Presentation of the MSFR reactor concept

E. MERLE-LUCOTTE

Professor at CNRS-IN2P3-LPSC / Grenoble INP - PHELMA

For the MSFR team - M. ALLIBERT, M. AUFIERO, M. BROVCHENKO, D. HEUER, V. GHETTA, A. LAUREAU, E. MERLE-LUCOTTE, P. RUBIOLO

merle@lpsc.in2p3.fr

With the support of the IN2P3 institute and the PACEN and NEEDS French Programs, and of the EVOL Euratom FP7 Project

Concept of Molten Salt Fast Reactor (MSFR)

Advantages of a Liquid Fuel

- ✓ Homogeneity of the fuel (no loading plan)
- ✓ Fuel = coolant ⇨ Heat produced directly in the heat transfer fluid
- ✓ Possibility to reconfigure quickly and passively the geometry of the fuel (gravitational draining)
- ✓ Possibility to reprocess the fuel without stopping the reactor

+ Gen4 criteria ⇒ step1= Neutronic optimization of MSR:

- **Safety: negative feedback coefficients**
- **Sustainability: reduce irradiation damages in the core**
- **Deployment: good breeding of the fuel + reduced initial fissile inventory**

2008: Definition of an innovative MSR concept based on a fast neutron spectrum, and called MSFR (Molten Salt Fast Reactor)

- ➢ All feedback reactivity coefficients negative
- ➢ No solid material in the high flux area: reduction of the waste production of irradiated structural elements and less in core maintenance operations
- ➢ Good breeding of the fissile matter thanks to the fast neutron spectrum
- ➢ Actinides burning improved thanks to the fast neutron spectrum

R&D objectives

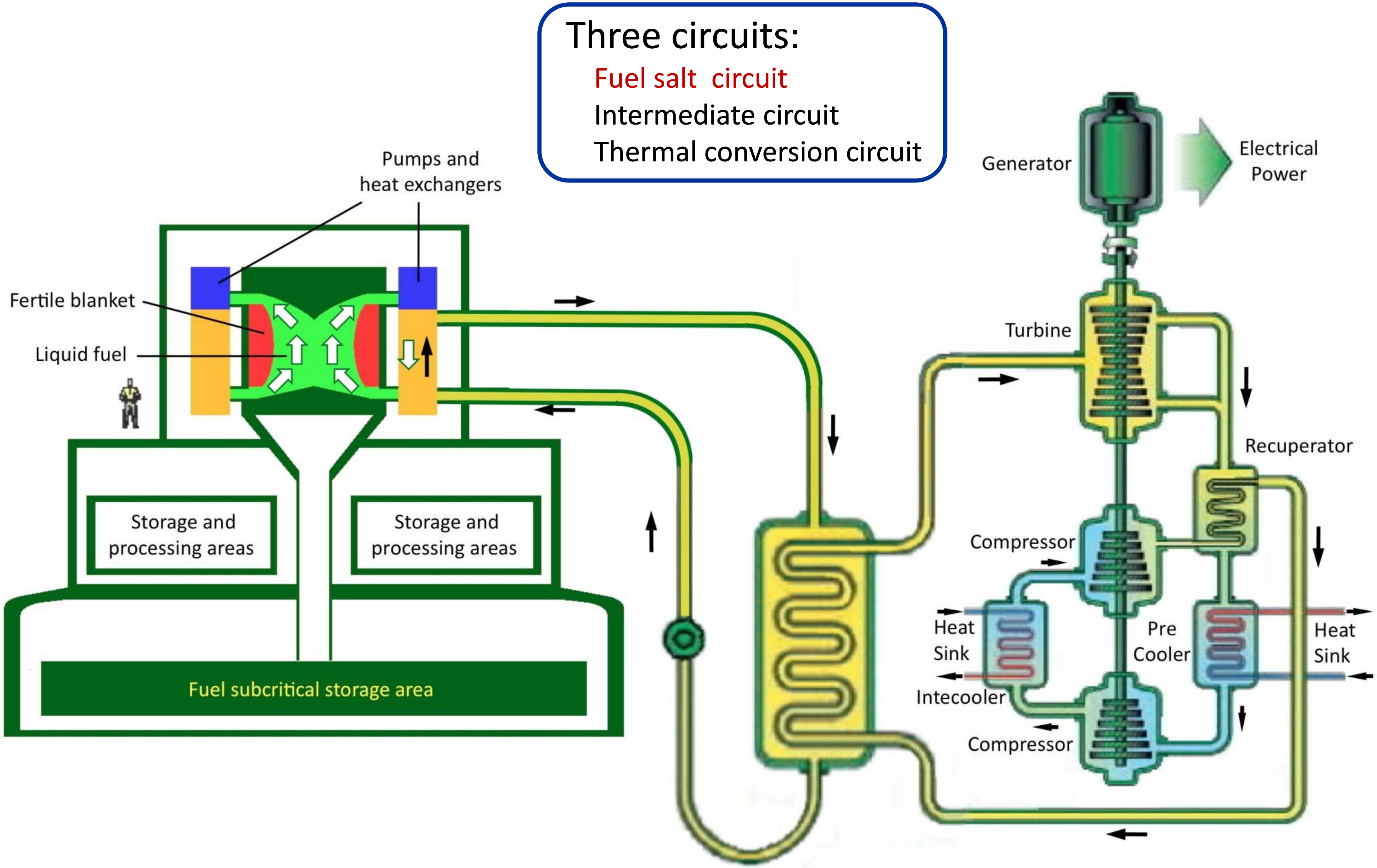
The renewal and diversification of interests in molten salts have led the MSR provisional SSC to shift the R&D orientations and objectives initially promoted in the original Generation IV Roadmap issued in 2002, in order to encompass in a consistent body the different applications envisioned today for fuel and coolant salts.

Two baseline concepts are considered which have large commonalities in basic R&D areas, particularly for liquid salt technology and materials behavior (mechanical integrity, corrosion):

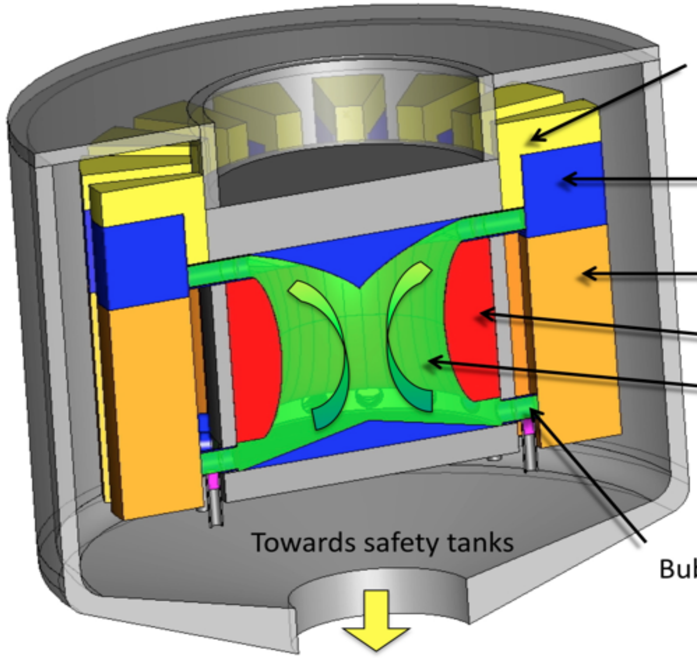
• The Molten Salt Fast-neutron Reactor (MSFR) is a long-term alternative to solid-fuelled fast neutron reactors offering very negative feedback coefficients and simplified fuel cycle. Its potential has been assessed but specific technological challenges must be addressed and the safety approach has to be established.

• The AHTR is a high temperature reactor with better compactness than the VHTR and passive safety potential for medium to very high unit power.

Molten Salt Fast Reactor (MSFR)



Molten Salt Fast Reactor (MSFR): fuel circuit



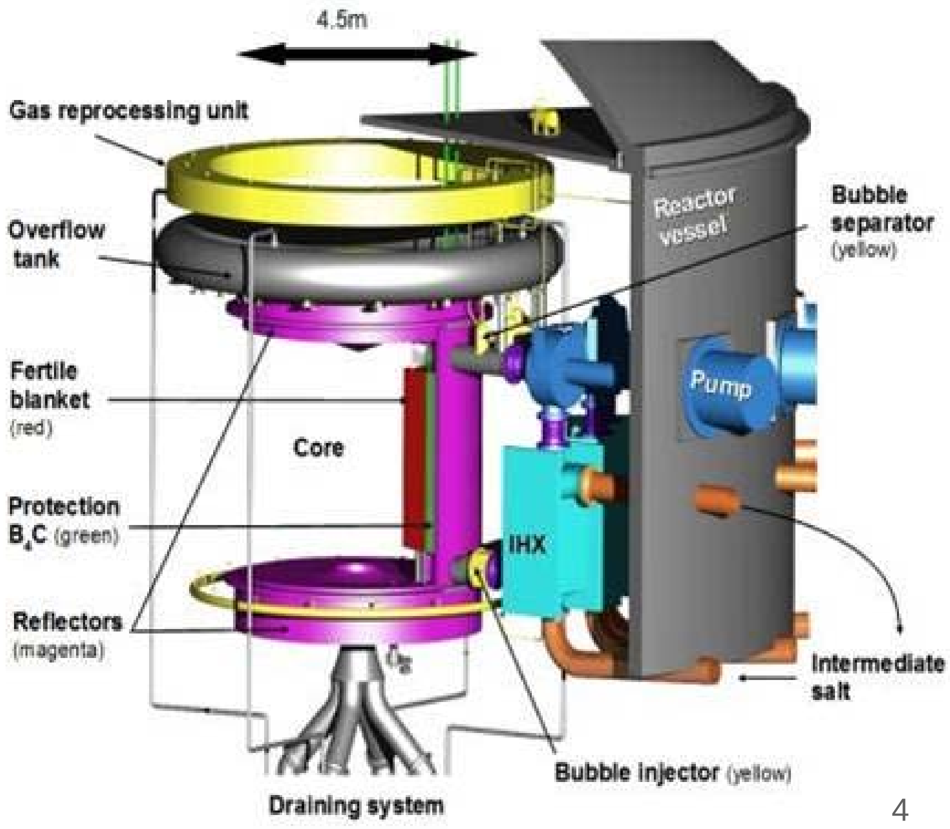
Core (active area):

No inside structure

Outside structure: Upper and lower Reflectors, Fertile Blanket Wall

+ 16 external recirculation loops:

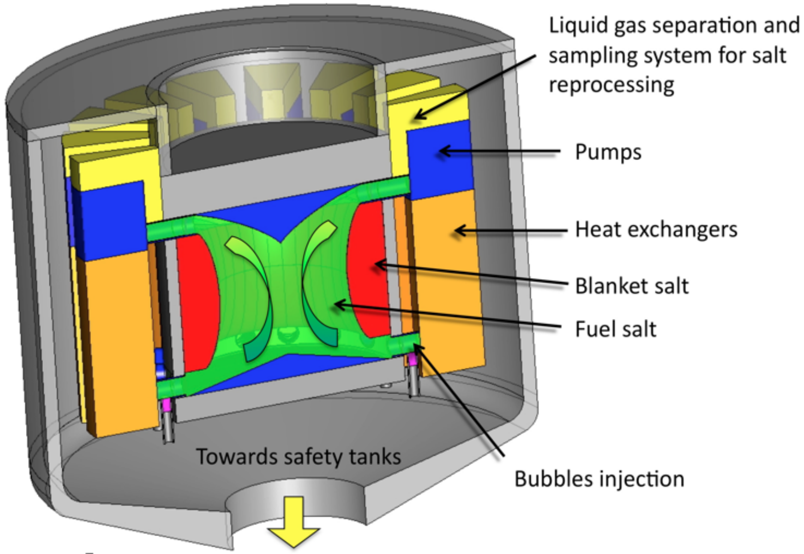
- Pipes (cold and hot region)
- Bubble Separator
- Pump
- Heat Exchanger
- Bubble Injection

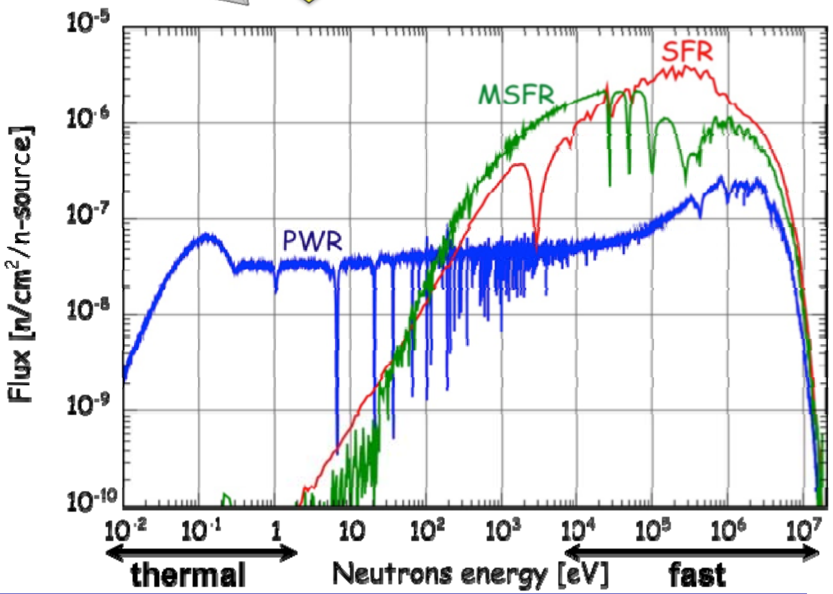


The concept of Molten Salt Fast Reactor (MSFR)

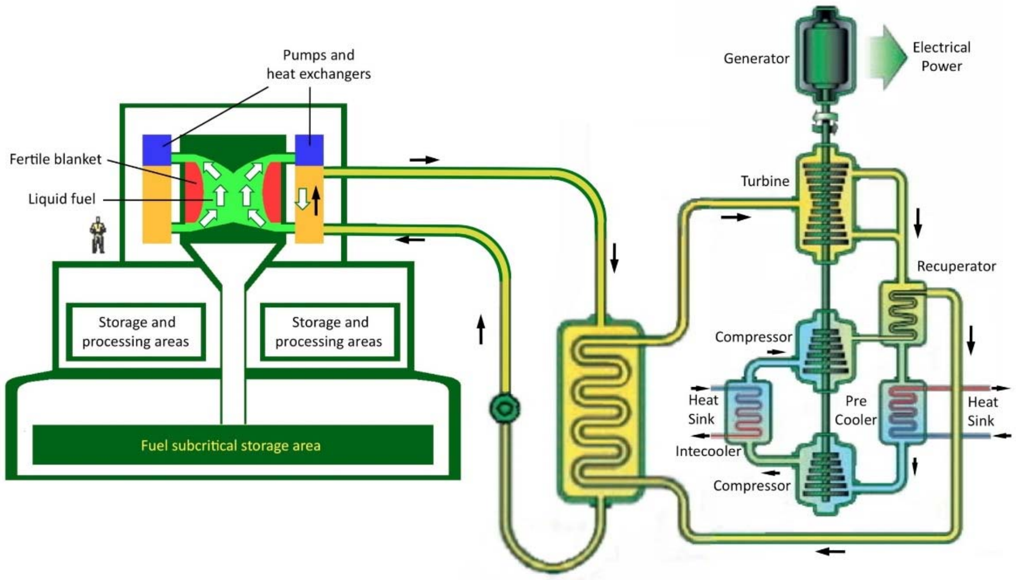
Thermal power	**3000 MWth**
Mean fuel salt temperature	**750 °C**
Fuel salt temperature rise in the core	**100 °C**
Fuel molten salt - Initial composition	**77.5% LiF and 22.5% [ThF_4+ (Fissile Matter)F_4] with Fissile Matter = ^{233}U / $^{enriched}U$ / Pu+MA**
Fuel salt melting point	**565 °C**
Fuel 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 pcm/K**
Core dimensions	**Diameter: 2.26 m Height: 2.26 m**
Fuel salt volume	**18 m^3 (½ in the core + ½ in the external circuits)**
Blanket salt volume	**7.3 m^3**
Total fuel salt cycle	**3.9 s**

Design of the 'reference' MSFR





Concept of Molten Salt Fast Reactor (MSFR)



Next step: requires multidisciplinary expertise (reactor physics, simulation, chemistry, safety, materials, design…) from academic and industrial worlds

Cooperation frames:

- **Worldwide:** Generation 4 International Forum (GIF)
- **European:** collaborative project Euratom / Rosatom EVOL (FP7) – European project SAMOFAR (H2020) + SNETP SRIA Annex
- **National:** IN2P3 / CNRS and interdisciplinary programs PACEN and NEEDS (CNRS, CEA, IRSN, AREVA, EdF), structuring project 'CLEF' of Grenoble Institute of Technology

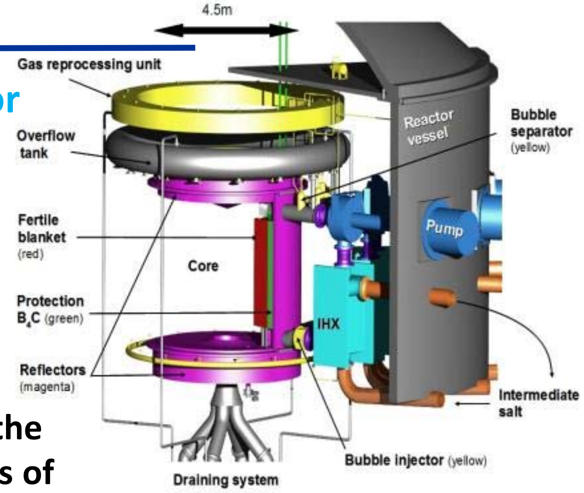
R&D objectives

The renewal and diversification of interests in molten salts have led the MSR provisional SSC to shift the R&D orientations and objectives initially promoted in the original Generation IV Roadmap issued in 2002, in order to encompass in a consistent body the different applications envisioned today for fuel and coolant salts.

Two baseline concepts are considered which have large commonalities in basic R&D areas, particularly for liquid salt technology and materials behavior (mechanical integrity, corrosion):

- The Molten Salt Fast-neutron Reactor (MSFR) is a long-term alternative to solid-fuelled fast neutron eactors offering very negative feedback coefficients and simplified fuel cycle. Its potential has been assessed but specific technological challenges must be addressed and the safety approach has to be established.
- The AHTR is a high temperature reactor with better compactness than the VHTR and passive safety potential for medium to very high unit power.

MSFR and the European project EVOL



European Project "EVOL" Evaluation and Viability Of Liquid fuel fast reactor

FP7 (2011-2013): Euratom/Rosatom cooperation

Objective : to propose a design of MSFR by end of 2013 given the best system configuration issued from physical, chemical and material studies

- **Recommendations for the design of the core and fuel heat exchangers**
- **Definition of a safety approach dedicated to liquid-fuel reactors - Transposition of the defence in depth principle - Development of dedicated tools for transient simulations of molten salt reactors**
- **Determination of the salt composition - Determination of Pu solubility in LiF-ThF4 - Control of salt potential by introducing Th metal**
- **Evaluation of the reprocessing efficiency (based on experimental data) – FFFER project**
- **Recommendations for the composition of structural materials around the core**

⇨ EVOL {
WP2: Design and Safety
WP3: Fuel Salt Chemistry and Reprocessing
WP4: Structural Materials

12 European Partners: France (CNRS: Coordinateur, Grenoble INP , INOPRO, Aubert&Duval), Pays-Bas (Université Techno. de Delft), Allemagne (ITU, KIT-G, HZDR), Italie (Ecole polytechnique de Turin), Angleterre (Oxford), Hongrie (Univ Techno de Budapest)
+ 2 observers since 2012 : Politecnico di Milano et Paul Scherrer Institute

+ Coupled to the MARS (Minor Actinides Recycling in Molten Salt) project of ROSATOM (2011-2013)

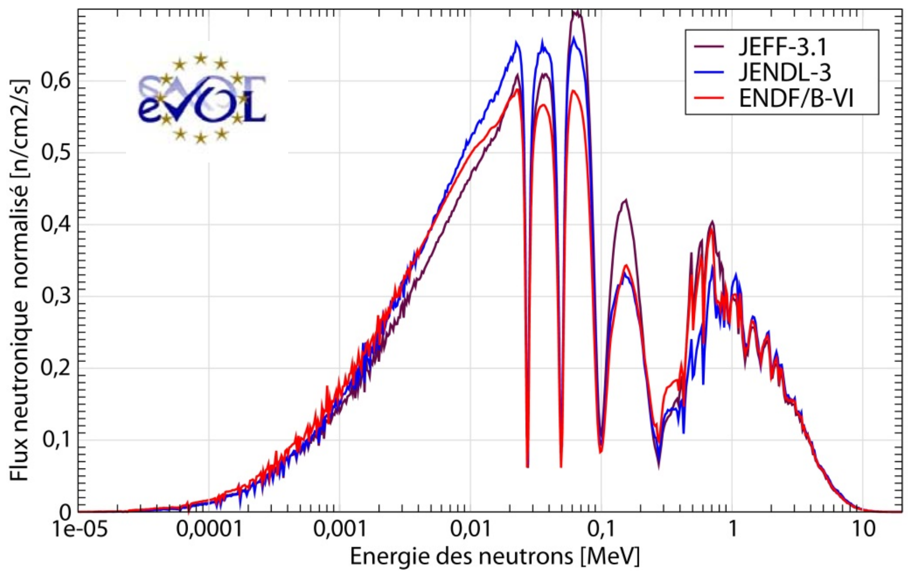
Partners: RIAR (Dimitrovgrad), KI (Moscow), VNIITF (Snezinsk), IHTE (Ekateriburg), VNIKHT (Moscow) et MUCATEX (Moscow)

MSFR optimization: neutronic benchmark (EVOL)

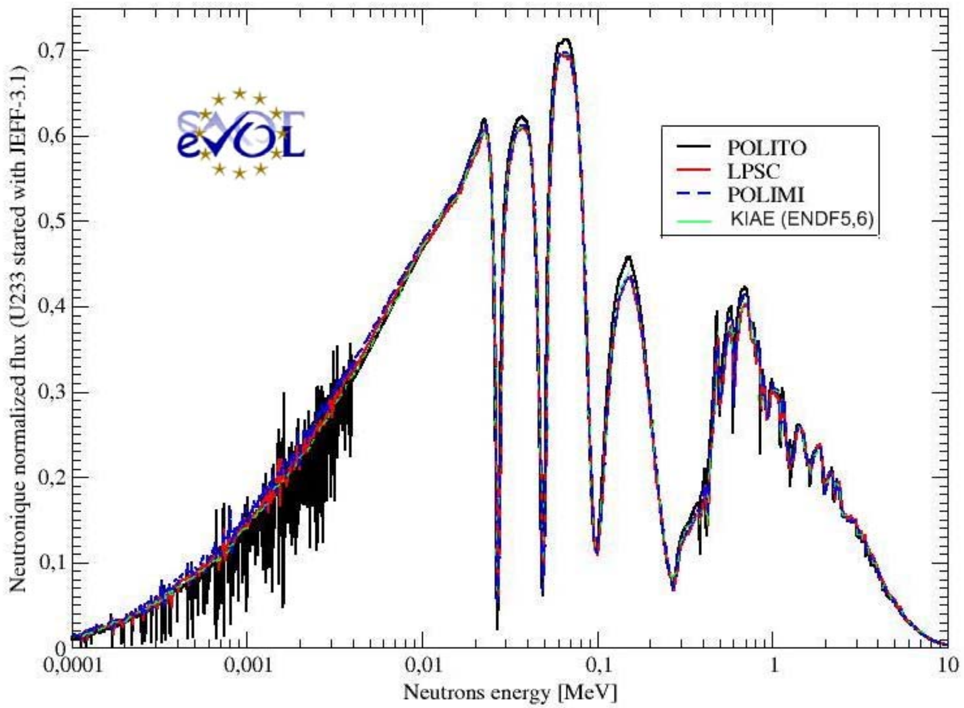
POLIMI calculations performed with SERPENT

Initial Fuel Salt Composition – EVOL Benchmark					
^{233}U-started MSFR		TRU-started MSFR			
Th	^{233}U	Th	Actinides		
38 281 kg 19.985 %mol	4 838 kg 2.515 %mol	30 619 kg 16.068 %mol	Pu	11 079 kg	5.628 %mol
			Np	789 kg	0.405 %mol
			Am	677 kg	0.341 %mol
			Cm	116 kg	0.058 %mol

PhD Thesis of M. Brovchenko

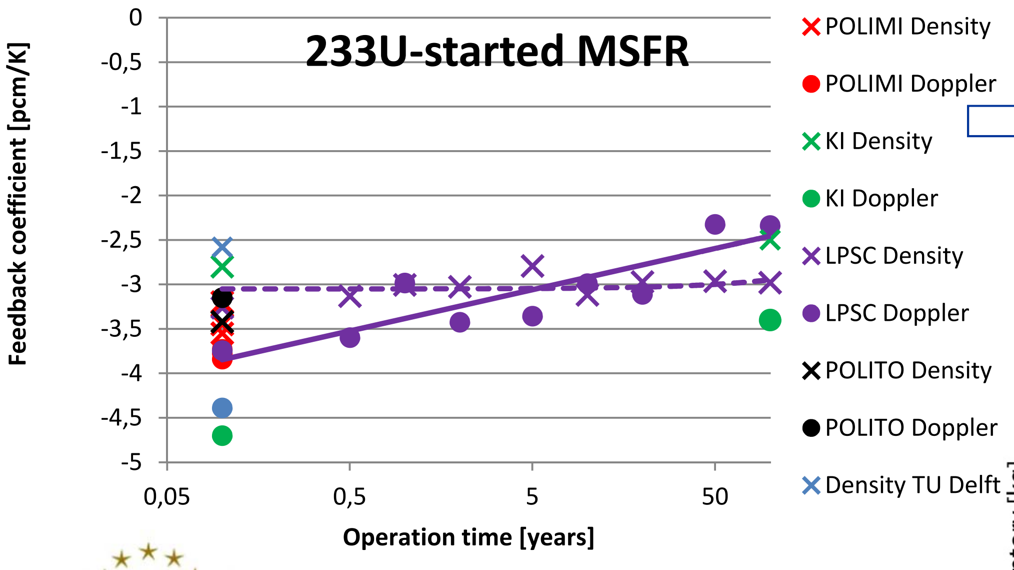


LPSC-IN2P3 calculations performed with MCNP (coupled to in-house material evolution code REM)

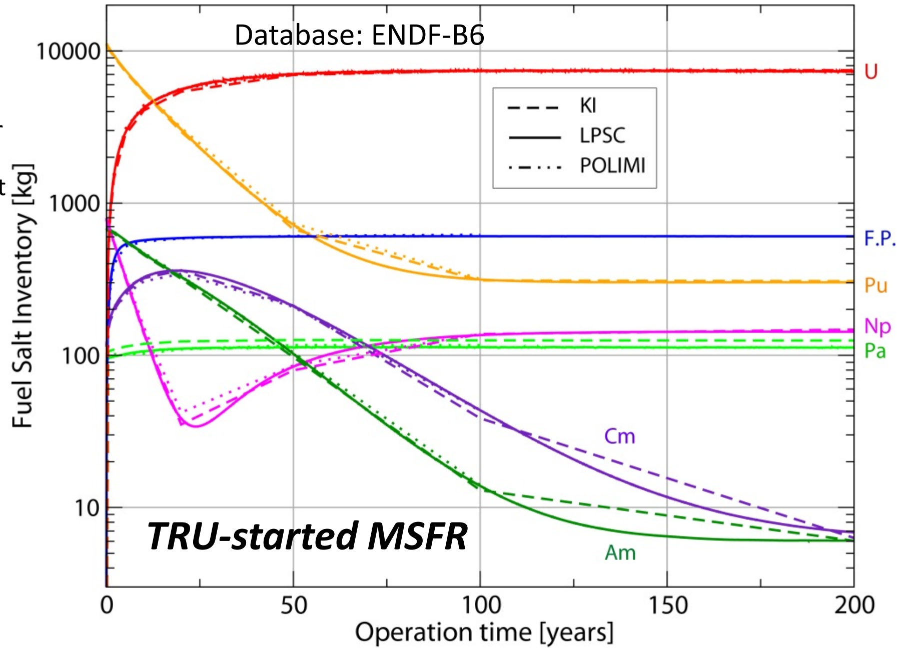


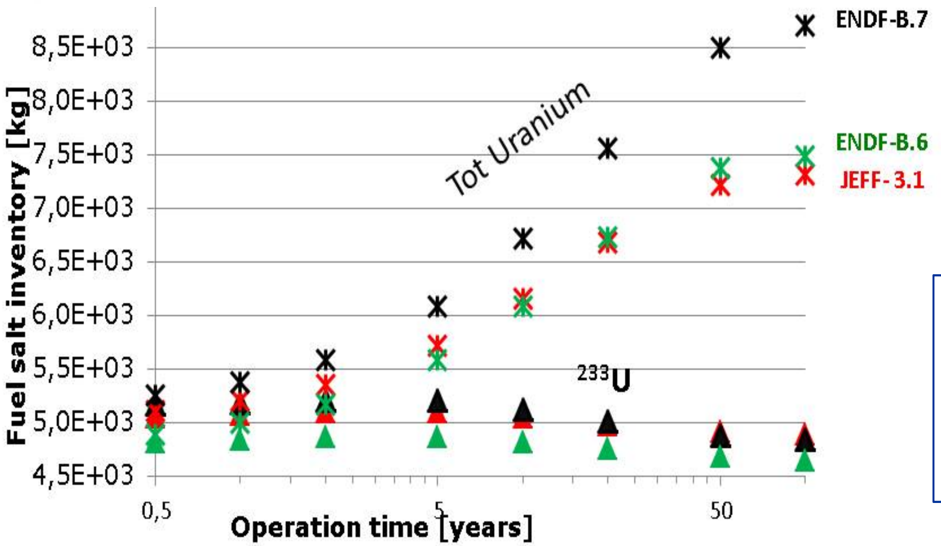
Static calculations (BOL here):
Good agreement between the different simulation tools – High impact of the nuclear database

MSFR optimization: neutronic benchmark (EVOL)



Largely negative feedback coefficients, ∀ the simulation tool or the database used





<u>Evolution calculations:</u>
Very good agreement between the different simulation tools – High impact of the nuclear database

MSFR and Safety Evaluation

Design aspects impacting the MSFR safety analysis

- Liquid fuel
  - ✓ Molten fuel salt acts as reactor fuel and coolant
  - ✓ Relative uniform fuel irradiation
  - ✓ A significant part of the fissile inventory is outside the core
  - ✓ Fuel reprocessing and loading during reactor operation

- No control rods in the core
  - ✓ Reactivity is controlled by the heat transfer rate in the HX + fuel salt feedback coefficients, continuous fissile loading, and by the geometry of the fuel salt mass
  - ✓ No requirement for controlling the neutron flux shape (no DNB, uniform fuel irradiation, etc.)

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

MSFR and Safety Evaluation

Safety analysis: objectives

- **Develop a safety approach dedicated to MSFR**
    - **Based on current safety principles** e.g. defense-in-depth, multiple barriers, the 3 safety functions (reactivity control, fuel cooling, confinement) etc. but adapted to the MSFR.
    - Integrate both **deterministic and probabilistic** approaches
    - Specific approach dedicated to **severe accidents**:
        - Fuel liquid during normal operation
        - Fuel solubility in water (draining tanks)
        - Source term evaluation
- **Build a reactor risk analysis model**
    - Identify the **initiators and high risk scenarios** that require detailed transient analysis
    - Evaluate the risk due to the **residual heat and the radioactive inventory** in the whole system, including the reprocessing units (chemical and bubbling)
    - Evaluate some potential design solutions (**barriers**)
    - Allow reactor designer to estimate impact of design changes (***design by safety***)

H2020 SAMOFAR project – Safety Assessment of a MOlten salt FAst Reactor

« A Paradigm Shift in Nuclear Reactor Safety with the Molten Salt Fast Reactor »

(2015-2019 – Around 3 Meuros)

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

5 technical work-packages:

WP1 Integral safety approach and system integration

WP2 Physical and chemical properties required for safety analysis

WP3 Experimental proof of i) shut-down concept and ii) natural circulation dynamics for internally heated molten salt

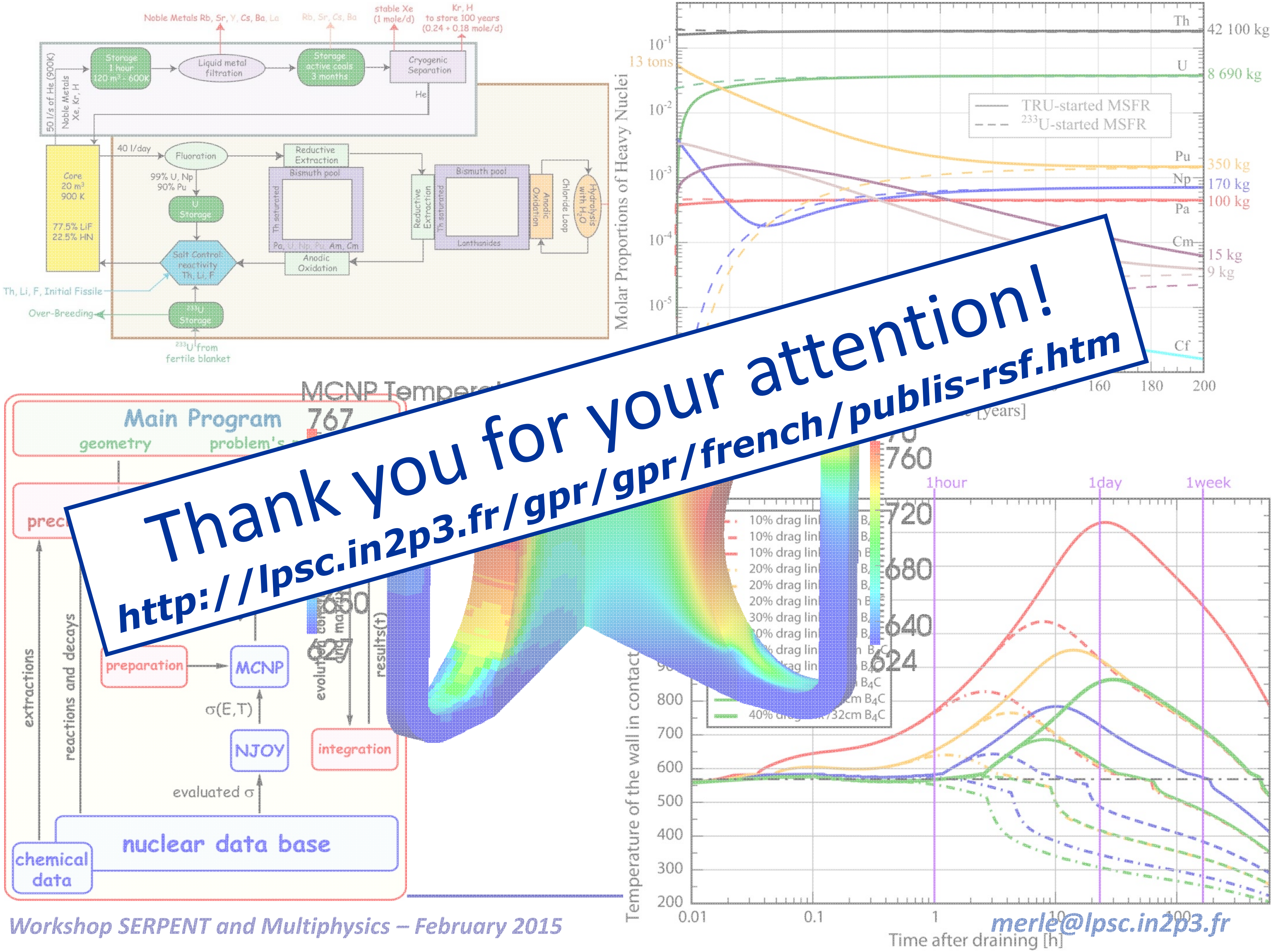
WP4 Accident analysis

WP5 Safety evaluation of the chemical plant

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020

SAMOFAR HORIZON 2020



Thank you for your attention!

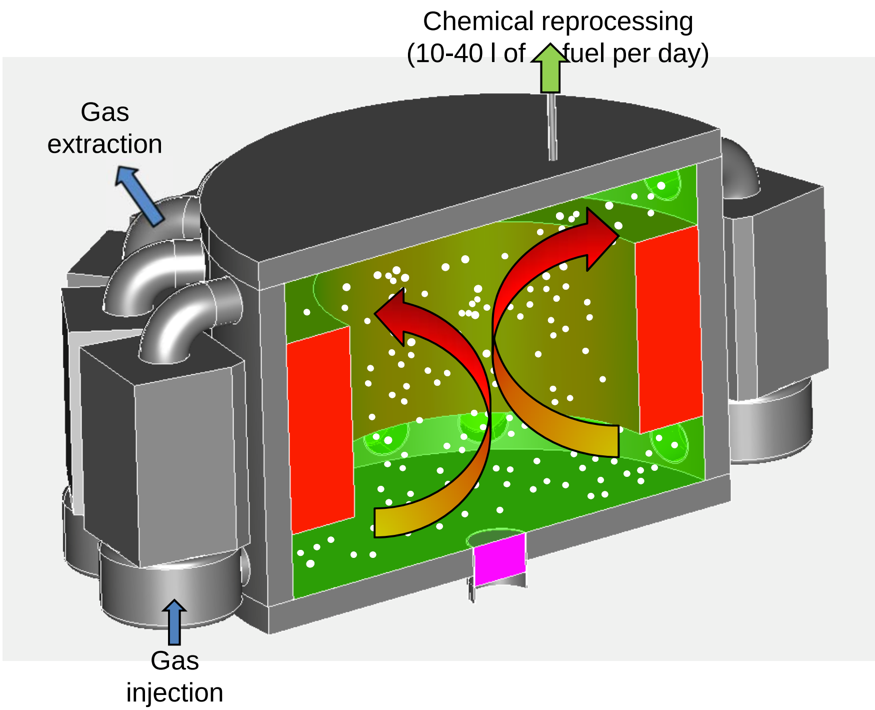
http://lpsc.in2p3.fr/gpr/gpr/french/publis-rsf.htm

merle@lpsc.in2p3.fr

MSFR: R&D collaborations

4th Generation reactors => Breeder reactors

Fuel reprocessing mandatory to recover the produced fissile matter – Liquid fuel = reprocessing during reactor operation



MSFR: R&D collaborations

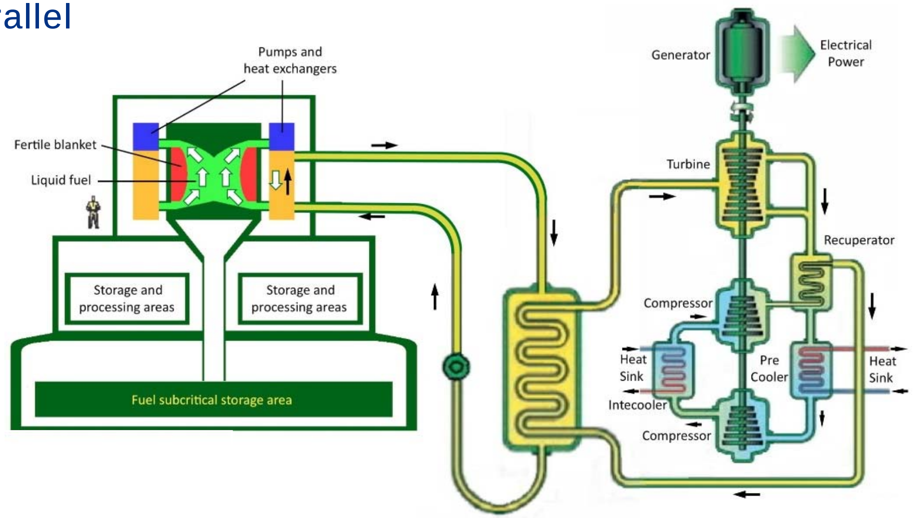
4th Generation reactors => Breeder reactors

Fuel reprocessing mandatory to recover the produced fissile matter – Liquid fuel = reprocessing during reactor operation

Conclusions of the studies: **very low impact of the reprocessings (chemical and bubbling) on the neutronic behavior of the MSFR thanks to the fast neutron spectrum** = neutronic and chemical (physico-chemical properties of the salt) studies driven in parallel

PhD Thesis of X. Doligez

Studies requiring multidisciplinary expertise (reactor physics, simulation, chemistry, safety, materials, design…)



Collaboration frames:

- **World: Generation 4 International Forum**
- **Europe: collaborative project Euratom / Rosatom EVOL (FP7) – European project SAMOFAR (H2020) + SNETP SRIA Annex**
- **National: IN2P3 / CNRS and interdisciplinary programs PACEN and NEEDS (CNRS, CEA, IRSN, AREVA, EdF), structuring project 'CLEF' of Grenoble INP**