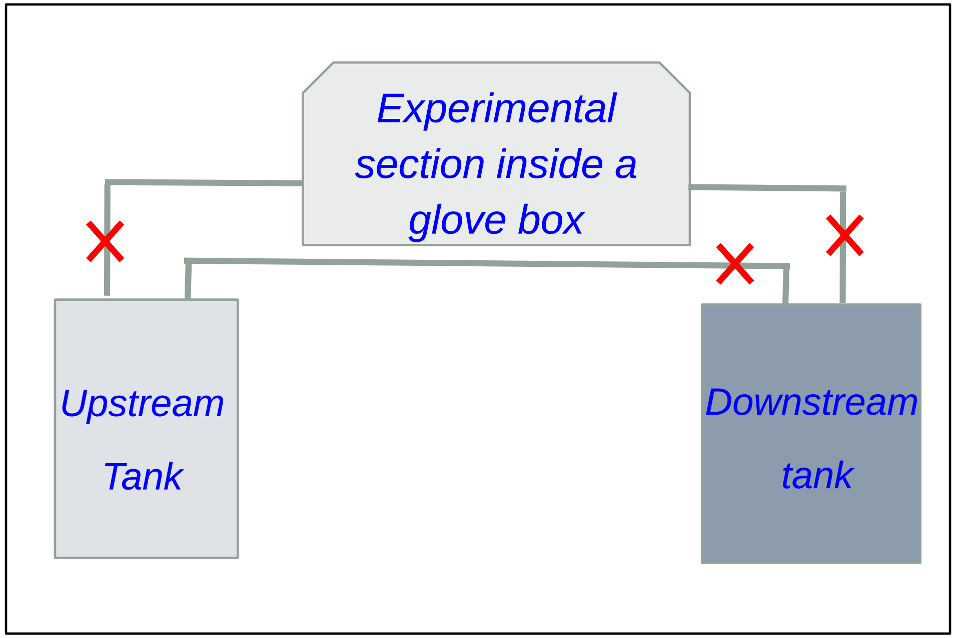
Flinak

T °C	Prandtl
475	24,0
500	20,0
525	16,8
550	14,3
575	12,3
600	10,7
625	9,3
650	8,2
675	7,2
700	6,5

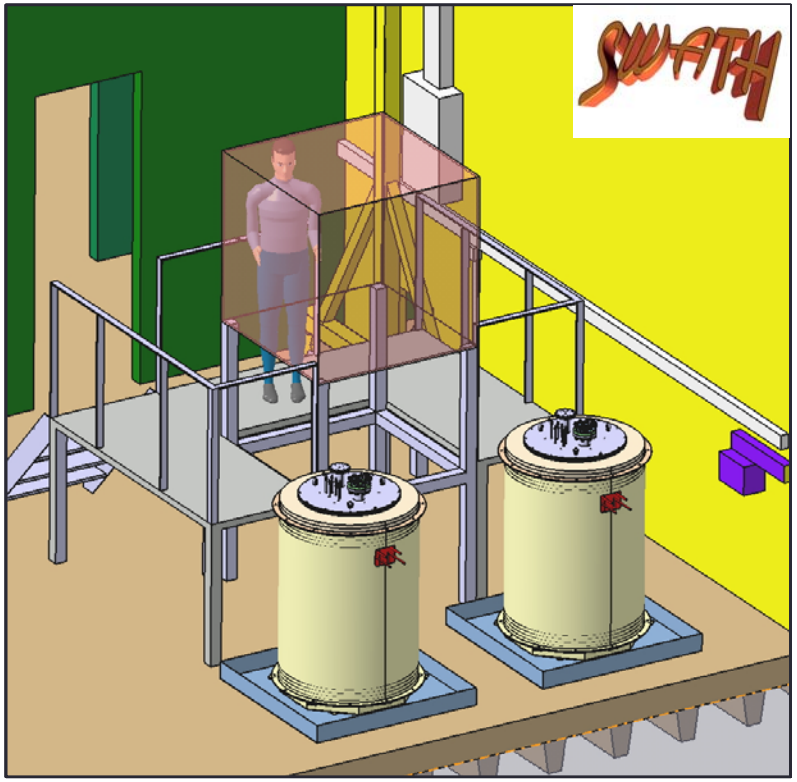
Hitec

T °C	Prandtl
175	27,6
200	22,8
225	18,8
250	15,4
275	12,6
300	10,4
325	8,6
350	7,1
375	6,1

SWATH Experimental Setup



Sketch of the SWATH facility working principles



- ✓ Discontinuous working principle (no pump)
- ✓ Salt flow is initiated and controlled by the pressure difference in the tanks
- ✓ Two different SWATH components: SWATH facility and the experimental section
- ✓ The experimental section included the test component and the instrumentation located inside the globe box
- ✓ The experimental facility will be designed to provide sufficient flow duration to obtain both a well hydraulic and thermal established flow inside the test component
- ✓ Possibility of study the dynamics effects during the flow establishment inside the tested components

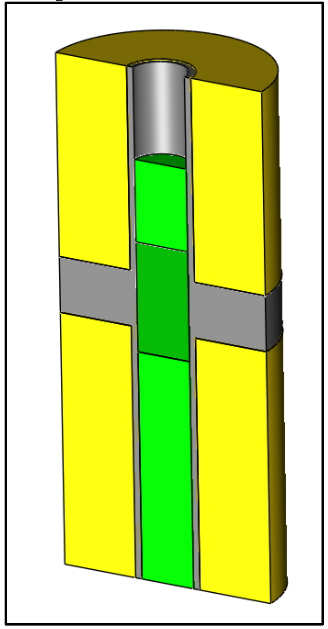
SWATH: Experimental Section

Two types of experiments

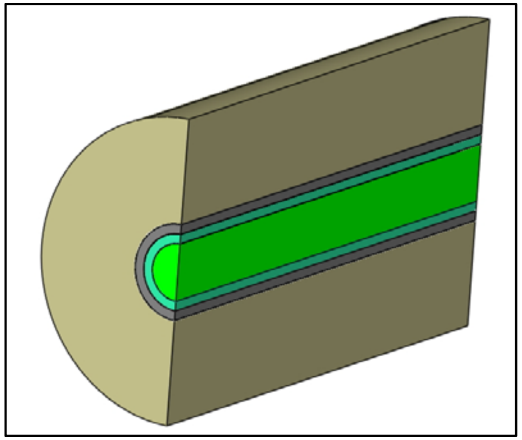
Phase change modeling

Pressure losses and HXs modeling

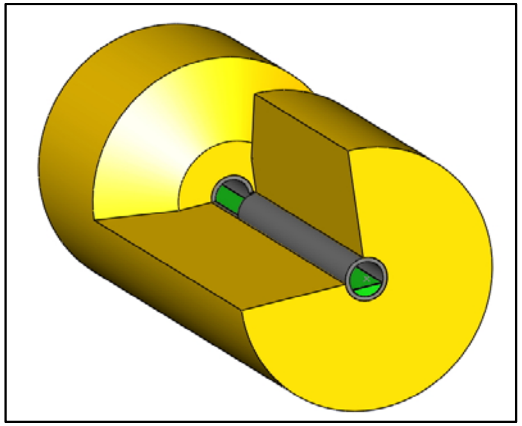
Cold plug crystallization



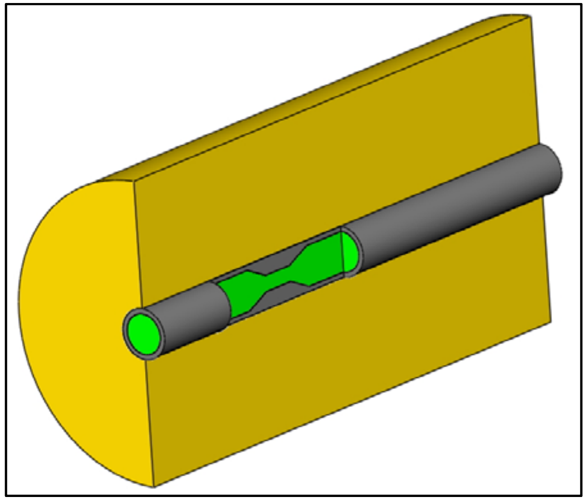
Flow over a cold wall



Flow in an open channel



Flow with an obstacle



SWATH Strategy and Work Organization

Experimental work in water models

- → Help designing the SWATH control systems (pressure, flow, etc.) and instrumentation
- → Allow defining/testing SWATH components (tanks, pipes, valves, experimental section, etc.)
- → Provide early experimental data that can be compared to numerical CFD models
- → Make detailed flow measurements

Numerical work

- → Help designing the SWATH facility components
- → Help designing the SWATH experimental section
- → Developing numerical models needed for the experiment

Development of More Accurate Numeric Models (PhD Tano Retamales)

- Development of RANS models more adapted to a fuel salt:
  - ☐ **Melting and solidification**
  - ☐ **Thermal radiative heat transfer**
  - ☐ **Internal heat source**
  - ☐ **Wall functions**

- Integration of these new models in the MSFR multiphysics model

- Use of a DNS (Direct Numerical Simulation) approach to study:
  - ☐ The effect of the near wall temperature profile on the salt viscosity
  - ☐ The solidification progress using a IBM (« Immersed Boundary Method »)

- Performing a full draining transient study

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Thank you !