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Overview on required R&D

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On behalf of the SAMOSAFER project

Simulation Models and Safety Assessment of Fluid-fuel Energy Reactors

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SAMOSAFER participants

List of Participants

Number	Organisation	Institution	Country
1 (Coord)	Technische Universiteit Delft (TU Delft)	University	The Netherlands
2	Centre National de la Recherche Scientifique (CNRS)	R&D/University	France
3	JRC - Joint Research Centre- European Commission (JRC)	R&D	Germany
4	Institut de Radioprotection et de Sûreté Nucléaire (IRSN)	TSO	France
5	Framatome (Framatome)	Industry	France
6	Commissariat a l'Energie Atomique et aux Energies Alternatives (CEA)	R&D	France
7	Nuclear Research and Consultancy Group (NRG)	R&D/Industry	The Netherlands
8	Paul Scherrer Institute (PSI)	R&D	Switzerland
9	Karlsruher Institut für Technologie (KIT)	R&D	Germany
10	Politecnico di Milano (POLIMI)	University	Italy
11	Politecnico di Torino (POLITO)	University	Italy
12	Electricité de France (EDF)	Industry	France
13	Research Centre Řež (CV REZ)	R&D	Czech Republic
14	University of Ontario Institute of Technology (UOIT)	University	Canada

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History of Euratom projects

- **MOST** aiming at the **recovery of data and simulation tools** for thermal reactor designs focusing on validation with historic data from the MSRE.
- **ALISIA** resulting in the **selection of the fuel salt and design choices** for a European MSR.
- **EVOL** focusing on **design of the Molten Salt Fast Reactor (MSFR)**, which is now the EU Gen-IV reactor.
- **SAMOFAR** focusing on the **safety analysis of the MSFR** and further development of the reactor design. Several experimental setups were designed and constructed, like SWATH-S and DYNASTY.
- **SAMOSAFER** expanding the experience and knowledge from previous projects with the aim to ensure that MSR technology can fully comply with the **more stringent safety requirements** expected in 30 years time.

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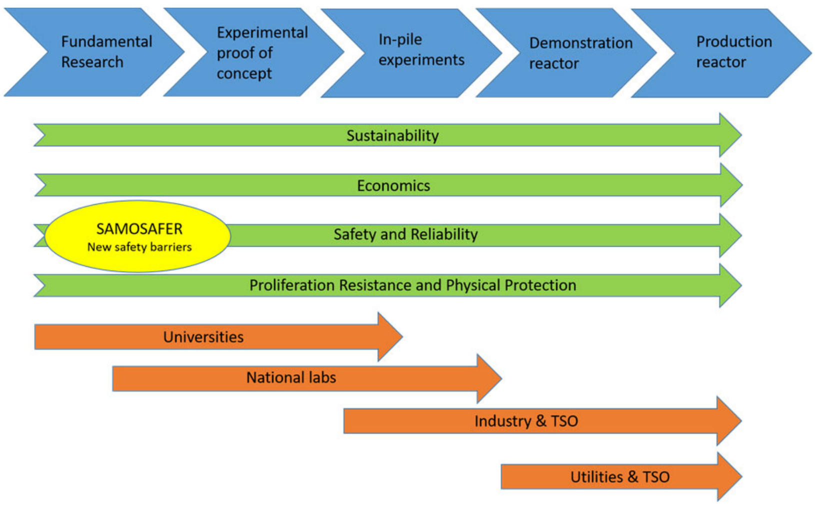
Positioning of SAMOSAFER



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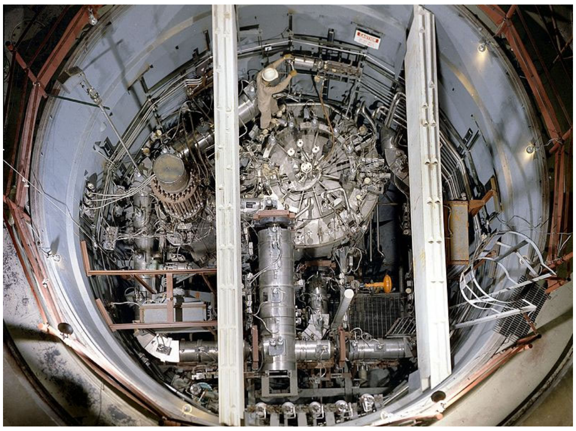
Molten Salt Reactor Experiment 1965-1969



https://en.wikipedia.org/wiki/Molten-Salt_Reactor_Experiment

See movie: http://energyfromthorium.com/2016/10/16/ornl-msre-film/

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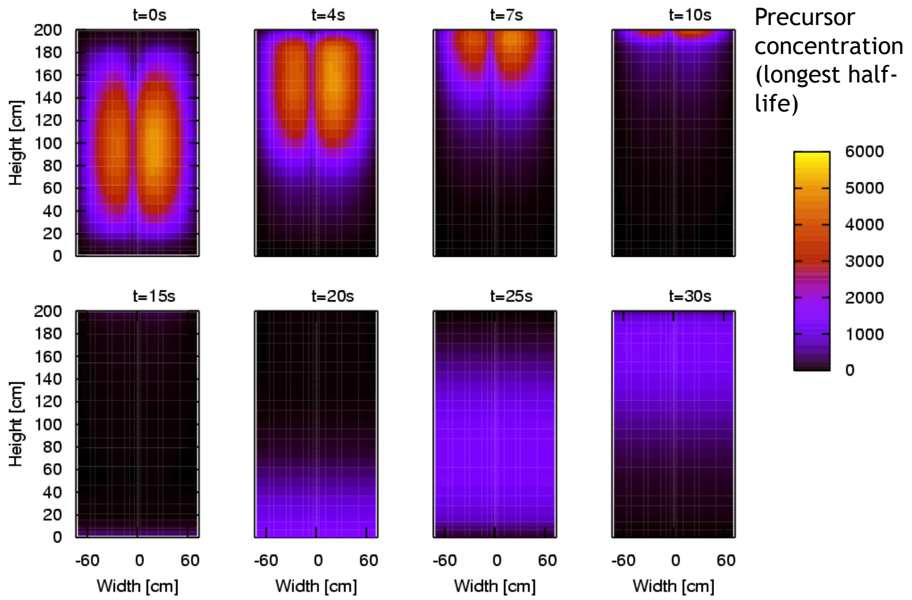
MSRE pump startup



Precursor concentration (longest half-life)

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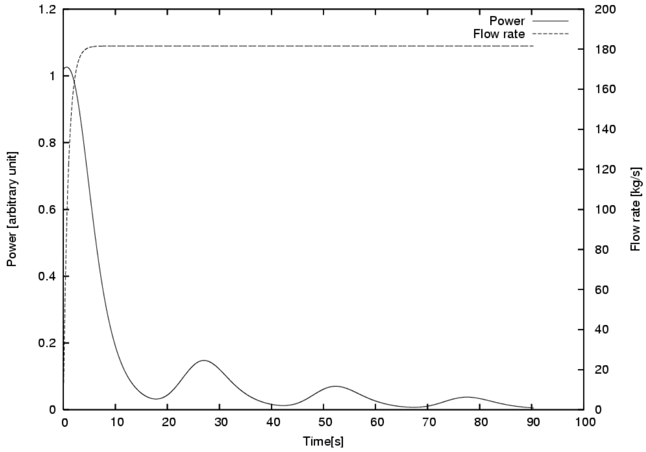
MSRE pump startup



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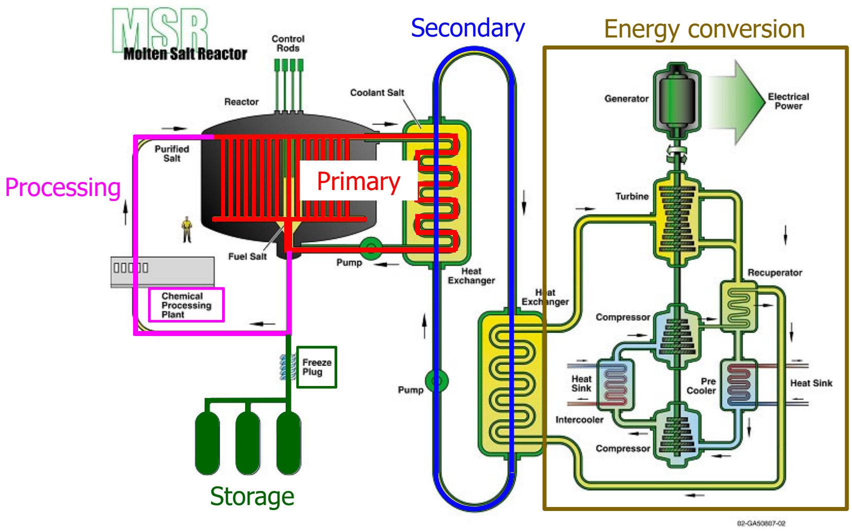
Molten Salt Reactor (MSR)



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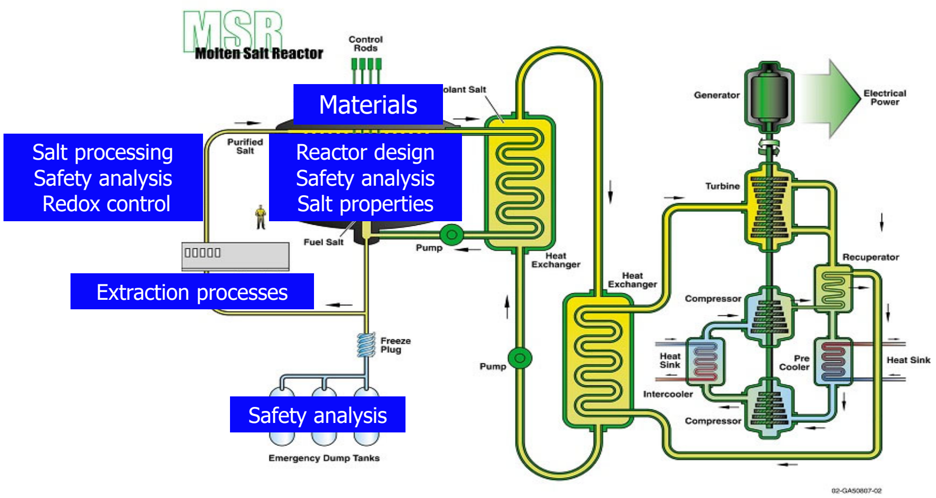
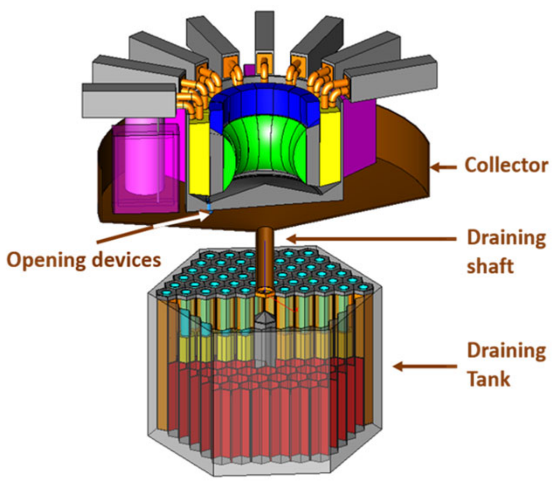
MSR research themes



Reference design MSFR

Thermal power	3000 MWth
Mean fuel salt temperature	725 °C
Fuel salt temperature rise in the core	100 °C
Fuel molten salt - Initial composition	LiF-ThF$_4$-UF$_4$ (77.5-20-2.5 mol%) LiF-ThF$_4$-UF$_4$-(TRU)F$_3$ with (77.5-6.6-12.3-3.6 mol%)
Fuel salt melting point	585 °C
Fuel salt density	4.1 g/cm^3
Fuel salt dilation coefficient	8.82 10^{-4} / °C
Fertile blanket salt - Initial composition	LiF-ThF$_4$ (77.5%-22.5%)
Breeding ratio (steady-state)	1.1
Total feedback coefficient	-5 to -8 pcm/K
Core dimensions	Diameter: 2.26 m Height: 2.26 m
Fuel salt volume	18 m^3 (50% in the core)
Blanket salt volume	7.3 m^3
Total fuel salt cycle	3.9 s



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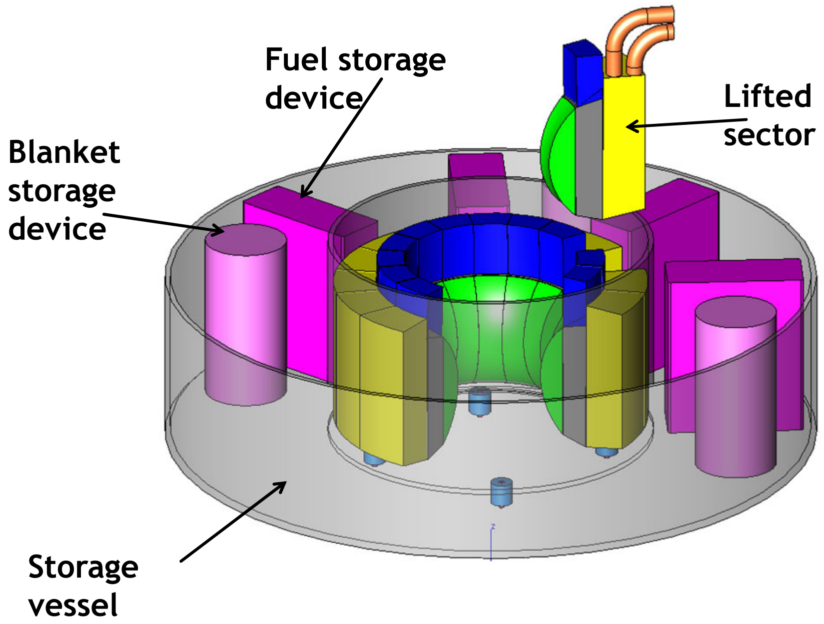

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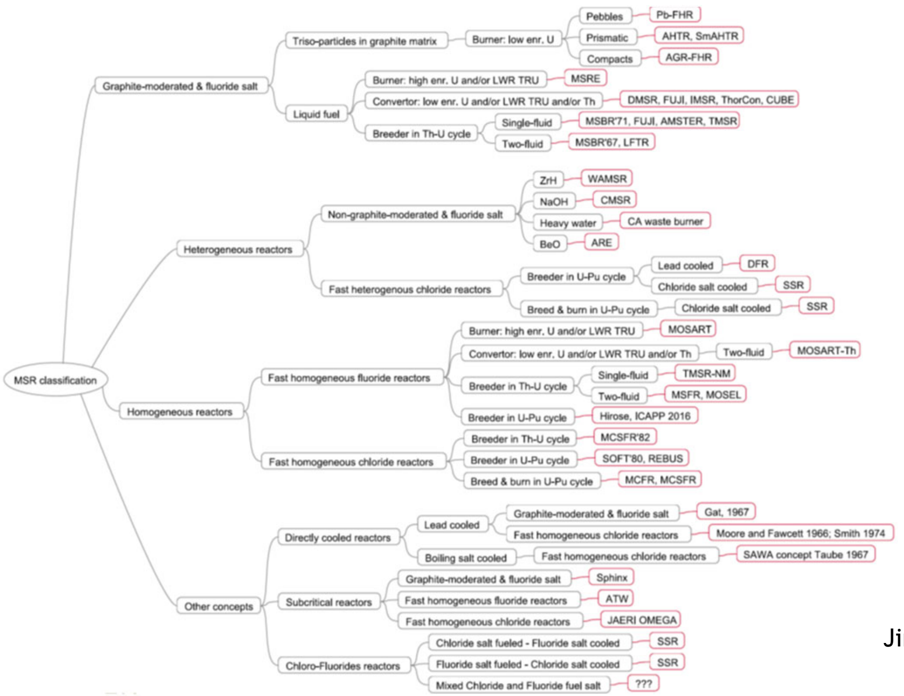
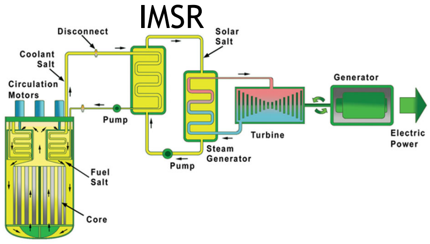


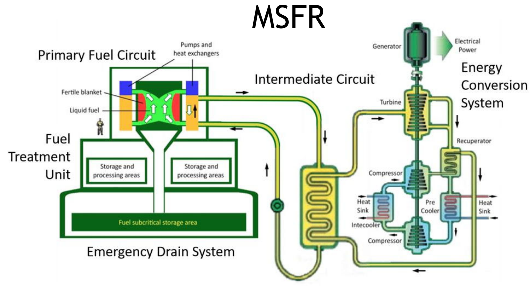
Jiri Krepel, PSI

Diversity Molten salt reactor concepts

IMSR



MSFR



IMSR	MSFR
Small modular units	Large single unit
Thermal spectrum	Fast spectrum
One-fluid core	Two-fluid core-blanket
Uranium-plutonium	Thorium-uranium
Batch-wise refueling	Continuous refueling
No fuel processing	Continuous processing
Integral cooling	Loop cooling

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Peculiarities of Molten Salt Reactors

- ✓ Molten fuel salt acts as fuel and coolant→no DNB, etc
- ✓ Part the fuel salt is outside core region→low $ß_{eff}$
- ✓ Primary circuit is radioactive→ modularity, robotization, maintenance, etc
- ✓ Homogeneous fuel load and uniform fuel burnup
- ✓ No need to control power distribution and flux shape
- ✓ Fuel processing and (un)loading during operation
- ✓ Strong negative feedback based on fuel salt expansion→easy load following
- ✓ Safety philosophy is based on fuel salt expansion and flow
- ✓ Fuel salt retention upon heating important as well as precipitation upon cooling
- ✓ Fuel salts typically have low heat conduction (high Prandtl)→solidification
- ✓ Emergency shut-down by draining the salt (passively or active)

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Phenomena investigated

- **Freezing** of the fuel salt against cold walls and subsequent **remelting;**
- **Internal heating** of the salt causing lower natural circulation and local overheating;
- **Overheating** of the fuel salt in the core during transients and in the drain tanks;
- Effects of transients on the **thermo-mechanical integrity** of the primary circuit;
- **Redistribution** of the source term in the processing unit via gas bubbling, fluorination and chemical extraction leading to changes in chemistry and mobility of radionuclides.
- **Thermo-chemical modelling** to evaluate the fission products retention properties, and the effects of various products on the thermo-physical properties (melting point, heat capacity, vapour pressure, viscosity, thermal conductivity, etc);
- **Radiative heat transfer** to calculate accurately decay heat removal;
- **Predictive reactor control** strategies to reduce the number of draining events;
- **Redox control** of the fuel salt to avoid corrosion in the primary circuit;
- **Reactor scaling** effects on the safety of nuclear reactors in general;
- **Uncertainty quantification methods** based on non-intrusive PCE and ROM methods.

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SAMOSAFER contents

1. Investigating the existing **defence-in-depth safety approach** to MSR.
2. Developing a rigorous and well-established **simulation code suite** through:
   - Developing theoretical models of physics and thermo-chemical phenomena relevant to safety;
   - Developing simulation models and tools to be included in cutting-edge computation codes;
   - Coupling existing computation codes to deliver an integral simulation approach;
   - Simulation models for the computation of multi-physics phenomena in existing codes.
3. Developing **experimental setups** for the **validation** of simulation models:
   - Developing experimental facilities for validation of theory and models and for validation;
   - Modifying and applying existing experimental facilities to generate data for validation;
   - Using experimental setups and computational schemes to generate data.
4. Design and demonstration of **barriers for severe accidents** in MSR.
5. **Update of the MSFR design** with all improvements from these studies.
6. Attracting and educating **students, postdoctoral researchers and trainees**.
7. Develop and train a software **user community**.

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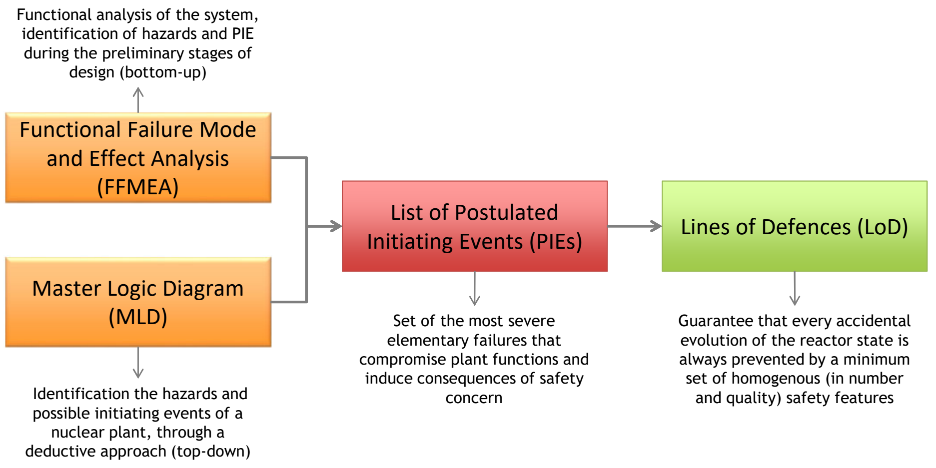
Safety approach



A. C. Uggenti, D. Gérardin et al, "*Preliminary functional safety assessment for molten salt fast reactors in the framework of the SAMOFAR project*", PSA 2017 International Topical Meeting, Pittsburgh, USA, 2017

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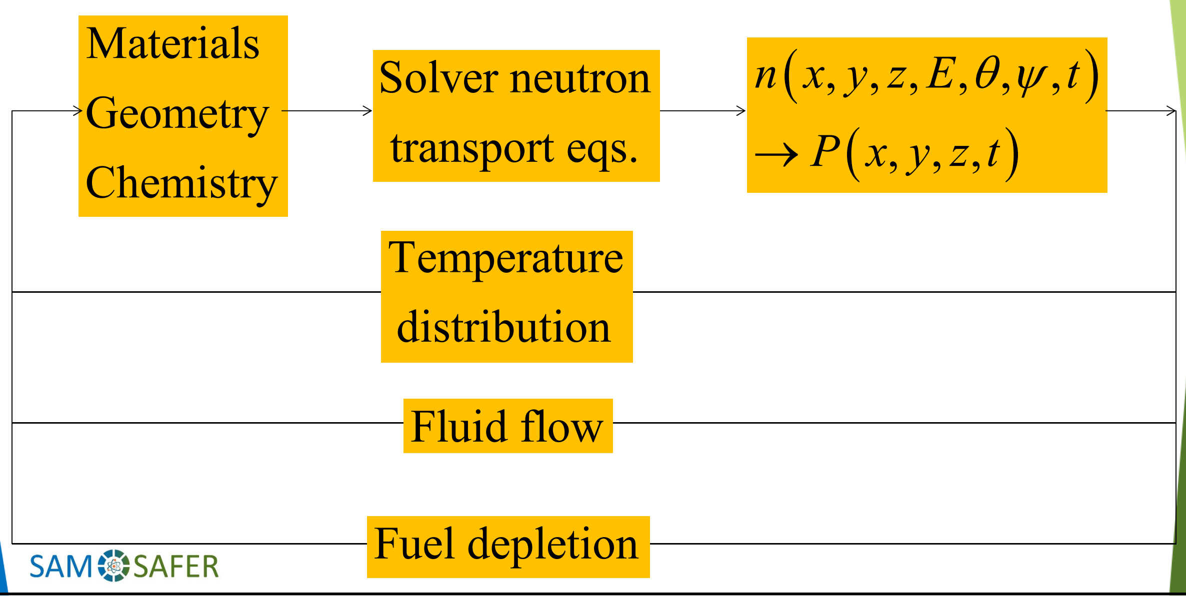
Simulation models



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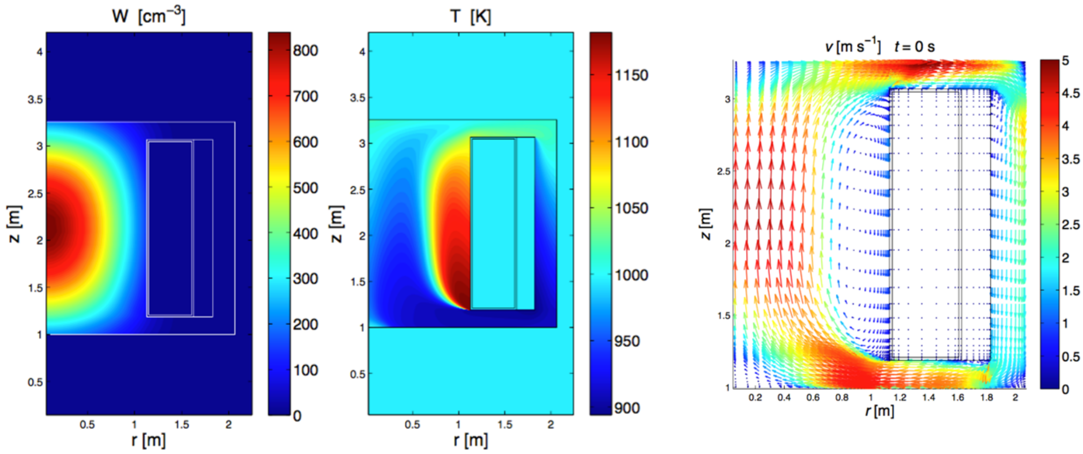
MSFR Multiphysics calculations



Marco Tiberga, TU Delft

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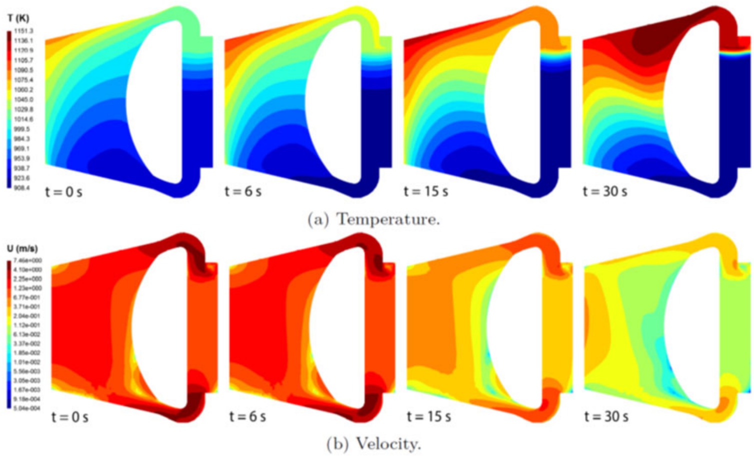
MSFR Transient analysis ULOFF



(a) Temperature.

(b) Velocity.

Fig. 5.14. ULOFF: evolution of the distributions of temperature and velocity along the reactor vertical mid-plane. The latter plot uses a logarithmic scale to magnify the low velocity magnitudes at the end of the transient.

Marco Tiberga, TU Delft

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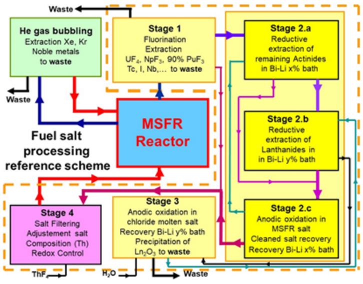
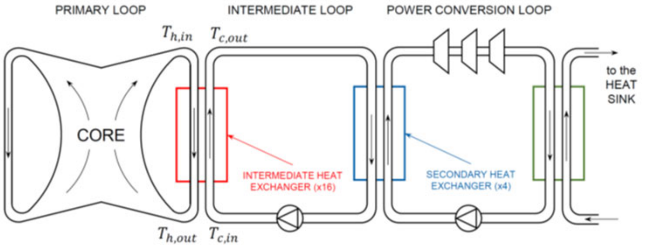
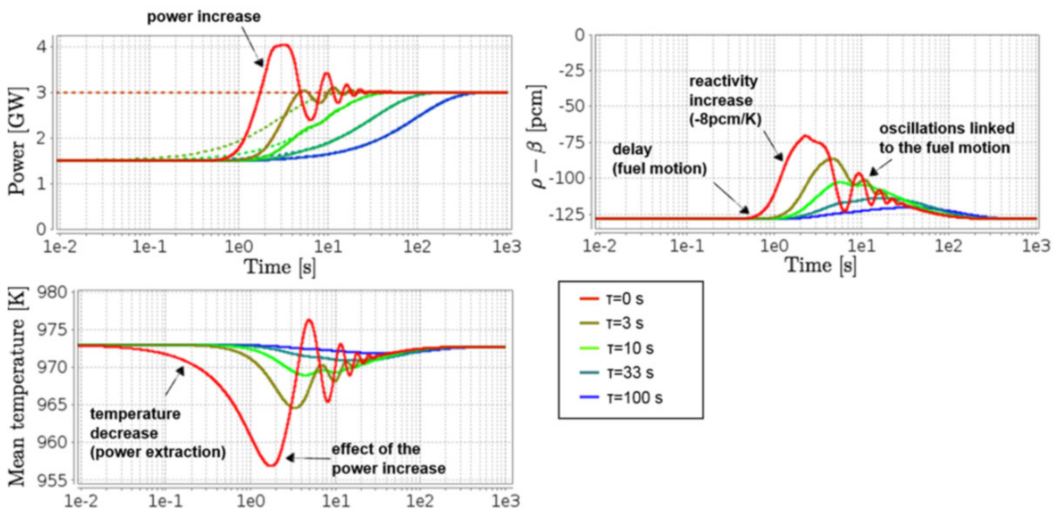
Simulation models





Fuel salt Processing ↔ Core physics ↔ Energy Conversion System

MSFR Simulator



Experimental setups

- **DYNASTY:** This is a 10 meters high facility at POLIMI to study the flow dynamics of internally heated salts. Two versions exist: a single loop system and two connected loops. The latter setup simulates the primary salt circuit (core region) connected to the salt flow in the intermediate circuit. DYNASTY is fully instrumented and can be used to study decay heat removal from the core region by natural circulation. DYNASTY has been modified in the SAMOFAR project to fully meet the needs of the MSR;
- **High Flux Reactor:** This 40 MWth material testing reactor is being used to irradiate samples of fuel salt containing ThF_4 in LiF for 2 years. Analysis in the **hot cell laboratories** of NRG and at JRC-Karlsruhe, focusing on the fission product composition, redox potential, and the interactions between the fuel salt and the graphite crucibles and between the fuel salt and metal encapsulation;
- **SWATH-S:** This is a facility at CNRS consisting of two vessels of which one is filled with liquid salt (FLiNaK). By pressure the salt can flow from one vessel to the other, thereby passing an experimental station in a glovebox. The experimental station can be adopted to the needs of the experiments, like the measurement of flow and temperature profiles of the salt in turbulent and laminar conditions, and freezing phenomena of the salt against cold walls.

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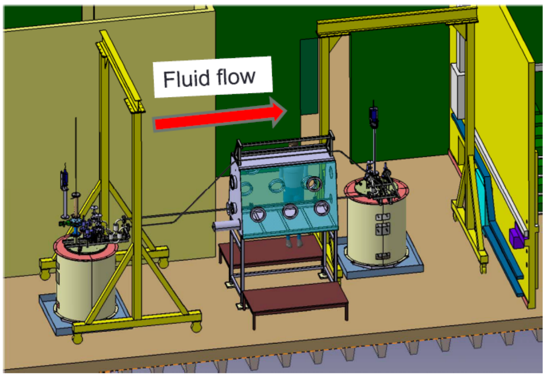
SWATH-S facility

Global performance :

- Salt : FLiNaK
- Total volume : 50 l
- Service temperature range : 550°c => 700°c

Velocity (m/s) 20 mm inner pipe diameter	Flow rate (l/min)	Time (minutes)
0.1	1.88	26.5
0.3	5.65	8.8
0.5	9.42	5.3



CNRS, Grenoble

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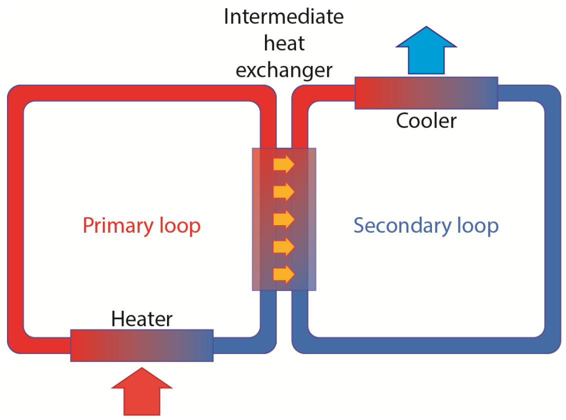
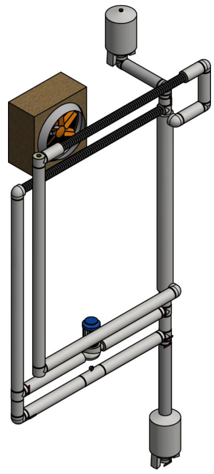
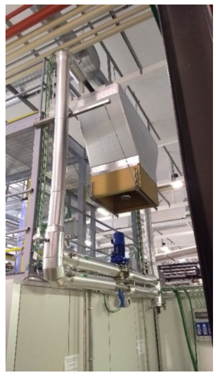
eDYNASTY coupled facility







POLIMI

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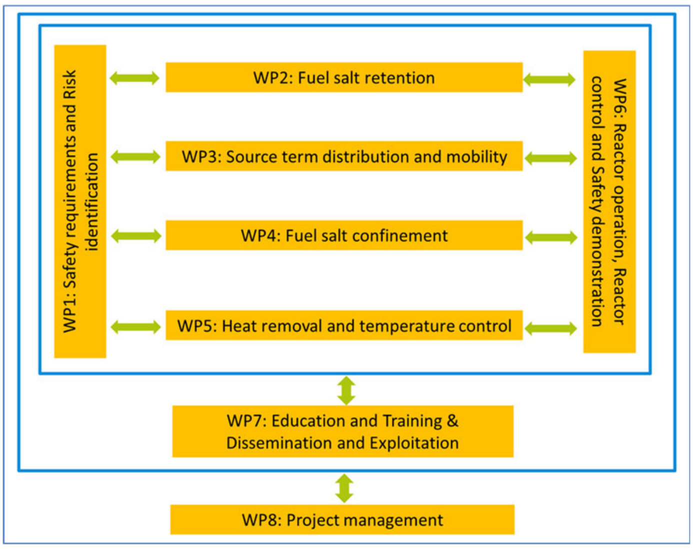
Structure and work packages



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Education and Training

- Education of bachelor, master and PHD students
- Student mobility scheme
- Webinars on MSR neutronics, thermal-hydraulics, chemistry, experiments, …
- Basic principle software simulator for training
- Summer school September 2021-Spring 2022
- Young-MSR conference Spring 2022
- Stakeholder workshop Summer 2023

Collaboration and joint efforts appreciated