SAM SAFER

Welcome in Avignon

Final Meeting

28-29 November 2023, Avignon

Agenda nov 28

08:30	*Registration & coffee*
09:00	Welcome & Overview of SAMOSAFER project
10:00	*Coffee break*
10:30	WP1 Safety requirements and risk identification
11:15	WP2 Fuel salt retention
12:00	*Lunch & Poster session*

13:30	WP3 Source term distribution and mobility
14:15	WP4 Fuel salt confinement
15:00	*Coffee break*
15:30	WP5 Heat removal and temperature control
16:15	WP6 Reactor operation, reactor control and safety demonstration
17:00	Poster session
19:00	*Cocktail*
20:00	*Social dinner*

Agenda Nov 29

08:30	*Registration & coffee*
09:00	Welcome & Introduction
09:15	Video presenting SAMOSAFER results
09:30	Presentation about the use of the SAMOSAFER results in a new project proposal, Stefano Lorenzi
09:45	Status and prospect of R&D at CEA on molten salt reactors, Jean-Claude Garnier
10:15	*Coffee break*
10:45	Keynote lecture: 'Pando's Lessons', Myriam Tonelotto
11:00	Presentations by Start-up companies about their designs and needs
12:30	*Lunch & Poster session*
14:00	Presentations by industrial companies
14:45	'Expert presentation', Rui Tang, Shanghai Institute of Applied Physics
15:15	Students from SAMOSAFER presenting their experiments.
16:00	*Coffee break*
16:30	MSR licensing from European perspective
17:00	Roundtable with regulators
17:15	US prospects on MSR
18:00	Conclusions and Adjourn

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WP1: Safety requirements and Risk identification

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Tasks of the WP

- 1 - General safety approach
- 2- Identification of reactivity insertion PIEs and reactivity insertion modelling and study
- 3 - Risk identification on the FTU
- 4 - Overview of integral experiments and key aspects for validation

Objectives of task 1:

- ♦ The objective of this deliverable is to examine **how to implement the DiD principles on MSR in a meaningful way**, including a thinking on the **relevance of Severe Accident notion for MSR**

- ♦ Examination of the notion of Severe Accident, and **proposition to define a generalized notion** (Severe Plant Condition), applicable to MSR

- ♦ According to this definition and the issues raised during the analysis, proposition to **implement DiD principles for a MSR**, considering its specificities

Methodology for definition of severe accidents:

Proposition to call this notion "**Severe Plant Condition**" (proposition of denomination mentioned in the RSWG)

- ♦ The guiding principle for the building of the SPC is the identification of the characteristics of the Severe Accident as generalized core melting, since the SPC definition should embrace its signification and implications on the safety approach

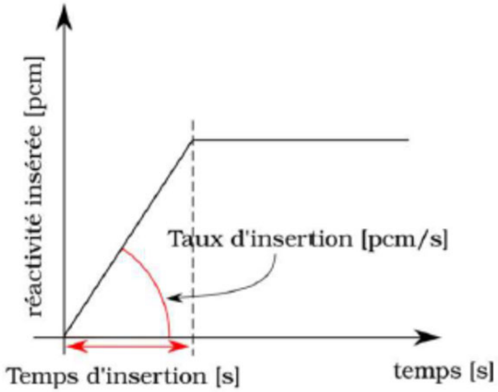
Task 1: main results at a glimpse

- **Definition of a Severe Plant Condition (SPC)**
  - A high quantity of radiological elements involved
  - A dispersable source term, including both that:
    - The source term physical condition is either liquid or gaseous (including aerosols)
    - The equipment ensuring its retention in normal operating mode lose their leak tightness
  - A vector (energy), enabling the transportation of the radiological elements
  - A risk of simultaneous failure of containment barriers induced by the accident, until potential alteration of the last containment barrier

- **Close link between the levels of Defense in Depth and the location of the fuel salt**
  - The possibility of salt transfers should be taken into account:
  - Fuel salt relocation provides opportunities to implement independent features, including diversity (less constraints to implement different technological solutions)
  - To keep the salt in the fuel circuit as far as possible

Objective of task 2

- **To make a focus of the MSFR behaviour when facing reactivity insertions**
  - Use of a physical cause-consequence top-down analysis in order to identify a preliminary list of PIEs
  - Starting from physics and the arriving to components or system related events
  - Investigate the key phenomena and the reactor behaviour at its limits



- **Simulate the MSFR behaviour**
  - Modelling of a chloride and fluoride version of the MSFR
  - Take into account the salt compressibility when important
  - Study postulated reactivity insertions (top-down approach)
  - Understand the reactor behaviour (energy release ?) in such situations and identify the mitigations strategy and devices

Task 2: main results at a glimpse

- **In case of slow and of small magnitude reactivity transients**
  - Density and Doppler reactivity feedback mitigate very efficiently the transient
  - Chloride concepts have a larger density effect but almost no Doppler effect
  - Fluoride concepts rely on both Doppler and density effects
  - The intermediate circuit management is essential for the final state of the transient

- **For large and fast postulated reactivity insertion**
  - Compressibility should be modelled otherwise results are too optimistic
  - When there are bubbles into the core region the two-phase medium lowers the speed of sound
  - When a reactivity ramp has been inserted the salt temperature increases to compensate reactivity increase
  - Terminating and mitigating a fast reactivity insertion is still to investigate (thermal effects, expansion tank, pressure discs, so on…)
  - In the investigates situations, the over-heating induced by a single and limited reactivity ramp is moderated

Task 2: main results at a glimpse

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Objective of task 3

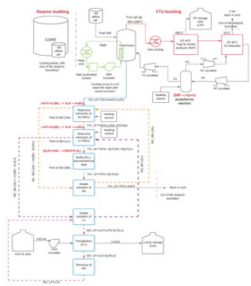
- **To make a preliminary list of PIEs in the FTU**
  - Assume a preliminary design of the FTU
  - Make a functional analysis
  - Expert group elicitation in order to envisage all events
  - Identify consequences of events on the FTU

- **Suggest some design measures to mitigate identified events**
  - Eventing, stopping reactant supply, inerting, cooling, etc.
  - Redundancy, back-up systems, diversification, etc.

Task 3: main results at a glimpse

- **Loss of Fuel Salt containment** – includes different PIEs

- *Leakage in the bottom part of the fluorination package* (liquid release)
- Possible consequences
  - Loss of liquid fuel salt
  - Possible fire and toxic release
- Detection/prevention/mitigation
  - Control the amount of the fuel salt exiting from the fluorination package (buffer tank)
  - Radioactivity detection triggering immediate shutdown of the FTU
  - F_2 detection in the FTU building



- *Leakage in the upper part of the fluorination package* (gas release)
- Possible consequences
  - Loss of gaseous fuel salt and gaseous fission products
  - The depressurization implies plausible enhancing of the chemical reaction in the fluorination reactor
  - Loss of F_2 gas, fire, toxic release
- Detection/prevention/mitigation
  - Radioactivity detection triggering immediate shutdown of the FTU and stopping the inlet of F_2
  - F_2 and H_2 detection in the FTU building

Objective of task 4

- **Identify the needs of validation at integral scale**
  - Well investigate and understand the reactor behaviour and what are specific phenomena of MSR
  - Make an inventory of existing integral experiment results
  - Identify among them which one can provide useful results for MSRs
  - Determine the targeted accuracy of each phenomenon to study

- **Make a preliminary PIRT**
  - Built an expert panel
  - Rank the phenomena regarding their relative importance on FoM
  - Rank the phenomena regarding their uncertainty
  - Prioritize R&D

Task 4: main results at a glimpse

Phenomena Identification and Ranking Table, domain of the System Thermal Hydraulics

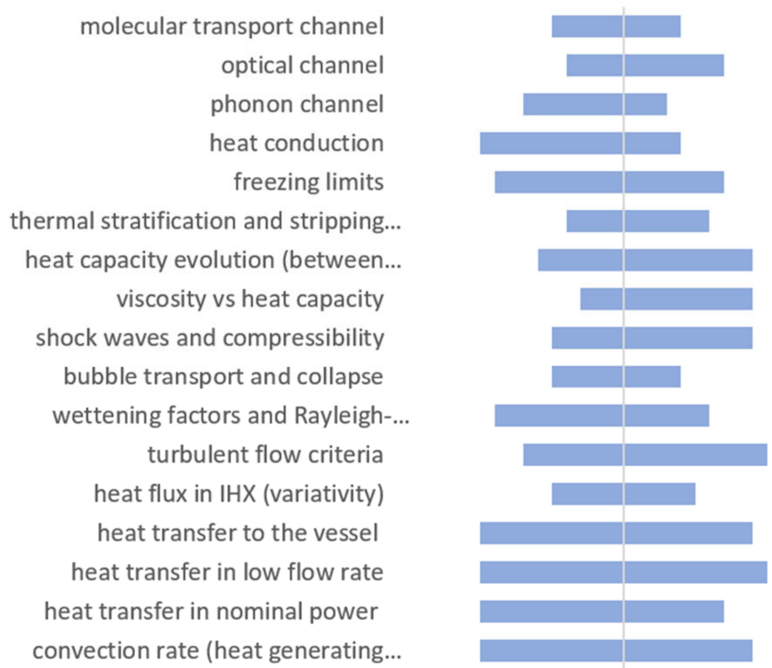
Comments and statements

- The knowledge of the heat conduction by components needs to be known to estimate the temperature gradients (impact through the REDOX)
  FOM : predictable ΔT at the boundary layer

- Factors of freezing, stripping, turbulence cells in the convective heat-generating fluid should be investigated in terms of stability of the flow modes/impurities separation/gas dissolution
  FOM : $\|\delta\| <$ TAR

- Heat flux, heat transfer coefficients ($h \sim u^{0.8}$[???]) in the nominal mode and in the stand-by modes are essential for the vessel protection, salt conditions and reactivity
  FOM : $\|\delta\| <$ TAR

Resultant PIRT notes



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Let’s go for WP2

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WP2: Fuel salt retention

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Objective of WP2

To understand the behaviour of corrosion & fission product in the molten salt reactor fuel and its influence on fuel properties.

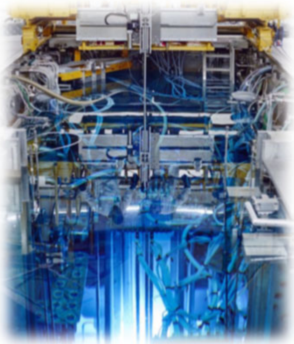
- New experimental data to fill the gaps and validate
- New simulation tools
- Data of irradiated fuel samples

OBJECTIVES of WP2

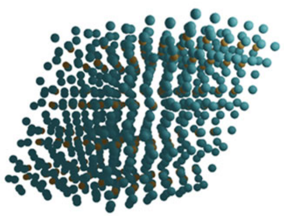
Experimental Data

Fundamental Data on Fuel Properties

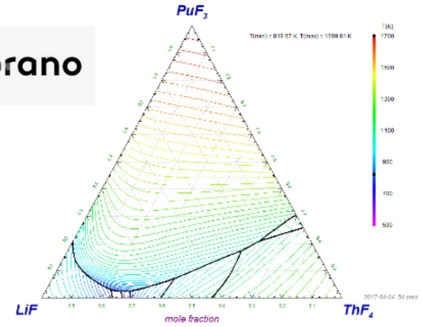
Data of Irradiated Fuels (PIE)



Molecular Dynamics

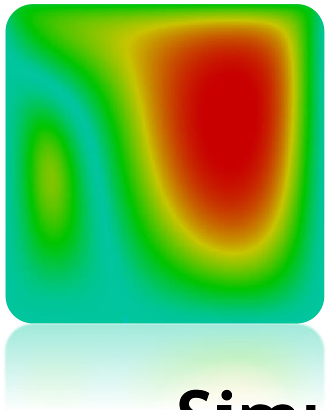


Thermochemical Database



Coupling (**Breakthrough in Science**)

Multi-Physics Simulations



Data Mining

Simulations

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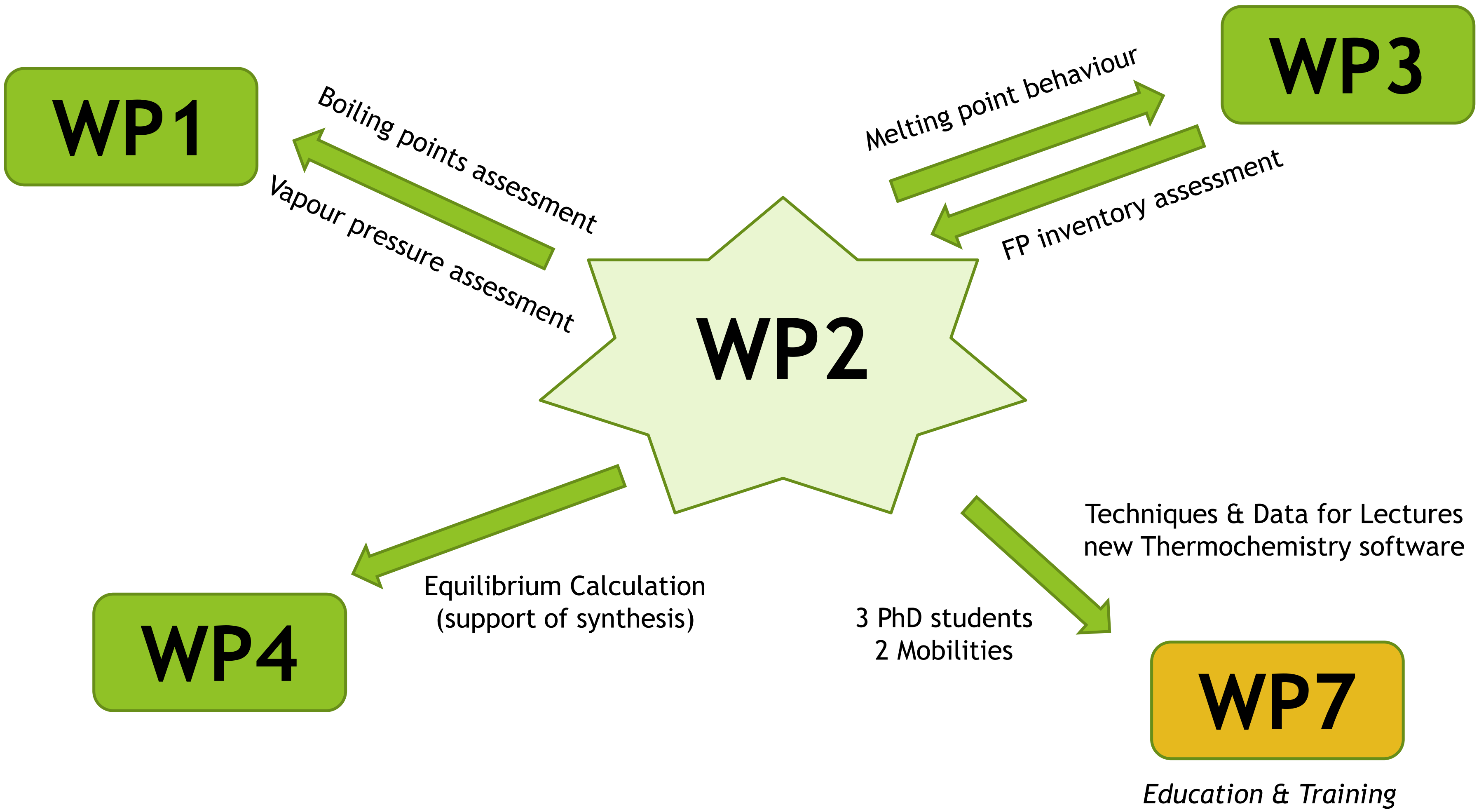
WP2 interaction with other WP’s



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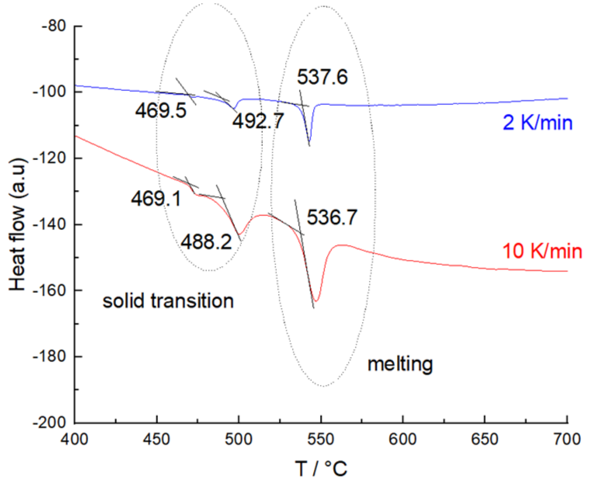
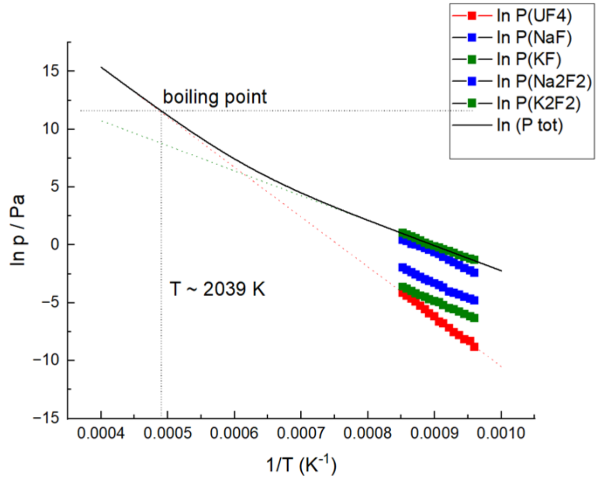
Technical Highlight #1 - Novel Data on Fuel Properties

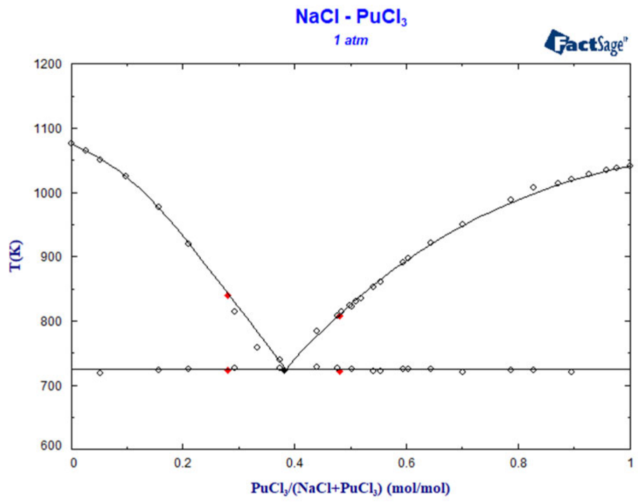
Melting points



Vaporization / Boiling

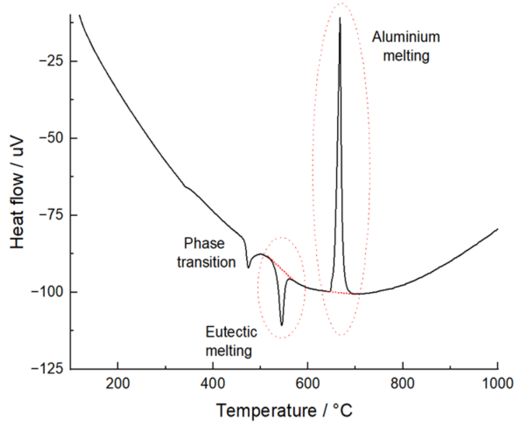


Phase diagrams



- Fluorides (FUNaK)
- Chlorides ($PuCl_3$-salts)

Fusion Enthalpy



	Melting point (liquidus)	Fusion Enthalpy	Boiling point
Funak #1	535.0 °C	16.7 kJ/mol	2039 K
Funak #2	537.2 °C	17.1 kJ/mol	-
$NaCl-PuCl_3$ (52-48 mol%)	534.7 °C	-	-
$NaCl-PuCl_3$ (72-28 mol%)	566.8 °C	-	-

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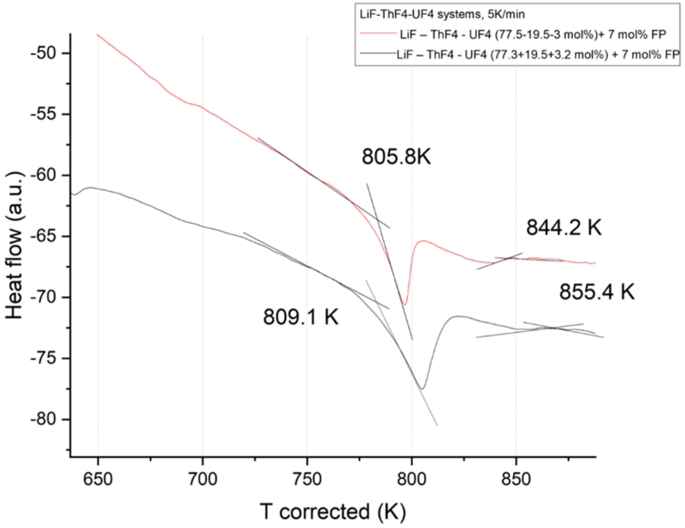
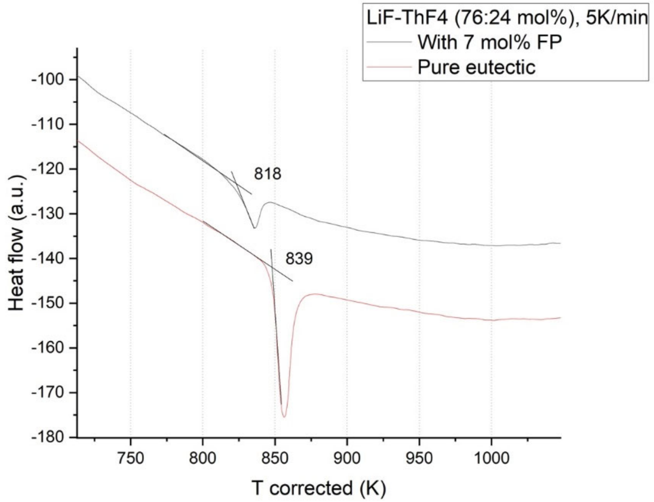
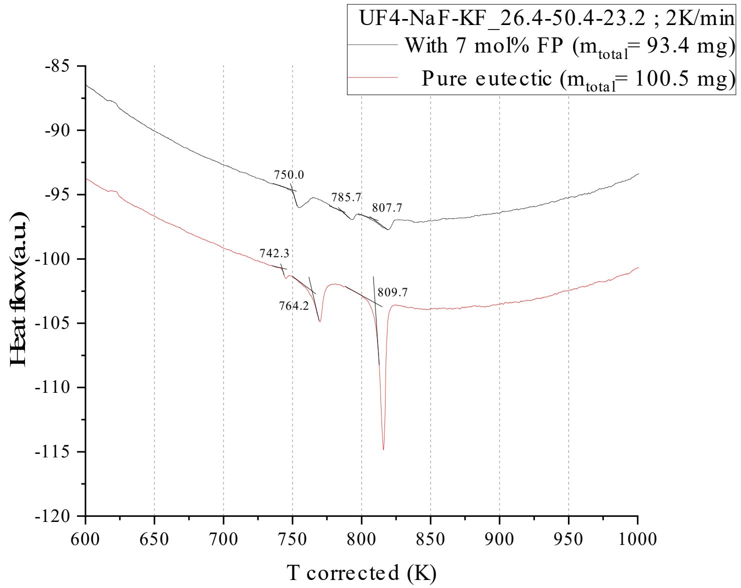
Technical Highlight #2 - FP influence on Fuel Properties



Sim-Fuel System with FP (mol%)	Liquidus point	Liquidus point of Fresh Fuel eq.
LiF-ThF_4-FP (70.7-22.3-7.0)	818.0 K	839.0 K
LiF-ThF_4-UF_4-FP (72.1-18.1-2.8-7.0)	844.2 K	850.0 K
LiF-ThF_4-UF_4-FP (71.9-18.1-3.0-7.0)	855.4 K	850.0 K
NaF-KF-UF_4-FP (46.9-21.5-24.6-7.0)	807.7 K	809.7 K





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Technical Highlight #3 - Molecular Dynamics Simulation

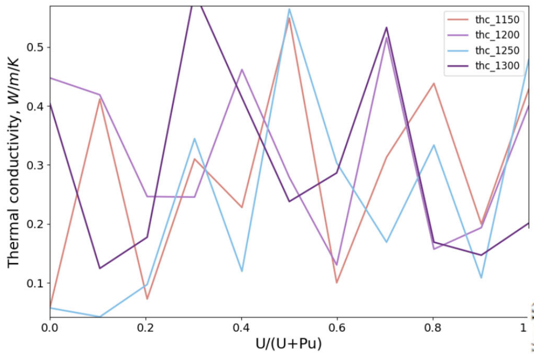
PAUL SCHERRER INSTITUT PSI

U-Pu-Cl system

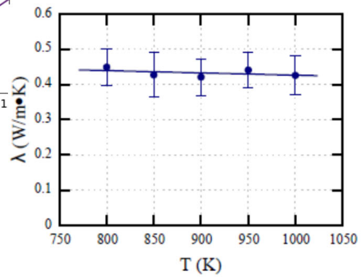
Viscosity of the U-Pu-Cl system

Using the newly obtained parameters it is possible to model multicomponent systems and obtain dynamic properties, e.g. viscosity and thermal conductivity

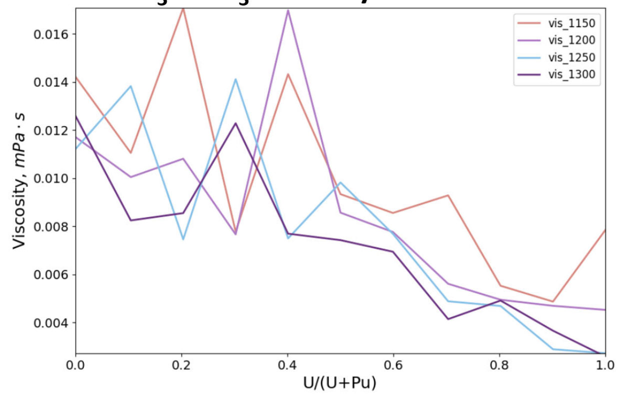
UCl_3-$PuCl_3$ thermal conductivity

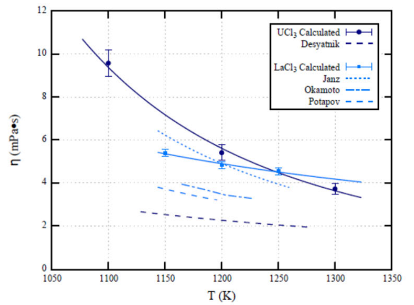


NaCl-PuCl3-LaCl3



UCl_3-$PuCl_3$ viscosity





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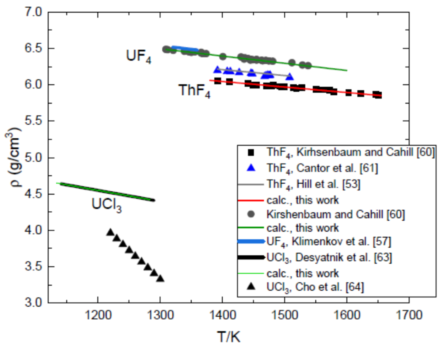
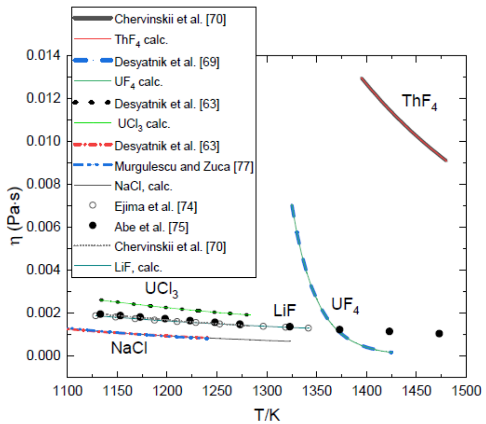
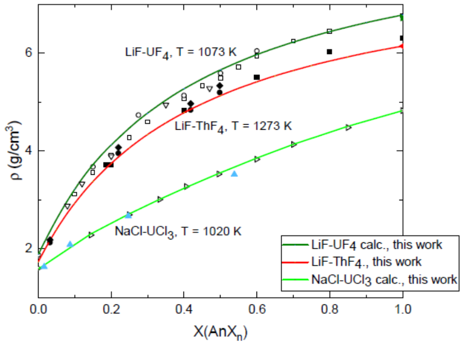
Technical Highlight #4 - Database and Viscosity-Density coupling

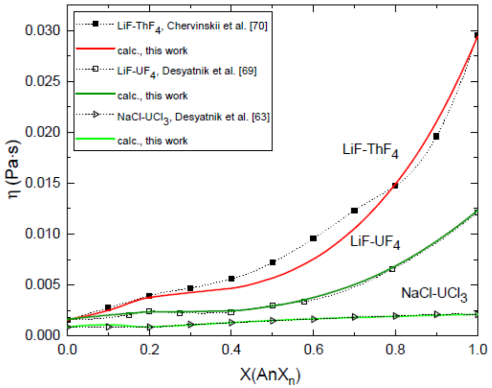


From End-members

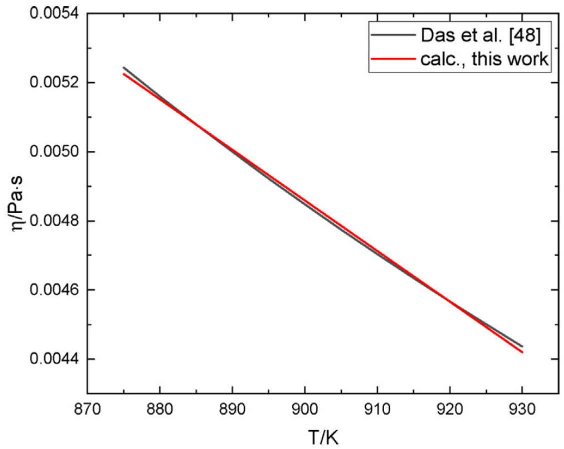




Binary mixtures



Viscosity LiF-ThF$_4$-UF$_4$ ternary mixture



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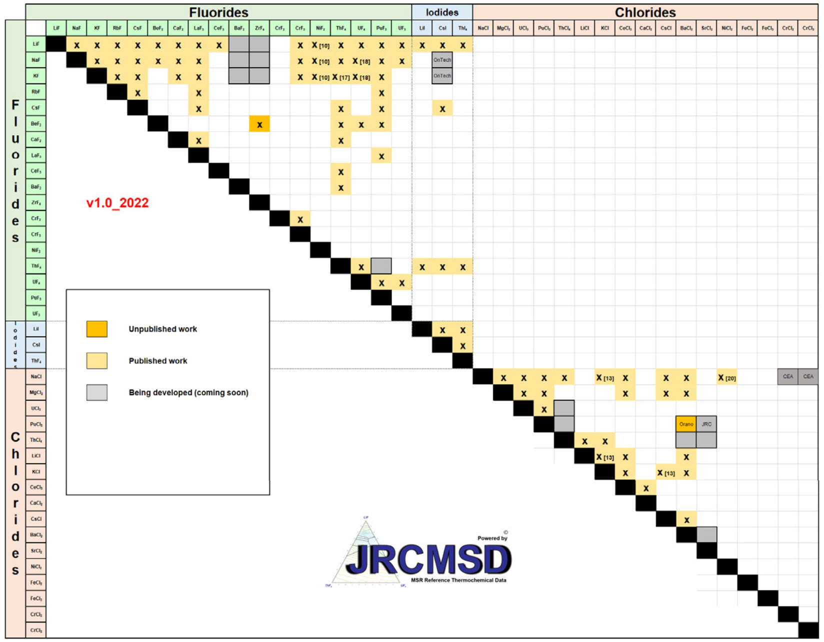
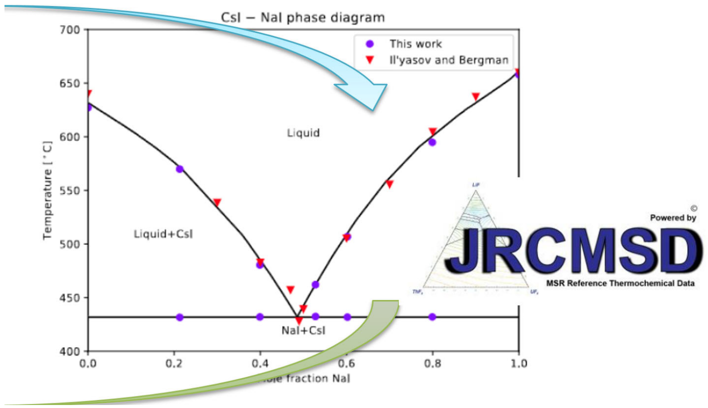
Technical Highlight #5 - Implementation of JRCMSD into Thermochimica



THERMOCHIMICA

- Computational Thermodynamics Code
- Open-Source, Fortran 90, C++ API
- Gibbs Energy Minimization, MQMQA
- Chemical Speciation, Solubility Limit
- Phase Transitions and Vapour Pressure



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Technical Highlight #6 - Coupling of Thermodynamics with Multi-Physics

OpenFOAM®

- Computational Fluid Dynamics Code
- Open-Source, C++
- Multiphase Solvers (liquid-gas-solid)
- Continuity, Momentum and Energy
- Species Transport Equation

THERMOCHIMICA

- Computational Thermodynamics Code
- Open-Source, Fortran 90, C++ API
- Gibbs Energy Minimization, MQMQA
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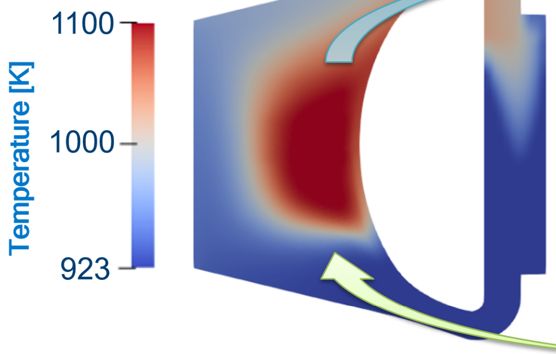
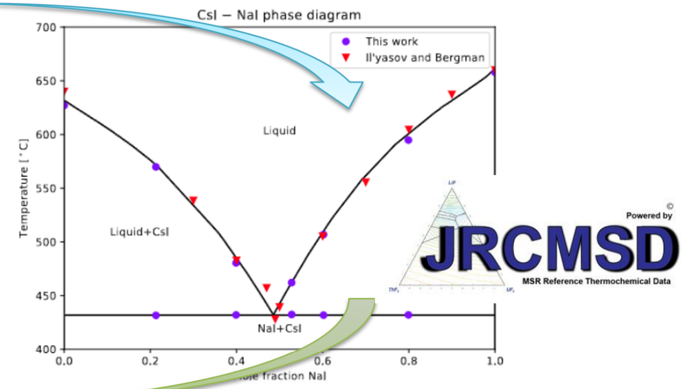




N. L. Scuro, O. Beneš, S. Lorenzi, M. Krstovic, S. Krepel, M.H.A. Piro (under review).

N. Scuro, B.W.N. Fitzpatrick, E. Geiger, M. Poschmann, T. Dumaire, O. Beneš, M. H. A. Piro (Under review). 2

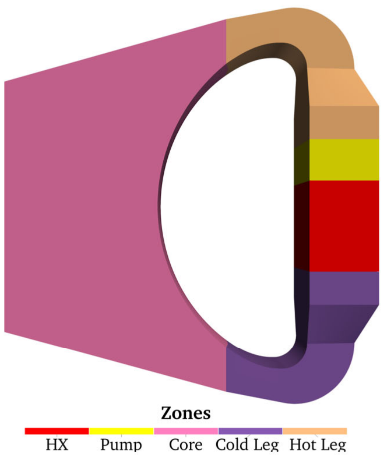
Technical Highlight #7 - Multiphysics Simulation

Main achievement

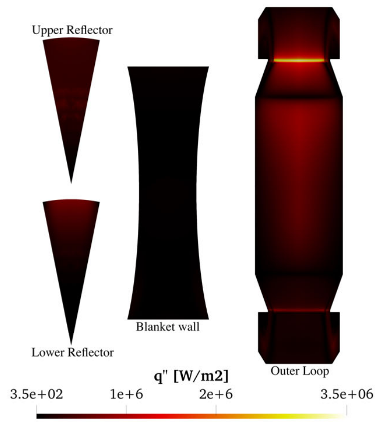
Development of a multiphysics tool for MSFR analysis, including the transport, precipitation and deposition of metallic Fission Product

Capabilities:

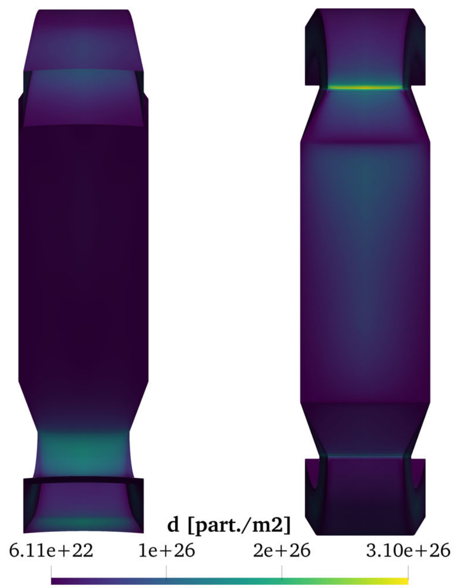
- Calculation of the deposition of metallic FP on the structural walls
- Calculation of the heat flux due to the decay of the metallic FP



3D MSFR geometry used



Decay heat flux due to the 5M deposition (no bubbling)



5Ms deposition on outer loop walls

Let's go for WP3

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WP3: Source term distribution and mobility

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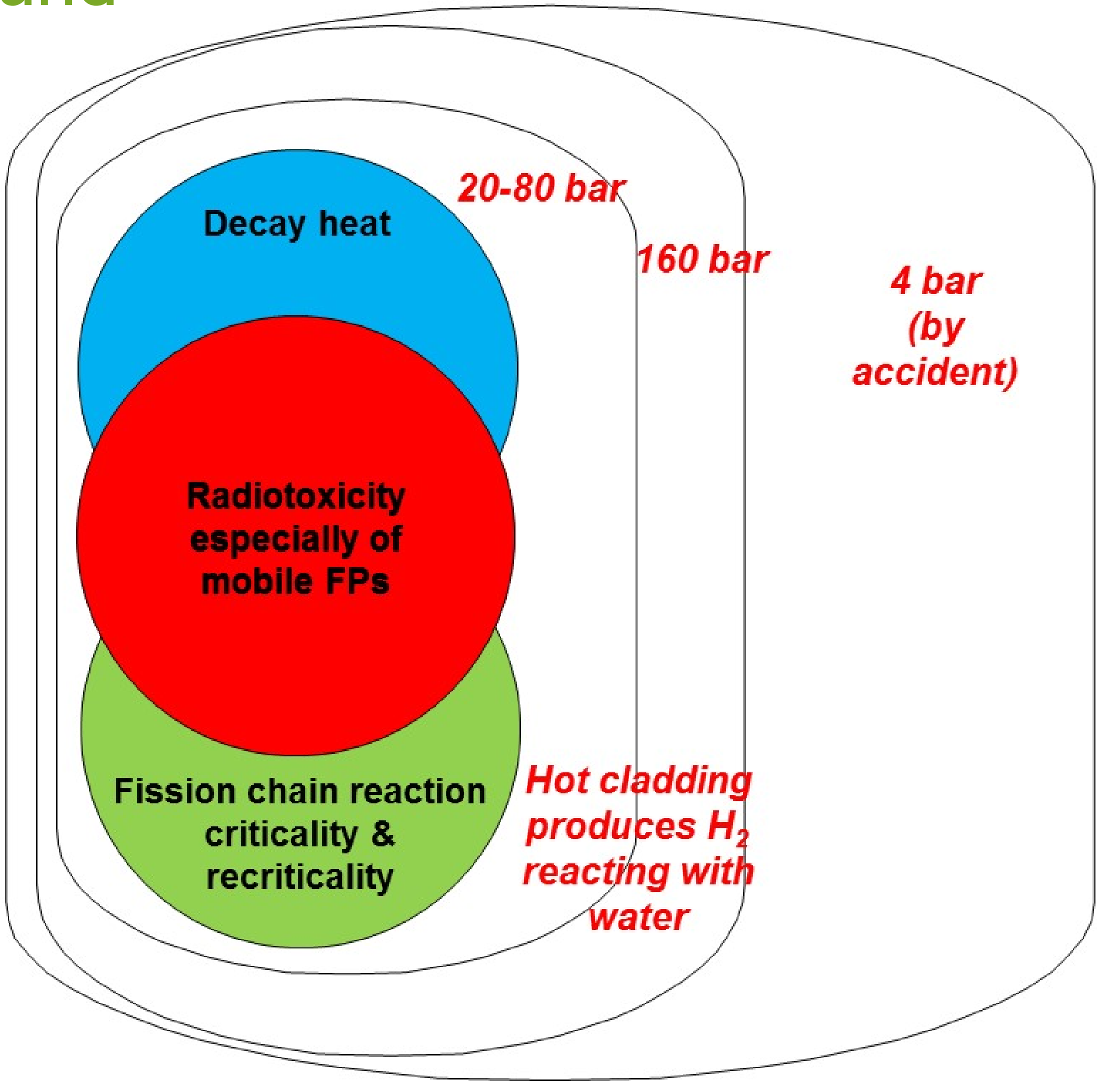
WP3: Scientific background

- **NRC source term definition:** Types and amounts of radioactive or hazardous material released to the environment following an accident.
- Its **complex assessment** is based on:
  - Radioactive material **composition**
  - Its chemical **mobility** / activity
  - Presence of **driving forces**
  - Presence of **barriers**
- Safety of **existing LWR** is high; nonetheless, based on substantial **driving forces**, **mechanical barriers***, and their **complex protection** system.

  ** filtered venting is the only non-mechanical barrier*



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WP3: Scientific background

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- Its **complex assessment** is based on:
  - Radioactive material **composition**
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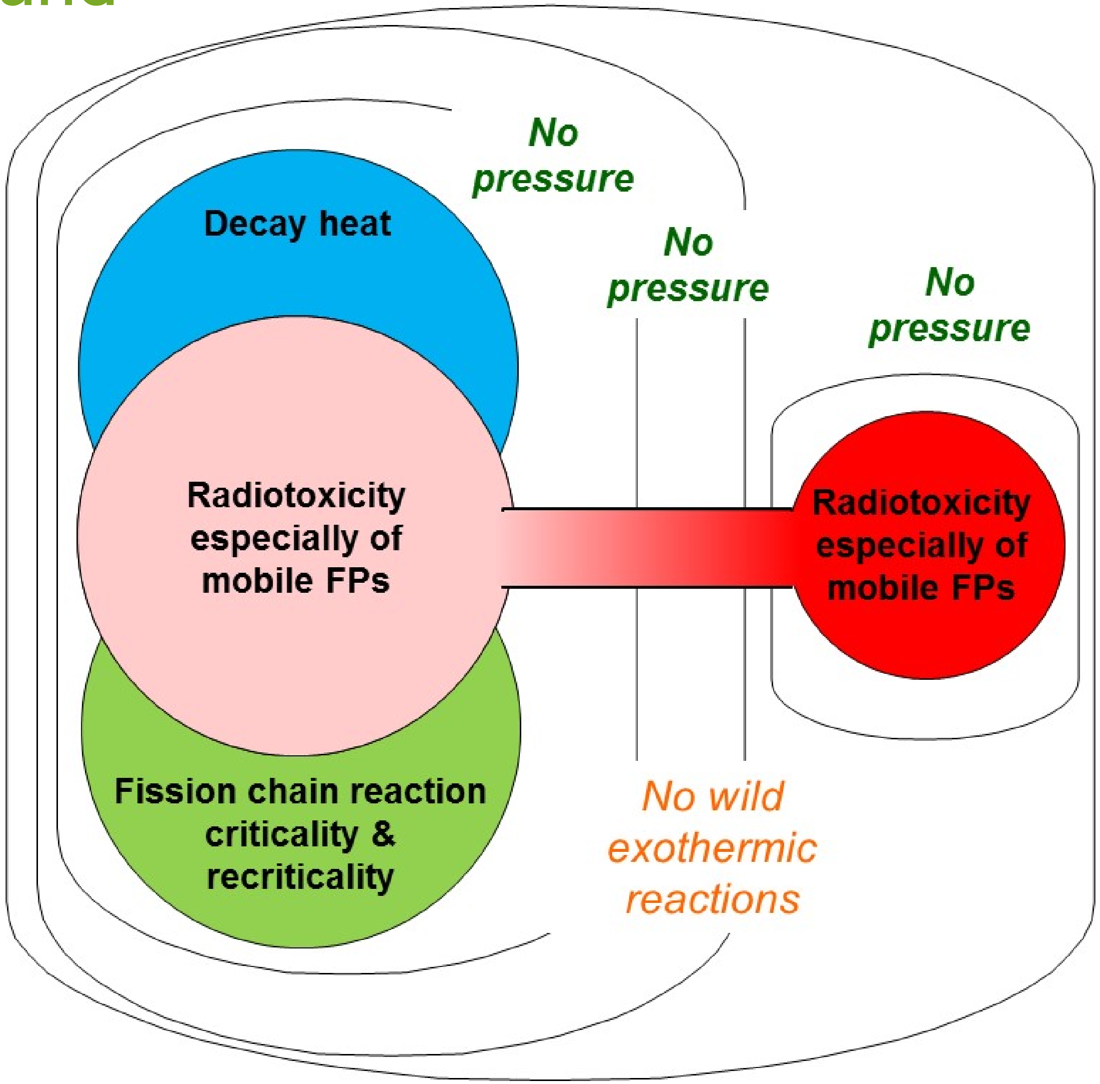
  - Presence of **driving forces**
  - Presence of **barriers**
- **MSR with liquid fuel** is special:
  - Chemical mobility can be controlled.
  - Driving forces can be avoided.
  - Mechanical barriers “robustness” can be reduced.
  - Barriers can/should be also chemical.
  - Safety philosophy can be oriented towards control of the fuel state (temperature, location, redox pot.) rather than on barriers protection.

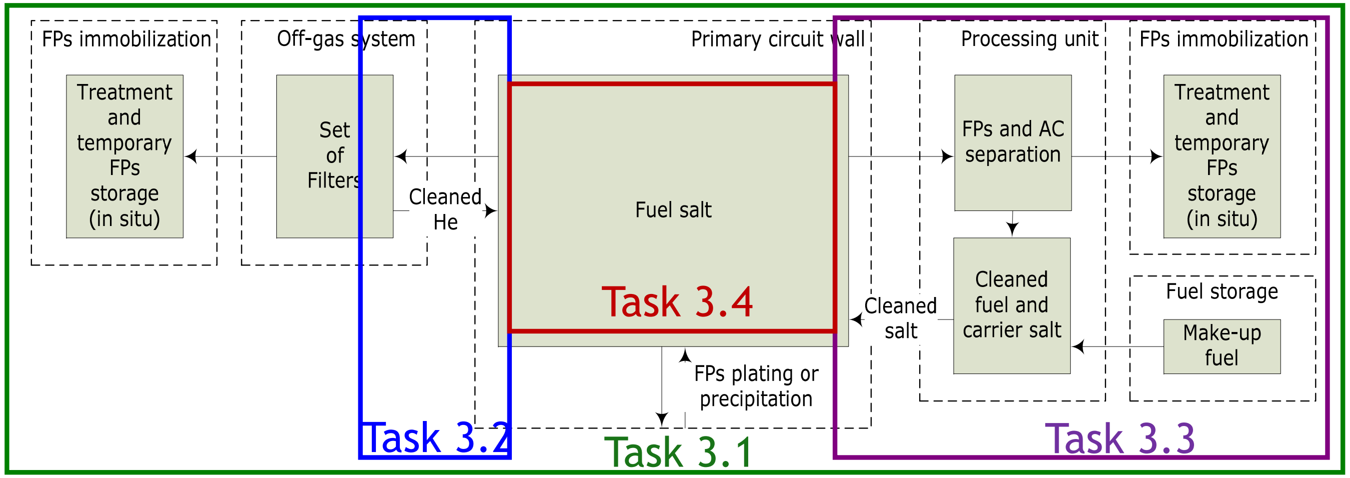


WP3: Four tasks, 68PM, 8 institutions

- Each of these tasks address different issue related to source term distribution.
- Task 3.2 (Removal rates to the off-gas system) and
  Task 3.3 (Source term in the reprocessing and storage) are dedicated to transfer rates.
- Task 3.4 (Source term in the core) is dedicated to severe accident conditions and salt evaporation
- Task 3.1 (Source term distribution) relies on these removal rates and provide detailed nuclides, radiotoxicity and decay heat distributions.

- *Source term as such is a complex problematic and many issues and not addressed:*

- Mechanical and chemical barriers (except for aerosol filters).
- Chemical and mechanical stability of barriers (e.g. vessel disintegration).
- Source term mobility at accidental conditions in FPU and off-gas system.
- Presence of driving forces: exothermic reactions within salt, metals, concrete, water, etc..



WP3: Task 3.2 Highlights

Frederix, E.M.A., 'Estimates of noble metal particle growth in a molten salt reactor', Colloids and Surfaces A: Physicochemical and Engineering Aspects, Volume 655, 20 December 2022.

Frederix, E.M.A., E.M.J. Komen, Simulation of noble metal particle growth and removal in the molten salt fast reactor, Nuclear Engineering and Design, Volume 415, 15 December 2023.

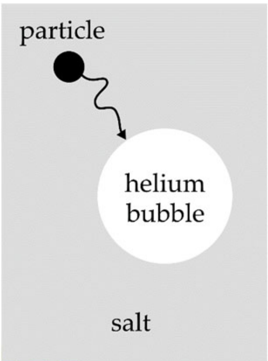
Di Ronco A, Lorenzi S, Giacobbo F and Cammi A An Eulerian Single-Phase Transport Model for Solid Fission Products in the Molten Salt Fast Reactor: Development of an Analytical Solution for Verification Purposes. Front. Energy Res. (2021) 9:692627.

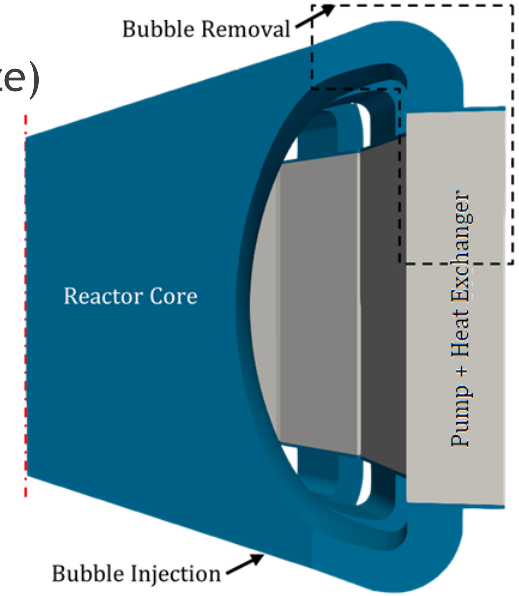
Need:

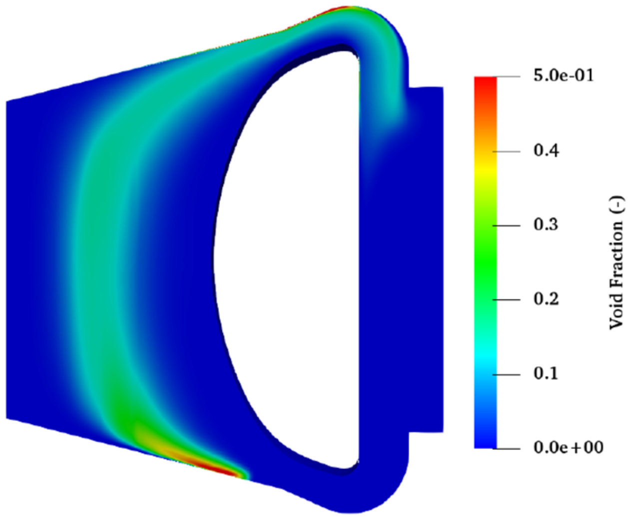
Need for assessing the effect of the online gaseous extraction with helium bubbling on the fission products. Relevant for the assessment of radioactive source in the nuclear plant.

How fast are Gaseous Fission Products (GFPs) and Solid Fission Products (SFPs) removed?

Different physics:
- FP diffusivity (dependent on particle size)
- migration of GFP to helium (solubility)
- flotation







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WP3: Task 3.2 Highlights

Frederix, E.M.A., 'Estimates of noble metal particle growth in a molten salt reactor', Colloids and Surfaces A: Physicochemical and Engineering Aspects, Volume 655, 20 December 2022.

Frederix, E.M.A., E.M.J. Komen, Simulation of noble metal particle growth and removal in the molten salt fast reactor, Nuclear Engineering and Design, Volume 415, 15 December 2023.

Di Ronco A, Lorenzi S, Giacobbo F and Cammi A An Eulerian Single-Phase Transport Model for Solid Fission Products in the Molten Salt Fast Reactor: Development of an Analytical Solution for Verification Purposes. Front. Energy Res. (2021) 9:692627.

Main achievements

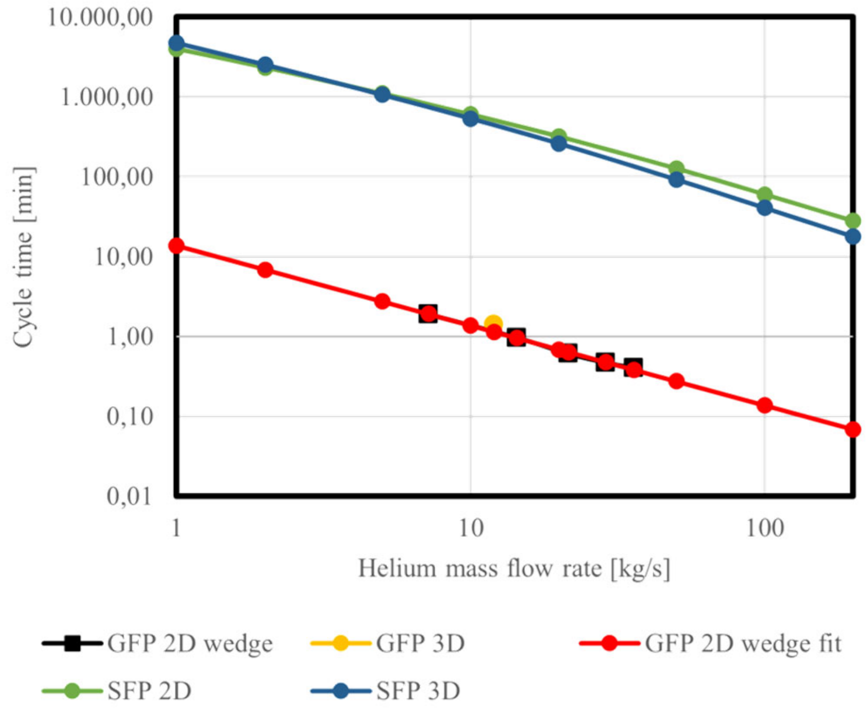
- Development of a noble metal flotation model to evaluate the evolution of the metal particle population in the MSR
- Development of multiphysics model for GFPs creation, diffusion, transport and interaction with He bubbles

Capabilities:

- Calculation of the GFPs and SFPs removal rates as a function of helium injection rate

Outcomes:

- For the same helium flow rare, SFPs removal rate is **140x** slower than GFPs removal rate.
- Cycle time of **30 s** can be achieved for GFPs, with **28 g/s** He flow rate. However, the cycle time for SFPs would be **4200 s**.



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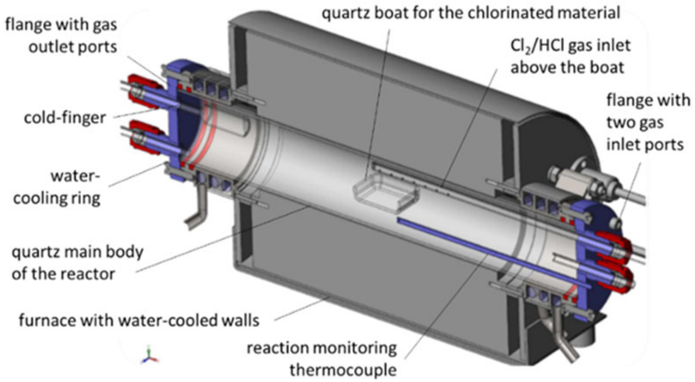
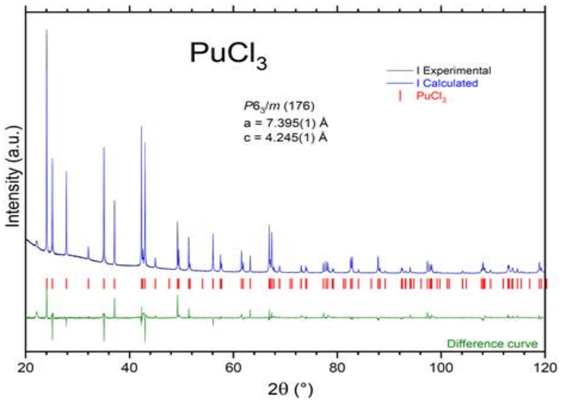
WP3: Task 3.3 Highlights

JRC

Fisrt step of experimental studies: Actinides fluoride and actinides chloride sysnthesis



Chlorination device



$PuCl_3$ synthesis

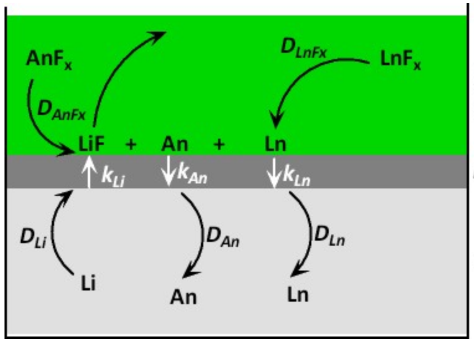
CVRez

Fluorination tests

Experiment was stopped prematurely (after 15 mn) due to high corrosion of the device and fluorination reactor gradually became clogged.
Technology has to be improved to decrease the corrosion.

WP3: Task 3.3 Highlights

Reductive extraction — CNRS



Fuel salt
LiF-ThF$_4$-UF$_4$

BiTh or Bi$_4$Th$_3$

Bi + Li

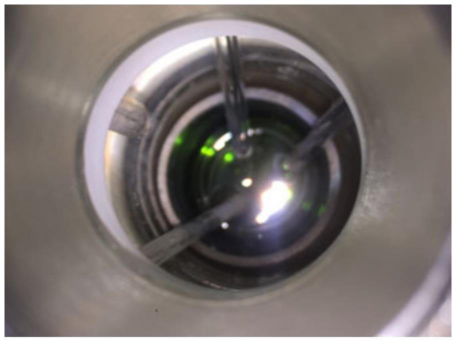
BiTh or Bi$_4$Th$_3$
produced by the chemical reactions:

$$4Li + ThF_4 + Bi \rightarrow ThBi + 4LiF$$
$$12Li + 3ThF_4 + 4Bi \rightarrow Th_3Bi_4 + 12LiF$$

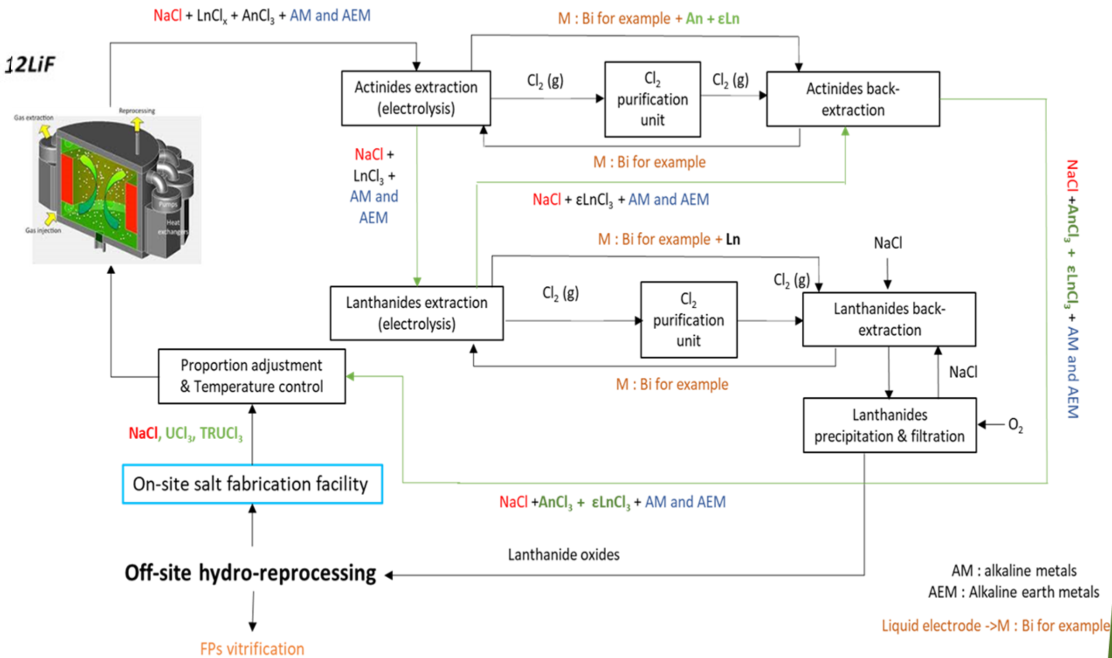
Reductive extraction principle

Low efficiency of U extraction on Bi
Electrolysis limited by Na reduction?

FLiNaK molten salt containing UF$_4$



CEA-CNRS — Fuel reprocessing scheme for chloride MRS concept



WP3: Task 3.4 Highlights

Reprocessing during nominal operation determines radiotoxicity release during accidents.

- cGEMS code application on severe accident simulation,
- in simplified geometry of the presumed containment
- the release from overheated fuel salt was observed
- identifying major radiotoxic components.

Species	Changes Made
$ThCl_4$	Imported as is from literature
Np	Imported as is from literature
$PuCl_3$	Adjusted previously existing data entry to conform with literature melting point
UCl_3	Missing liquid phase data manually matched based on literature values
NpF_3	Missing liquid phase constructed from melting-/boiling points and similarity to UF_3
AmF_3	Solid adjusted and liquid designed from assumed similarity to UF_3
ZrF_4	Imported as is from literature
$NdCl_3$	Imported as is from literature
$PrCl_3$	Imported as is from literature
PrF_3	Imported as is from literature
Na_2ThCl_6	Created in GEMS function ReacDC
Pr	Imported as is from literature

For the simulation Heracles database of the GEMS code was extended.

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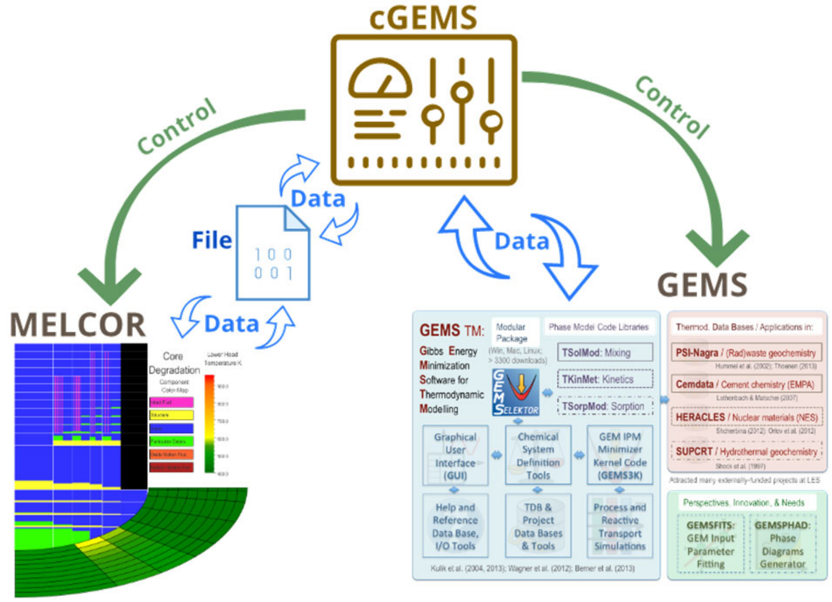
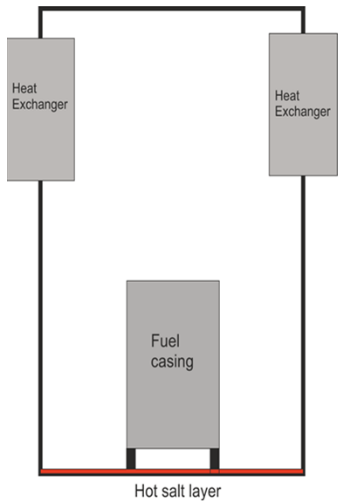
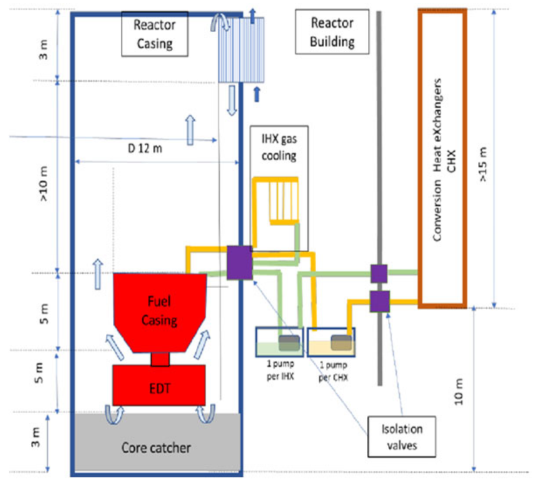






From the SAMOFAR Final meeting, E. Merle et al.

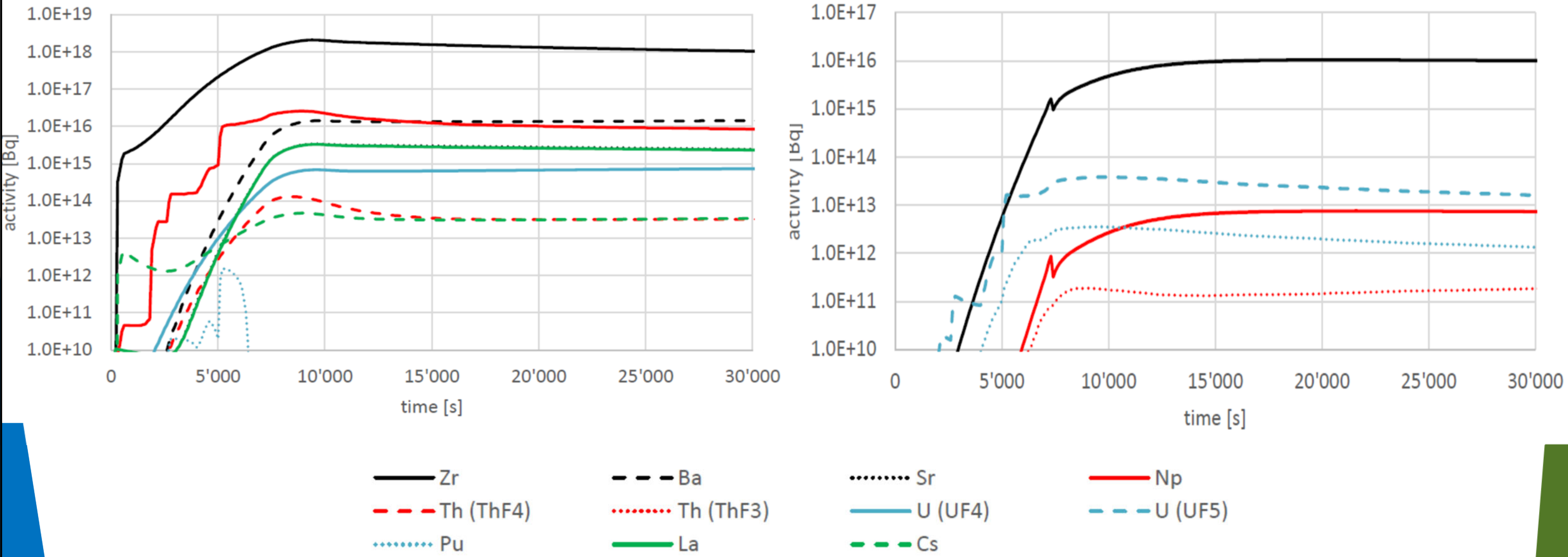
WP3: Task 3.4 Highlights

Nichenko, Sergii , Jarmo Kalilainen and Terttaliisa Lind, 'MSR simulation with cGEMS: Fission product release and aerosol formation', J. Nucl. Eng. 2022, 3(1).

Kalilainen, Jarmo, Sergii Nichenko, Jiri Krepel, 'Evaporation of materials from the molten salt reactor fuel under elevated temperatures', Journal of Nuclear Materials 533 (2020).

Kalilainen, Jarmo, Sergii Nichenko, Jiri Krepel, MSR simulations with cGEMS, to be presented at the 2021 VIRTUAL CSARP Meeting, June 7-11, 2021.

- Characterization of released activity in form of aerosols and vapors



Total released activity in form of aerosols (left) and vapors (right) during the accident.

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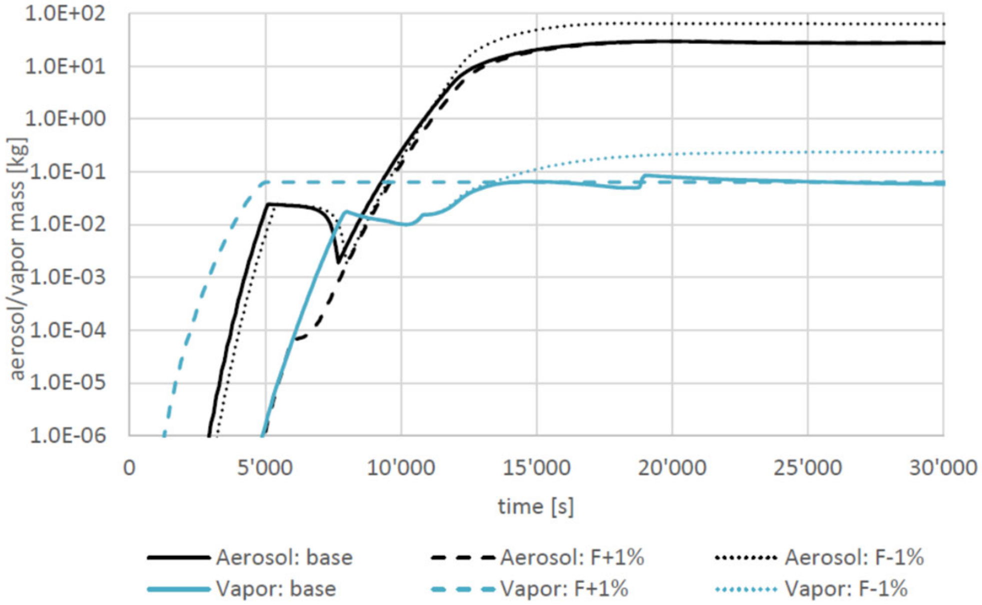
WP3: Task 3.4 Highlights

Nichenko, Sergii , Jarmo Kalilainen and Terttaliisa Lind, 'MSR simulation with cGEMS: Fission product release and aerosol formation', J. Nucl. Eng. 2022, 3(1).

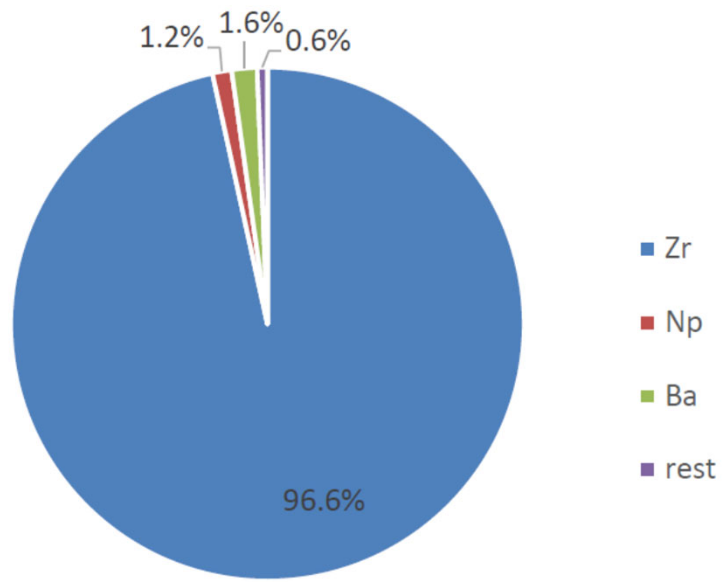
Kalilainen, Jarmo, Sergii Nichenko, Jiri Krepel, 'Evaporation of materials from the molten salt reactor fuel under elevated temperatures', Journal of Nuclear Materials 533 (2020).

Kalilainen, Jarmo, Sergii Nichenko, Jiri Krepel, MSR simulations with cGEMS, to be presented at the 2021 VIRTUAL CSARP Meeting, June 7-11, 2021.

- Based on the applied reprocessing scheme, ZrF_4 in form of aerosols seems to be the major activity carrier during the postulated accident.



Activity break-down at the end of simulation (t=30'000s) of the accident (salt heat up from 800°C to 1500°C)



Total released activity in form of aerosols and vapors during the accident (salt heat up from 800K to 1500K)

WP3: Task 3.1 Highlights

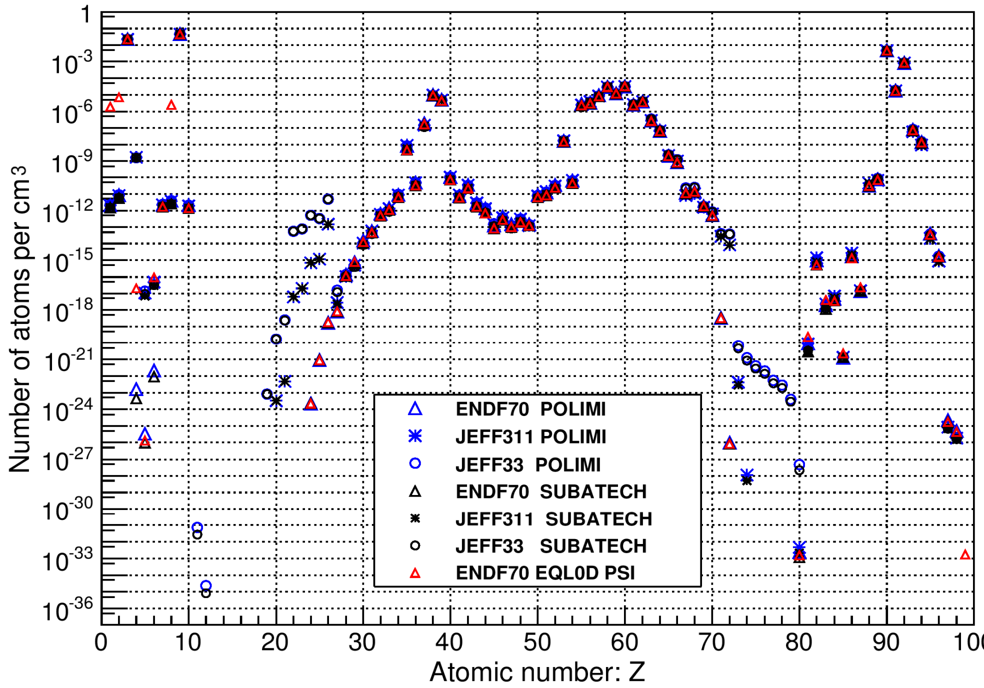
Dietz, J., J. Krepel, S. Nichenko, 'MSR fuel cycle and thermo-dynamics simulations', International Conference on Fast Reactors and Related Fuel Cycles (FR22), Viena, Austria, 22 April 2022, IAEA-CN-291/34

Krepel, Jiri, Fuel handling and waste issues for Molten Salt Reactors. Presentation at the FISA 2022/EUREDWASTE 22 conference in the embedded SNETP forum meeting, 2 June 2022

- Benchmarking of calculation tools
- Adoption of new removal rates from D3.2, D3.3, and D3.4

GFPs cycle time [s]	GFPs cycle time [min]	Helium mass flow rate [g/s]	SFPs cycle time [min]	SFPs cycle time [s]
15	0.25	56.4	35	2100
30	0.5	27.8	70	4200
60	1	13.7	140	8400
120	2	6.8	280	16800
240	4	3.3	560	33600
480	8	1.6	1120	67200
960	16	0.81	2240	134400
1920	32	0.40	4480	268800
3840	64	0.20	8960	537600
7680	128	0.10	17920	1075200

Element	WS1	Fluor.	WS2	LME1	LME2	WS3	LMRE	Storage2	Effective cycle time Fuel salt	Effective cycle time Blanket salt
H	1	0	0	0	0	0	0	0	**450**	**18250**
He	1	0	0	0	0	0	0	0	**450**	**18250**
Li	0	1	0	1	1	0	1	1	**Not rem.**	**Not rem.**
Be	0	1	0	1	0.85	0.255	0.745	0.745	**1765**	**71581**
B	0.98	0.02	0.02	0	0	0	0	0	**450**	**18250**
C	0.5	0.5	0.495	0.005	5E-05	4.95E-05	0.004951	0.004951	**452**	**18331**
N	1	0	0	0	0	0	0	0	**450**	**18250**
O	0	1	1	0	0	0	0	0	**450**	**18250**
F	0	1	0	1	1	0	[illegible]		[illegible]	**Not rem.**
Ne	1	0	0	0	0	[illegible]				[illegible]
[illegible]	0	1	0	1	[illegible]					
~										
						[illegible]	0.001	0.001	**450**	[illegible]
Se					[illegible]	0	0.002	0.002	**451**	**18291**
Br	0	1	0.99	0.01	0.01	0	0.01	0.01	**455**	**18453**
Kr	1	0	0	0	0	0	0	0	**450**	**18250**
Rb	0	1	0	1	0.978	0.515406	0.484594	0.484594	**873**	**35405**
Sr	0	1	0	1	0.2	0.198	0.802	0.802	**2273**	**92183**
Y	0	1	0	1	0.2	0.18	0.82	0.82	**2500**	**101389**
Zr	0.2	0.8	0.16	0.64	0	0	0.64	0.64	**1250**	**50694**
Nb	0.5	0.5	0.495	0.005	0	0	0.005	0.005	**452**	**18331**



Nuclides concentration after 5 EFPD irradiation grouped per atomic number Z

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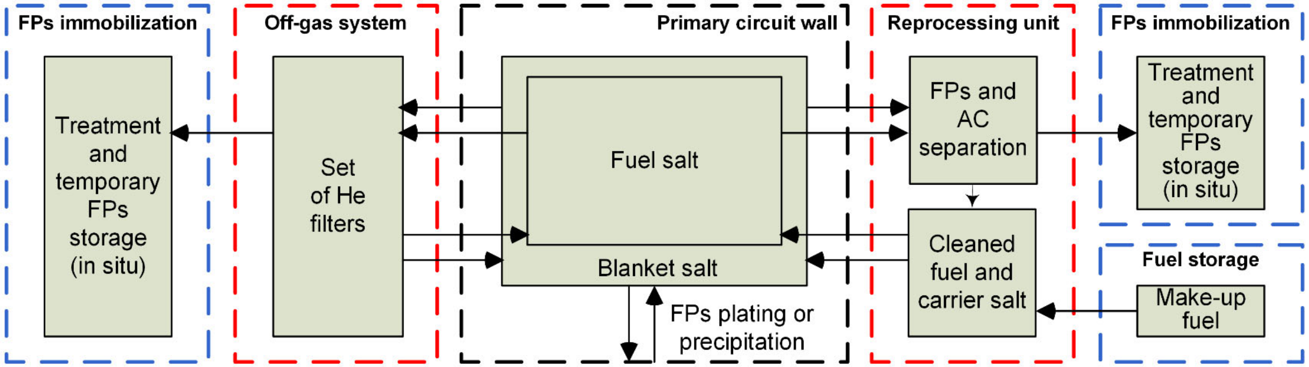
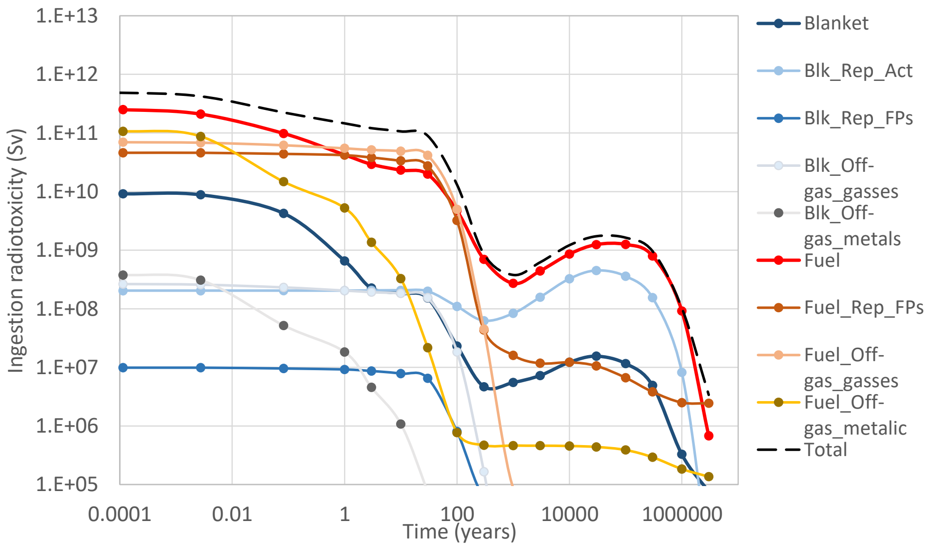
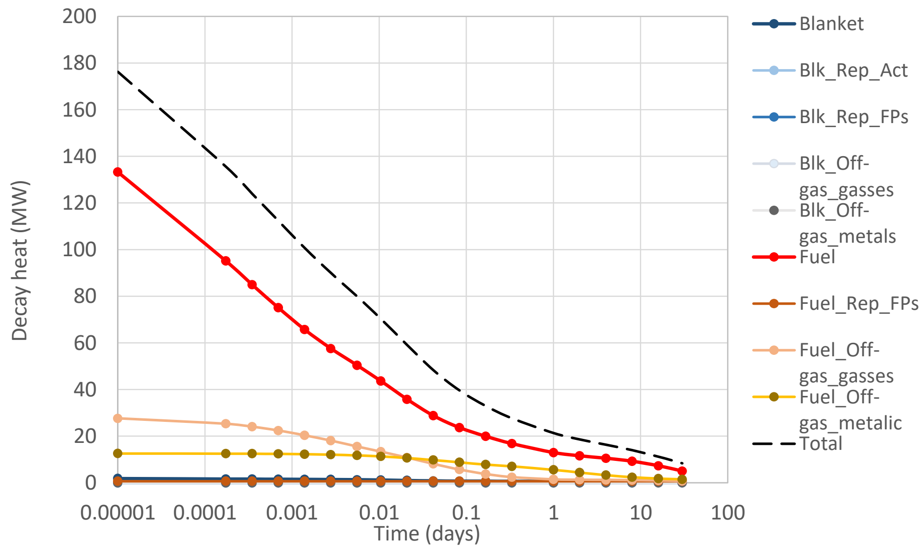
WP3: Task 3.1 Highlights

- Decay heat and radiotoxicity distribution in the MSFR system.





Distribution of ingestion radiotoxicity between several locations (Blk. – blanket salt, Fuel – fuel salt, Rep. –reprocessing unit) after 20 EFPY of irradiation.



Distribution of decay heat between several locations (Blk. – blanket salt, Fuel – fuel salt, Rep. –reprocessing unit) after 20 EFPY of irradiation.

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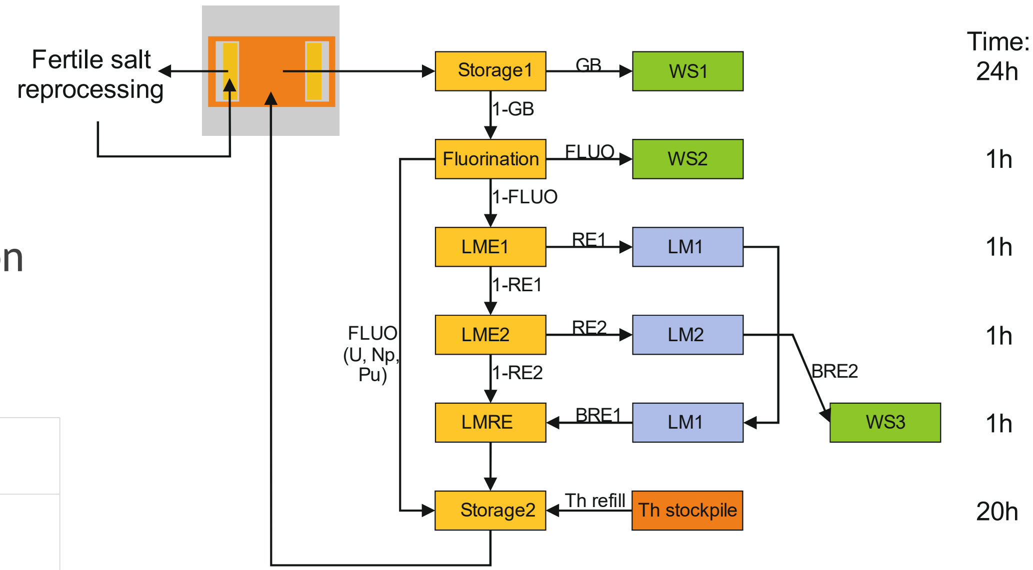
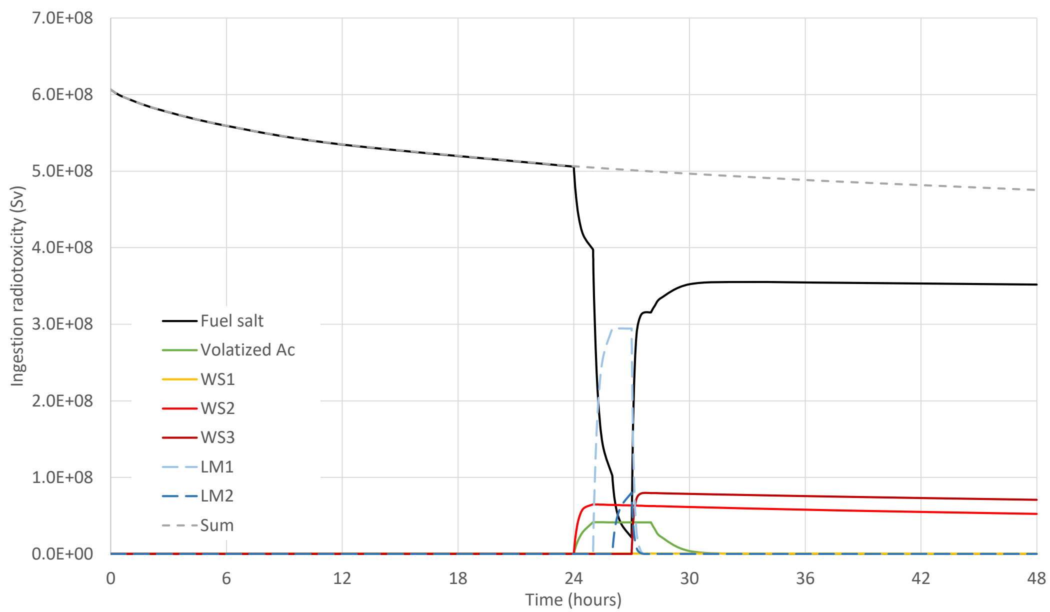
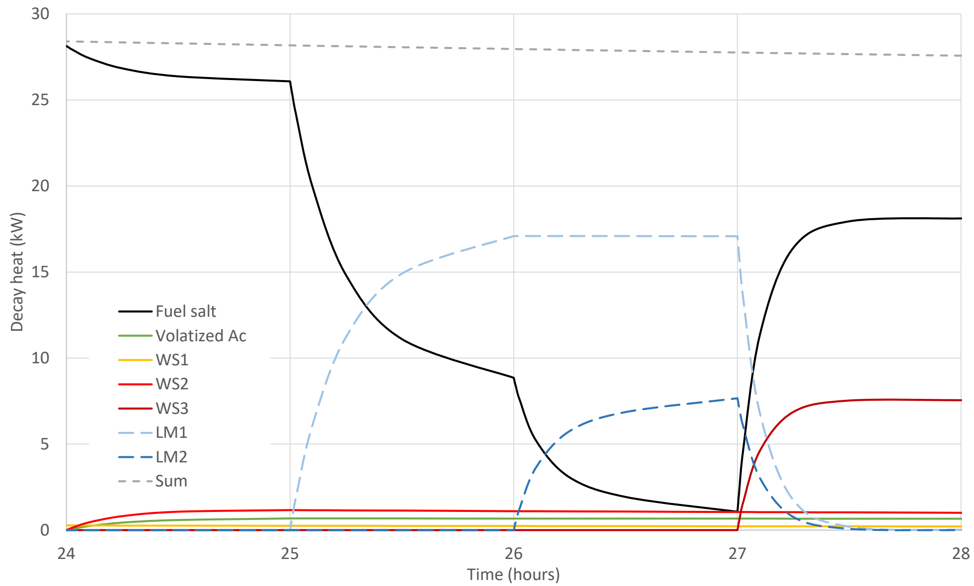
WP3: Task 3.1 Highlights

- Decay heat and radiotoxicity distribution in the MSFR reprocessing system.





Distribution of ingestion radiotoxicity during the 48 hours of salt residence time in reprocessing unit.



Distribution of decay heat during the 4 hours of salt processing.

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WP3 conclusion and outlook

- **Task 3.2**, based on a complex CFD simulations, identified a ratio of 140 between gaseous and metallic FPs removal rates.
  - **Outlook:** In the future these activities may focus on passive off-gas system without He as working medium (simplicity, safety, economy).
- **Task 3.3** analyzed the major reprocessing techniques and identified a high temperature issue for volatilization and back extraction efficiency for liquid metal extraction. Chloride salt reprocessing scheme and elements valence states were proposed, but without transfer coefficients and residence time.
  - **Outlook:** the transfer coefficients for chlorides salt should be calculated. The reprocessing schemes reviewed and possibly simplified (divided into in-situ and ex-situ parts).
- **Task 3.4** provided insight to severe accident behavior, compounds evaporation and formation of gases and aerosols. It also showed, that the containment would be pressurized by air heat up.
  - **Outlook:** further extension of the thermo-dynamics database for fluoride and chloride salts. Iterative approach between fuel burnup calculations, off-gas CFD simulation and severe accident simulations.
- **Task 3.1** was acting as an integrating factor and used results from the other task to provide distribution of nuclides, ingestion radiotoxicity and decay heat. It confirmed several weaknesses of the reprocessing scheme and explicitly simulated individual recycling efficiencies.
  - **Outlook:** Application of the methodology on other MSR systems and focusing on the safeguarding of the reprocessing schemes and waste treatment.

Let’s go for WP4

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WP4: Fuel salt confinement

Final Meeting

28-29 November 2023, Avignon

Main contributors

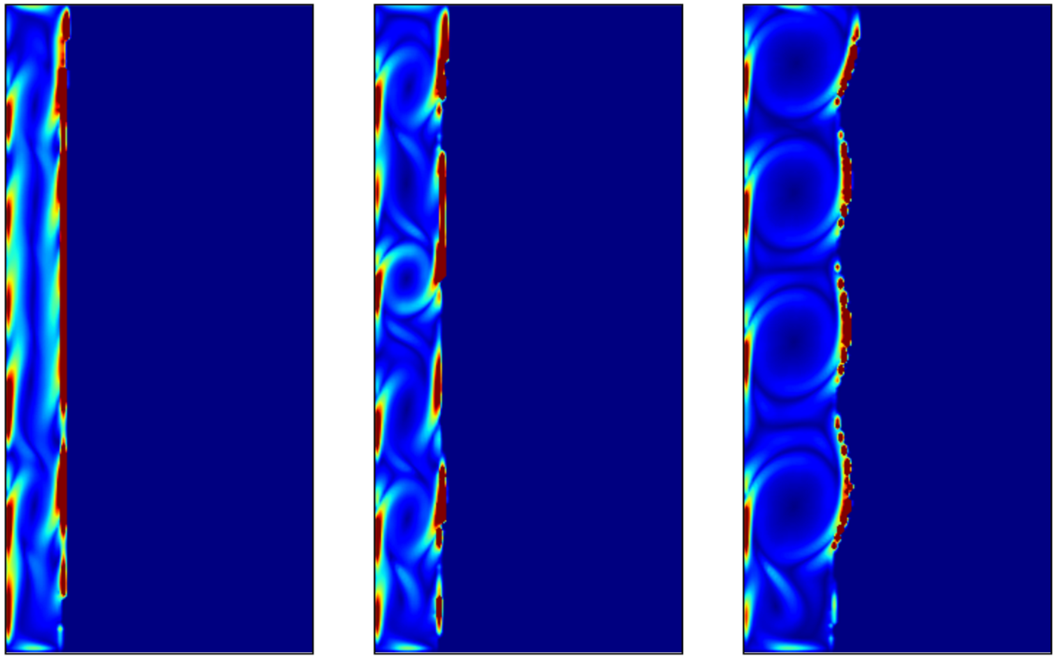
- CNRS: Elsa Merle, Thibault le Meute
- CEA: Frederic Bertrand
- POLIMI: Stefano Lorenzi, Antonio Cammi, Davide Pizzocri, Davide Tartaglia, Carolina Introini
- DTU: Matt Pater, Bent Lauritzen
- TUD: Bouke Kaaks, Martin Rohde, Jan Leen Kloosterman Danny Lathouwers

Main work performed

- Code development for phase-change modeling including benchmark study
- Experimental validation
- Analysis of salt confinement (freeze plug, emergency dump tank
- Thermo-mechanical analysis

Task 4.1 *Improvement of melting/solidification modelling capabilities*

1. An energy-conservative DG-FEM approach for solid-liquid phase change
   - DG-FEM numerical method.
   - Energy conservation guaranteed through convergence criterion.
2. A finite-volume parallel adaptive mesh refinement method for solid-liquid phase change.
   - Adaptive mesh refinement based on numerical discretization error control.
   - High parallelization efficiency through dynamic load balancing.



Estimated numerical discretization error of the velocity solution for the 2D Gallium melting in a rectangular enclosure case.

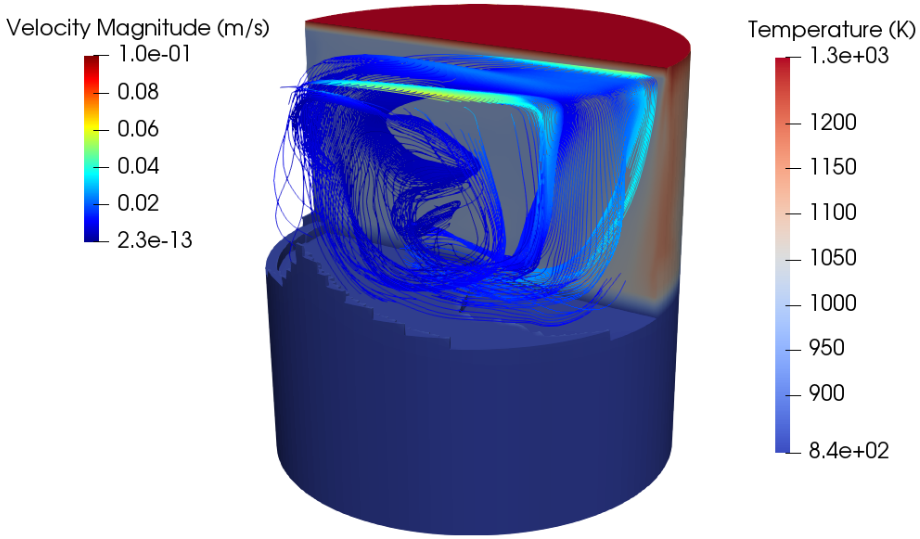
Modelling of melting/solidification phenomena

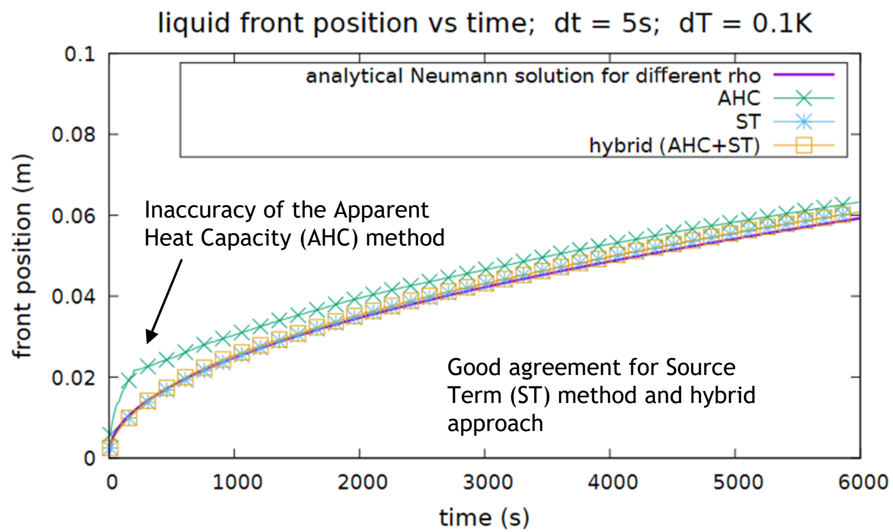
Main achievements

- Development of an OpenFOAM solver for modelling meltii and solidification to be included in the current analysis tool
- Hybrid Approach implemented to balance accuracy and computational time

Outcomes:

- Verification of conduction solver with analytical solution
- Verification of conduction & convection solver with numerical solution
- Adoption of the solver in a freeze plug-like simulation





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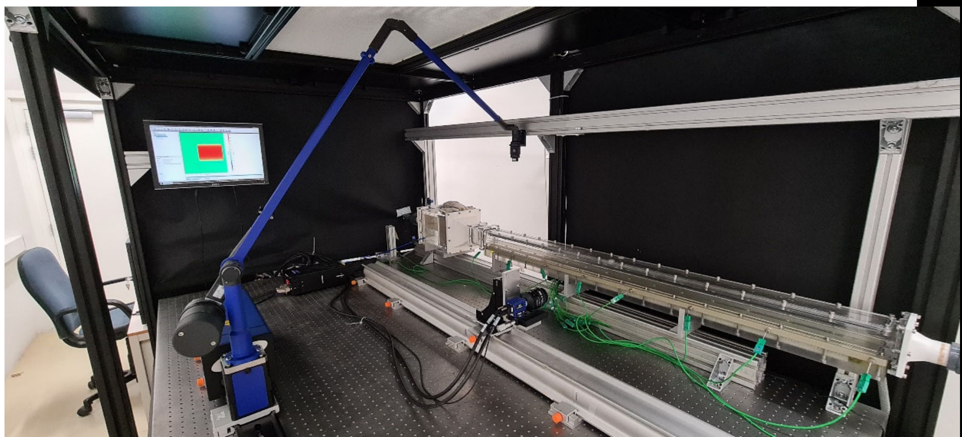
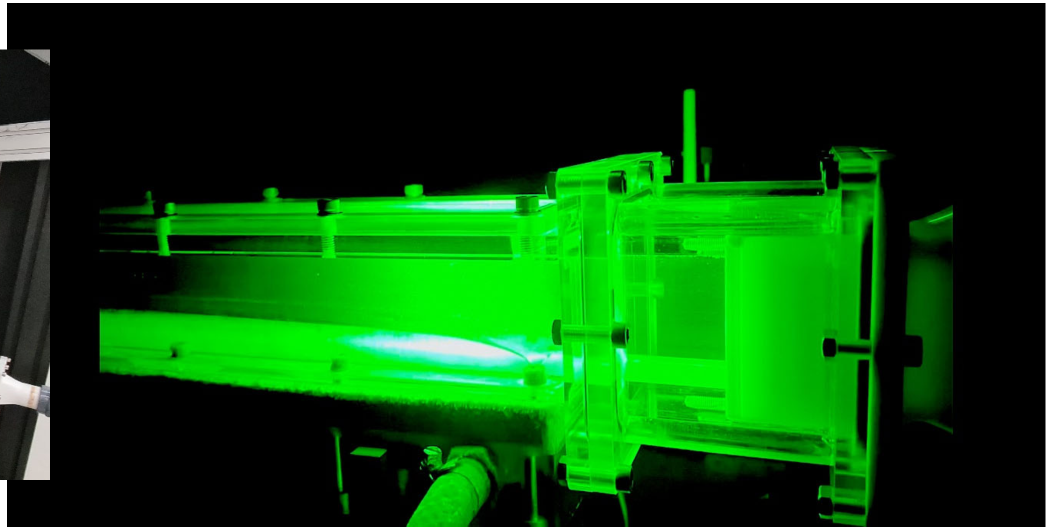
Task 4.2 *Experimental Validation of Melting/Solidification Modelling Capabilities*

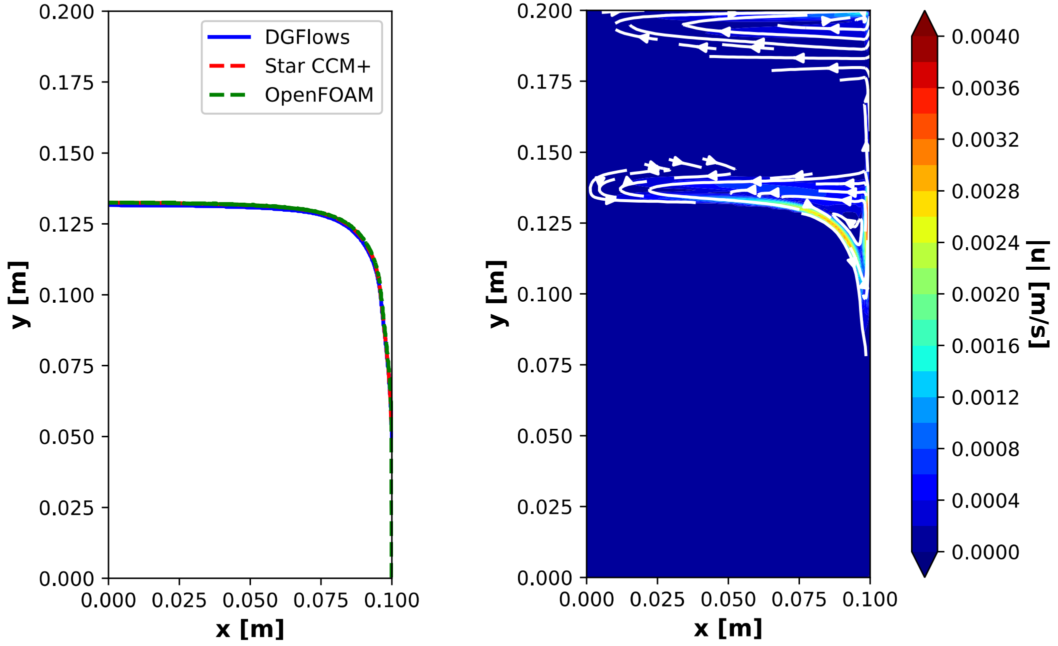
1. ESPRESSO facility: experiments for transient ice-growth in forced internal flow.
2. Well described boundary conditions: generated data suitable for numerical validation purposes
3. Good agreement between the experimental results and numerical simulations.



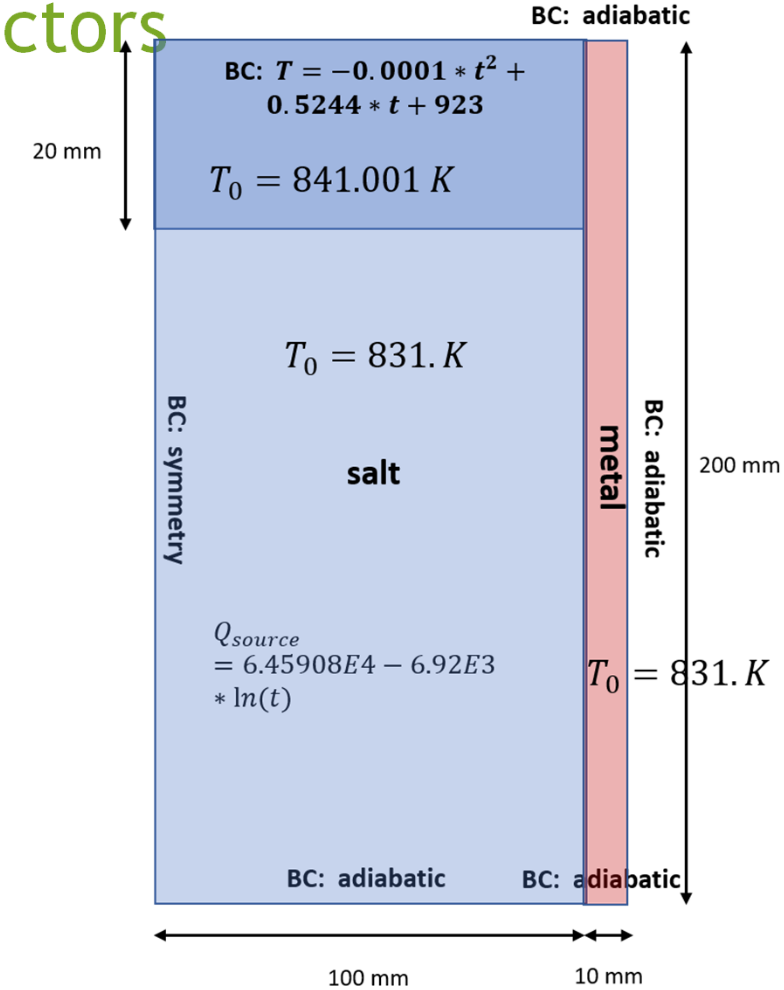


4.3 A numerical benchmark for modelling phase change in Molten Salt Reactors

- Modelled after the MS(F)R freeze-valve.
- Step-wise addition of complexity



Interface positions and velocity contours for stage 4.



Geometry and boundary conditions used in stages 3-5. Blue refers to the salt, and red refers to the hastelloy wall.

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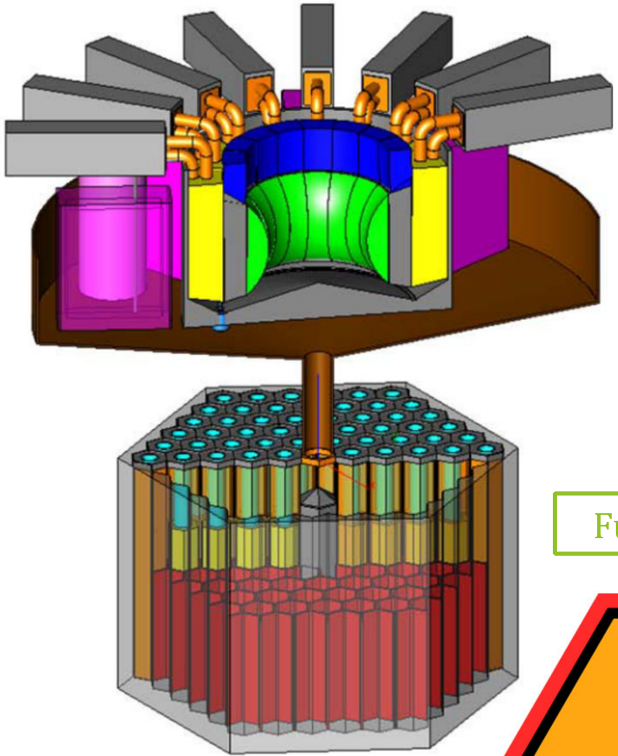
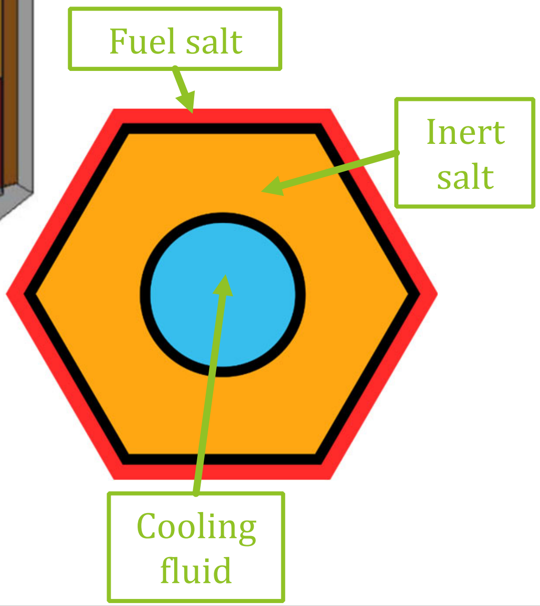
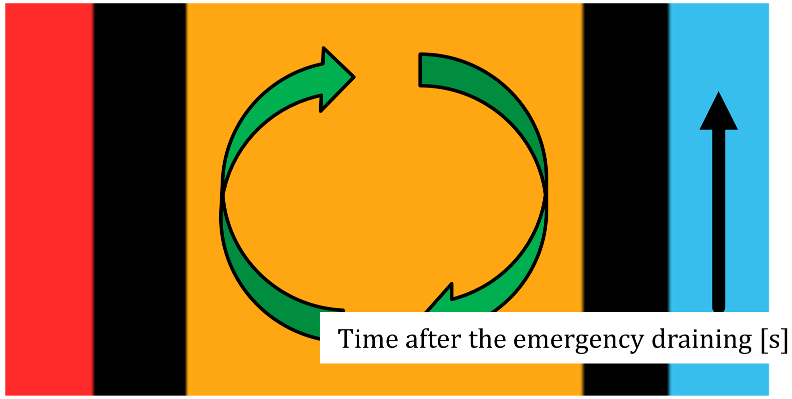
4.3 Analysis of the EDS

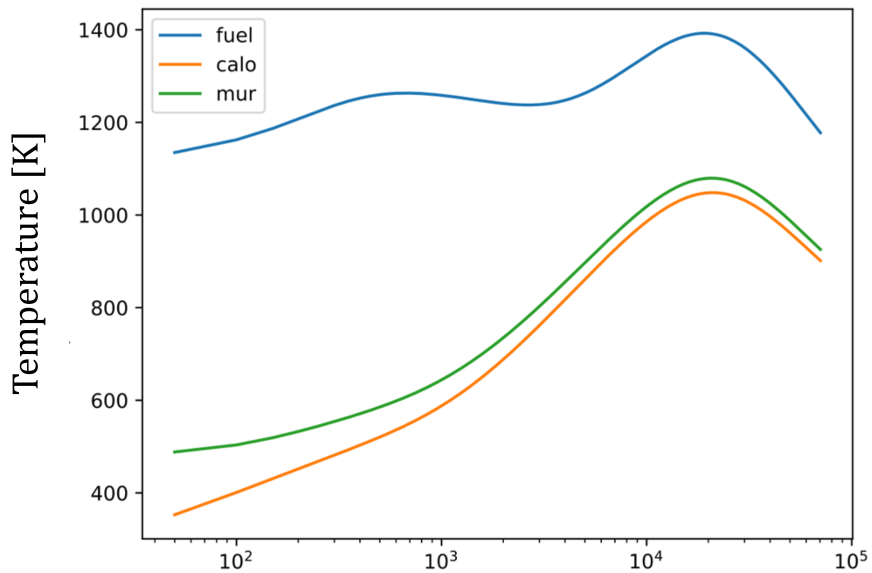




Pure convection:

- Don't take into account melting
- Optimistic situation for safety





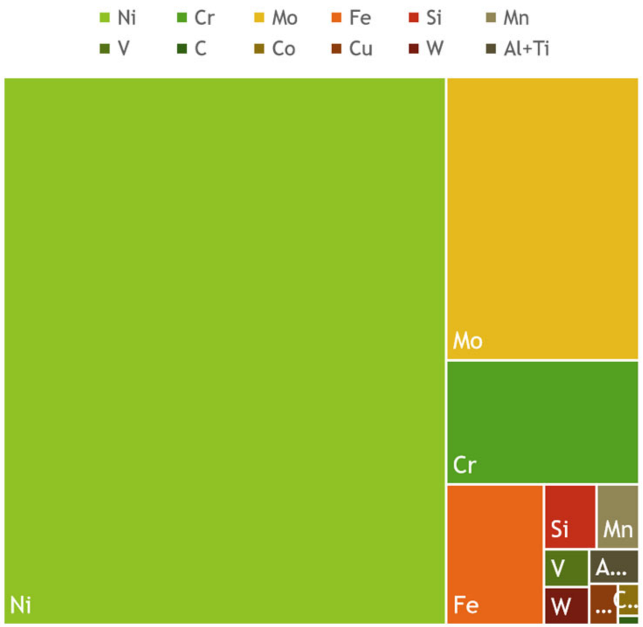
4.4 Thermo-mechanical issues of the confinement

Need:

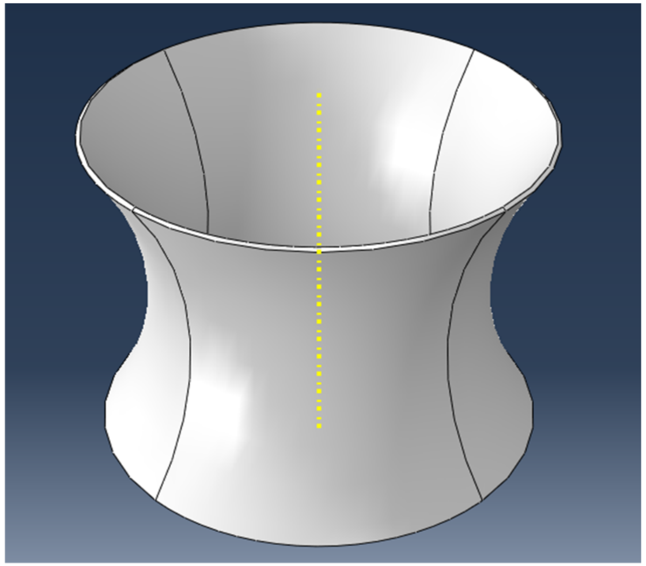
Need for performing a preliminary thermo-mechanical analysis of the reactor containment

Approach:

- Definition of material properties and behavioral models (Hastelloy N)
- Map of thermal load, pressure and fluence on the reactor confinement (OF multiphysics solver)
- Thermo-mechanical analysis



Composition of Hastelloy N



Geometry used for the thermo-mechanical analysis

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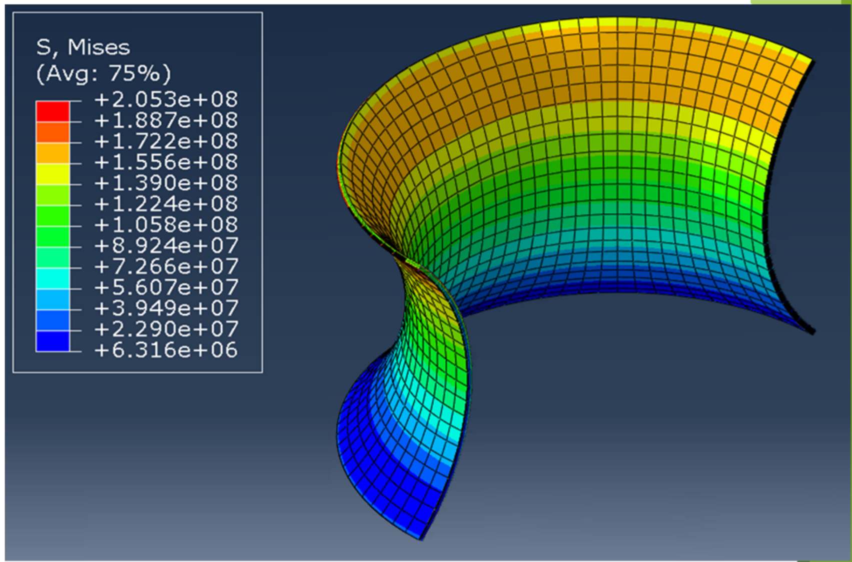
Thermo-mechanical issues of the confinement

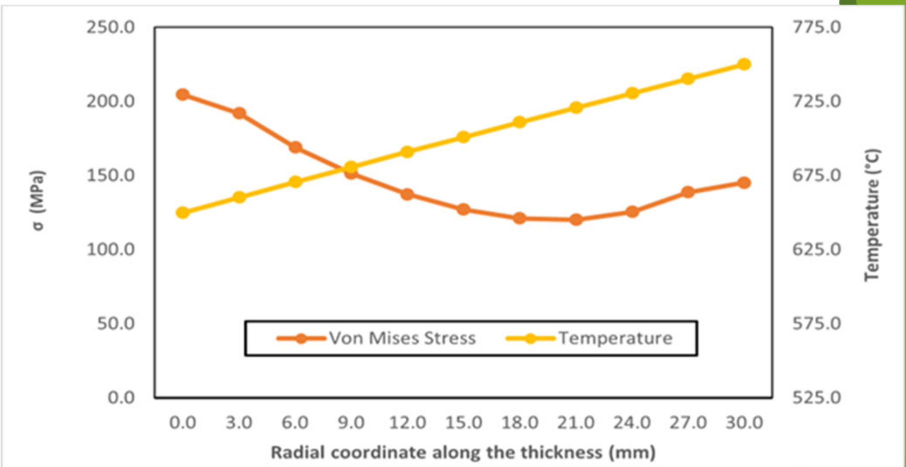
Main achievements

- Preliminary evaluation of stresses, displacements, and thermal creep in normal operating conditions

Outcomes:

- Thermal stresses in the confinement are below the yield strength of the material
- Hastelloy N, with a thickness of 3 cm, and a uniform outer temperature of 650°C is considered as a reliable preliminary design
- Thermal creep not negligible in the top part of the core, calling for optimization in the design of the confinement design (e.g., reducing thermal stress along the thickness)





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Scientific output

- 3 PhD thesis, 1 Postdoc
- O(10) Papers
- O(5) Conference proceedings
- 10 MSc/BSc theses
- More to come …

Let’s go for WP5

WP5: Heat removal and temperature control

Final Meeting

28-29 November 2023, Avignon

WP5 on Heat removal and temperature control

Objective: Development and validation of heat transfer models for MSR safety studies.

Application of models/codes to support WP6 activities. Design and salt properties from other WPs.

- **Task 5.1** Extension and validation of the SIMMER multiphase fluid-dynamics model; KIT, EDF
- **Task 5.2** Multiphase phenomena and heat transfer in MSFR; EDF, KIT
- **Task 5.3** Effects on heat transfer by free surface, radiation heat, solidification/melting; CNRS, TUD
- **Task 5.4** Natural convection and heat transfer in MSR; POLIMI, CNRS

Milestones M14, M26 and Deliverables D5.1-D.5.6

2020 (M14): SWATH-S ready for experiments (CNRS); Verification: Technical note (TN): Done

2021 (M26): e-Dynasty ready for experiments (POLIMI); Verification: TN: Done

D5.1 (M48) Extension and validation of the SIMMER code for treating gas-liquid interface, KIT: In progress

D5.2 (M48) Assessment of calculation models for study DHR capability in MSR, KIT: In progress

D5.3 (M30) Report on the SWATH experiments, CNRS: Done

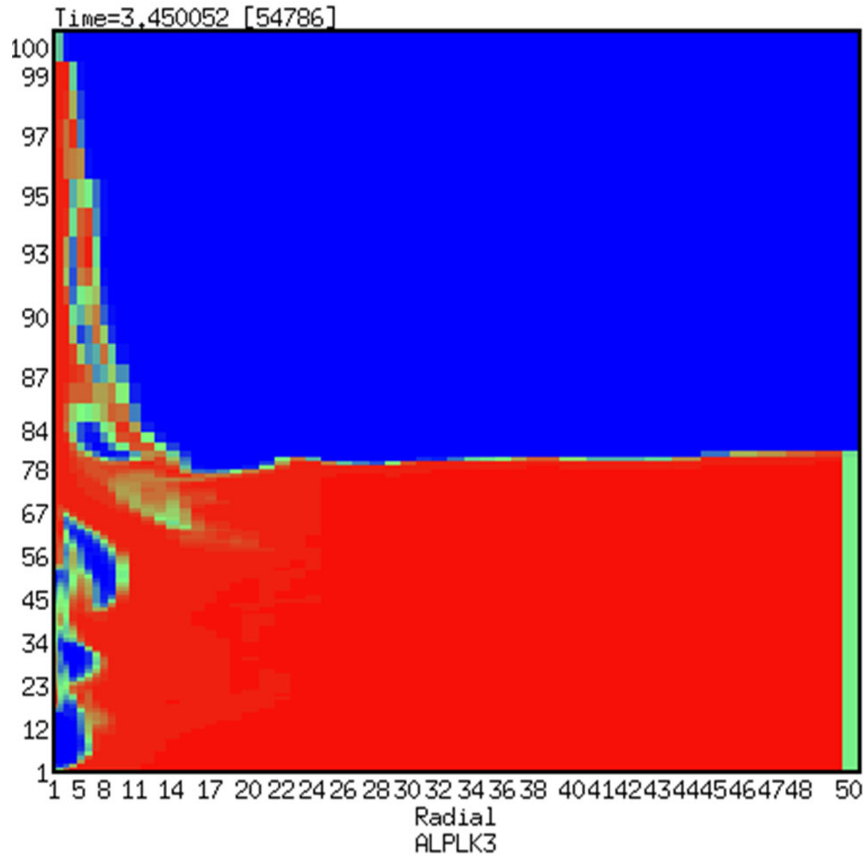
D5.4 (M48) Radiation heat transfer: model development and validation (R,CO), TU Delft: In progress

D5.5 (M36) CNRS natural circulation stability experiment (R,CO), CNRS: In progress

D5.6 (M42) Experimental and simulation results of the e-DYNASTY natural circulation experiment, POLIMI: Done

Task 5.1 Extension & Validation of SIMMER multiphase fluid-dynamics model

- SIMMER is a coupled, multiple velocity, multi-component code, developed mainly for SFR studies
- KIT extended it for MSR, LFR, etc.; SIMMER with some KIT extensions is used by some EU partners
- Castillejos experiment on gas injection in water: used for initial SIMMER validation
- More recent model in SIMMER for momentum transfer between liqiud-gas: developed for an experiment on gas injection in HLM
- We now show that the model improves the results also for gas in water
- Average gas fraction: now more accurate in 2D
- Spatial distribution of the fraction: less accurate, expected to be more accurate in 3D
- Benchmark on gas injection in molten salt proposed



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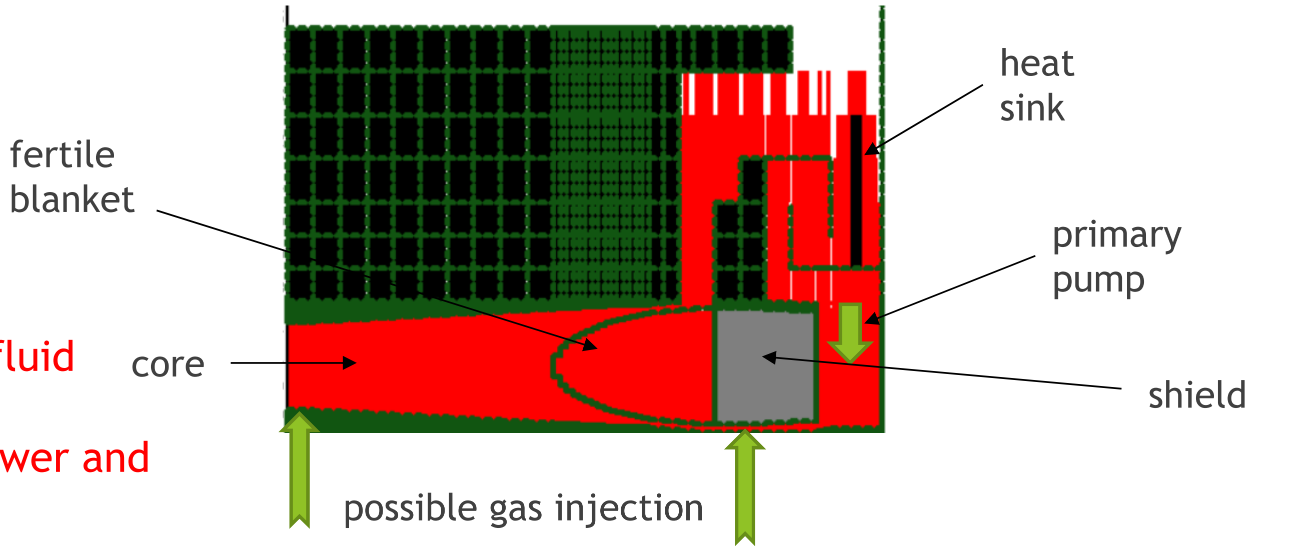
Task 5.2 MSFR modelling in SIMMER

- SIMMER features
  - Turbulence-diffusion effect on the viscous drag term
  - Modification of bubble drag coefficient, interpolated between ellipsoidal bubbles and cap bubble's (Suzuki 2003)

conclusions from Castillejos

- Improved primary circuit model
  - Simplified IHX (heat sink)
  - Adjusted cover gas section
  - Modified downcomer
  - Start-up procedure



Observations:
Very strong coupling: neutronics and fluid dynamics.
Gas injection brings instabilities in power and flow pattern

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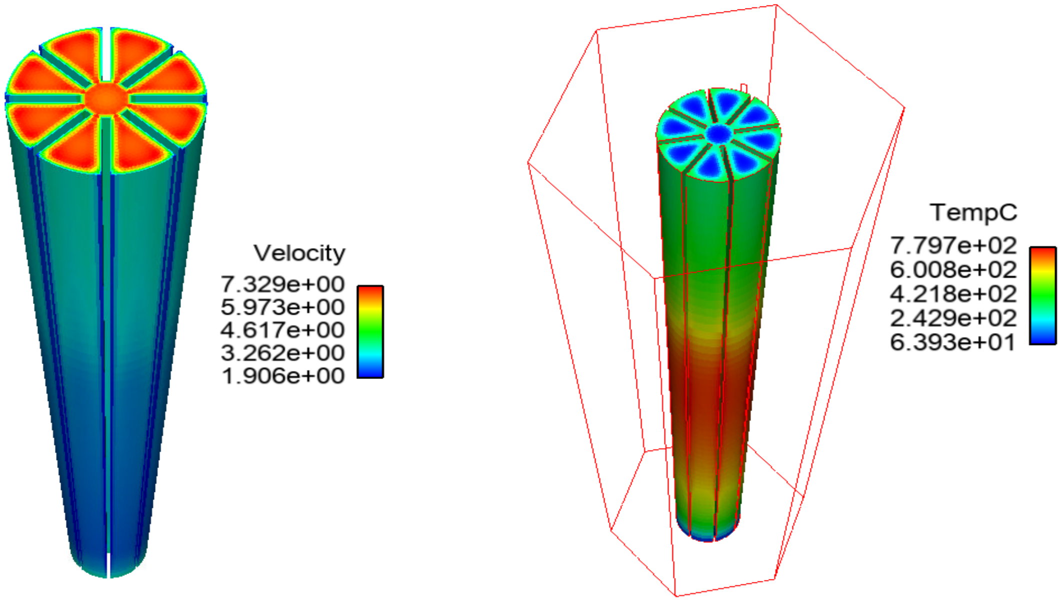
Task 5.2 Multiphase phenomena and heat transfer in MSFR, decay heat removal (DHR) in EDT (Emergency Draining Tank): a channel in 3D



- EdF applied industrial codes (SYRTHES, Code_Saturn), for DHR simulation from the core and EDT, see the considered EDT element design above
- The simulations show the viability, importance and limits of different simulation options and physical phenomena
- Natural air convection seems to be insufficient for this design, taking into account of radiation heat transfer and convection effects should be considered

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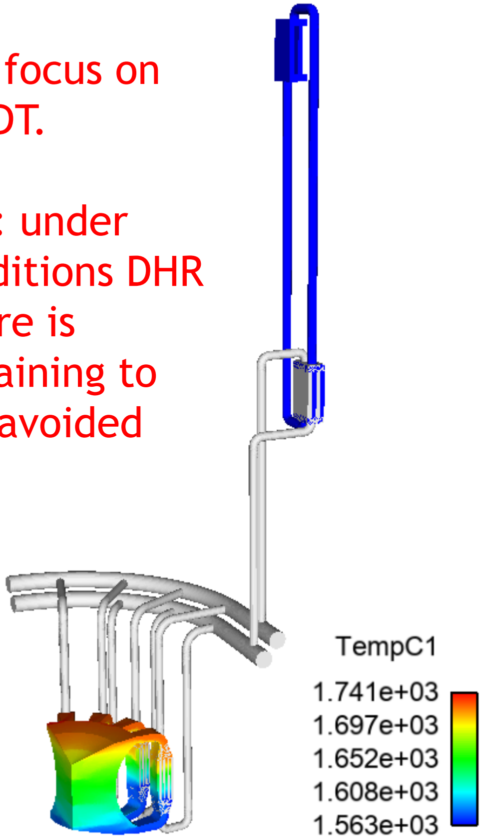
Task 5.2 Multiphase phenomena and heat transfer in MSFR: simulation of decay heat removal from the core

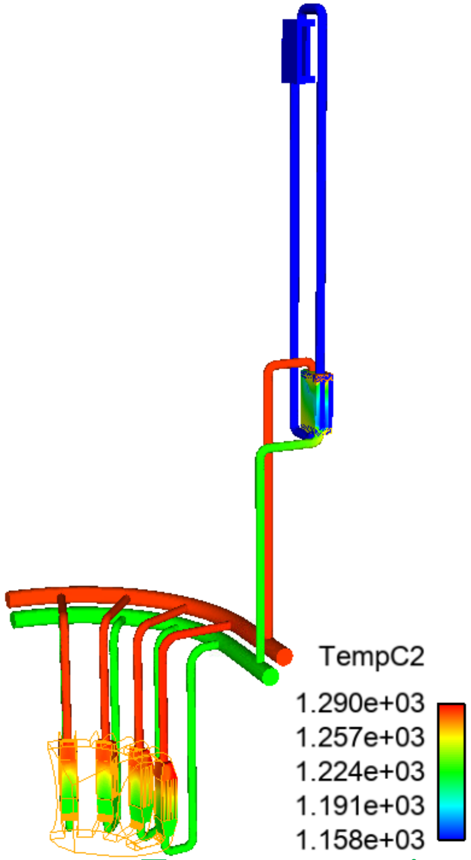
- 3 passive circuits simulations at EdF: with industrial codes Code_Saturne code.

In the past: focus on DHR from EDT.

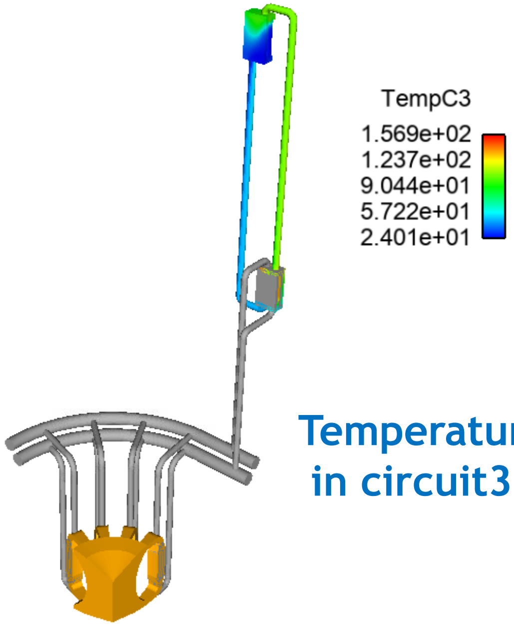
SAMOSAFER: under certain conditions DHR from the core is possible, draining to EDT can be avoided



Temperature in circuit1



Temperature in circuit2



Temperature in circuit3

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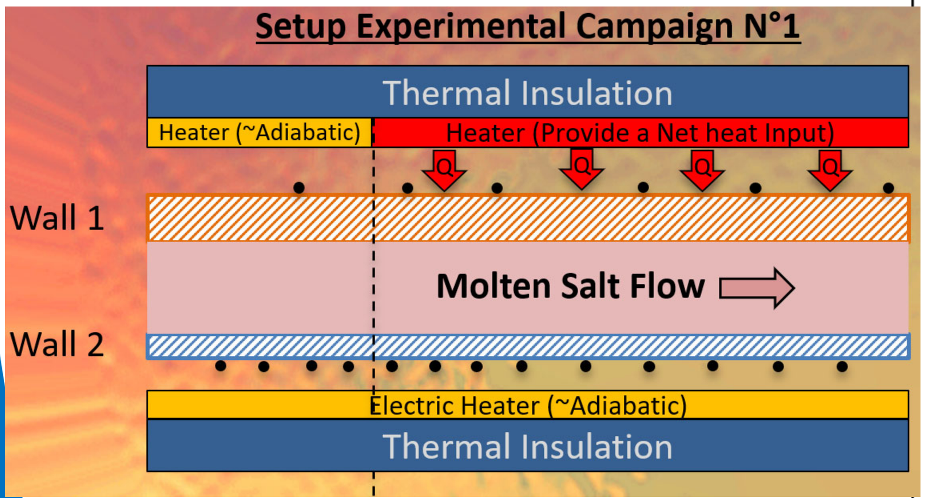
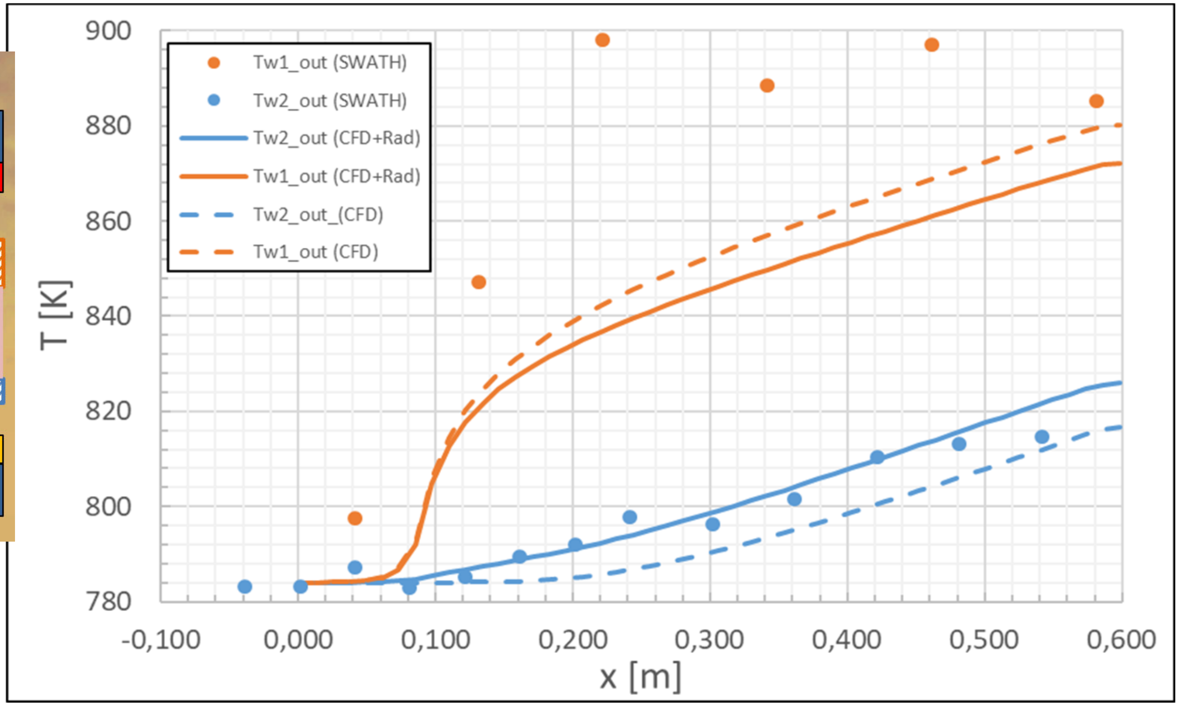
Task 5.3 Heat transfer effects in SWATH experiments

- CNRS performs experiments in SWATH-S with circulating salt in a flat section and
- in SWATH-W with water, using PIV measurements to characterize the flow field, using ANSYS and OpenFOAM.
- Conjugated CFD simulations at CNRS using a uniform heat flux (fixed according the SWATH electric heaters power) over the heated Wall 1 and adiabatic conditions at Wall 2: see experimental and CFD results below
- Experimental results can match simulation ones if radiation heat transfer (+Rad) between 2 walls is considered





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Task 5.3 Radiation heat transfer code development

- A new development at TU Delft for simulation of radiation heat transfer
- Optical properties depend on salt composition, not well-known
- Preliminary studies and developments at the beginning of the project
- Then adaption of a neutral particle Sn transport code: with respect to sources, boundary conditions, sets of ordinates
- First results for a SWATH-like case are shown in this slide
- Stringer radiation effects compared to ones shown earlier
- Stronger effects are due to higher salt T (700K)

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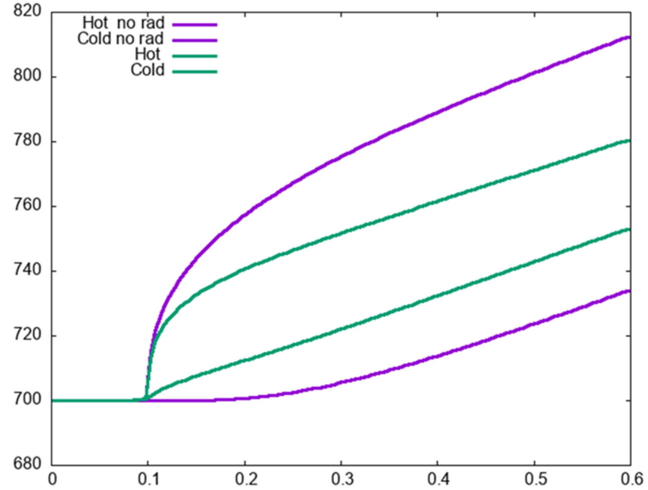

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Task 5.4 Natural circulation experiments

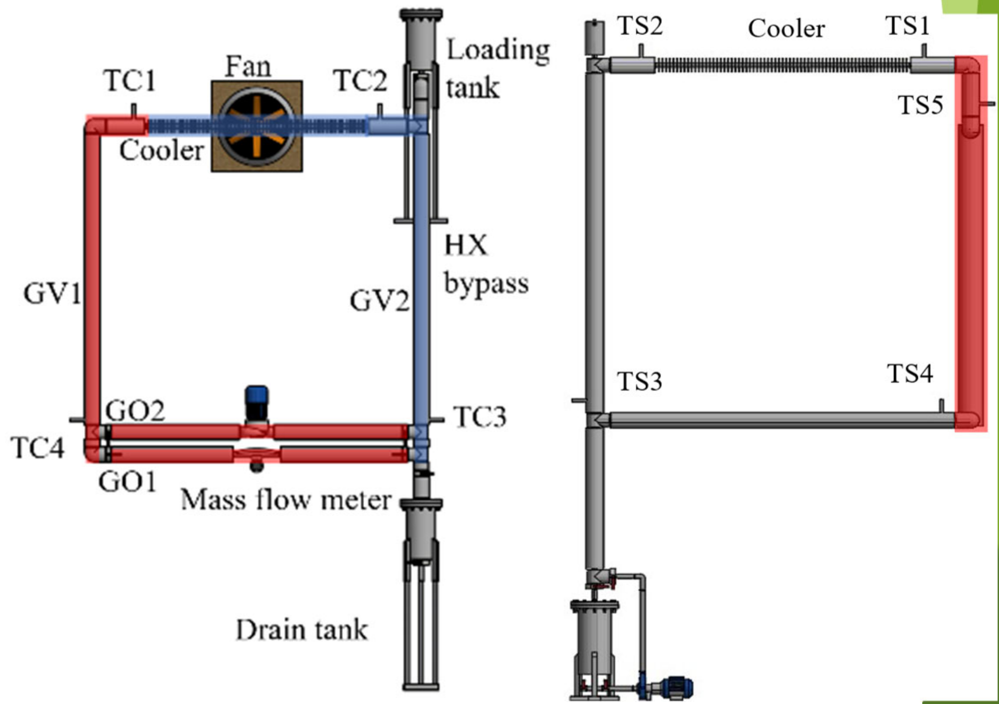
Need:

Need for having experimental datasets to analyze natural circulation phenomena in presence of distributed heating systems and to validate numerical tools

Dynamics of the natural circulation studied through the DYNASTY-eDYNASTY facilities at POLIMI, i.e., natural circulation loops. Three main cases:

1. Startup of natural circulation
2. Transition from forced to natural circulation
3. Passive heat removal during cool-down

Modelling part performed with Modelica system code



Dynasty and eDynasty facilities

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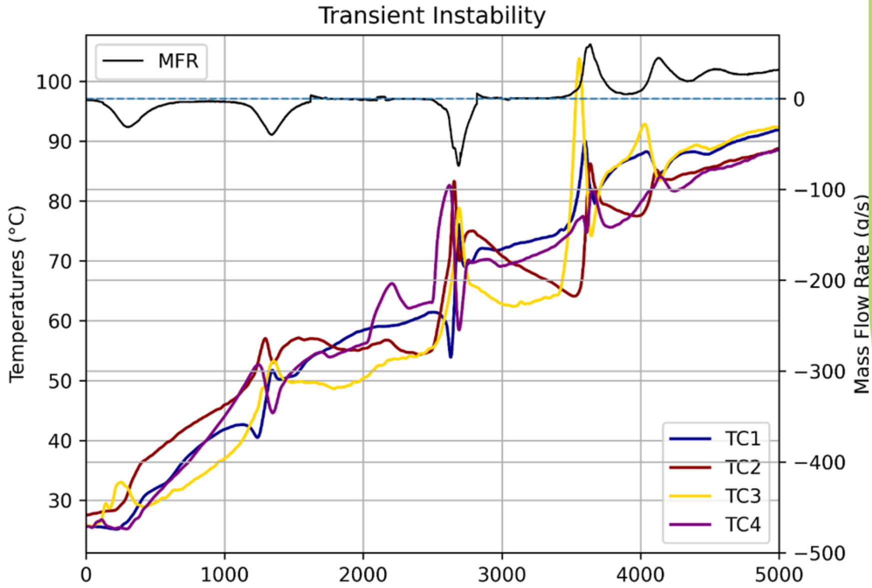
Task 5.4 Natural circulation experiments

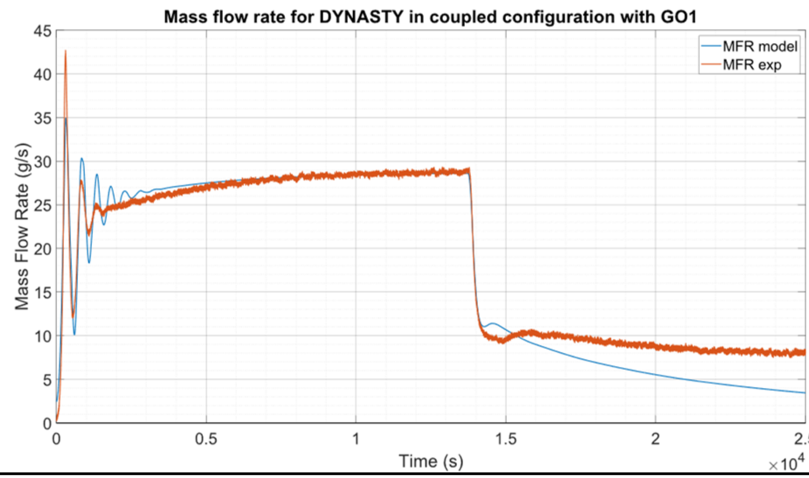
Main achievements

- Experimental datasets on natural circulation in different configurations (power, fan velocity) and with high Pr number (glycole)
- 1D Model of DYNASTY-eDYNASTY facilities

Outcomes:

- Startup of natural curculation depends on the creation of cold/hot fluid packets
- Glycole simulations show instable behaviour
- Estimation of heat losses is of paramount importance in the numerical modelling to represent the experimental behaviour





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Conclusions

- WP5 on “heat removal and temperature control”: mainly as planned
- COVID issues: minor delays
- Experimental activities, code/model developments, simulations: mainly finished
- Interesting results and appreciable progress in all tasks, by all WP5 partners
- Using data on design and salt properties from respective WPs
- Support of WP6 studies
- Documentation needs further effort, it should be possible to finish it soon.
- **Delays in documentation do not influence progress in other WPs**

Let’s go for WP6

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WP6: Reactor operation, Reactor control and Safety demonstration

Final Meeting

28-29 November 2023, Avignon

WP6 Reactor operation, Reactor control and Safety demonstration

Lead. Elsa Merle *(Full Professor at Grenoble Institute of Technology / CNRS-IN2P3-LPSC - elsa.merle@lpsc.in2p3.fr)*

WP6 objectives:

- Improve the safety margins evaluation of the reactor during operational states
- Define the monitoring / inspection / maintenance process and devices (accident prevention)
- Deviation identification and correction, regulations
- Safety demonstration following the requirements defined in WP1 applied on the MSFR in WP3, WP4 and WP5
- Complement the safety demonstration of MSR including design and scaling effects

In conclusion: WP6 aimed at demonstrating the effectiveness of the validated simulation models and tools and the effectiveness of the barriers to reduce the risks and to prevent and mitigate severe accidents in the MSFR

Deliverables

D6.1: (M27) Drawings of the MSFR, CEA

D6.2: (M30) List and description of the plant operational states with the corresponding safety margins, CNRS-Grenoble

D6.3: (M36) Innovative control model and strategy development and applications to MSFR, POLITO

D6.4: (M42) Fluoride analysis, CNRS-Orsay

D6.5: (M42) Measurement of the salt redox potential in the fuel circuit, CNRS-Orsay

D6.6: (M42) Decay heat removal in MSFR, KIT

D6.7: (M48) Uncertainty quantification of safety demonstration calculations, TU Delft

D6.8: (M48) Scaling effects and potential safety improvements, CNRS-Grenoble

Milestones

MS6.1 (M10) Preliminary drawings of the MSFR, CEA; Verification: Draft of D6.1

MS6.2 (M21) Identification of the operational states of the reactor, CNRS; Verification: Technical note

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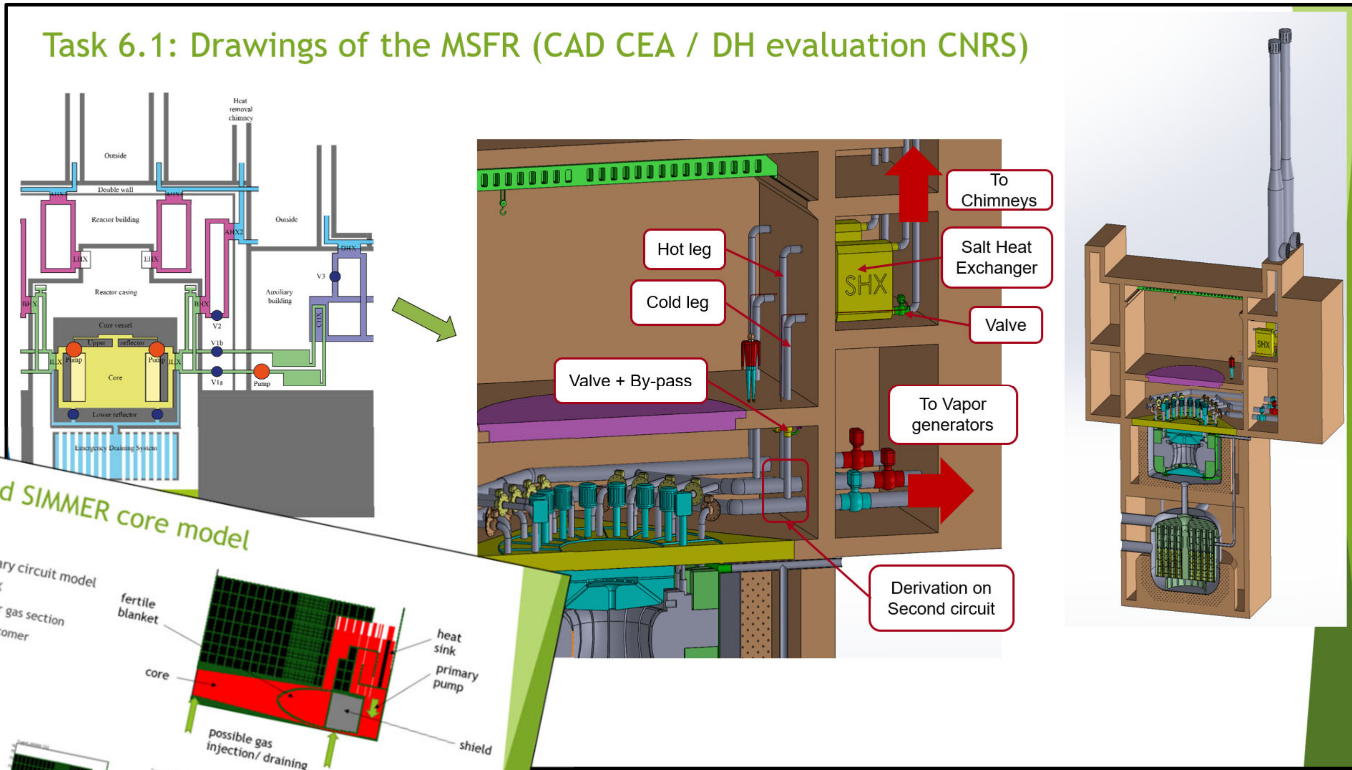
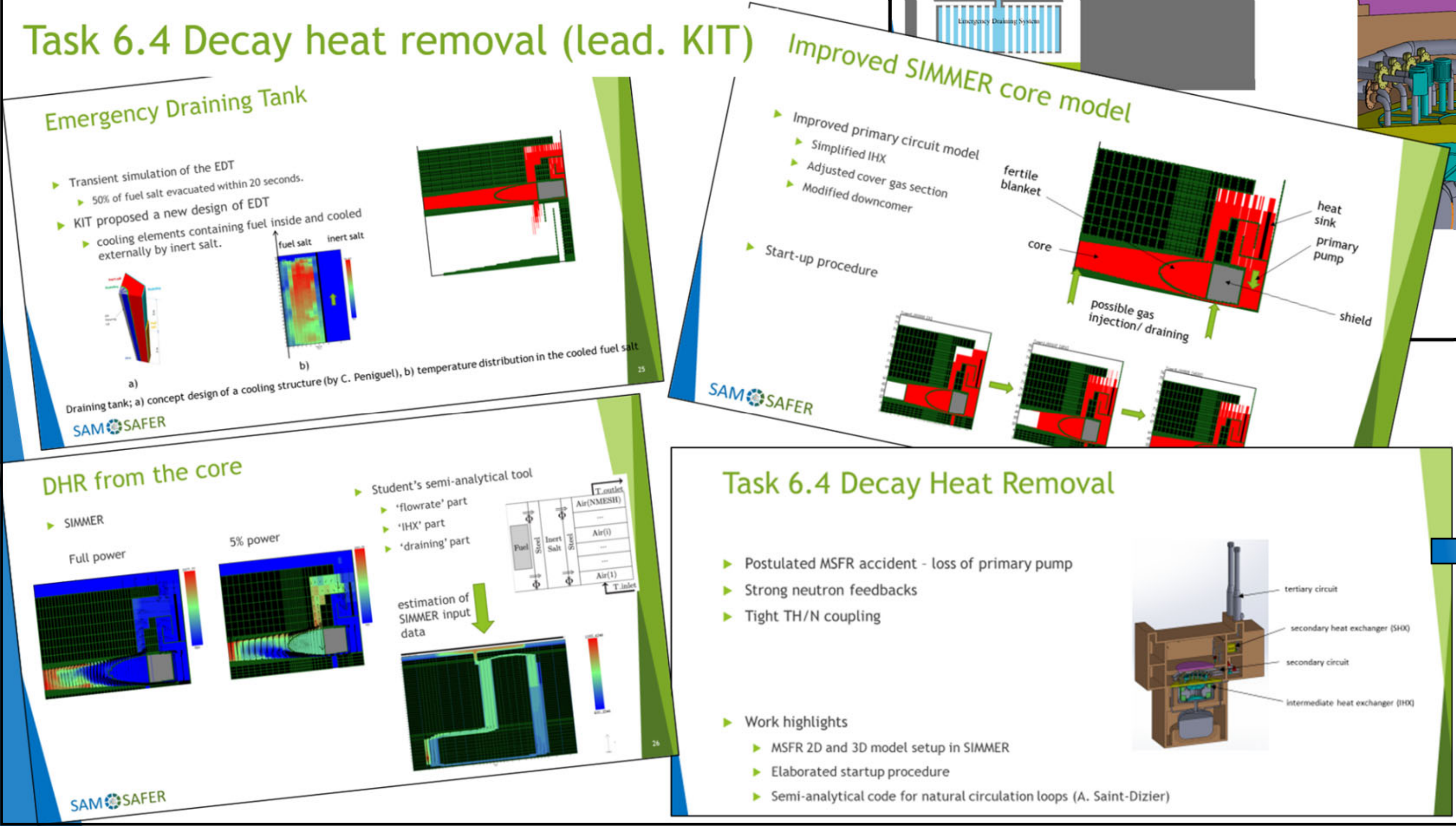
WP6 results and outcomes on design

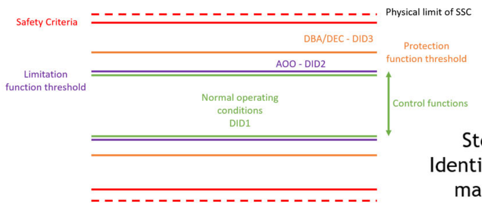




See WP5 session

WP6 results and outcomes on safety demonstration

Task 6.2.1: Safety margins and plant operational states (Framatome / CNRS)



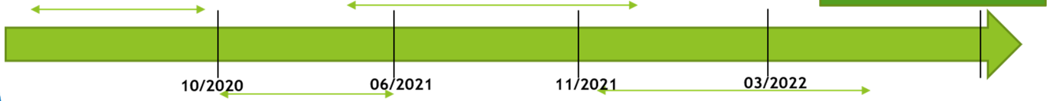
Dependencies between main plant parameters

What happens to parameter in column A when the parameter in the other column increases? (considering other parameters constant)	Fuel salt temperature	Fuel salt flowrate	Reactor thermal power	Reactivity	Fuel salt level
Fuel salt temperature		Average T is stable (critical T) DT decreases as long as IHX is able to remove heat. Does fuel flow has an impact on heat production?	Average T is stable (critical T) DT increases	Average T increases and comes back to critical T DT increases	No impact (but reversely, if T increases, lvl increases)
Fuel salt flowrate (forced flow)			No impact	No impact	No impact
Reactor thermal power				Increases	No impact
Reactivity					Depends on reactor status: - during reactor filling: increase of reactivity - while reactor is full: no impact
Fuel salt level					

Methodology definition

Step 2&3 Identification of main plant parameters and their range

Deliverable D6.2

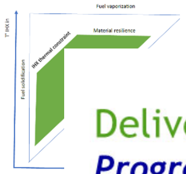


- Startup of the reactor
- Power production
- Shutdown without draining
- Shutdown with draining

Step 1 Definition of the normal operating states

Milestone S15

Step 4 Definition of the limitation and the protection strategy



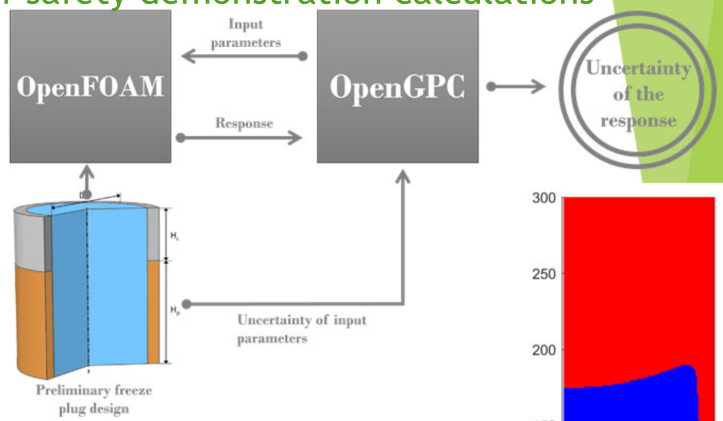
See presentation by T. Boisseau in WP6 session

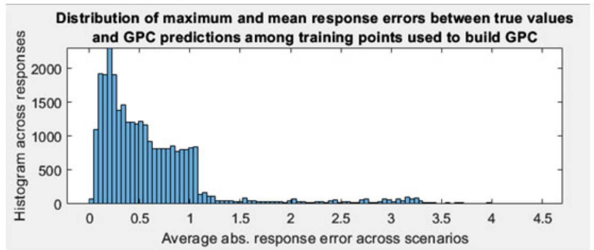
Uncertainty quantification of safety demonstration calculations

Deliverable 6.7 (lead. TU Delft)

Progress and Needs

- √ Overview of MSFR design.
- √ Overview of PCE method (openGPC)
- √ Freeze plug design and melting calculations (openFOAM).
- √ Interfacing openGPC and openFOAM.
- ➢ Input from:
  - ➢ Task 1: safety approach and limits.
  - ✓ Tasks 4.2 & 4.3: freeze plug design, melting model, parameters/uncertainties.
  - ! (Optional) Task 5: Transient model with scriptable code, uncertainties.
- ➢ Perform calculations, analysis.





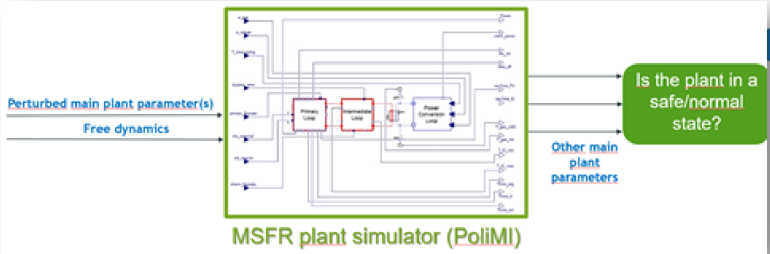
Melted (red) plug at 2500 s (nominal)

Under finalization

WP6 results and outcomes on reactor control

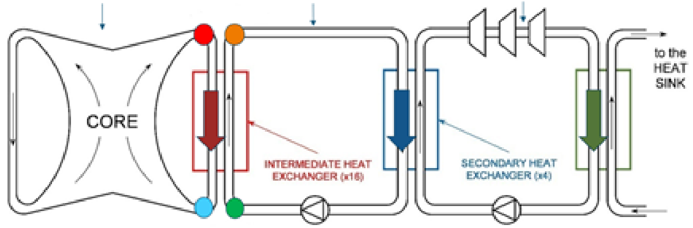
Task 6.3: Monitoring systems, inspection and maintenance procedures (lead. POLITO)

Objective: development of incident detection methods, based on measurable plant parameters, to identify abnormal conditions



Physical tresholds:
- T_{min} = 858 K *Salt freezing*
- T_{max} = 1373 K *Structural damage*

Fuel Circuit (FC) Intermediate Circuit (IC) Gas Circuit (GC)



Control variables (model input)
- **Fuel circuit** salt mass flow rate
- **Intermediate circuit** salt mass flow rate
- **Gas circuit** salt mass flow rate

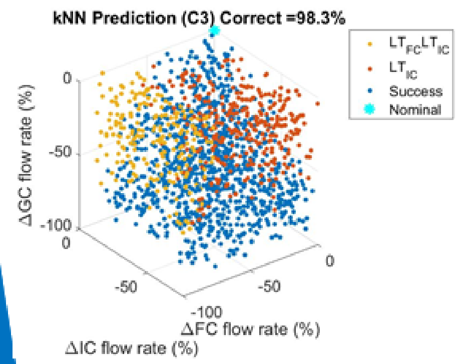
Controlled variables (model output)
- **Fuel circuit** inlet temperature
- **Fuel circuit** outlet temperature
- **Intermediate circuit** cold temperature
- **Intermediate circuit** hot temperature

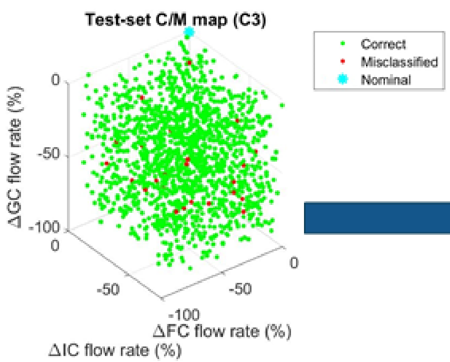
The kNN classifier is trained with a set of training transients with the aim of classifying new signals from a real MSFR plant

Evaluation metrics

Accuracy $= \frac{\text{Correct predictions}}{\text{Total cases}}$ **Precision** $= \frac{TP}{TP+FP}$ **Recall** $= \frac{TP}{TP+FN}$

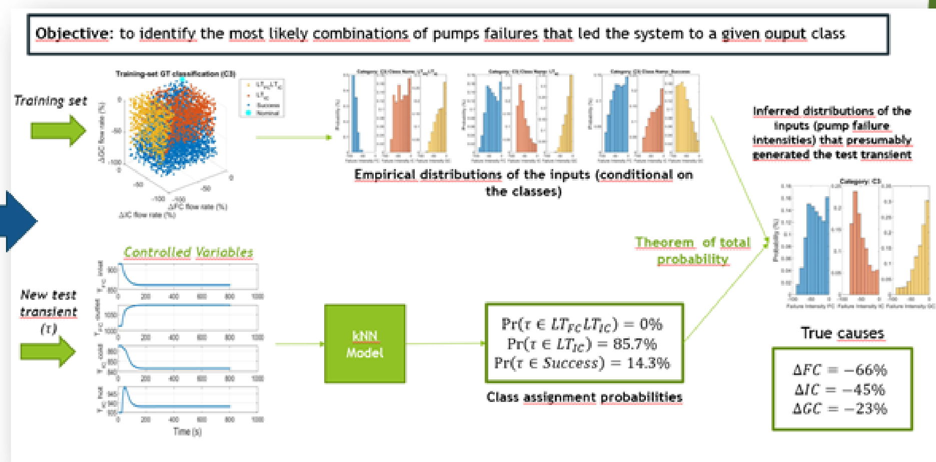
- *TP* True Positive
- *FP* False Positive
- *FN* False Negative





Accuracy = 98.3%
Average Precision = 97.9%
Average Recall = 97.2%

Application of the kNN classifier for fault detection in the MSFR plant



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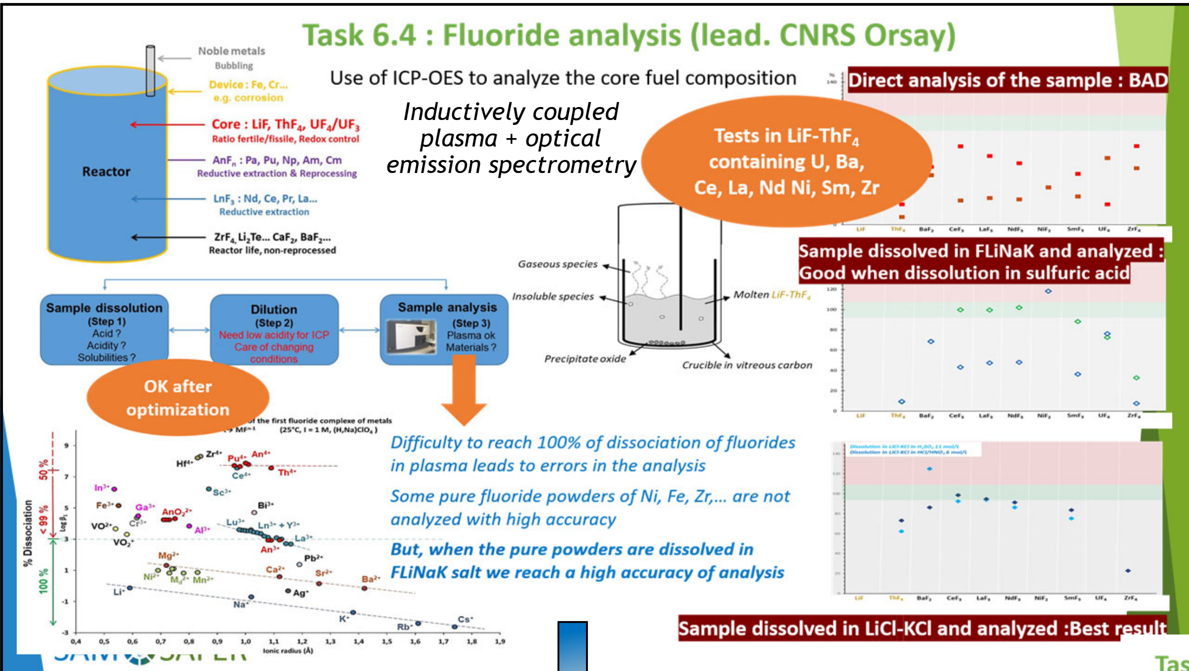
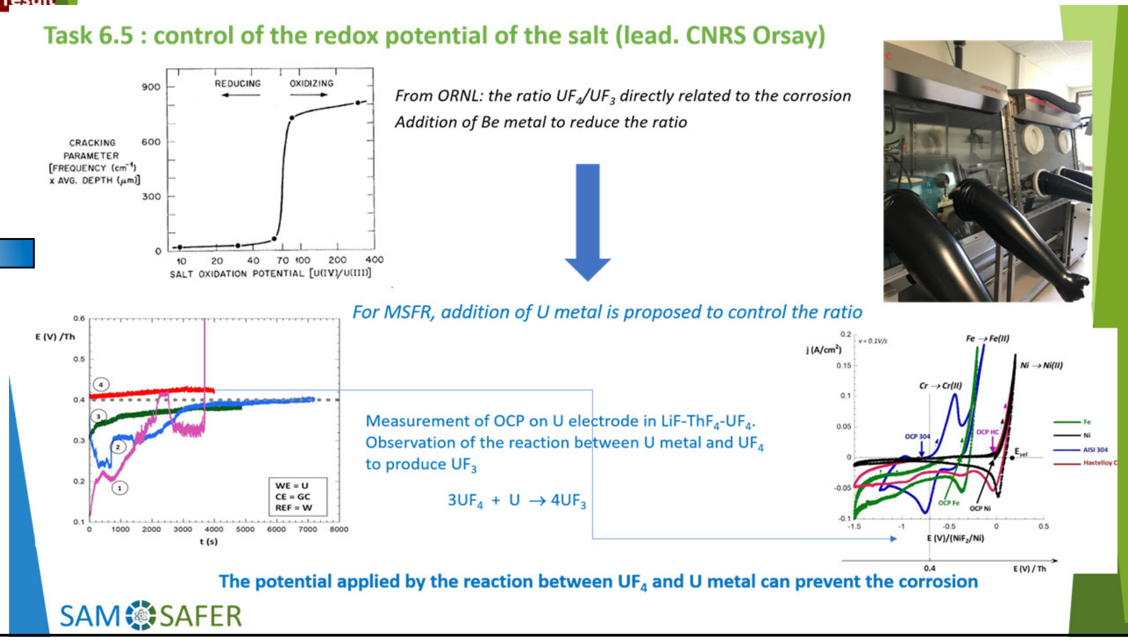
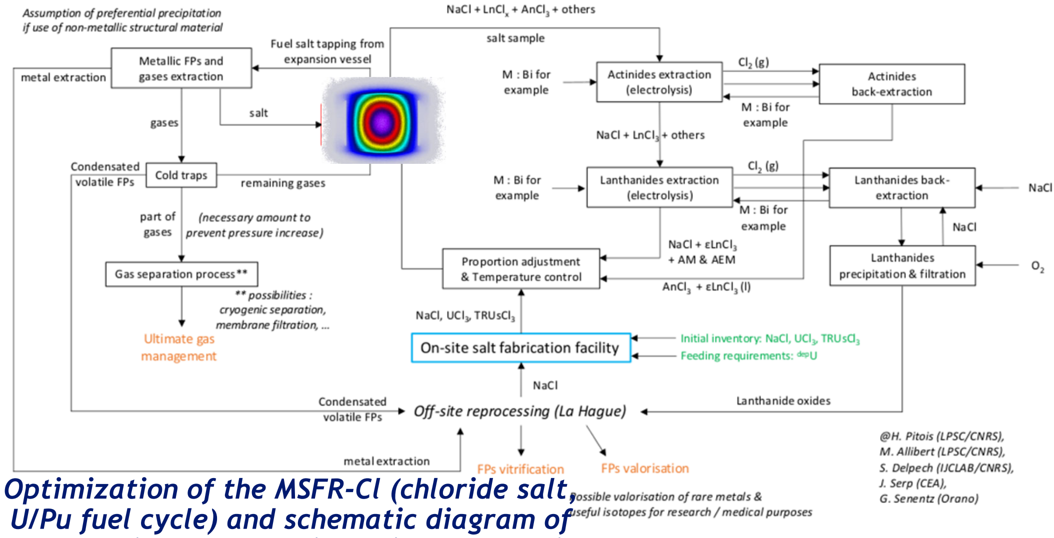


WP6 results and outcomes on reactor chemistry

See presentation by S. Delpech in WP6 session



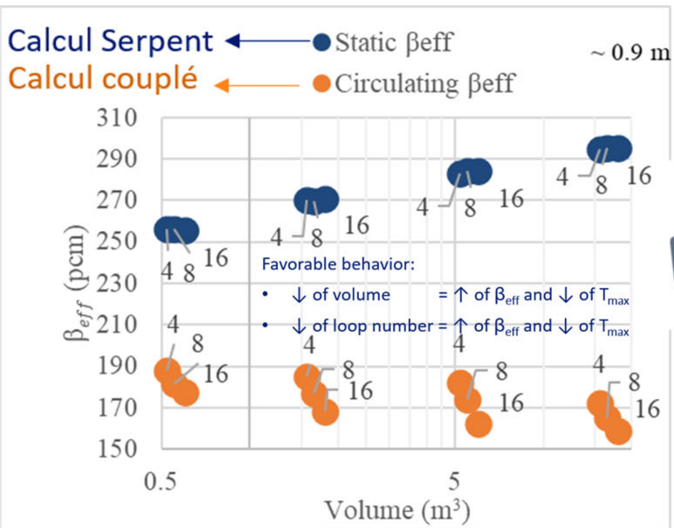
WP6 bonus results and outcomes ☺

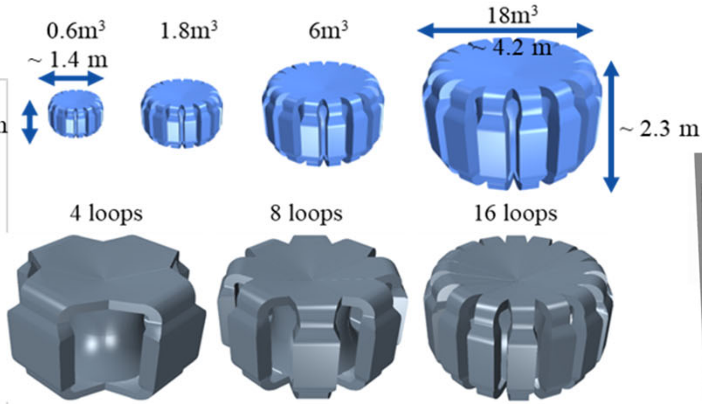


Optimization of the MSFR-Cl (chloride salt, U/Pu fuel cycle) and schematic diagram of the associated processing unit - PhD thesis H. Pitois @CNRS-LPSC (task 6.6)

Physical state of the elements in the molten salt @CNRS-IJCLab

H_2(g)																	He(g)
LiCl	$BeCl_2$											B(s)	C(s)	N_2(g)	O(-II)	NaF	Ne(g)
NaCl	$MgCl_2$											$AlCl_3$(g)	Si(s)	P(g)	S_2 (g)	Cl(-I)	Ne(g)
KCl	$CaCl_2$	$ScCl_3$	$TiCl_3$	VCl_2	$CrCl_2$	$MnCl_2$	Fe(s)	Co(s)	Ni(s)	Cu(s)	$ZnCl_2$	Ga(l)	Ge(s)	As_4(g)	$SeCl_2$(g)	NaBr	Kr(g)
RbCl	$SrCl_2$	YCl_3	$ZrCl_4$(g)	$NbCl_5$	Mo(s)	Tc(s)	Ru(s)	Rh(s)	Pd(s)	Ag(s)	Cd(l)	In(l)	Sn(l)	Sb(l)	Te(l)	NaI	Xe(g)
CsCl	$BaCl_2$	$LaCl_3$	$HfCl_4$(g)	Ta(s)	W(s)	Re(s)	Os(s)	Ir(s)	Pt(s)	Au(s)	Hg(g)	TlCl	Pb(l)	Bi(l)	Po(l)	At_2(g)	Rn(g)
FrCl	$RaCl_2$	$AcCl_3$															
			$CeCl_3$	$PrCl_3$	$NdCl_3$	$PmCl_3$	$SmCl_2$	$EuCl_2$	$GdCl_3$	$TbCl_3$	$DyCl_3$	$HoCl_3$	$ErCl_3$	$TmCl_3$	$YbCl_2$	$LuCl_3$	
			$ThCl_4$	$PaCl_3$	UCl_3	$NpCl_3$	$PuCl_3$	$AmCl_3$	$CmCl_3$								

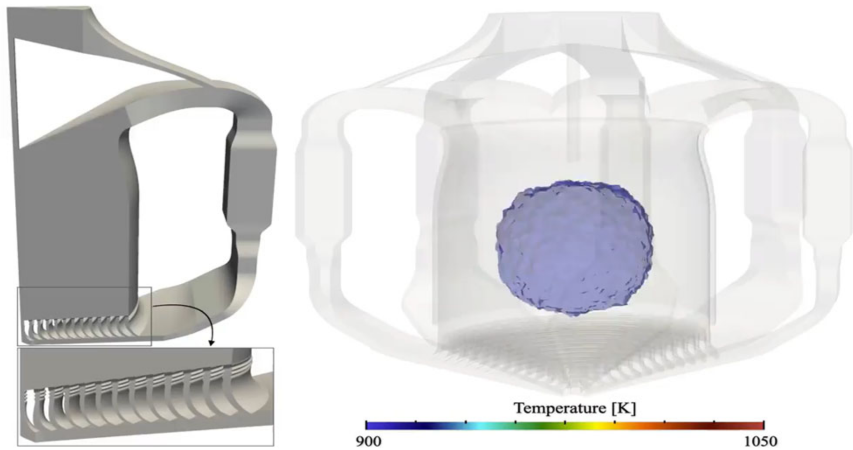




Study of threshold effects in terms of safety/operation of an SMR MSR in the U/Pu fuel cycle @CNRS-LPSC/ Framatome - PhD thesis T. Sornay (task 6.6)

The study of the flow turbulence (DES calculations) provides information on reactivity fluctuations and then a feedback on the core design optimization itself. A new design has been proposed, reducing the power fluctuations from 7 to 1% @CNRS-LPSC/Subatech

➡ See presentation by A Laureau in WP6 session



Let's go for WP7

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WP7 “Education and Training, Dissemination and Exploitation”

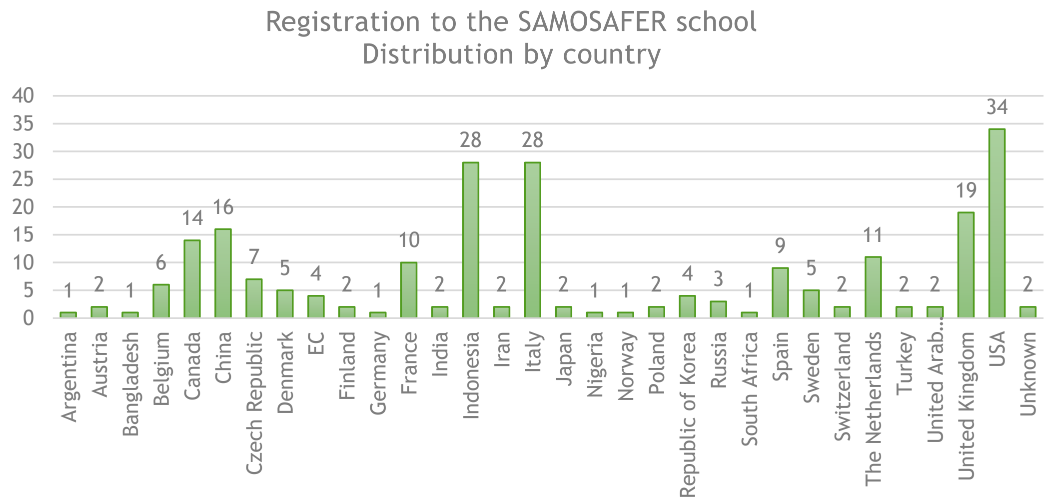
Final meeting

28/11/2023

WP7 overview: E&T activities

Online School

- The SAMOSAFER online school has been organized adopting a distributed approach, with 7 different teaching modules, focused on 7 topics of interest for MSR research, to be given in a 4-months time frame in the fall of 2021.
- Attendees from 31 countries, 50% European and 50% non European countries
- All lectures have been recorded, having previously obtained permission from the lectures, and are going to be made freely available (after some editing) on the YouTube channel of the SAMOSAFER project (https://www.youtube.com/@samosafer4017/videos).



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WP7 overview: E&T activities

Module	Level	Title	Instructor	Participants
1 –Neutronics	Bas.	Basics of MSFR neutronics	S. Dulla	128
	Adv.	MSF fuel cycle	J. Krepel	
	Int.	Exercises on MSR neutronics and fuel cycle	S. Dulla and J. Krepel	
2 –Thermal-hydrauilcs	Bas.	MSR thermal hydraulics	P. Rubiolo	115
	Web.	Overview of SAMOSAFER experimental facilities	J. Giraud, S. Lorenzi, M. Stempniewicz	133
3 –Multiphysics	Bas.	Introduction to MSR Multiphsyics	D. Lathouwers	96
	Adv.	Advanced multi-physics tools dedicated to fast-spectrum MSRs	M. Tiberga	
	Int.	Use of OpenFOAM for MSR multiphysics	S. Lorenzi	
4 – Thermochemistry	Bas.	MSR thermochemistry	S. Delpech	91
	Int.	The Thermochimica code	M. Piro	
	Web.	Measurements of thermophysical properties of molten salts	O. Benes	77
5 – Design	Bas.	Physical Principles and Design of MSR	E. Merle	81
	Web.	Panel session on MSR designs (start-up participation included)	J.L. Kloosterman (moderator)	104
6 – Operation and Control	Bas.	MSR operation and control	A. Laureau, E. Merle	78
	Int.	MSFR Modelica simulator	S. Lorenzi	
	Web.	Focus on differences among PWR, SFR and MSFR	F. Bertrand	88
7 - Safety	Bas.	Introduction to MSR safety	T. Boiseeau	79
	Adv.	Global regulatory environment	E. Ivanov	
	Int.	Uncertainty quantification for safety calculations	Z. Perko	

WP7 overview: E&T activities

YMSR Conference (Lecco, June 6-8, 2022)

- A conference tailored for PhD students, PostDocs and young researchers interested to present and discuss their research on MSR with senior scientists to provide feedback and transfer experience to the young people through special mentoring activities.
- 34 contributions, 2 keynote speech, 60 attendees (young and senior)
- Book of abstract and presentations available at https://samosafer.eu/2022/06/07/young-msr-conference-6-8-june-2022/
- Special issue on NSE issued one in mid November https://www.tandfonline.com/toc/unse20/197/12

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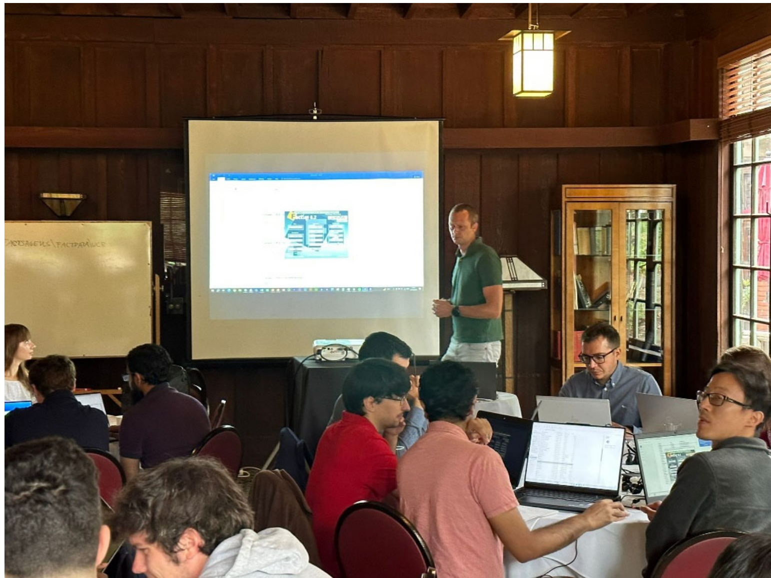
WP7 overview: E&T activities

MSR Bootcamp (Berkeley, September 6-8, 2023)

- Three days of lectures, discussions and hands-on activities on multi-disciplinary aspects of molten salt science and technology supported by world experts.
- Co-organized with UC Berkeley
- 31 attendees, 8 from SAMOSAFER project



WP7 overview: E&T activities

Mobility scheme

- Mobility scheme organized within the SAMOSAFER project
- Students get access to labs and to capabilities of research centers and university
- 4 PhD students and 8 MSc students granted for a total of 36 months
- Institutions involved: DTU, TU Delft, CNRS, IMT Atlantique, INP Grenoble, PoliMi, KIT, Ontario Tech, JRC.

Students involved in the SAMOSAFER projects:

- 12 PhD students develop their research activities within SAMOSAFER
- +25 BSc/MSc students made their thesis on SAMOSAFER topics

WP7 overview: Dissemination activities

Scientific Papers and communication activities

- XX Journal Papers, YY Conference papers disseminating the results of the project. Find the full list here https://samosafer.eu/publications-2/
- Zenodo community in which OA papers and dataset are published https://zenodo.org/communities/samosafer
- >45 Outreach events

Exploitation Event

- Tomorrow! Exchanges with startups, regulators, industry to valorize the SAMOSAFER results

09:15	Video presenting SAMOSAFER results
09:30	How SAMOSAFER results will be used in new project proposal?
09:45	Status and prospect of R&D at CEA on molten salt reactors
10:45	‘Pando’s Lessons’, Myriam Tonelotto
11:00	Start-up companies presenting their designs and needs
14:00	Industry and their interests in MSR
14:45	‘Expert presentation’, Rui Tang, SINAP
15:15	SAMOSAFER students presenting their experiments.
16:30	MSR licensing from European perspective
17:00	Roundtable with regulators
17:15	US prospects on MSR

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Let’s go for presents


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