This project has received funding from the
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SAMOFAR Final Meeting

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Numerical and Experimental Thermal Hydraulics Studies at the Salt at WAll Thermal ExcHanges (SWATH) Experiment

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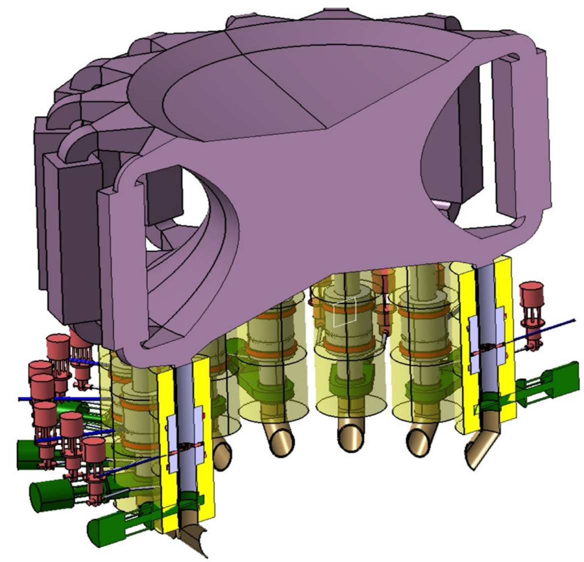
LPSC – University of Grenoble-Alpes, CNRS/IN2P3

Overview

- Starting point: the MSFR concept and SAMOFAR project
- SWATH experimental strategy
- Description of SWATH-W (Water)
- Description of SWATH-S (Salt)
- Conclusion

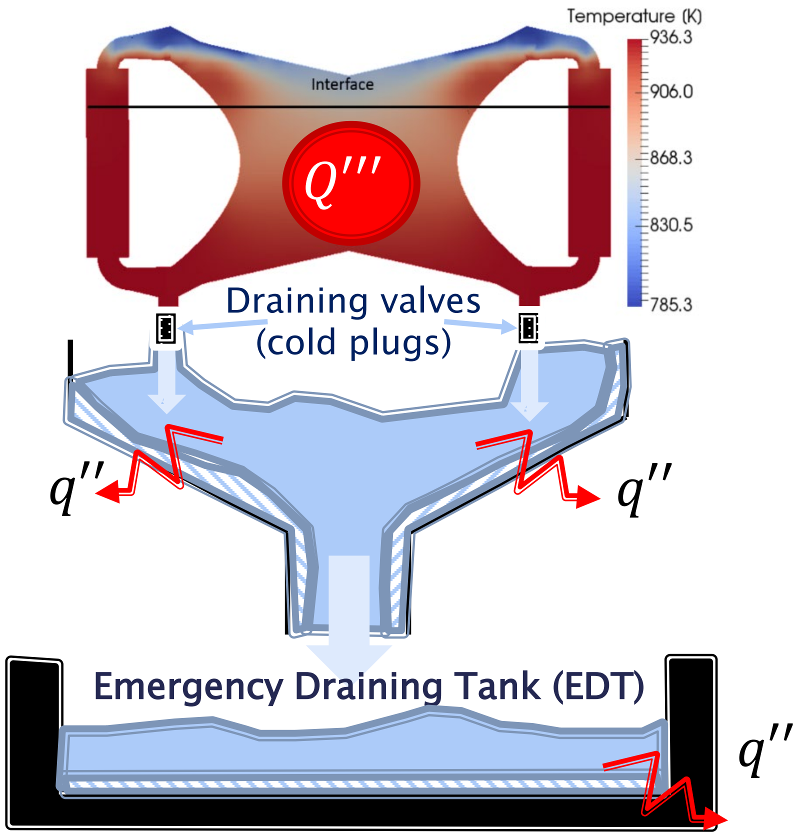
Important MSFR Design Features

- Liquid fuel
  - Molten salt acts as nuclear fuel and coolant
  - A significant part of the fissile inventory is outside the core
  - Components of the fuel circuit exposed to high temperatures/neutron flux



- No control rods in the core
  - Reactivity is controlled by the heat removal in the HXs and fuel salt feedback coefficients, continuous fissile loading and geometry of fuel salt mass
  - Not need to control 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 and cooling margins
  - Fuel draining can be done passively or by operator action

Example of Design/Safety study: Draining transient following a Station Blackout



- Initial event: Station blackout or total electric power failure (t = 0 sec)
- Draining of the fuel salt starts following the opening of the draining valves (e.g. cold plugs melt)
- PIRT analysis: different phenomena may occur during this transient
  - Gas–liquid flow with thermal exchanges
  - Gas–liquid flow mechanical interactions
  - Buoyancy effects
  - Turbulent effects
  - Decay heat source term
  - **Radiative heat transfer**
  - **Fuel salt solidification/melting**

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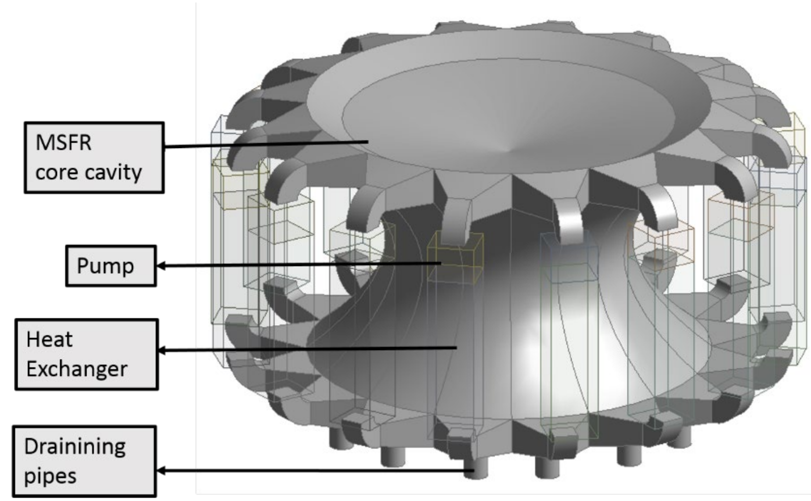
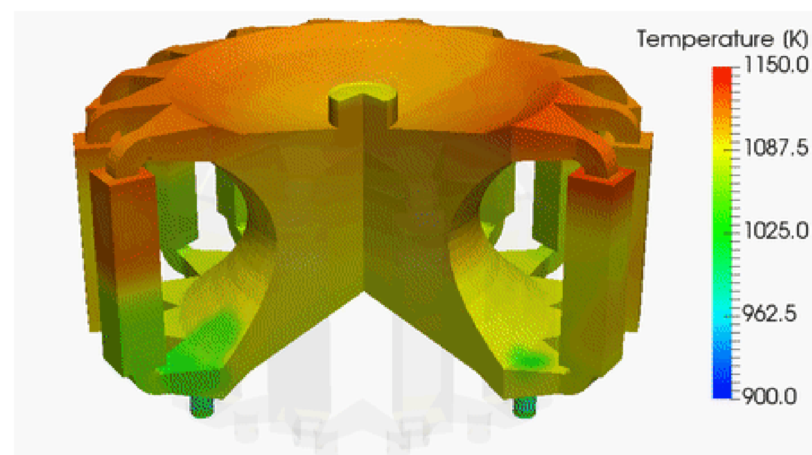
Example of Design/Safety study: Draining transient following a Station Blackout

- All draining valves open at t=0 sec
- Example of numerical model (PhD M. Tano Retamales):
  - ✓ Homogenized two phases model (mixture),
  - ✓ Fission power + residual heat,
  - ✓ Incompressible flow with Boussinesq approximation,
  - ✓ RSS RANS model,
  - ✓ Salt solidification,
  - ✓ Radiative heat transfer,
  - ✓ HXs modeled as porous medium,
  - ✓ All fuel circuit walls are adiabatic (except in the HXs)





M. Tano-Retamales, P.R. Rubiolo, O. Doche, « Multiphysics study of the draining transients in the Molten Salt Fast Reactor », 2018 International Congress on Advances in Nuclear Power Plants (ICAPP 18), pp.215-225, Charlotte (USA), Avril 2018.

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SWATH Contribution to SAMOFAR Objectives

- Demonstrate that the physical principles on which are based the components of the fuel salt draining system are well understood
- A novel safety evaluation methodology is required
- The concept of defense in depth needs to be adapted: radiative products confinement barriers have to be clearly identified
- Some of the most important reactor system has to be further designed (cold plug, salt storage system, salt cooling, etc.)
- The reactor operation modes in normal conditions need also further definition

Numerical models more adapted to the specific molten salt phenomena were needed

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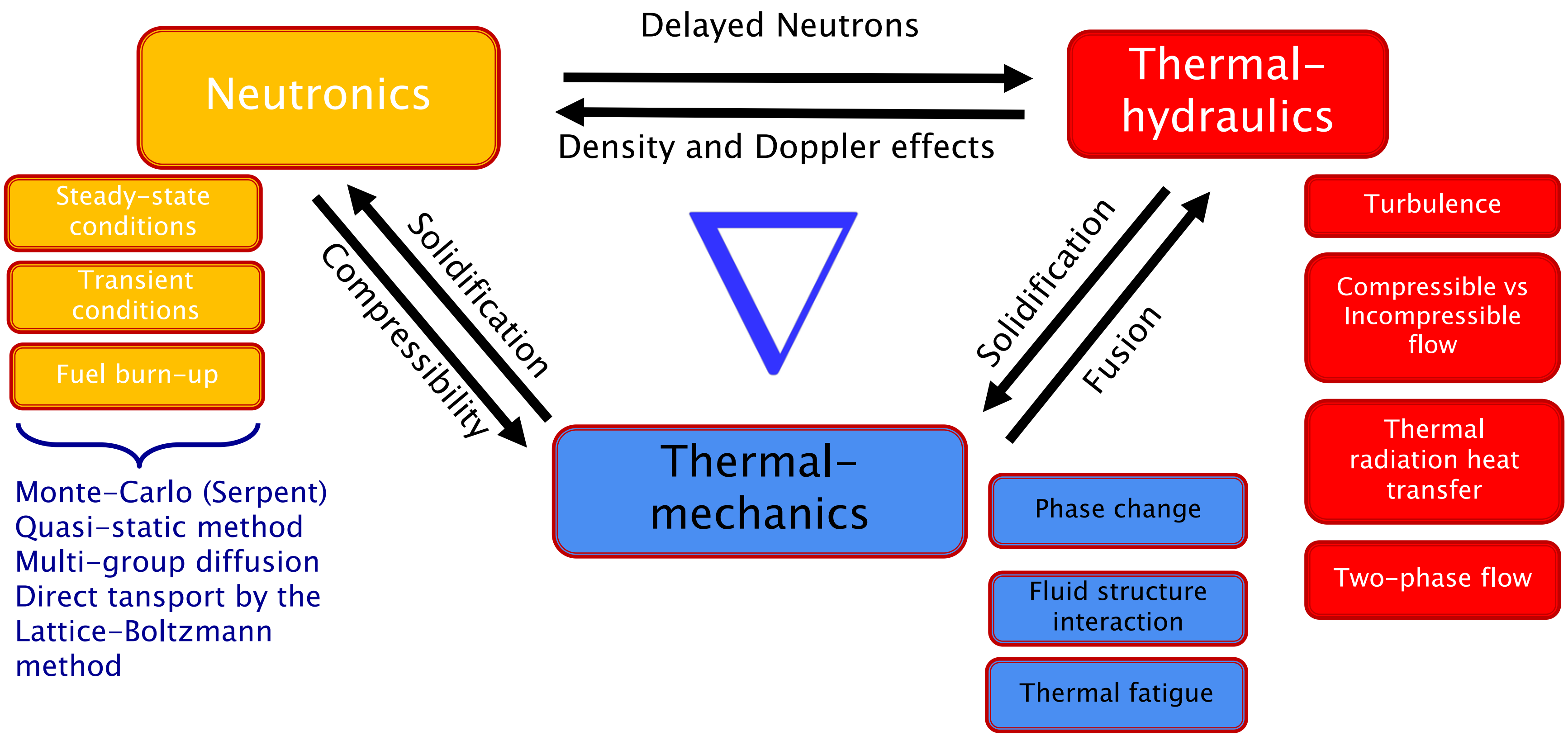
Molten Salts Model Development Requirements

Some of the key molten fuel salt phenomena requiring more accurate numerical models for performing design and safety studies:

- Complex heat transfer:
  - Conduction, convection, radiative
  - Salt optical properties are not well known and depend on salt composition
  - Volumetric heat source: nuclear fissions and decay heat
- Phase change: possibility of undesirable fuel salt solidification in the fuel loop with complex solid phase morphology (and properties)
- 3D flow patterns and turbulence regime (e.g. core cavity)
  - Possible presence of recirculation zones impacting the temperature distributions
  - Natural convection may be established under some specific situations
- Strong coupling between neutronics and thermal hydraulics (feedback coefficients, transport of delayed neutron precursors and PFs)
- Coupling of the T&H with some thermomechanical phenomena (salt compressibility and wall effects)

… but should also consider corrosion and chemistry

Multi-physics Modeling of a MSR



- Monte-Carlo (Serpent)
- Quasi-static method
- Multi-group diffusion
- Direct tansport by the Lattice-Boltzmann method

SWATH Experimental Strategy

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Salt at Wall: Thermal ExcHanges (SWATH Experiments)

- Main objectives:
  - Improve molten salt numerical models
  - Demonstrate cold plug working principles
- Key point: ensure that experimental data uncertainties are smaller than the effects of the studied thermal hydraulics phenomena
- Phenomena investigated in SWATH (PIRT):
  1. Heat transfer in very simple geometries
  2. Evolution of the salt solidification interface with and without forced convection
  3. Solidification along a cold wall after successive molten salt flows (lava flow like)
  4. Flow characteristics in an open channel
  5. Turbulence effects on the flow velocity
  6. Radiative heat transfer in the salt

P. Rubiolo, M. Tano Retamales, V. Ghetta and J. Giraud, "High temperature thermal hydraulics modeling of a molten salt: application to a molten salt fast reactor (MSFR)", ESAIM: Proceedings and surveys, Vol. 58, pp. 98–117 (2017).

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Salt at Wall: Thermal ExcHanges (SWATH Experiments)

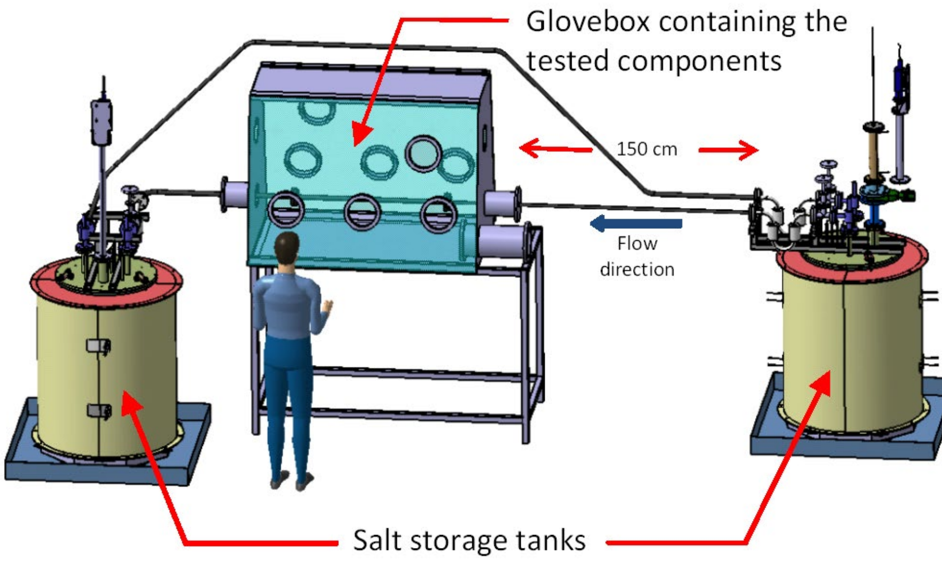
- SWATH experimental setup is composed of two elements:

    1) **SWATH facility**: allows stablishing a controlled flow

    2) **Tested components**: simple geometries were phenomena are investigated

- Discontinuous working principle: stable flow is established by regulating pressure difference between two tanks

- Tank pressure control system relies on pressure drop measurements at specific loop components and on tank level measurements



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SWATH Experimental Strategy

Design of SWATH components poses significant challenges:

- High working temperature (e.g thermal expansion)
- High melting point of salts (need of electrical heaters and thermal insulation)
- Salts chemical reactivity with water vapor (glovebox filled with argon)
- Lack of adapted instrumentation (flow visualization techniques are challenging)
- Variation of the thermodynamics properties of the salt due to contamination

To overcome these difficulties two facilities were built:

SWATH-W (water at room temperature): to study velocity field

SWATH-S (molten salt): to investigate salt heat transfer and phase change

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Geometries Investigated in SWATH

Geometry	Facility	Measurements
Backward Facing Step (BFS)	**SWATH-W**	• Flow rate • Velocity profile
Close and open channels	**SWATH-W** **SWATH-S**	• Flow rate • Velocity profile • Temperature
Molten cavity	**SWATH-S**	• Temperature • Solidification thickness • Solid phase structure
Cold plug	**SWATH-S**	• Electrical and cooling power • Melting time • Molten salt level in the cavity

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Description of SWATH-W (Water)

Objectives of SWATH-W

- Working fluid: water at room conditions
- Various purposes for SWATH-W isothermal hydraulic tests
  - Flow velocity measurements by PIV (Particle Image Visualization)
  - Support SWATH-S facility design work:

    - Performance of the pressure control system

    - Verify instrumentation for pressure and flow

    - Verify tank levels measurement system
  - Aide to the definition of experiment procedures (e.g flow startup)
  - Support modeling efforts:

    - Improve CFD hydraulic models (RANS et LES)

    - Identify/understand potential systemic errors arising from the circuit (inlet test conditions, flow fluctuations, control system, etc.

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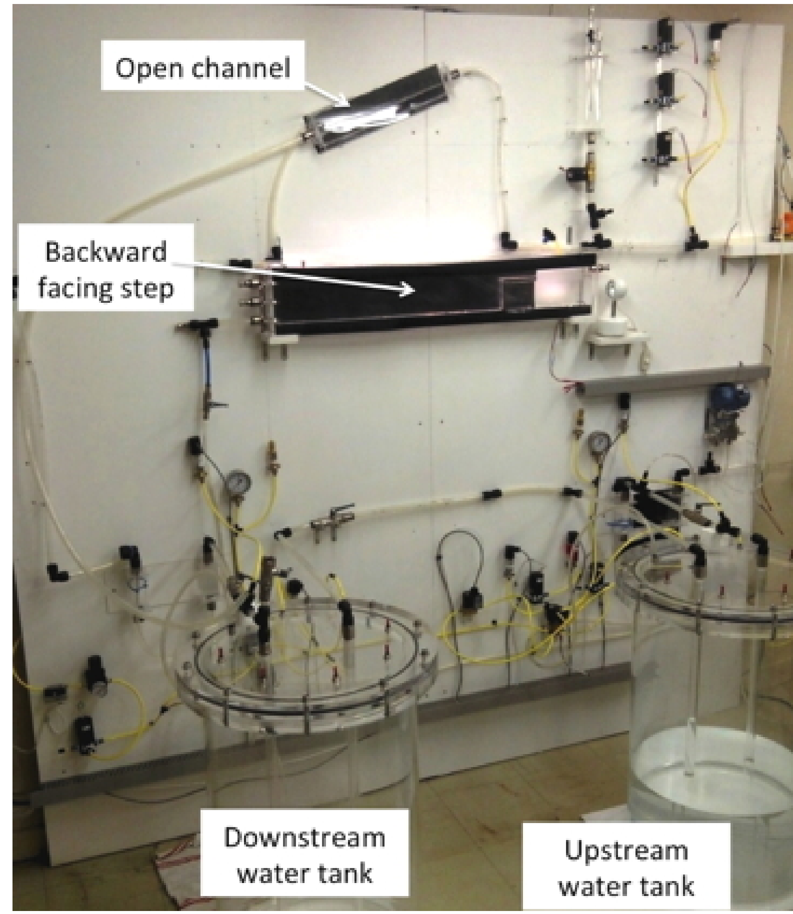
Main SWATH-W Characteristics

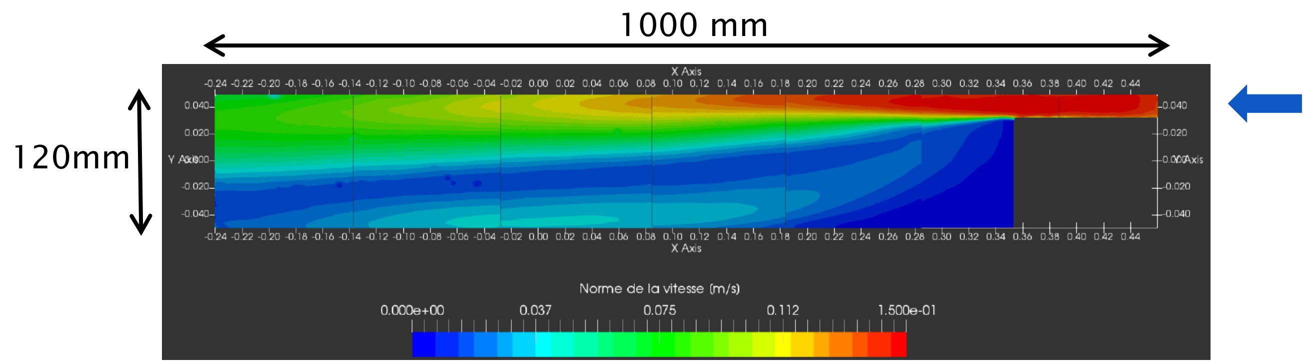
Fluid	Water at room temperature/pressure
Tank material	Plexiglas
Tank dimension	Inner/Outer diameters : 480 mm/500 mm Inner height : 810 mm
Fluid volume	60 liters
Piping	Inner/Outer diameters : 11 mm/16 mm
Flow rate measurements	Compact Ultrasonic Flowmeter
Water level	Laser measurements and electronic contactors
Min-Max flow	By pressure control: 0.5 l/min to 7 l/min By pump : 0.5 l/min to 10 l/min



PIV Measurements to Improve SWATH RANS Models

- A widely tested Back Step geometry was investigated in SWATH-W because of its high sensibility to the turbulence modeling.
- Predictions using standard RANS approaches (k-epsilon, k-omega, etc.) for this geometry show to differences up to 10 to 20% in the recirculation zone
- PIV measurements have been made at three different regimes (Re= 200, 1100 and 3900) while flow circulation in SWATH-W was established using either a pump or the pressure control system

PIV averaged velocity field at Re = 3900



- Experimental results were used to:
  - Verify similarity of flow conditions using a pump and the pressure control system
  - Improve RANS models

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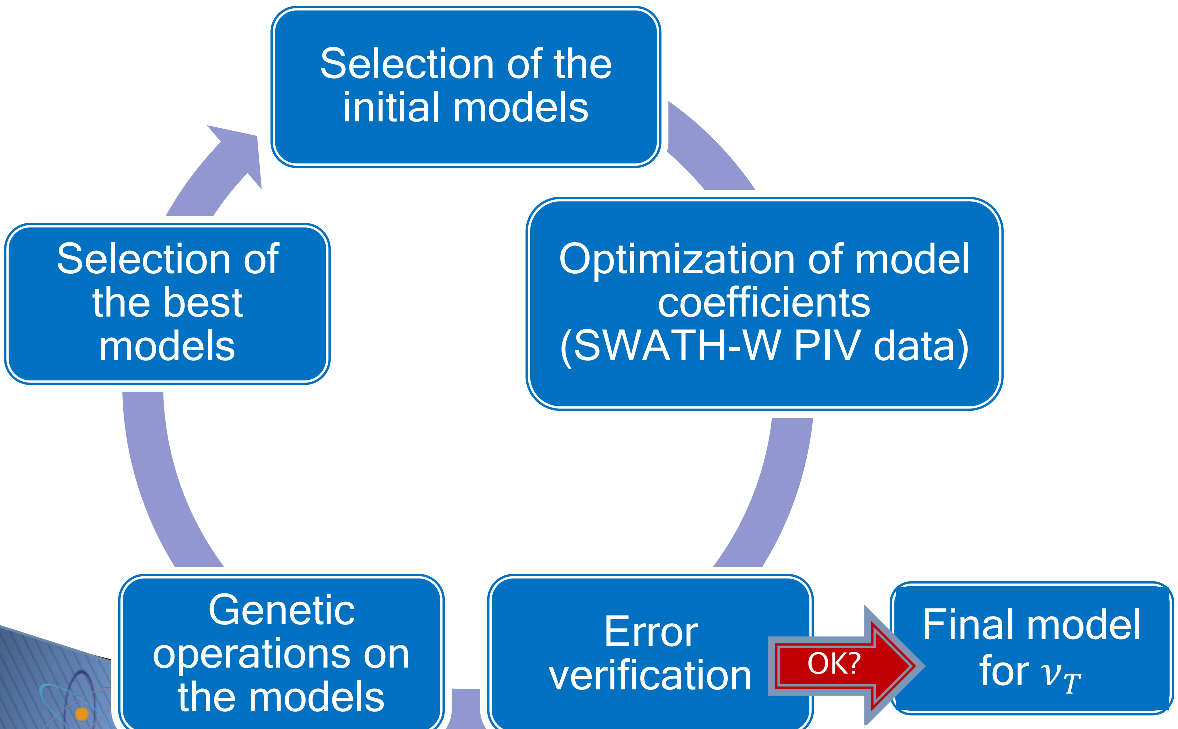
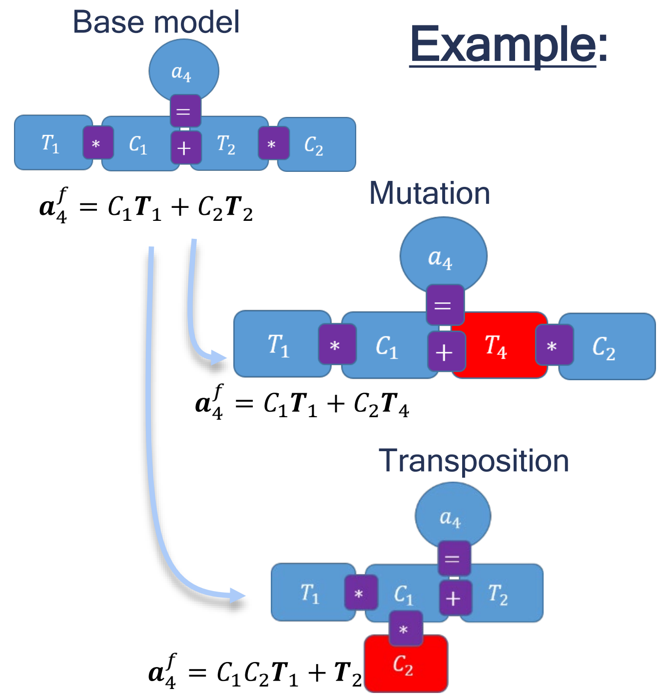
GEATFOAM

- A methodology has been developed to calibrate RANS models (GetFOAM) based on experimental data with target error < 5% (PhD M. Tano Retamales)
  - Improving the Reynolds Shear Stress Tensor modeling by data driven approaches
  - Developing specific turbulence modeling

$$\boldsymbol{\tau}^f = \boldsymbol{\tau}^f_{iso} + \boldsymbol{a}^f = -\frac{2}{3}\rho k \boldsymbol{I} + 2\rho\nu_t \sum_{k=1}^{10} c_k(I_1, \dots, I_5)\boldsymbol{T}_k$$



Example:



M. Tano-Retamales, P.R. Rubiolo, O. Doche, « Development of Data-Driven Turbulence Models in OpenFOAM – Application to liquid fuel nuclear reactors », Proceedings 11th OpenFOAM workshop, pp. 106-118, Guimaraes (Portugal), November 2016.

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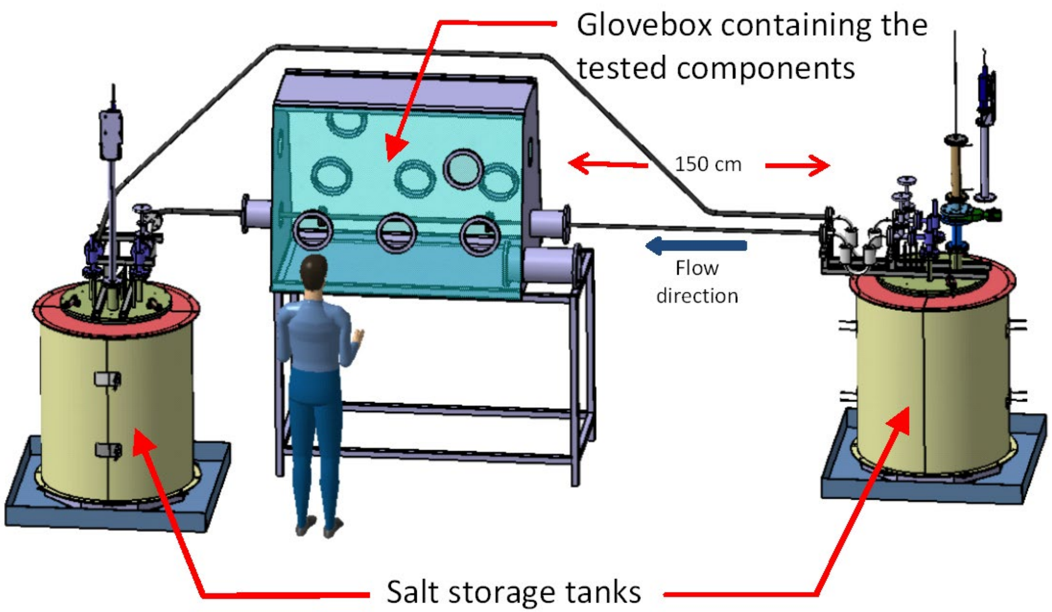
Description of SWATH-S (Salt)

Objectives of SWATH-S (Molten Salt)

- Objective: investigate the accuracy of salt heat transfer and phase change models
- Salt mass flow rate is calculated from tank level variations according to two methods: laser beam system and electrical contactors system
- Straight inlet pipe to ensure fully developed flow
- All components are electrically heat and thermally isolated
- Mechanical stresses arising from thermal expansion are reduced by using deformable connections, pipe bends and free moving components
- All components made on SS 304L



Selection of the Salt Model

- Molten salts such as LiF-ThF_4 have excellent heat storage capabilities but less good thermal conductivity

$LiF-ThF_4$				
Temperature [°C]	**Density** [kg/m³]	**Heat capacity** [KJ/(m³.K)]	**Thermal conductivity** [W/(m.K)]	**Viscosity** [Pa.s]
900	3948	8489	≈ 1,03	≈ 5.10^{-3}

- The heat transport mechanism by convection become relatively more important and require a good precision in the T&H models

- It is thus 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 requires to consider at least Reynolds (Re), Prandtl (Pr) and Grashof (Gr) numbers ($\mathrm{Gr} = \beta \Delta T g L^3 (\rho / \mu)^2$)

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Selection of the Salt Model

- **Flow regime** ($\mathrm{Re} = \dfrac{\rho L U}{\mu}$):

  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** ($\mathrm{Pr} = \dfrac{\mu C_p}{\lambda}$):

  The most likely normal and accidental Prandtl ranges are covered by FLiNaK and HITEC

✓ **Re** and **Gr** numbers can be adjusted to obtain reasonable similitude by changing L, U and ΔT

✓ **Pr** depends only on the fluid intrinsic characteristics (i.e. temperature)

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

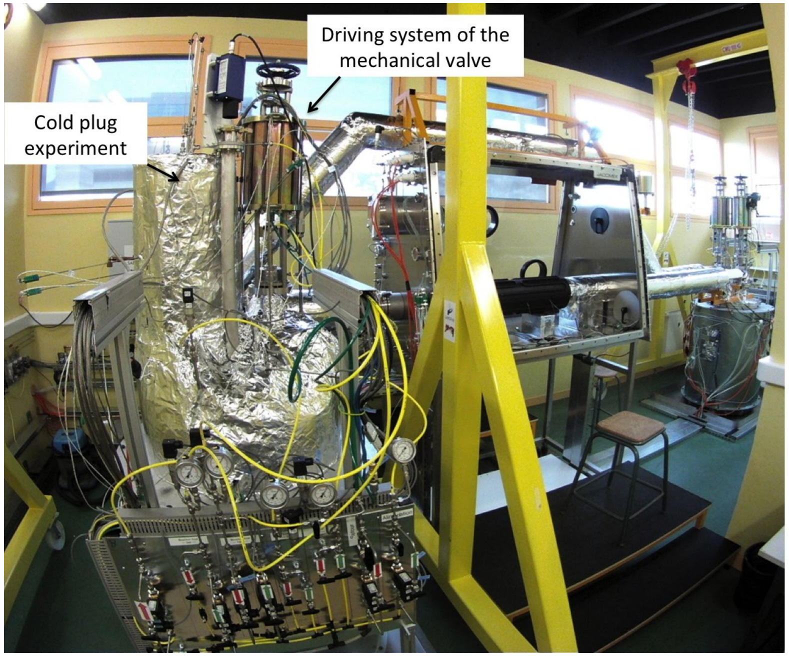
T °C	Prandtl
475	24,0
500	20,0
525	16,8
550	14,3
575	12,3
600	10,7
625	9,3
650	8,2
675	7,2
700	6,5

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

Main SWATH-S Characteristics

Fluid	FLINAK Service temperature : 500°C to 700°C
Tank volume	60 liters (steady flow duration between 5 to 30 minutes depending the volumetric flow rate)
Tank material	304 L
Tank dimension	Inner/Outer diameters : 440 mm/456 mm Inner height : 938 mm
Design Pressure	1 bar at 600°C
Piping	Inner/Outer diameter : 20 mm/25 mm Material : 304 l (seamless tube)
Flow rate	1 l/min to 8 l/min



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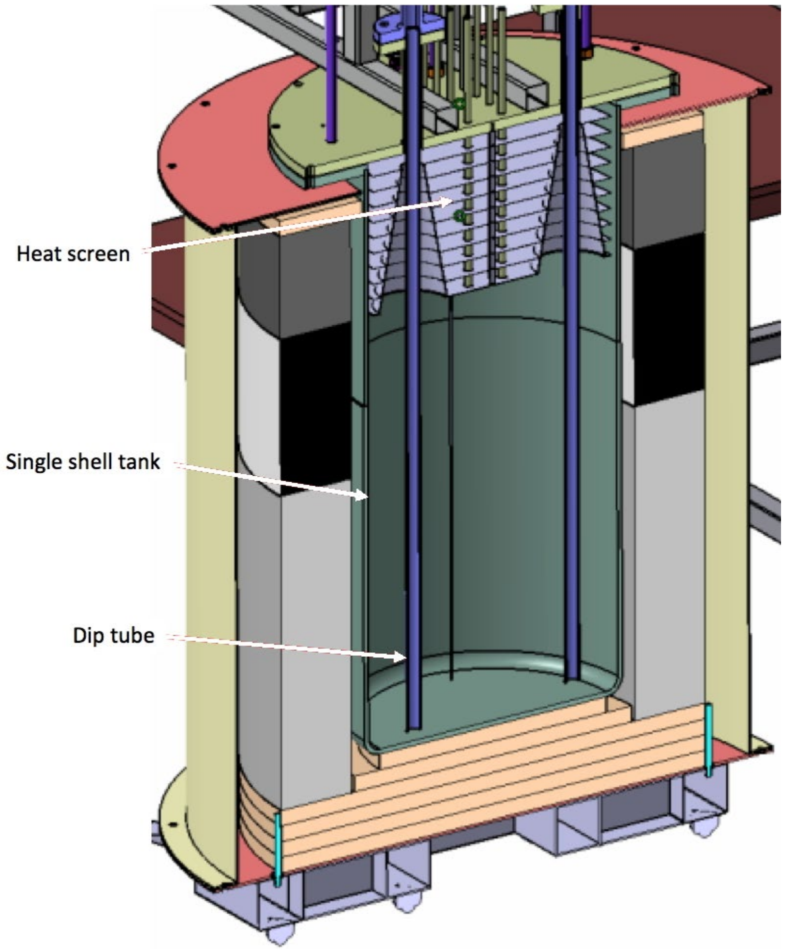
Molten Salt Tanks

- The salt tanks volume has been dimensioned to about 60 liters of molten salt
- This allows establishing a steady flow for several minutes (longer than the section thermal inertia)
- To avoid welds in contact with the molten salt, the molten salt tanks are made of a single stainless steel shell. The shell was manufactured by machining in a bulk cylinder of SS304
- Heat screens to avoid upper structures overheating
- Each tank has two dip tubes for allowing the inlet and outlet flow of the molten salt
- The tank is surrounded by a thermal insulation and the temperature is controlled by an electric heating system



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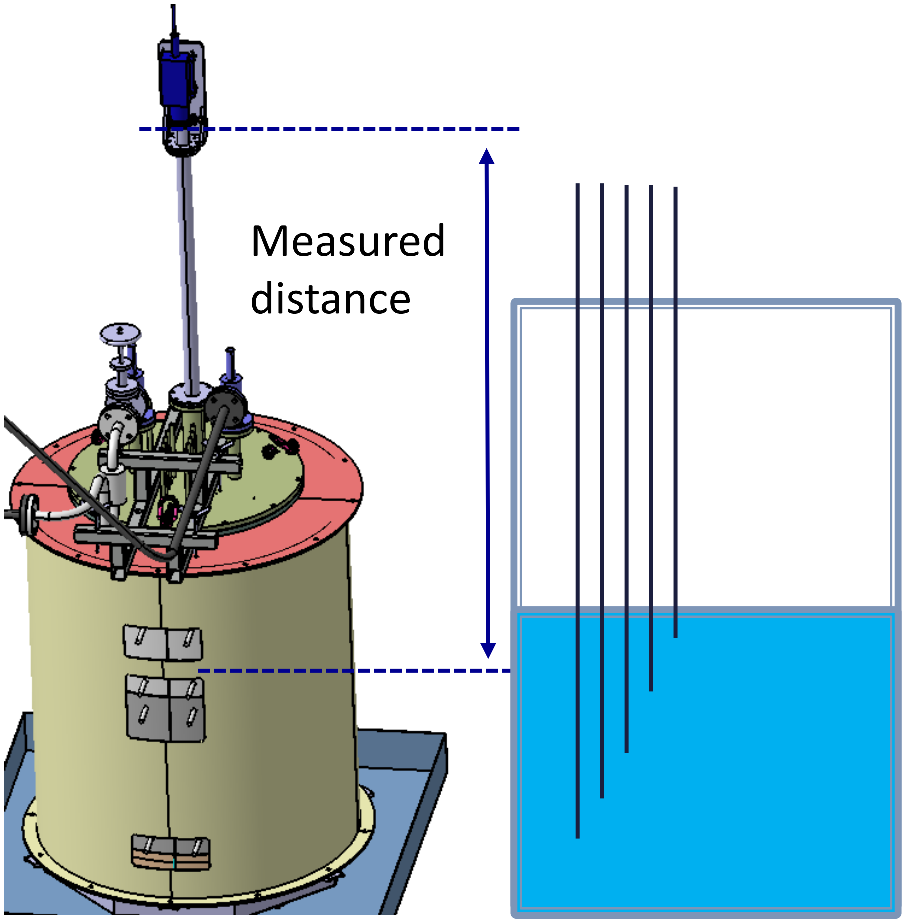
Flow Rate Measurement

- The SWATH-S flow rate is a critical experimental measurement
- Two different techniques:
  - Laser system: proportional level measurement
  - Electrical contactors system: stepped measurement thanks to electrical contactors (f = of 10 KHz)
- The pressure control system uses two sources of information:
  - Pressure drop caused by the expansion chamber in the phase change valve
  - Flow rates measured from tank levels



Laser system **Contactors system**

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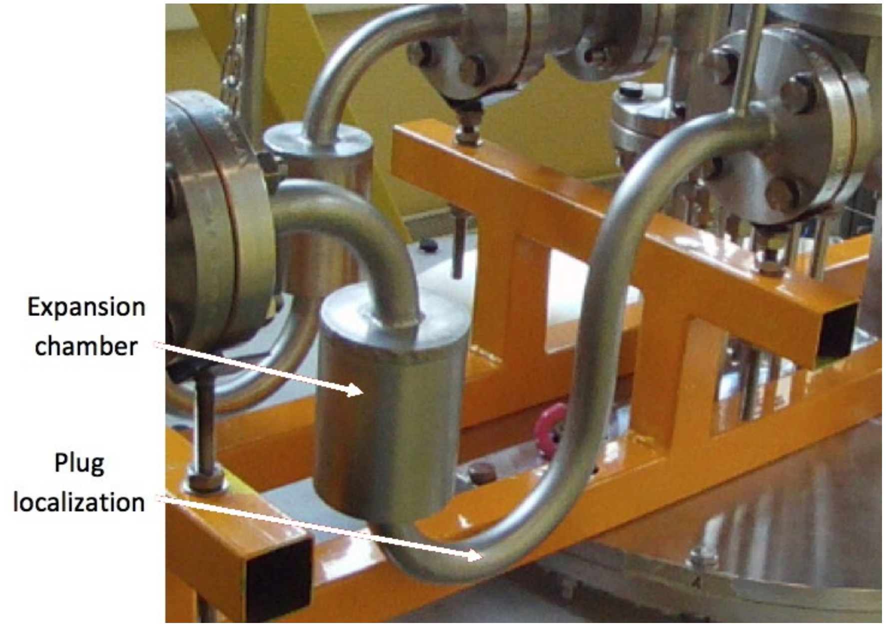
Phase Change Valves

- The inlet and outlet pipes used for the molten salt flow between the two tanks are equipped with valves
- Two different valve designs arranged in series :
  - Phase change valves
  - Industrial valves
- Phase change valves used bended tube and an expansion chamber



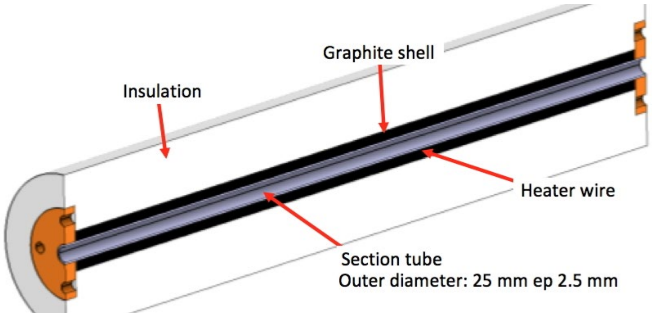
- Valve is closed after the formation of a solid salt plug inside the bended part of the pipe
- Volume of the expansion chamber is designed to allow forming a solid plug after the other sections of the pipe has been voided of molten salt

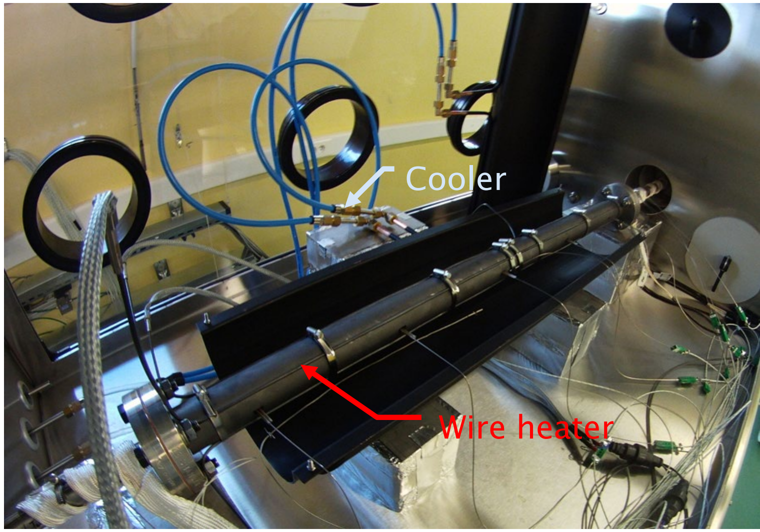
Design of the Test Sections

- The test sections geometries designed to study various flow phenomena
- Main experimental measurements are: pressure drop in some facility components, the temperature variations in the test section and circuit flow rate
- In some of the experiments involving solidification process the solid phase size will be measured
- Experimental design should minimize thermal inertia
- Experiments can be divided into two categories:
    - Sections used to study heat exchange experiments in closed or open channels
    - Sections used to perform molten salt phase change experiments

Close Channel Section

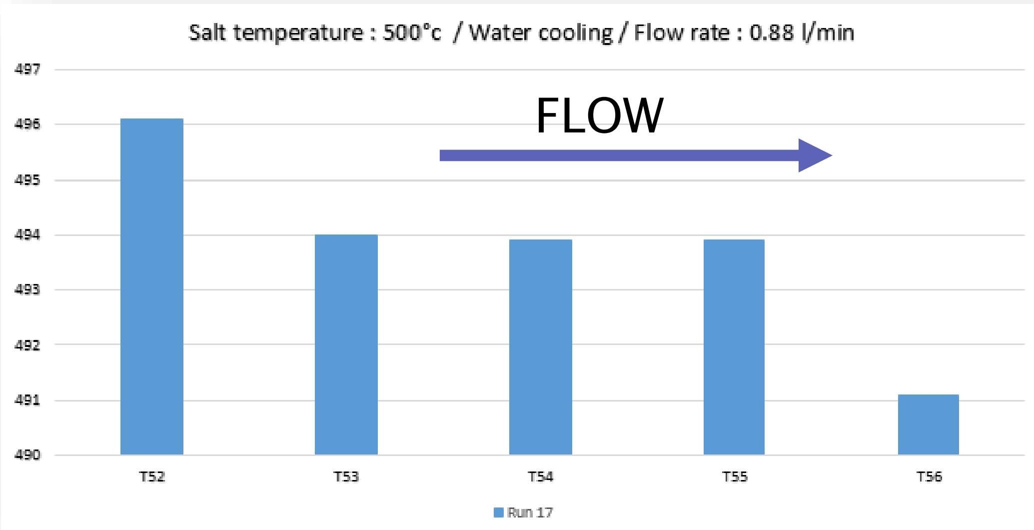
- Used to study heat transfer in relatively simple geometries: heat transfer models for circular and rectangular channels
- Channel is thermally insulated and has electrical heaters to control wall temperature
- Channels length of about 100 cm
- Different inner diameters
- Flow rates ranging from 1 to 8 liters per minute were investigated. Various inlet temperatures
- Maximum channel heating is about 2-3 kW
- Test section contains a graphite shrew to obtain a more uniform temperatures on the wall
- Section instrumentation: thermocouples on the external wall of the channel, inside the thermal isolation and at the inlet/outlet of the channel

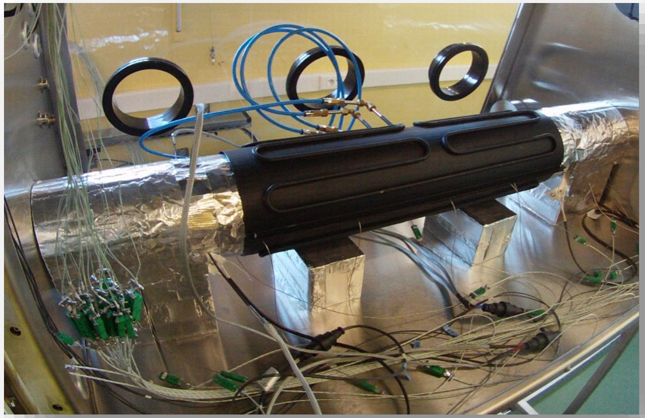


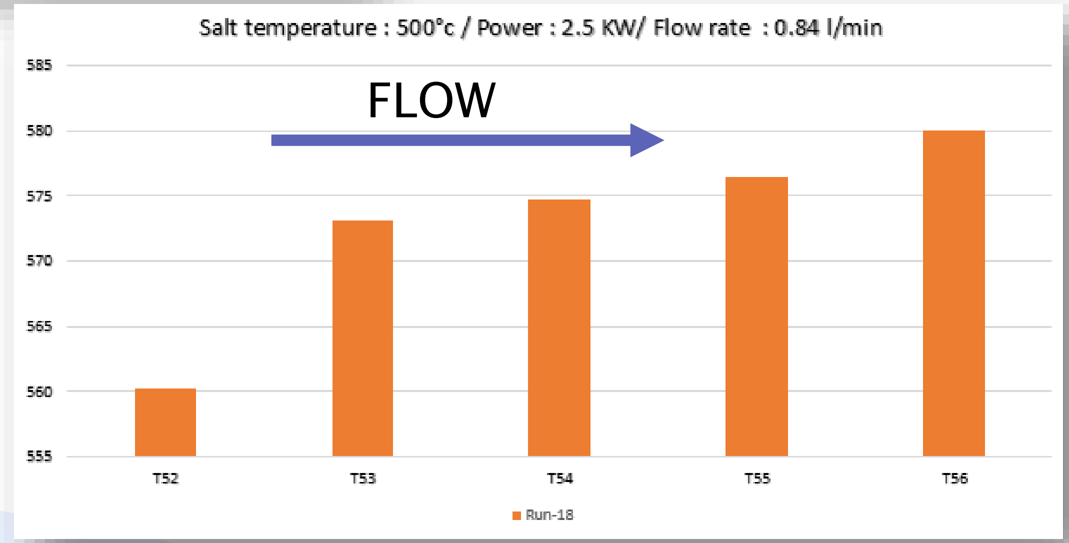


P. Rubiolo, M. Tano-Retamales, J. Giraud, V. Ghetta, J. Blanco, O. Doche, N. Capellan, « Design of close and open channel experiments to study molten salt flows », 2018 International Congress on Advances in Nuclear Power Plants (ICAPP 18), Charlotte (Etats Unis), Avril 2018.

Close Channel Section







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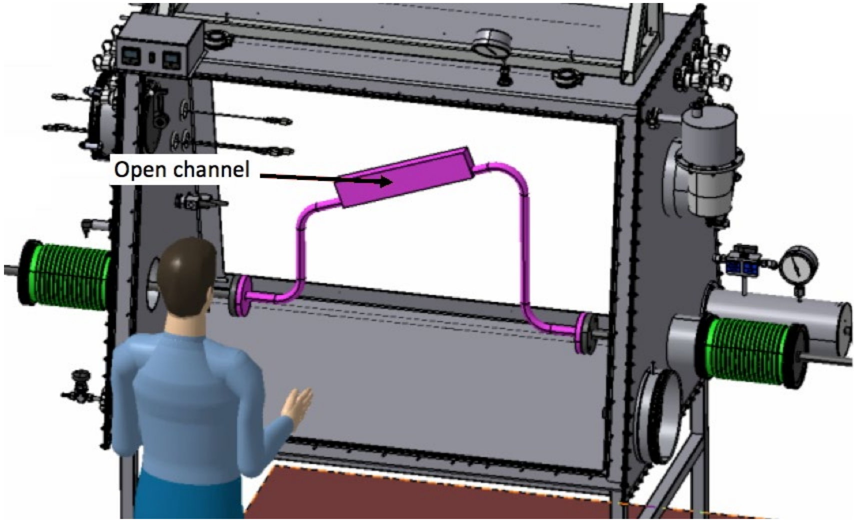
Open Channel Section

- Objective: investigate the flow characteristic in presence on a free surface: free surface flow models
- Same design principles as the close channels (i.e. require a heating system and a thermal isolation to control the temperature)



- Flow rate is no longer controlled by the pressure differential but by the inclination angle
- Surface tension effects can be neglected
- The section could be used to investigate the radiative heat losses at the surface and also the solidification process if cooling in the lower plane

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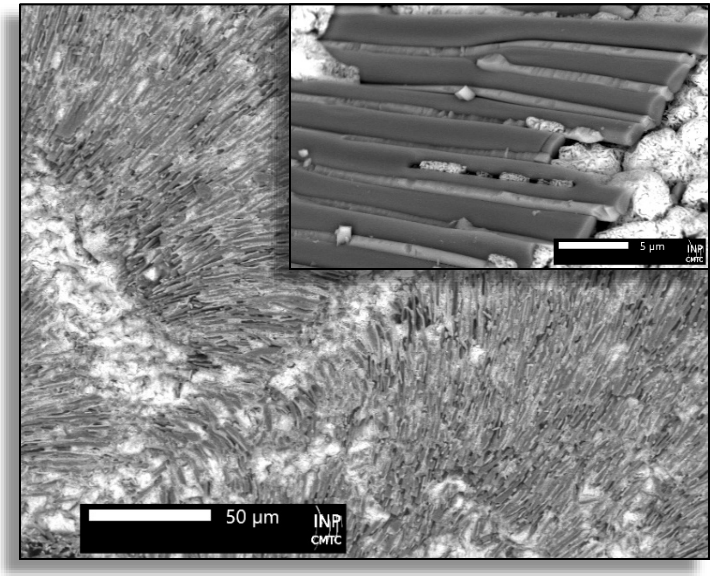
Phase Change Experiments and Modeling

- Objective: investigate the accuracy of the two solidification models developed for the ternary system Fli-KF-NaF (PhD Tano Retamales):
  - **MASOFOAM** (MAcro-scale SOlification Foam): implements a solidification-convection coupled solver based on a mixture model
  - **MUSOFOAM** (MUlti-scale SOlification Foam) improve the accuracy of the previous model by solving the species diffusion equation with a length adaptable phase field model
- Two conditions studied for salt solidification:
  - Natural convection
  - Forced convection
- Experimental setup has to be installed in a glovebox



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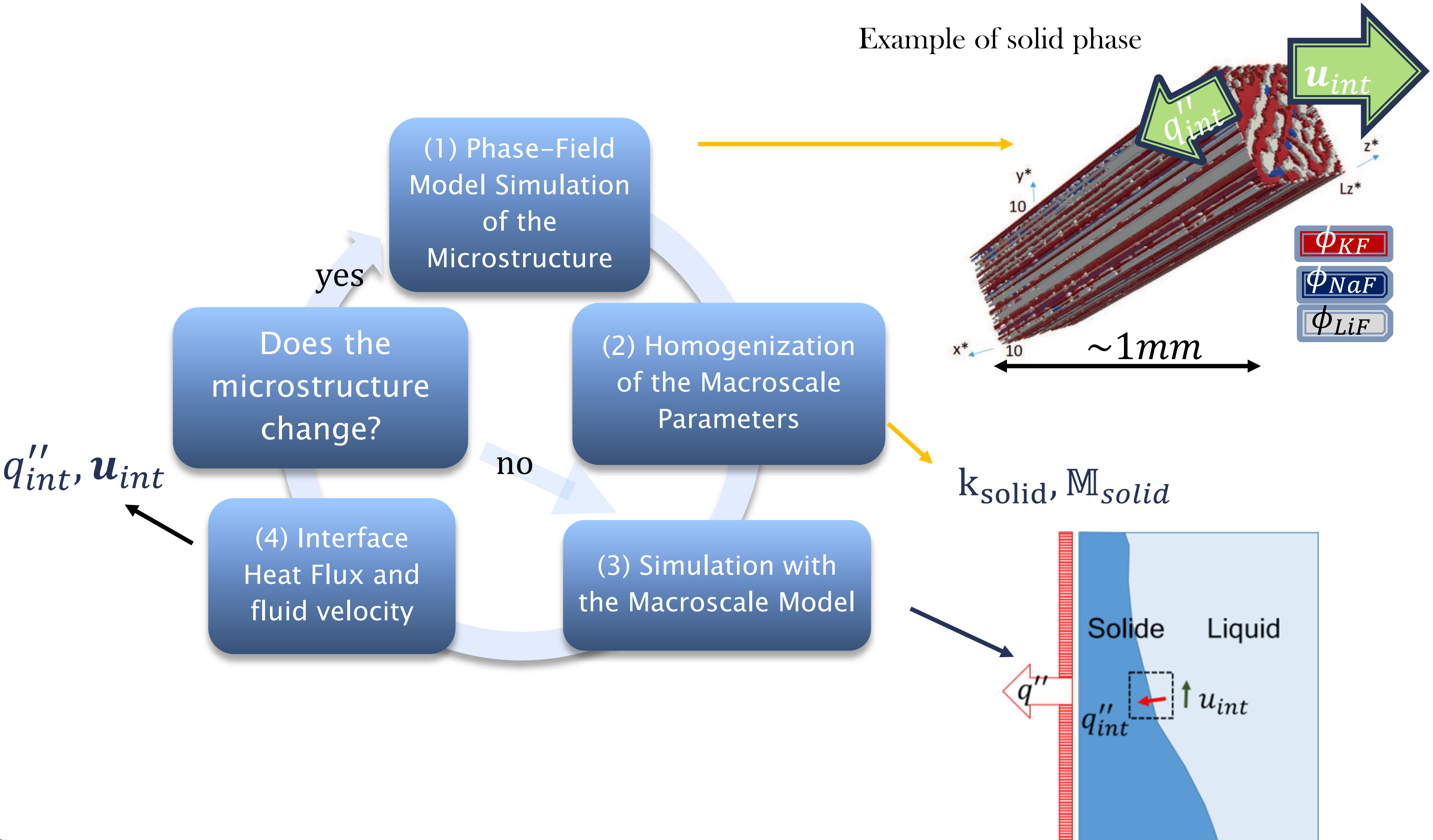
Coupling the Macroscale and Mesoscale Models



M. Tano-Retamales, P.R. Rubiolo, O. Doche, « Progress in modeling solidification in molten salt coolants », International Journal of Modelling and Simulation in Materials Science and Engineering, Vol. 5, Issue 7 (2017).

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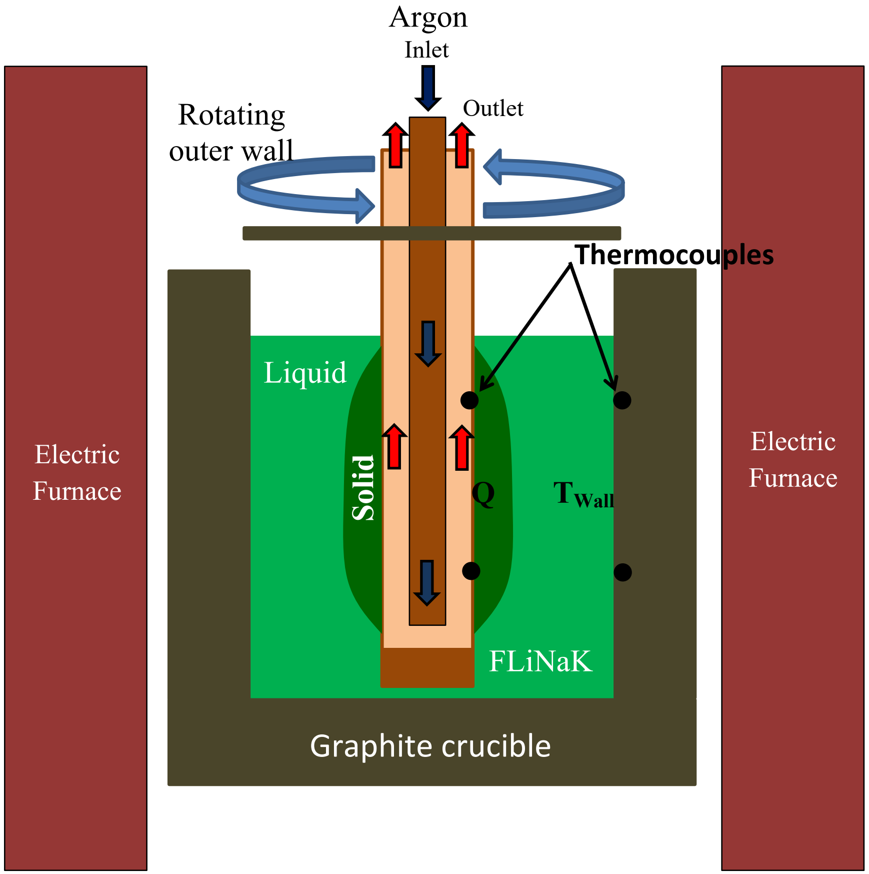
Solidification Experiment Setup

- Cylindrical annular cavity formed by an inner pipe and graphite crucible
- The cavity is filled with molten FLiNaK
- External wall temperature is regulated by the electric resistance
- Heat is removed by argon flowing inside the annular tube causing solidification on the external wall
- Several temperature are measured at various elevations on the tube wall and on the crucible wall
- To investigate solidification in a force convection environment, the external wall of the annular pipe is rotated (up to 20 rpm)



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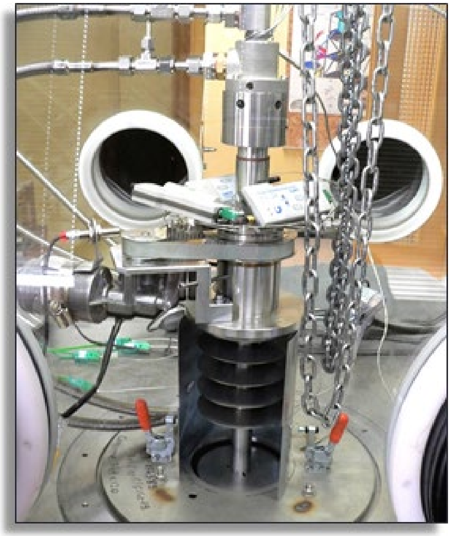
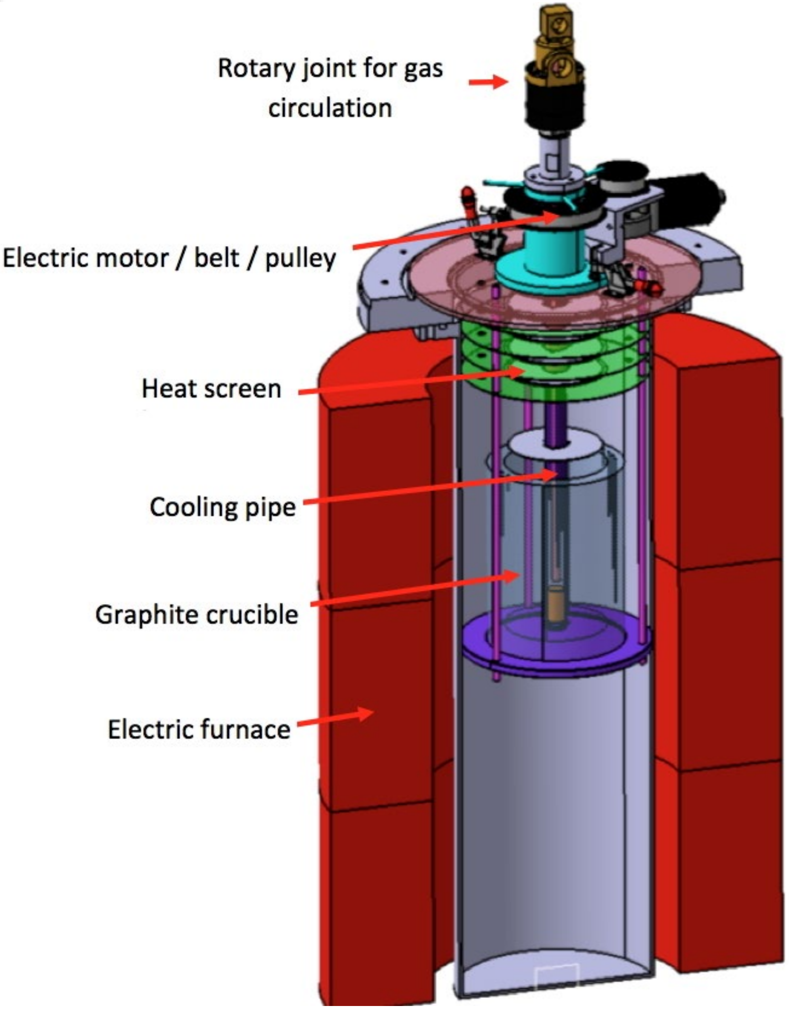
Solidification Experiment Layout

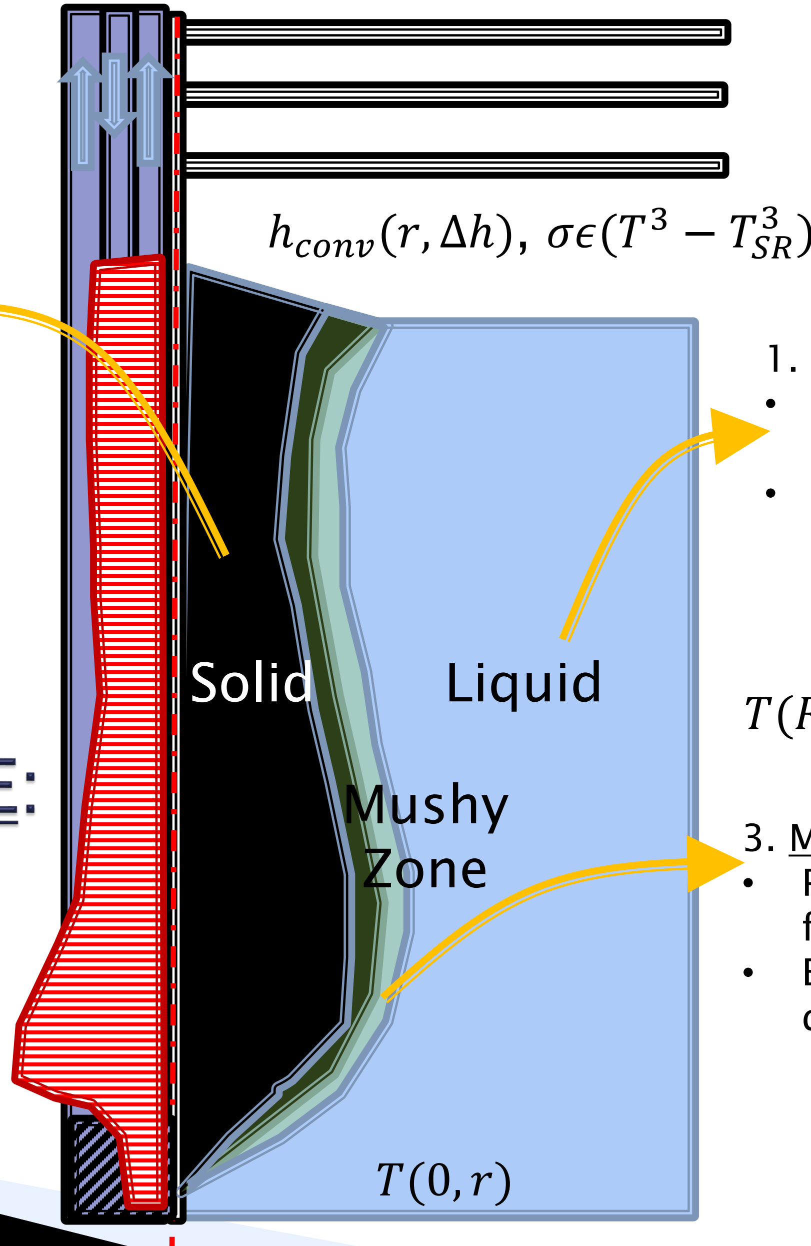
Salt	FLINAK
Graphite crucible	Outer/Inner diameters: 160 mm /120 mm Height : 220 mm
Cooling tube (outer tube)	Outer/Inner diameters: 25 mm / 20 mm Material : 304 L Maximum RPM : 20
Cooling gas	Argon Flow rate : 15 Nl/min to 60 Nl/min





MASOFOAM Model

2. Solid:
- Duhamel – Neumann (thermo-elasto-plasticity) equations
- Energy diffusion equation with $\boldsymbol{k}$ matrix computed with phase-field model

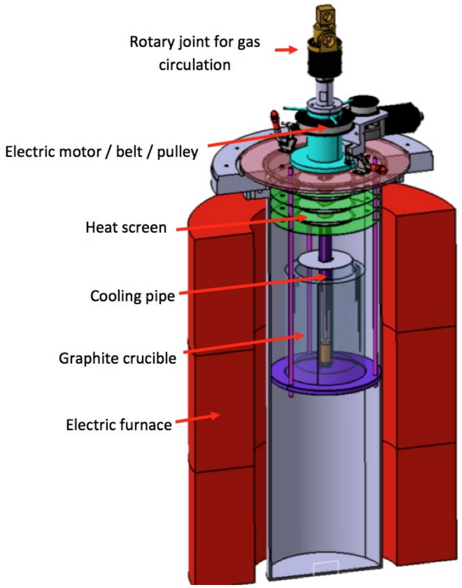


1. Liquid:
- Navier-Stokes equations
- Energy convection-diffusion equation

3. Mushy zone:
- Porous media equations for fluid flow
- Energy convection-diffusion equation

COOLING DEVICE:

Solidification Profiles



- Solidification front profiles are measured at any time by extracting the rotating tube from the molten salt bath
- Flow field established in the cavity is relatively simple although flow instabilities may appear (Taylor-Couette instability)

Ar 30 litres/min
No rotation
4 hours

Ar 30 litres/min
9 rpm
8 hours

- Significant differences are observed in the solidification progression with and without annular tube rotation

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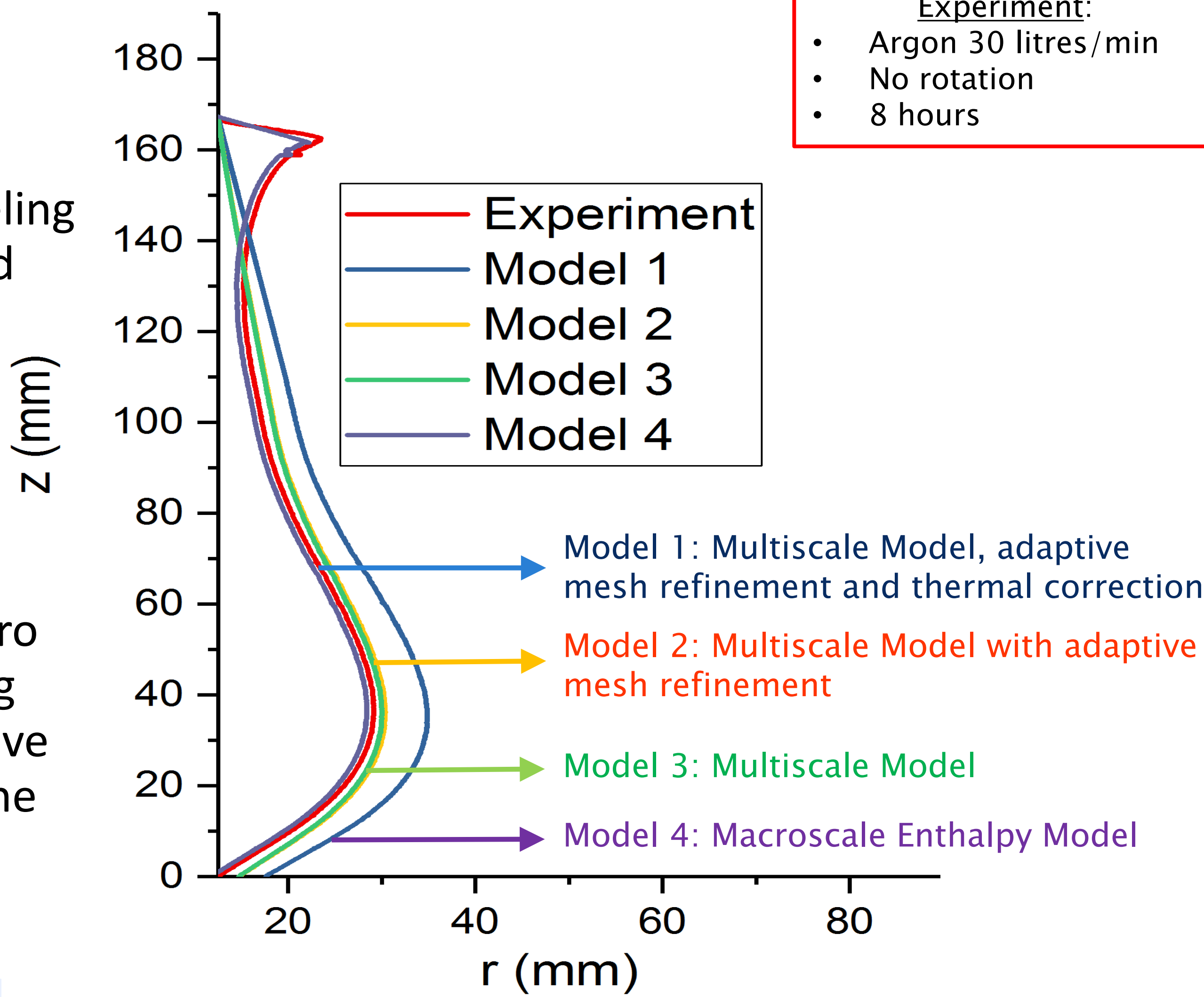
Comparison Between Measured Profiles and Models

→ Various levels of modeling details were implemented

→ Good agreement was found for the predictions obtained considering micro and macro scales coupling (MUSOFOAM) and radiative heat transfer effects on the free surface



Experiment:

- Argon 30 litres/min
- No rotation
- 8 hours

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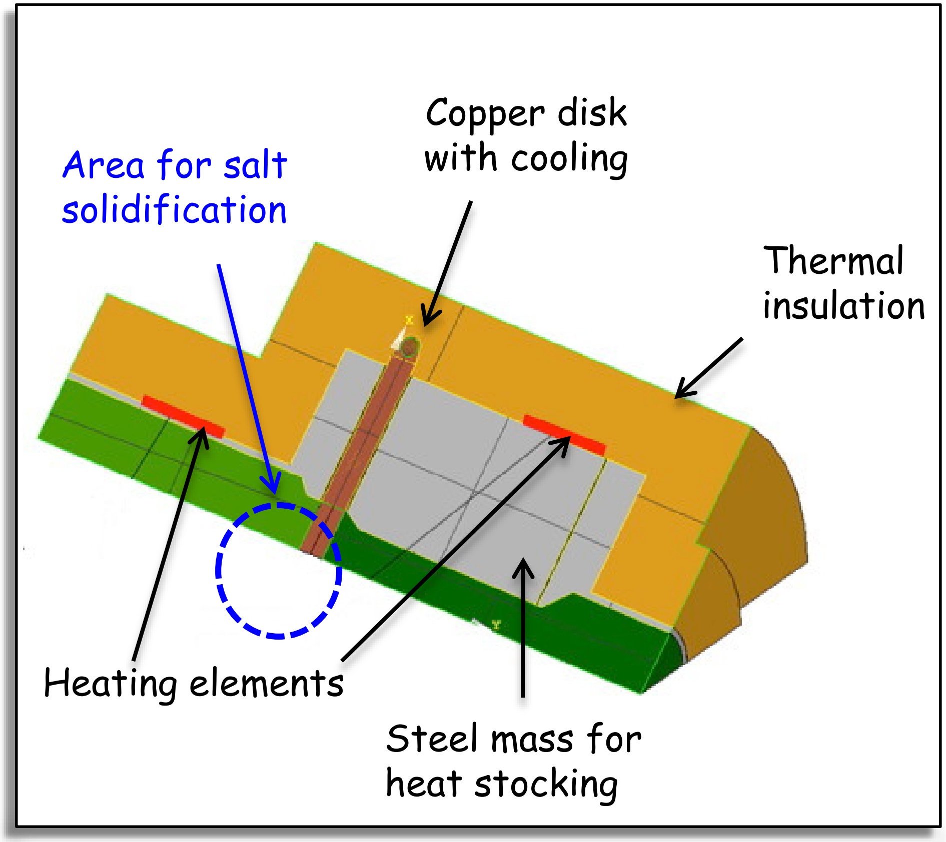
Cold Plug Experiment

- Objective: investigate the working principle of a proposed cold plug design
- Cold plug is a key component of the MSFR fuel salt draining system
- Working principle: control of the heat transfer balance inside the device
- The heat balance determines if the salt in the plug region solidifies or melts
- When copper disk cooling is stopped (e.g. due to a loss of electrical power), the thermal energy stored in the steel mass is transferred by conduction to the cooper disk causing the solidified salt region melt



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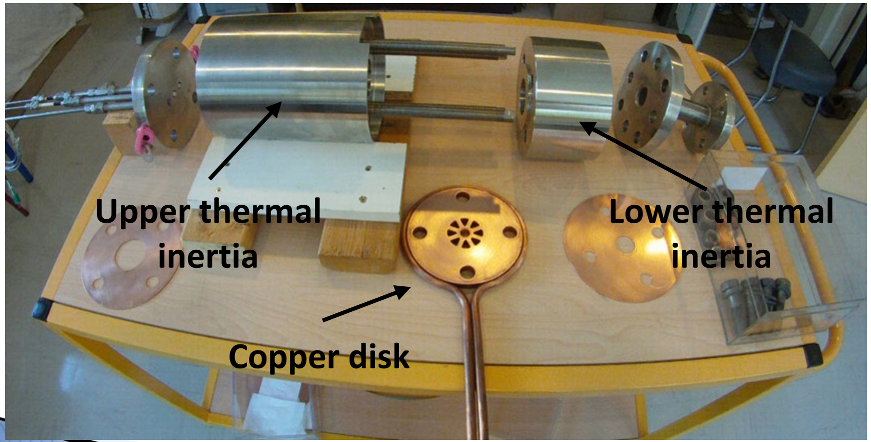
Cold Plug Experiment in SWATH-S

- Cold plug experiment is mounted on the downstream molten salt tank
- Thickness of the cold plug versus the cooling rate were measured in the experiments
- Melting time for various cold plug thickness was also measured from the stop of the cooling
- Results showed that a weak relationship exists between the cold plug thickness and the melting time



J. Giraud, V. Ghetta, P.R. Rubiolo, M. Tano-Retamales, "Development and Test of a Cold Plug Valve with Fluoride Salt", 12th International Topical Meeting on Reactor Thermal-Hydraulics, Operation, and Safety (NUTHOS-12), Qingdao City, Shandong Province, China, Octobre 2018.

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Conclusions: Modeling Aspects

- A new set of numerical tools have been developed to address specific molten salt phenomena needed for design and safety studies:
  - Macros scale and meso-scale solidification/melting models for molten salts
  - Improve turbulence RANS models to allow for a better description of the turbulence and also the specific phenomena near the wall
  - Radiative heat transfer in the salt

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Conclusions: Experiments Design

- Some of the T&H phenomena have been investigated in SWATH experiments during the SAMOFAR project
  - RANS turbulence, radiative heat transfer and solidification/melting
  - Numerical models for molten salts have been compared against experimental results. In general a good agreement has been found.

- SWATH-S facility has also been used to test the design principles on which are based some molten salts components such as:
  - Flow measurements,
  - Valves (passive and active),
  - Pipe joints,
  - Cold plug device

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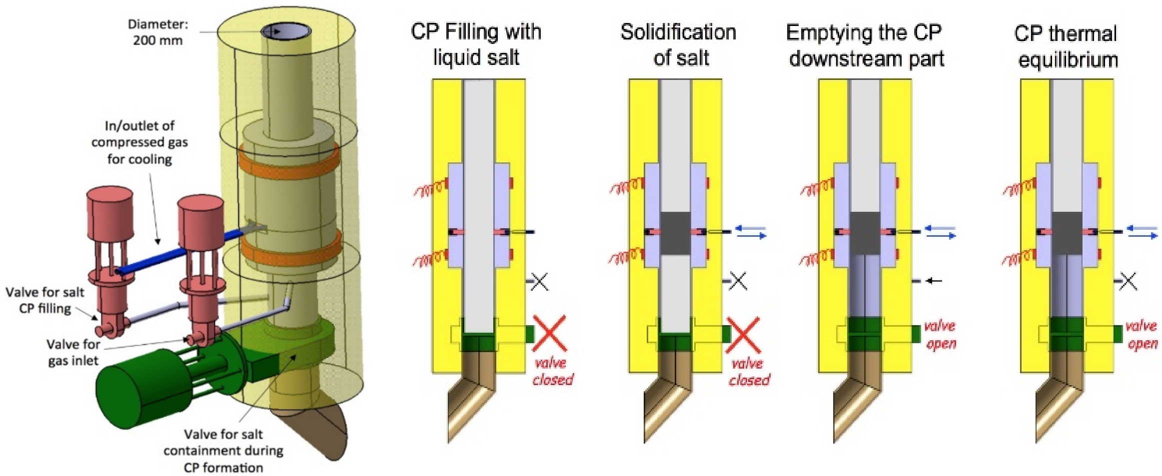
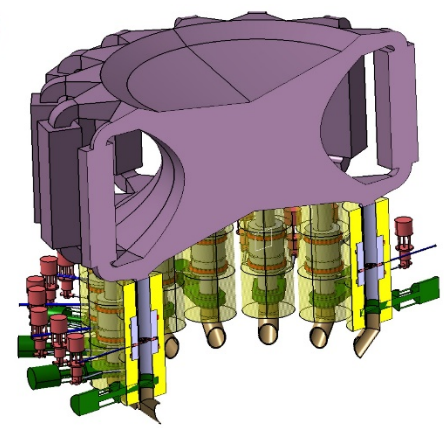
Conclusions: Fuel Salt Draining System

- A novel cold plug design has been proposed by CNRS



- The experiments and numerical simulations show that the proposed design can be scale-up for the reactor



- The design seems to provide a good compromise between meeting adequate opening time and having a very high reliability (avoiding unattended opening)

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Conclusions: Fuel Salt Draining System

- Key recommendations for the cold plug design:
  - Must be independent from temperature and flow rate in the reactor core
  - Must include in the design all the component to rebuild the cold plug after opening
- Further points that need be investigated in the future
  - Principles of diversity and redundancy requires the implementation in the MSFR design of alternative devices to perform the core cavity molten fuel draining. These devices could include for example:

    a) Mechanical valves,

    b) A draining system based on a syphon principle,

    c) Dedicated heat exchanger that could ensure a Passive Decay Heat Removal inside the core cavity.
  - Performance of the fuel salt draining system with the cold plug and other devices have to be further studied in the whole spectrum of accidental scenarios

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Thank you!