MSR provisional System Steering committee

J. Serp, France – chair

Presented by David Holcomb – U.S. representative

MSR Workshop / MSRE 50th Anniversary Commemoration
Oak Ridge, TN
October 15, 2015

Studied Concepts

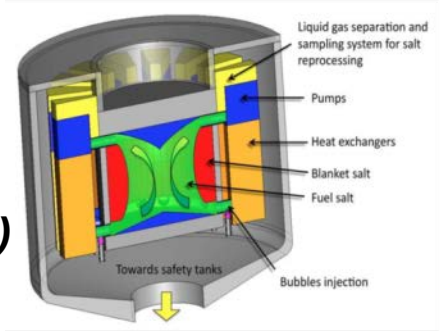
High temperature (750°C)
Low pressure (1 bar)
1000 MWe

Two reactor concepts using molten salt are discussed in GIF MSR meetings

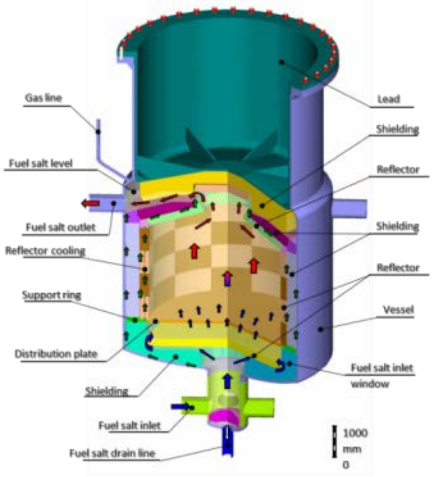
- ***Molten salt reactors, in which the salt is at the same time the fuel and the cooling liquid***
  - » ***MSR MOU Signatories France and EU work on MSFR (Molten Salt Fast Reactor)***
  - » ***Russian Federation works on MOSART (Molten Salt Actinide Recycler & Transmuter). Russian Federation joined the Memorandum of Understanding (11/2013)***

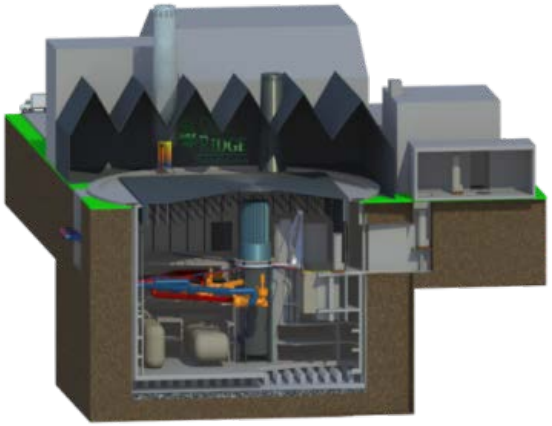
- ***Solid fueled Reactors cooled by molten salt***
  - » ***USA and China work on FHR (fluoride-salt-cooled high-temperature reactor) concepts and are <u>Observers</u> to the PSSC***

MSFR



MOSART





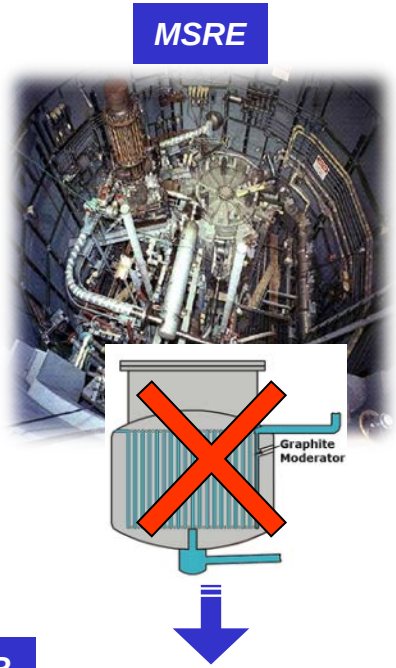
FHR 3,400 MWth

Reference concept :

From thermal to fast neutron spectrum

The first Molten Salt Reactors (MSR) developed in the USA (1960s and 1970s) were thermal-neutron-spectrum graphite-moderated concepts

Since 2005, European R&D interest has focused on fast neutron MSR (MSFR) as a long term alternative to solid-fueled fast neutrons reactors

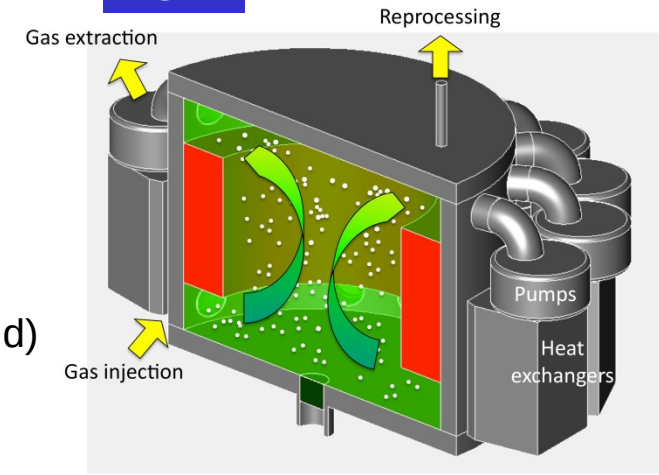


General characteristics of MSR

- Molten fluorides as fuel fluid (no loading pattern)
- Low-pressure and high boiling-point coolant
- Possibility to drain fuel passively towards non-critical volumes
- On-site fuel reprocessing unit

Specific *features* of MSFR

- Strongly negative reactivity feedback coefficients (thermal and void)
- Processing needs decreased (from several m^3 to 40 liters/day)
- No graphite elements in the core (maintenance)



GIF MSR Project

- ***A Provisional Project Management Board has been set up***
  - ***Two meetings per year where members and observers report on their activities and recent progresses***

- ***The project is devoted to Molten Salt Reactors***
  - ***Information is also exchanged on solid fueled reactors cooled by molten salt***

- ***The various molten salt reactor projects like FHR, MOSART, MSFR, and TMSR have common themes in basic R&D areas, of which the most prominent are:***
  - ***liquid salt technology,***
  - ***materials behavior,***
  - ***the fuel and fuel cycle chemistry and modeling,***
  - ***the numerical simulation and safety design aspects of the reactor***

Collaborations (1/2)

SAMOFAR Project – Safety Assessment of a MOlten salt FAst Reactor

4 years (2015-2019), 3,5 M€

Partners: TU-Delft (leader), CNRS, JRC-ITU, CIRTEN (POLIMI, POLITO), IRSN, AREVA, CEA, EDF, KIT + PSI + CINVESTAV

SAMOFAR will deliver the experimental proof of the following **key safety features**:
The **freeze plug** and draining of the fuel salt
New materials and new coatings to materials
Measurement of safety related data of the fuel salt
The dynamics of **natural circulation** of (internally heated) fuel salts
The **reductive extraction processes** to extract lanthanides and actinides from the fuel salt

5 technical work-packages:

WP1 Integral safety approach and system integration

WP2 Physical and chemical properties required for safety analysis

WP3 Proof of concept of key safety features

WP4 Numerical assessment of accidents and transients

WP5 Safety evaluation of the chemical processes and plant

Collaborations (2/2)

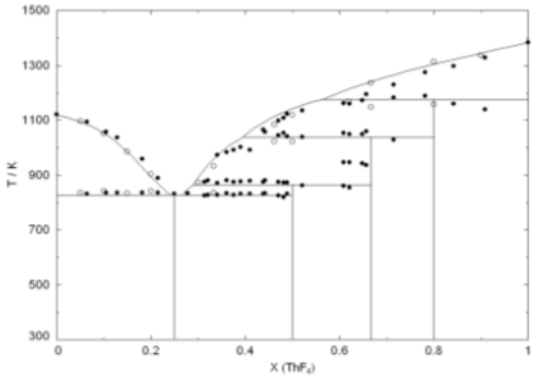
US and China Have Initiated a Cooperative Research and Development Agreement (CRADA) on FHRs

- **Collaboration supports the US-China memorandum of understanding on cooperation in civilian nuclear energy science and technology**
- **ORNL and the Shanghai Institute of Applied Physics (SINAP) are the lead organizations**
- **Project is intended to benefit both countries through more efficiently and rapidly advancing a reactor class of common interest**
- **FHR remain at a pre-commercial level of maturity**
  - All of the results are intended to be openly available
  - Project is scheduled to end after SINAP's higher-power test reactor has completed its operational testing program
- **Collaboration includes research and development to support the evaluation, design, and licensing of a new reactor class**
  - Does not include fissile material separation technology

In the last decade ITU (European Commission) has developed an expertise in determination of high temperature properties of An fluorides and mixtures

Phase diagrams

Melting points

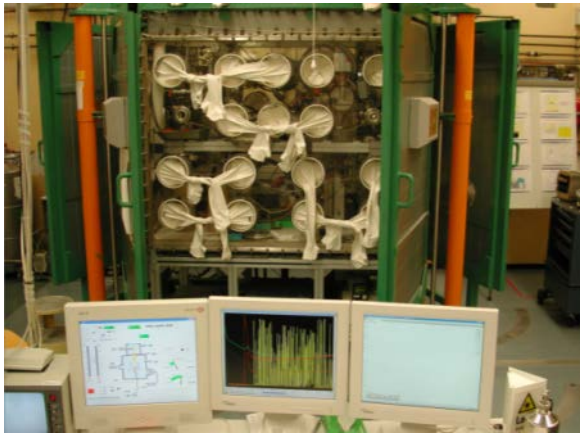


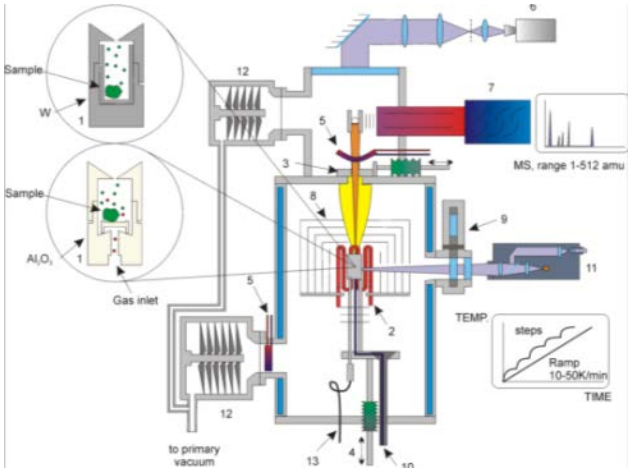
Heat capacity

Drop and DSC calorimeters up to 1800 K

Vapour pressure

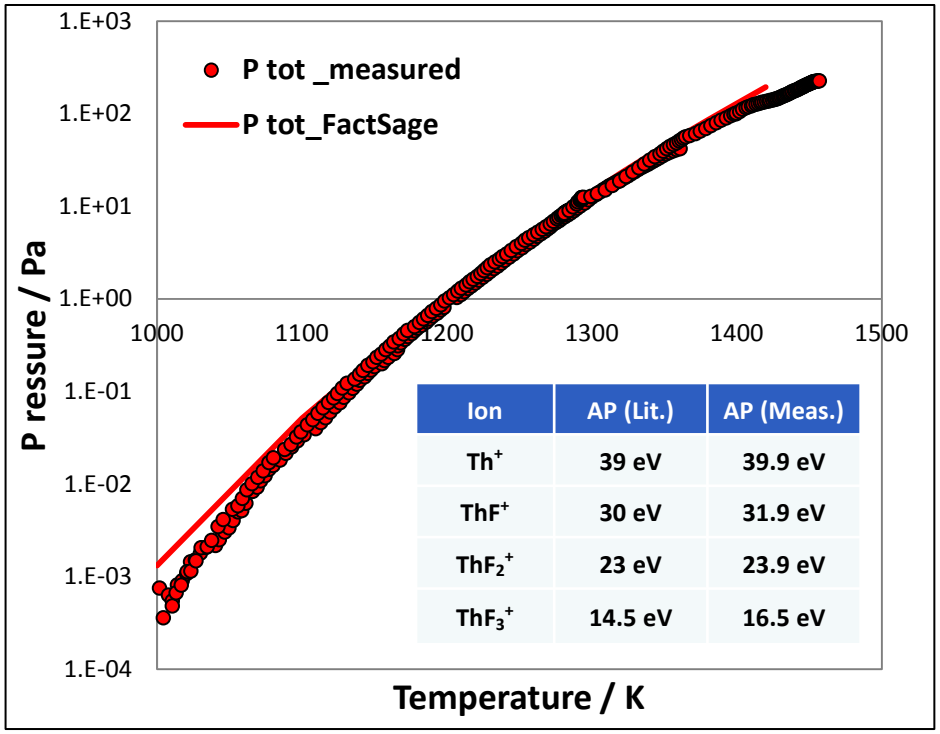
Knudsen cell with MS up to 2800 K



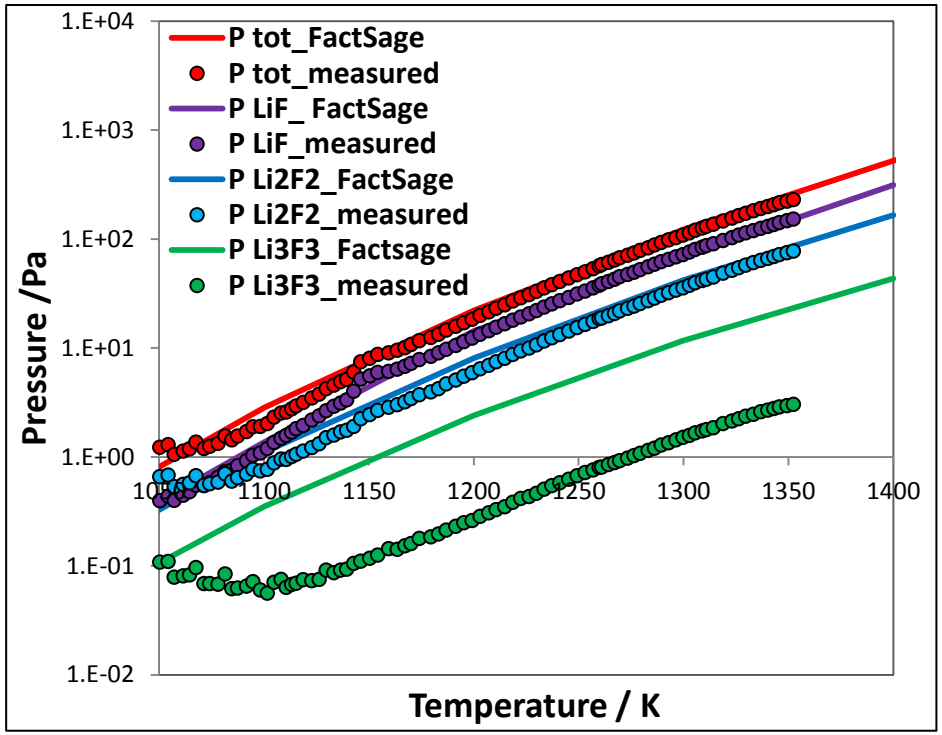


LiF-ThF_4 system

- The vapour pressure of the end members LiF and ThF_4 were measured, obtaining a very good agreement with the literature data. The appearance potential of the different species has been also measured.



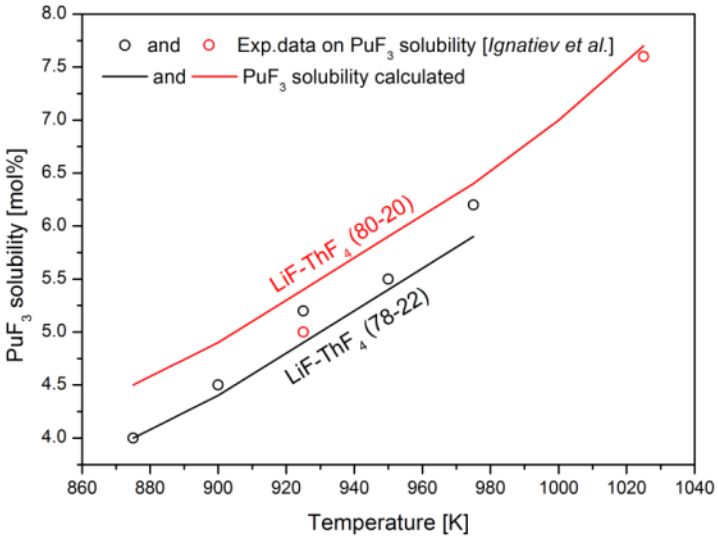
Ion	AP (Lit.)	AP (Meas.)
Th^+	39 eV	39.9 eV
ThF^+	30 eV	31.9 eV
ThF_2^+	23 eV	23.9 eV
ThF_3^+	14.5 eV	16.5 eV

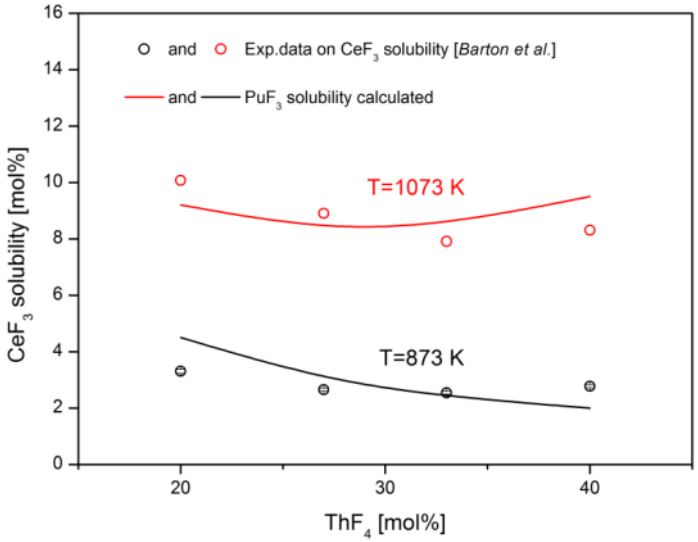


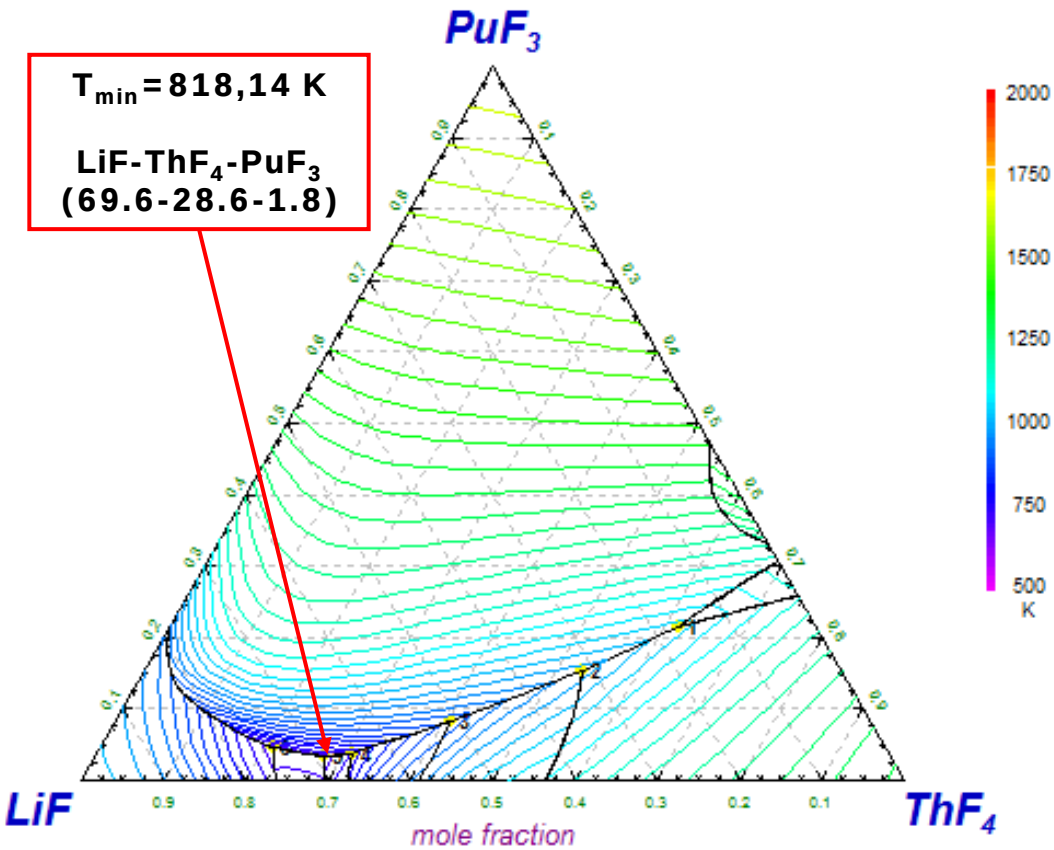
Vapour pressure ThF_4

Vapour pressure LiF

LiF-ThF_4-UF_4-PuF_3 ternary system assessed







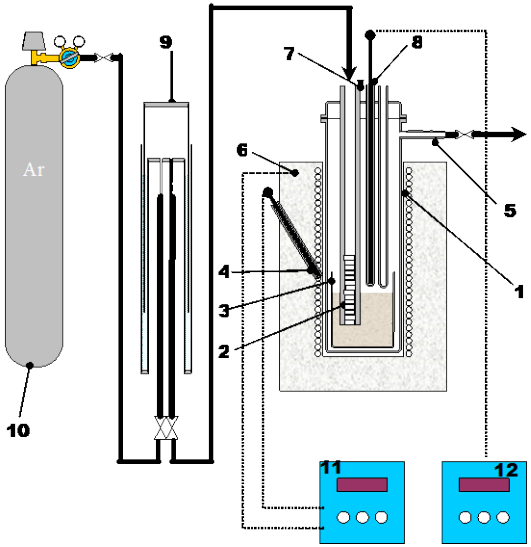
Actinides and lanthanides solubility measurements

Individual and joint solubility of PuF_3 and UF_4 in LiF-NaF-KF eutectic, mol. %

Temperature, K	Individual Solubility, mol.%		Joint Solubility, mol. %	
	PuF_3	UF_4	PuF_3	UF_4
823	6.1±0.6	15.3±0.8	1.16±0.06	1.75±0.09
873	11.1±1.1	24.6±1.2	2.9±0.1	3.5±0.2
923	21.3±2.1	34.8±1.7	13.2±0.6	11.0±0.6
973	32.8±3.3	44.7±2.2	19.1±1.0	17.3±0.9
1023	-	-	21.0±1.1	19.0±1.0
1073	-	-	22.5±1.2	20.0±1.1

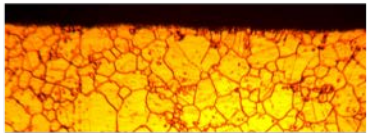
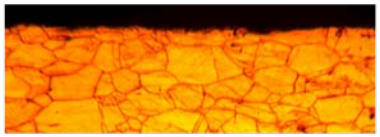
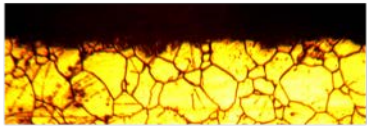
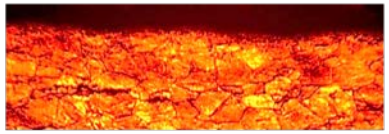
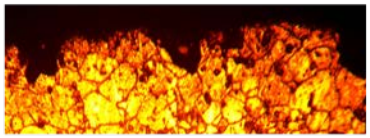
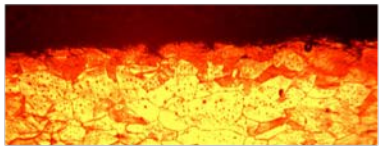
Temperature, K	$72{,}5LiF\text{-}7ThF_4\text{-}20{,}5UF_4$		$78LiF\text{-}7ThF_4\text{-}15UF_4$	
	PuF_3	CeF_3	PuF_3	CeF_3
873	0,35±0,02	1,5±0,1	1,45±0,7	2,6±0,1
923	4,5±0,2	2,5±0,1	5,6±0,3	3,6±0,2
973	8,4±0,4	3,7±0,2	9,5±0,5	4,8±0,3
1023	9,4±0,5	3,9±0,2	10,5±0,6	5,0±0,3

Isothermal saturation method



Near the liquidus temperature for $78LiF\text{-}7ThF_4\text{-}15UF_4$ and $72.5LiF\text{-}7ThF_4\text{-}20.5UF_4$ salts, the CeF_3 significantly displace plutonium trifluoride

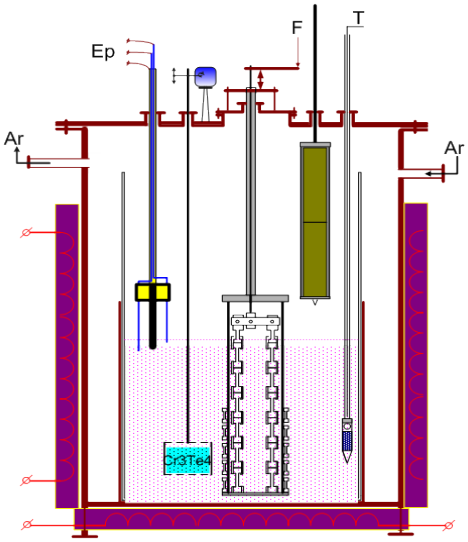
Material corrosion

U(IV)/(UIII)	Hastelloy N	HN80MTY
30 without loading at 760°C	No  K = 3500pc×µm/cm ; l = 69µm	No 
60 without loading at 760°C	 K = 4490pc×µm/cm ; l = 148µm	No  K = 530pc×µm/cm ; l = 26µm
90 without loading at 800°C		

$$UF_3 + n \longrightarrow LnF_3 + M$$

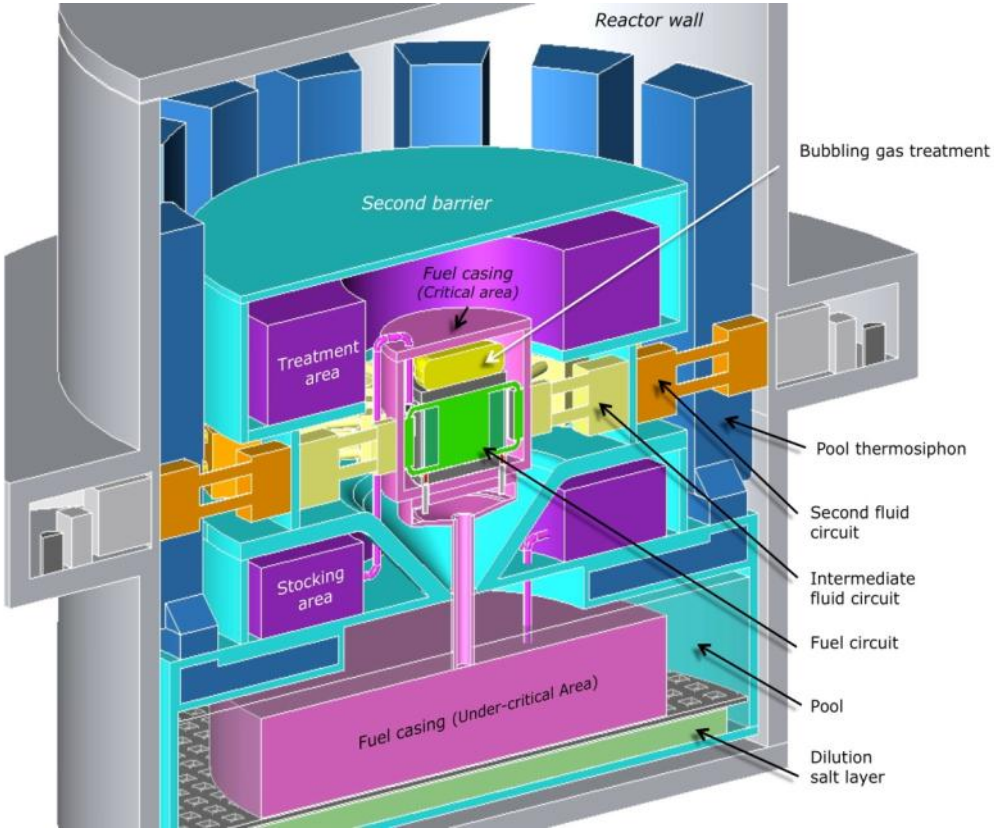
$$UF_4 + n \longrightarrow LnF_3 + M + \tfrac{1}{2}F_2(g)$$

$$UF_3 + \tfrac{1}{2}F_2\,(g) \longrightarrow UF_4$$



- The corrosion facility allows to test the alloy specimens in the nonisothermal dynamic conditions
- For the fuel salt with [U(IV)/]/[(III)] ratio = 90 at 800° C, the tellurium intergranular corrosion for the HN80MTY alloy (Russian Federation) is by about **ten times lower as compared to unmodified Hastelloy N**

Design aspects impacting the MSFR safety analysis



LOLF accident (Loss of Liquid Fuel) → no tools available for quantitative analysis but qualitatively:

- Fuel circuit: complex structure, multiple connections
- Potential leakage: collectors connected to draining tank

Proposed Confinement barriers:

First barrier: fuel envelop, composed of two areas: critical and sub-critical areas

Second barrier: reactor vessel, also including the reprocessing and storage units

Third barrier: reactor wall, corresponding to the reactor building

Safety analysis: accident types

Classified by the initiators of the transient:

TOP - Transient Over Power (or RAA - Reactivity Anomalies Accident)

LOF - Loss Of Flow (in the fuel circuit)

✗ Pumps of the fuel salt & ✓ Pumps of the intermediate fluid

LOH - Loss Of Heat sink (in the fuel circuit)

✓ Pumps of the fuel salt & ✗ cooling of the fuel salt

TLOP - Total Loss Of Power

OVC – Fuel salt OVer-Cooling

LOLF - Loss Of Liquid Fuel

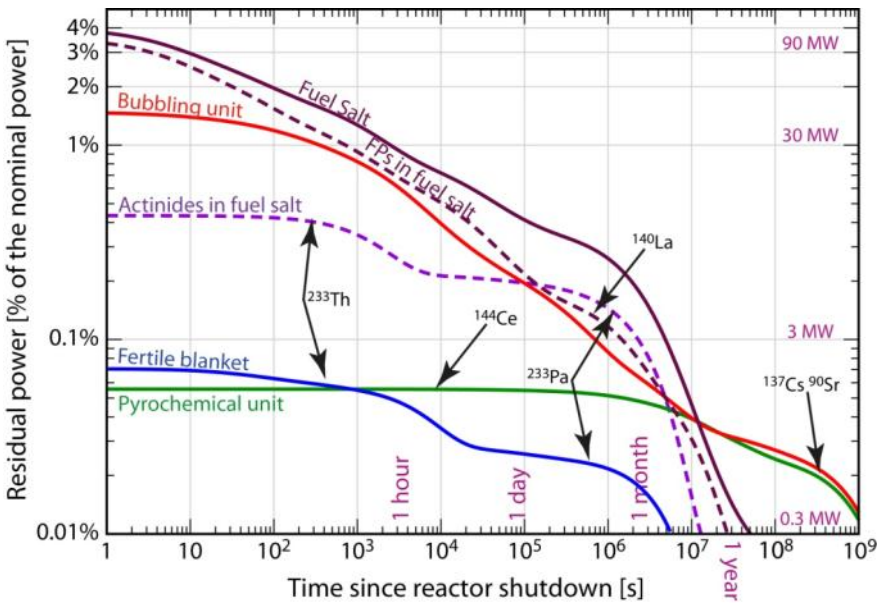
✗ Confinement of the fuel salt in the fuel circuit

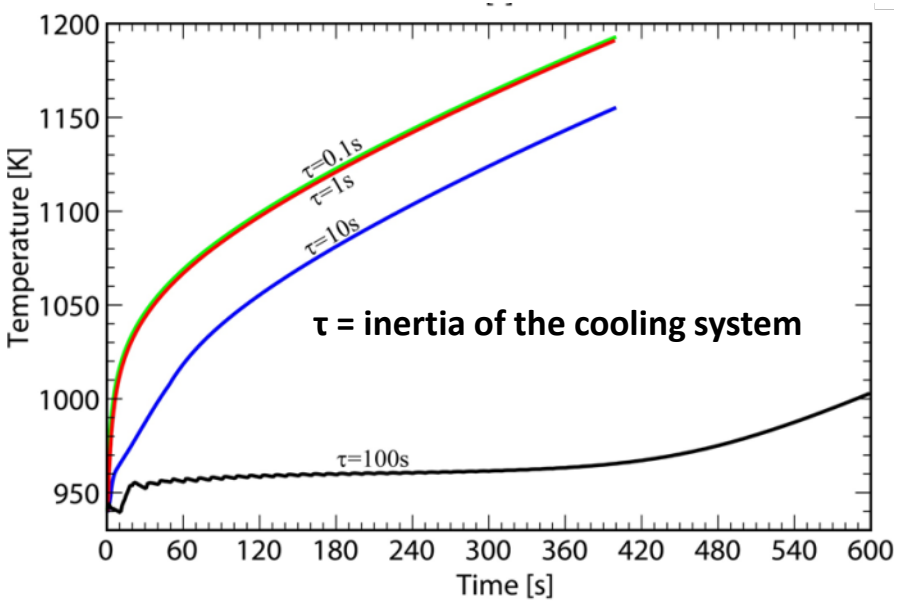
MSFR and Safety Evaluation: example of accident scenario

Initiators (failure mode) → Dangerous Phenomena → **Transient** → Consequences → Concept adaptation

Initiators (failure mode)	Dangerous Phenomena	**Transient**	Consequences	Concept adaptation
Identification + occurrence probability	Accident classification	Physical study of the reactor	Identified risks? Loss of barriers?	Prevention barrier? Protection? Damages limitation?

Scenario = passive decrease of the chain reaction (thermal feedback coefficients) + increase of the fuel salt temperature due to residual heat





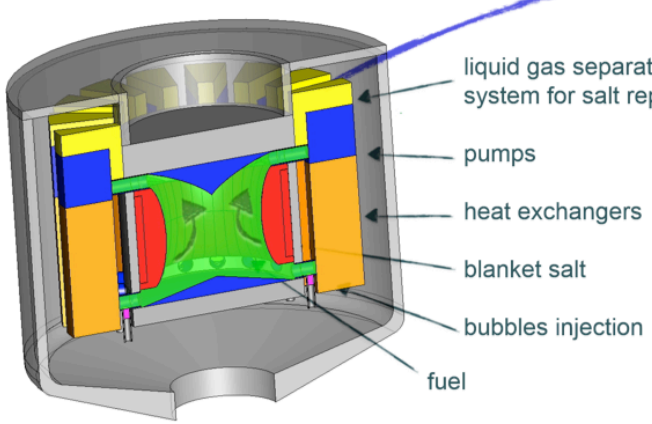
MSFR TRANSIENT CALCULATIONS: THE TFM (TRANSIENT FISSION MATRIX) APPROACH

- Liquid fuel (precursor motion)
- Fuel = coolant
- Fast neutron spectrum
- Circulation time ~ 3 s
- Reynolds in core: ~ 500000
- Power: 3GWth
- Molten Salt : LiF - $(Th/^{233}U)F_4$
  - density: 4 x water
  - viscosity: 2 x water (oil ~ 1000x water)
  - low pressure
  - mean fuel temperature ~ 900 K

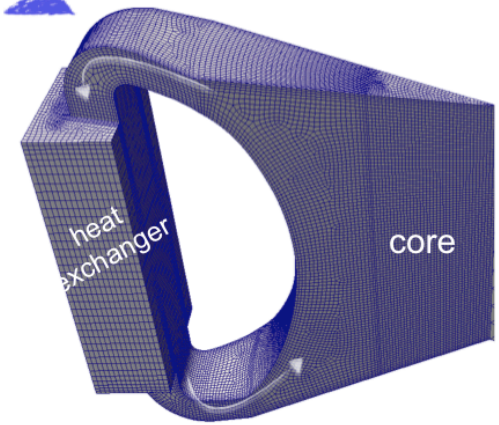
Objective : multiphysics simulations of liquid-fuelled reactors – here optimized coupling of neutronics + thermal-hydraulics:

- high precision of the T&H modeling (flow distribution)
  → CFD code - OpenFOAM
- high precision of the neutronics modeling …
  → Monte Carlo code - MCNP or SERPENT codes
- … with a low computational cost (many cases to perform)
  → Diffusion? Improved point kinetics? …
  innovative method: TFM approach

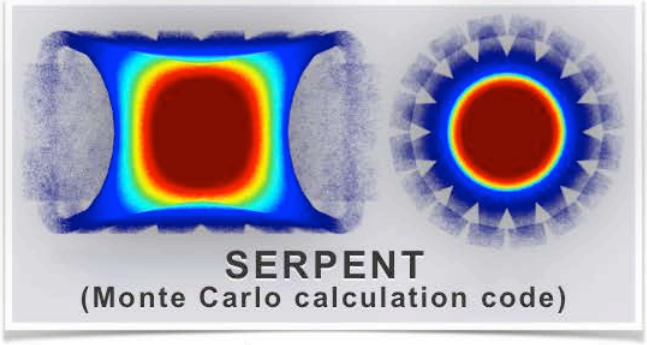
1/16 of the reactor modeled



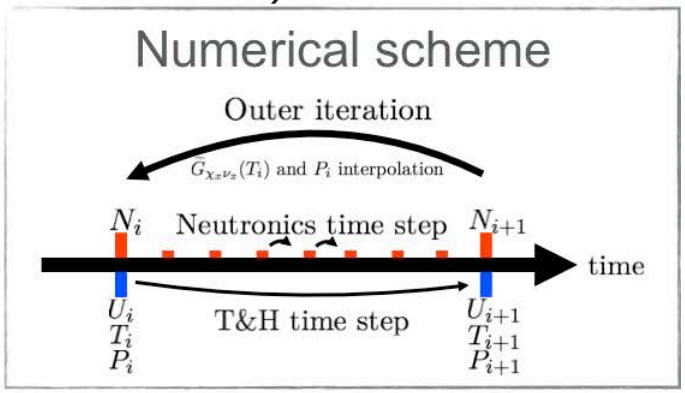
MSFR scheme



MSFR TRANSIENT CALCULATIONS: THE TFM (TRANSIENT FISSION MATRIX) APPROACH



GENERAL COUPLING STRATEGY



matrices calculation

power

temperature
buoyancy effect
precursor production

TFM
(developed model)

neutronics

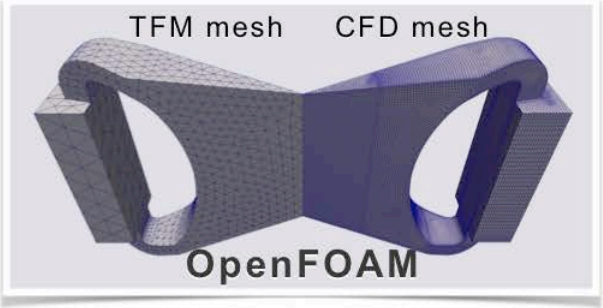
thermal-hydraulics

CFD
k-ε realizable turbulence model

delayed neutron source
Doppler feedback effect
density feedback effect

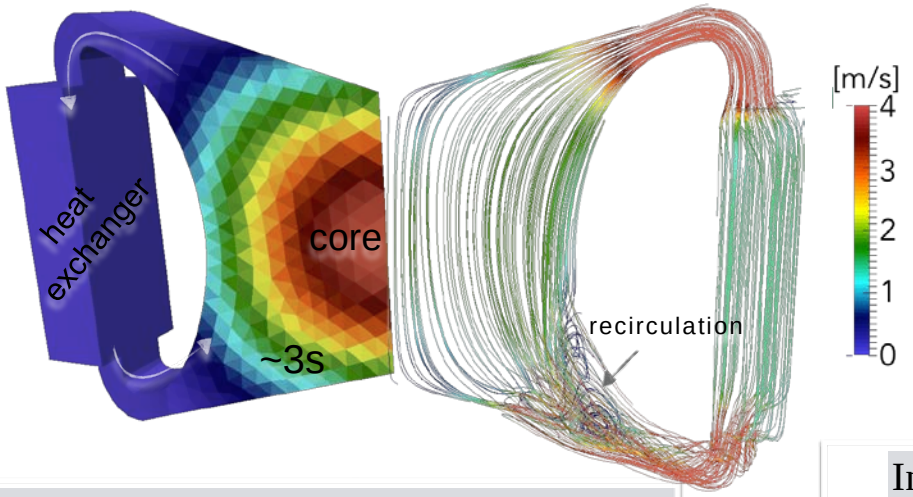
temperature field
precursor decay position

directly implemented and performed in

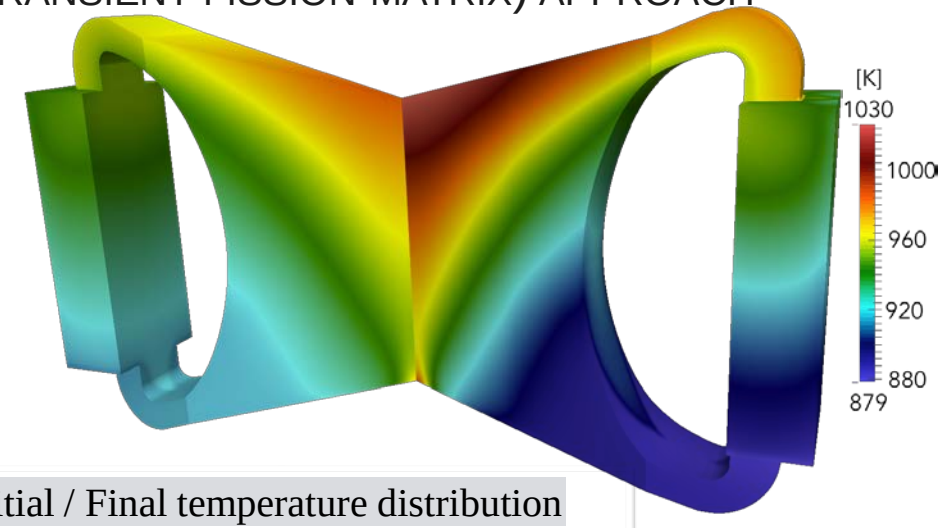


performed by

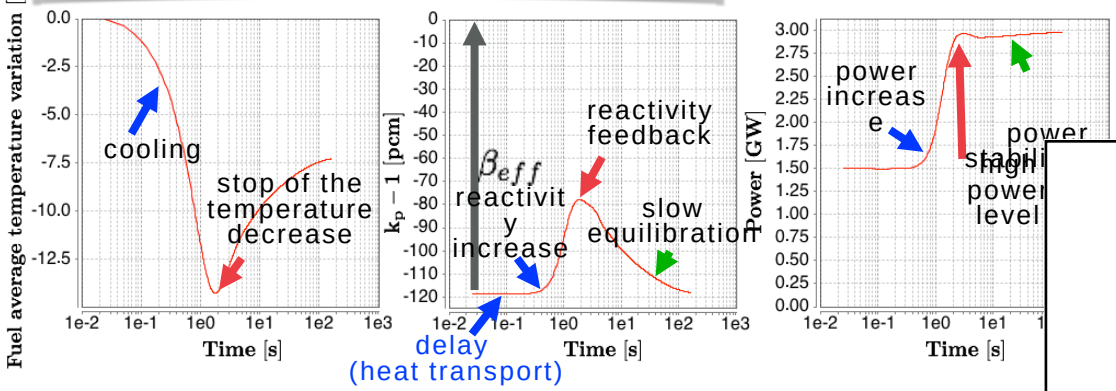
MSFR TRANSIENT CALCULATIONS: THE TFM (TRANSIENT FISSION MATRIX) APPROACH



Initial conditions (steady state)



Initial / Final temperature distribution



- **Good behavior of the MSFR for load-following transients**
- **Coupling code (OpenFoam – TFM) operational**
- **Calculations with high precision & low computational cost**

MSR offer many options: thermal or fast neutron spectrum, breeder or burner, with or without thorium support

Although MSR-pSSC partners interests are focused on different baseline concepts (MSFR, MOSART and FHR), large commonalities in basic R&D areas (*liquid salt technology, materials, safety aspects*) do exist and the Generation IV framework can be useful to coordinate the R&D effort

Thank you for your attention