Physical Assessment of the Load Following and Starting Procedures for the Molten Salt Fast Reactor

E. MERLE-LUCOTTE , D. HEUER, A. LAUREAU, M. BROVCHENKO, M. ALLIBERT, M. AUFIERO

merle@lpsc.in2p3.fr *– Professor at Grenoble INP/PHELMA and in the Reactor Physics Group of Laboratoire de Physique Subatomique et de Cosmologie de Grenoble (CNRS-IN2P3-LPSC / Grenoble Alpes University)*

With the support of the IN2P3 institute of CNRS and the NEEDS French Program, of the EVOL Euratom FP7 Project, of Grenoble Institute of Technology

The 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

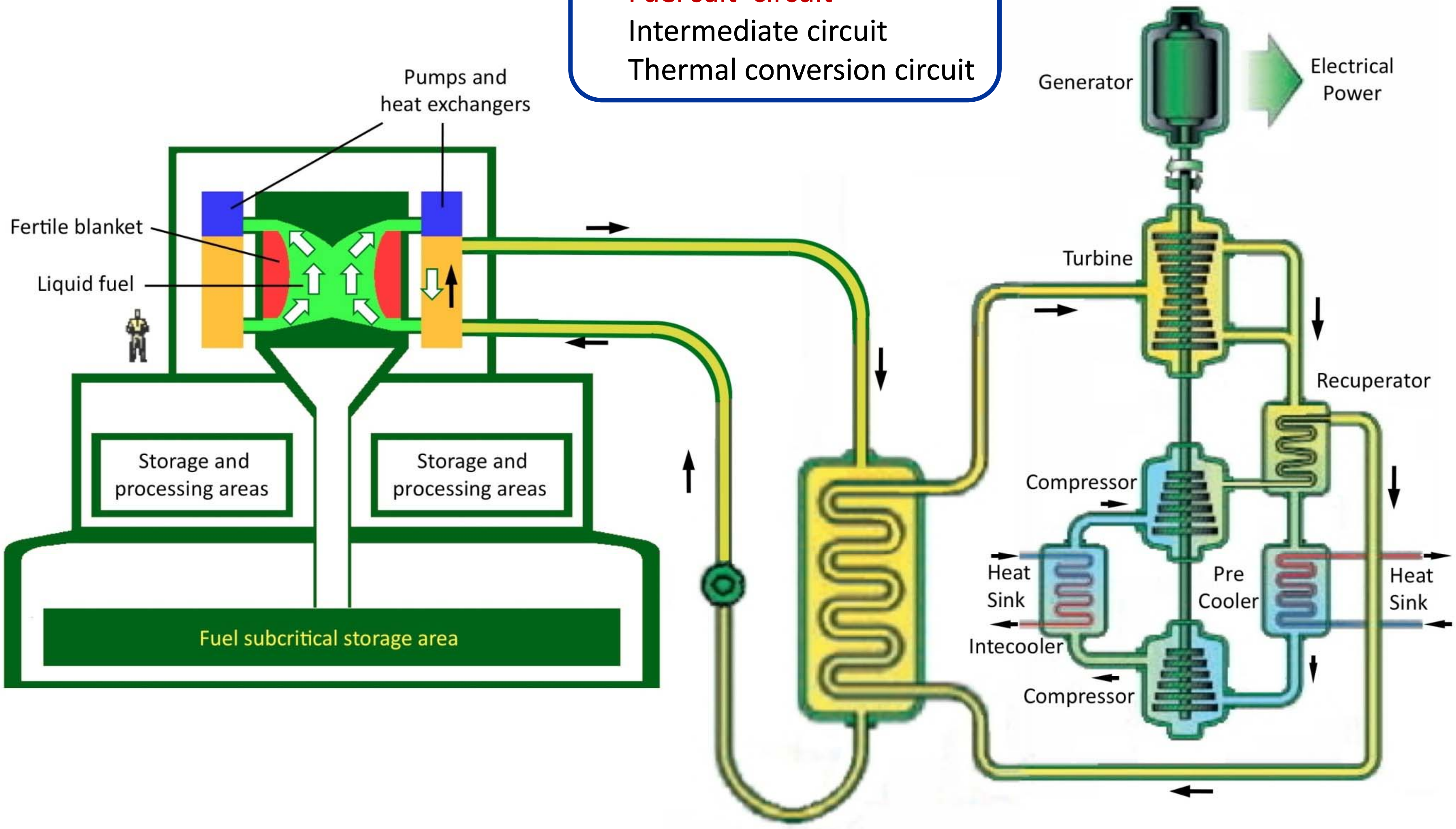
The renewal and diversification of interests in molten salts have led the MSR provisional SSC to shift the R&D orientations and objectives initially promoted in the original Generation IV Roadmap issued in 2002, in order to encompass in a consistent body the different applications envisioned today for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

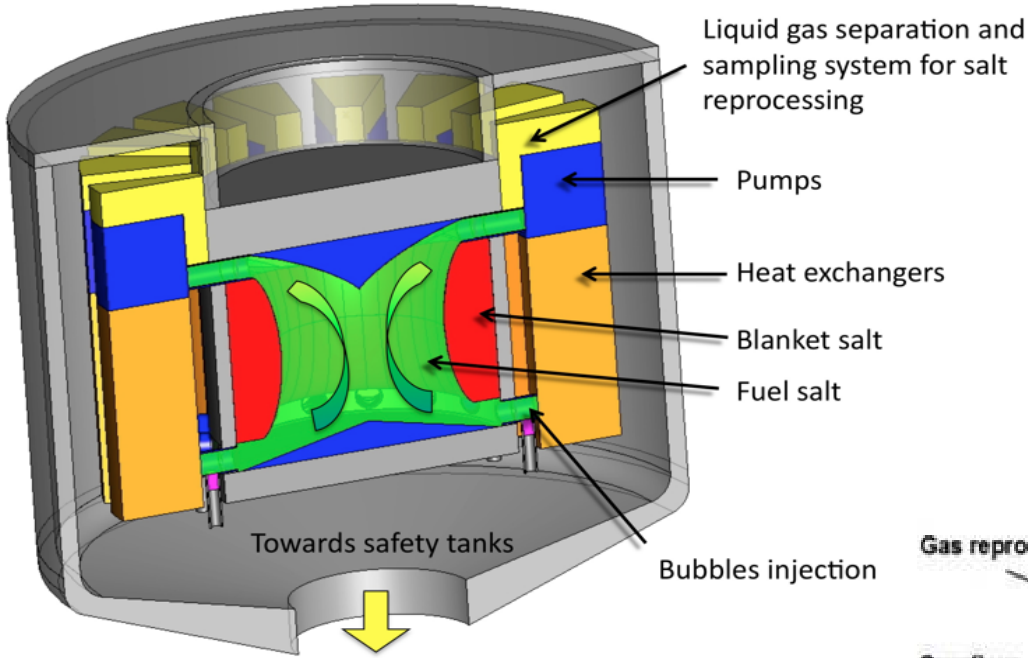
- The Molten Salt Fast-neutron Reactor (MSFR) is a long-term alternative to solid-fuelled fast neutron reactors offering very negative feedback coefficients and simplified fuel cycle. Its potential has been assessed but specific technological challenges must be addressed and the safety approach has to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

The concept of Molten Salt Fast Reactor (MSFR)

Three circuits:
- Fuel salt circuit
- Intermediate circuit
- Thermal conversion circuit



Molten Salt Fast Reactor (MSFR): fuel circuit



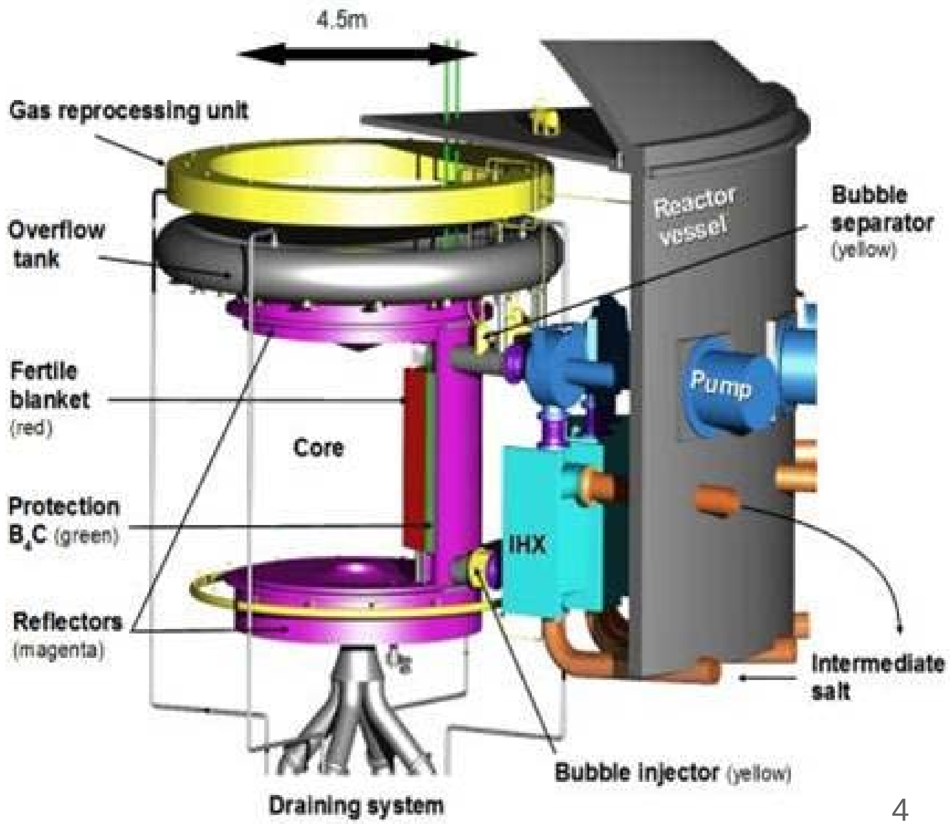
Core (active area):

No inside structure

Outside structure: Upper and lower Reflectors, Fertile Blanket Wall

+ 16 external recirculation loops:

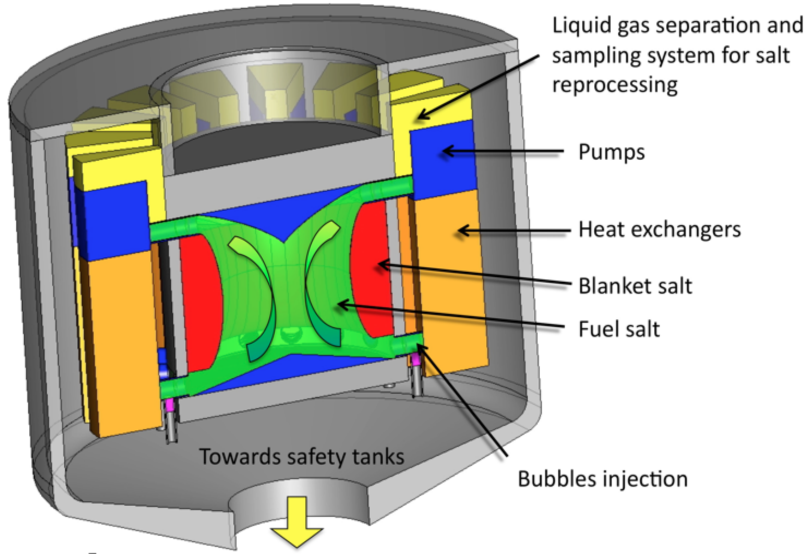
- Pipes (cold and hot region)
- Bubble Separator
- Pump
- Heat Exchanger
- Bubble Injection

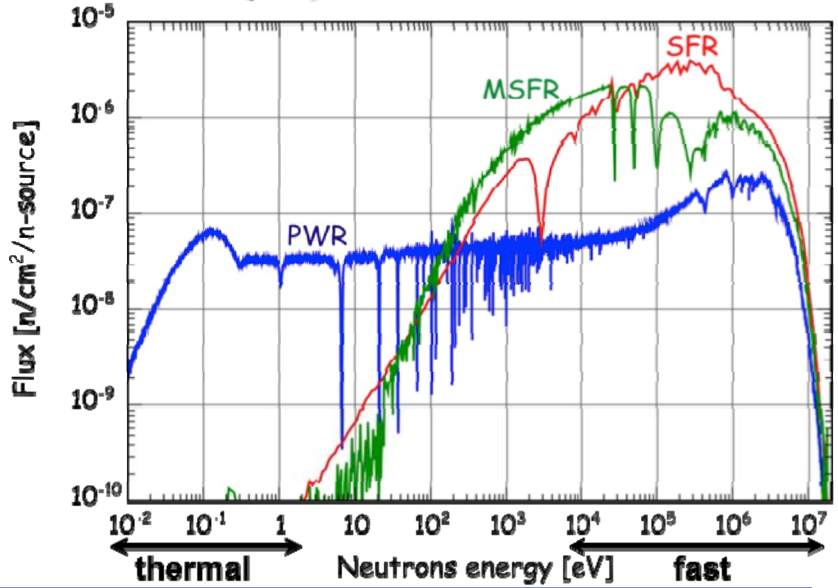


The concept of Molten Salt Fast Reactor (MSFR)

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/cm³**
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 -7 pcm/K**
Core dimensions	**Diameter: 2.26 m Height: 2.26 m**
Fuel salt volume	**18 m³ (½ in the core + ½ in the external circuits)**
Blanket salt volume	**7.3 m³**
Total fuel salt cycle	**3.9 s**

Design of the 'reference' MSFR





The concept of Molten Salt Fast Reactor (MSFR)

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

FP7 (2011-2014): Euratom/Rosatom cooperation

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

⇒ **MSFR reference design** { Thermo-hydraulic design optimization / Neutronic benchmark

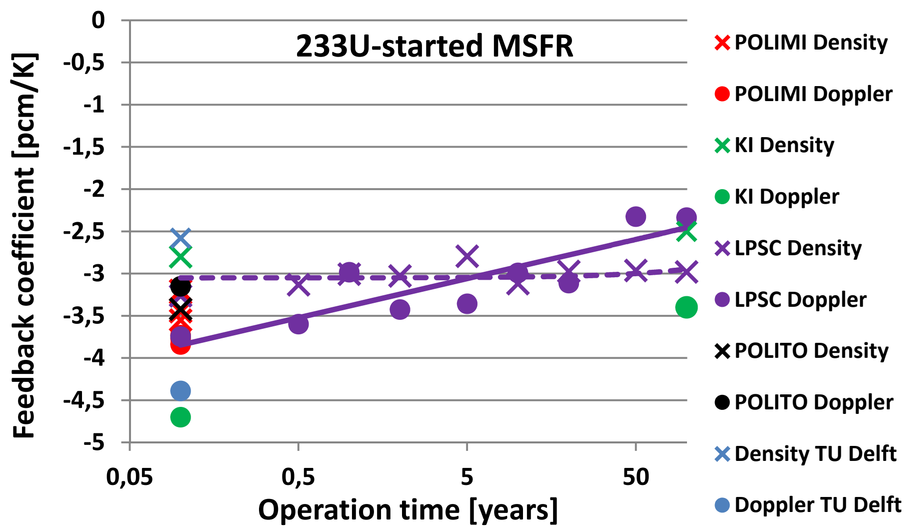
Fraction of delayed neutrons:

	β	$\beta_{circulation}$
BOL ^{233}U started MSFR	332 pcm	165 pcm

← *Evaluated with 1D kinetic point model*

Temperature feedback coefficients:

In pcm/K	Void	Doppler	Total
BOL ^{233}U-started	-3.26	-3.74	-6.67



MSFR and Safety Evaluation

Some 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.)

+ Combined to the negative thermal feedback coefficient

⇒ **Possibility of large and fast load following**

MSFR: Physical Analysis of Load-Following – Neutronics calculations

Point-Kinetic (PK) model:

$$\rho(t) = \frac{dk}{dT}\left(1 - \rho(t)\right)^2 [T(t) - T_0] + \mathrm{I}(t)$$

$$\frac{\partial P}{\partial t}(t) = \frac{\rho(t) - \beta_{circ}}{l\,(1 - \rho(t))} P(t) + A.\sum_i \lambda_i C_i(t)$$

$$\frac{\partial C_i}{\partial t}(t) = \frac{\beta^i_{circ}.P(t)}{l\,(1 - \rho(t)).A} - \lambda_i\, C_i(t)$$

$$\frac{\partial T}{\partial t}(t) = \frac{P(t) - P_0}{C_P\, d}$$

Precursor motion taken into account with $\beta^i_{circ} = \beta^i \, \frac{\lambda_i}{\lambda_i + a_i}$ with the coefficients a_i defined as (*)

$$\frac{\left[1 - e\left(-\lambda_i\, \tau\, (1 - \delta)\right)\right].\left[1 + e(-\lambda_i\, \tau\, \delta)\right]}{\tau\,\delta\left[1 - e\left(-\lambda_i\, \tau\, (1 - \delta)\right).\frac{\left[1 - e(-\lambda_i\, \tau\, \delta)\right]}{\lambda_i\, \tau\, \delta} + 2\frac{\lambda_i\, \tau\, \delta}{\pi^2}\left[1 - e(-\lambda_i\, \tau\,)\right]\right]}$$

With δ = the fuel salt fraction in the core and τ = the salt circulation time in the fuel circuit

Limits: Follow-up of the precursors is evaluated here only for a constant fuel velocity during the transient + stationary precursor production density + heat extraction considered as instantaneous

(*) D. Lecarpentier, PhD Thesis, Conservatoire National des Arts et Métiers (2001)

MSFR: Physical Analysis of Load-Following – Neutronics calculations

Improved Point-Kinetic (IPK)(*) model:

Reactivity:

$$\rho(t) = \sum_{f\subset core} \left(\frac{dk}{dT}\right)_f \left[T_f(t) - T_f^0\right] + I_f(t)$$

Power:

$$\frac{\partial P}{\partial t}(t) = \frac{\rho(t) - \beta_{eff}}{l\left(1 - \rho(t)\right)} P(t) + A \sum_{f\subset core} \sum_i \lambda_i C_f^i(t)$$

Precursor density of family i:

$$\frac{\partial C_m^i}{\partial t}(t) = \frac{\beta^i . P_m(t)}{l\left(1 - \rho(t)\right). A} - \lambda_i C_m^i(t)$$

Temperature: $\frac{\partial T_m}{\partial t}(t) = \frac{P_m(t)}{C_P\, d_m}$

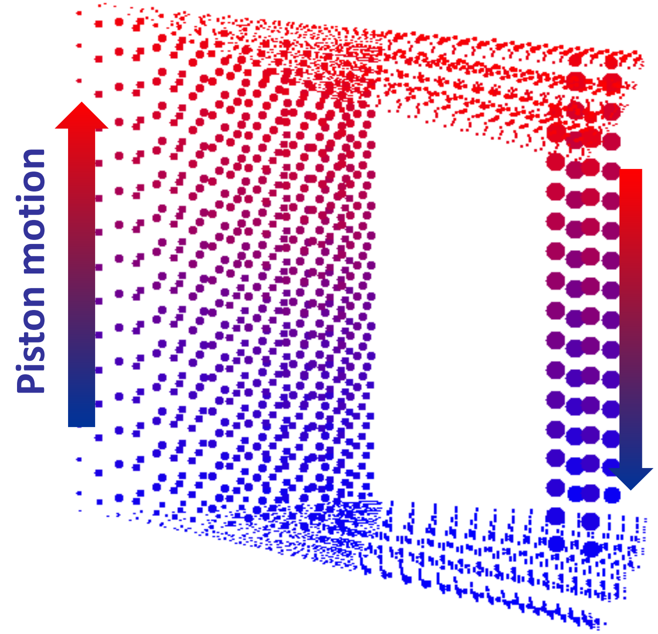
With $\beta_{eff} = \sum_i \beta_i \left.\frac{\sum_{f\subset core} C_f^i}{\sum_{f\subset reactor} C_f^i}\right|_{equ}$

and $\frac{dk}{dT} = \sum_{f\subset core} \left(\frac{dk}{dT_f}\right) = -5\ \mathrm{pcm/K}$

(*) A. Laureau. "MSFR - Etude des transitoires Cinétique point par zone", *Master Internship, Grenoble Institute of Technology/LPSC-IN2P3-CNRS* France (2011)

Utilization of two meshes:

- fixed mesh used to calculate neutronics variables (reactivity, fission power)
- mobile mesh linked to the motion and local properties of the fluid (precursor abundance, temperature…



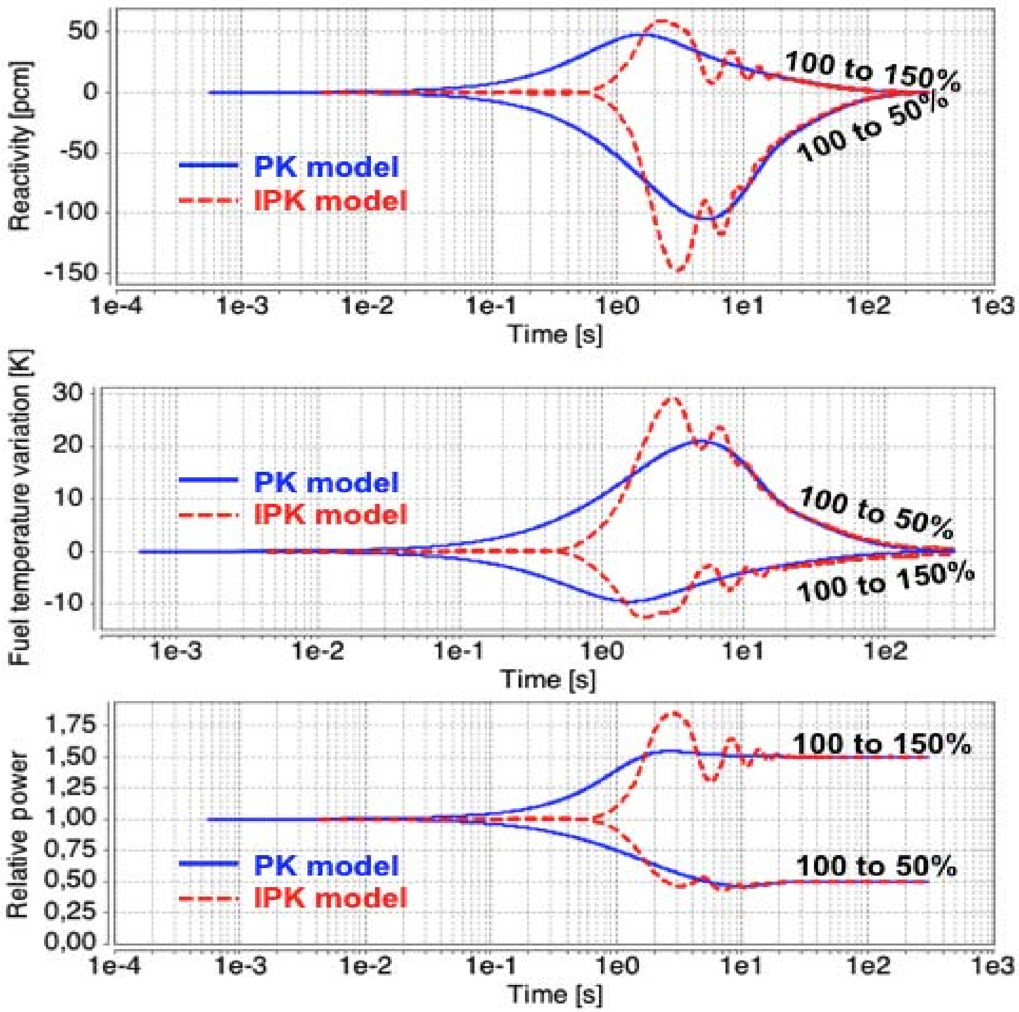
- Heat exchanger = power extraction in the cells located in the downstream area outside the core
- Power distribution in core (sine x Bessel functions)
- Residual heat taken into account
- Salt volume expansion (overflow tank)

MSFR: Physical Analysis of Load-Following – Neutronics calculations

Model comparison: Instantaneous variation of the extracted power

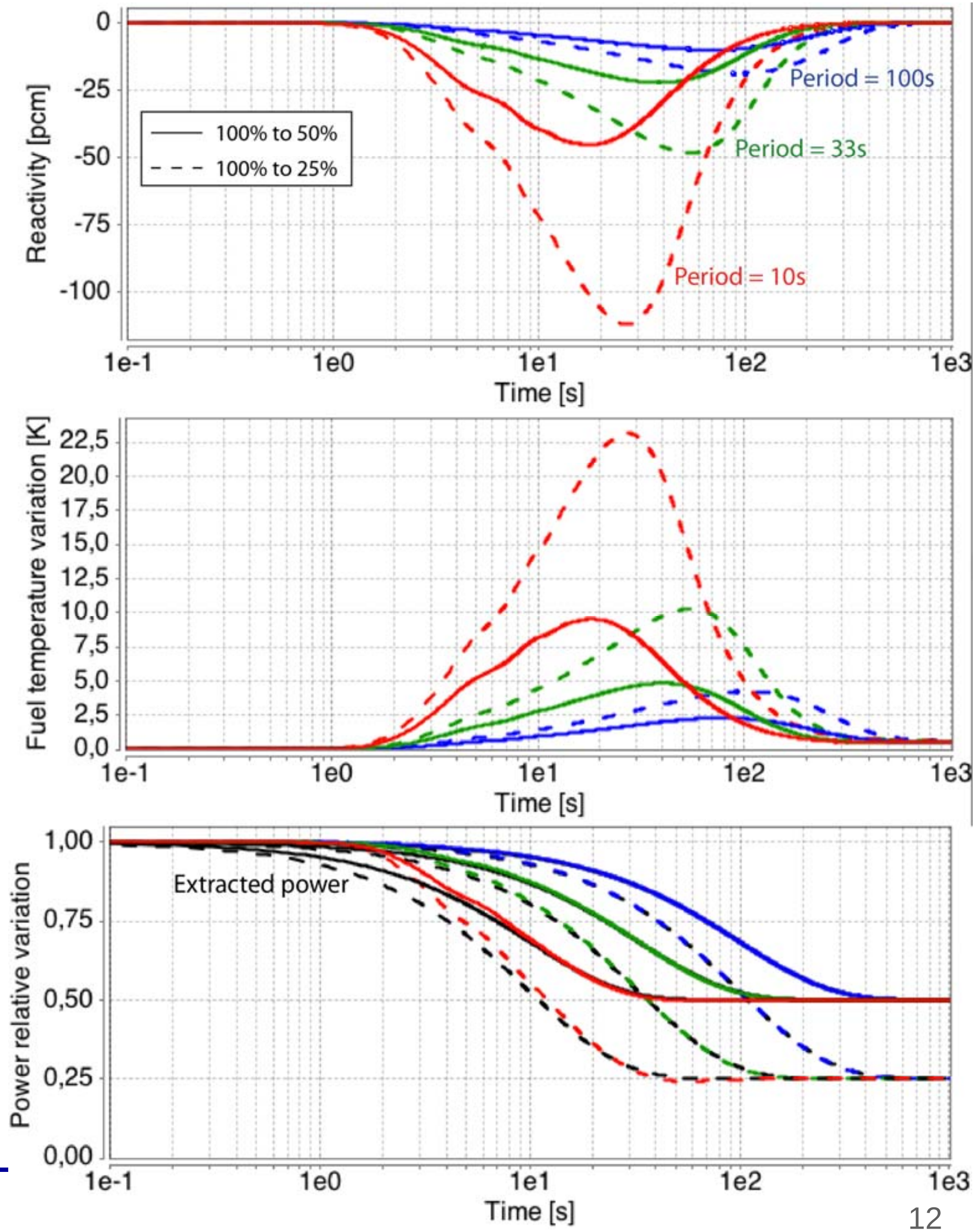
IPK model ⇨ oscillations physically explained by the fuel salt circulation, due to the variation of temperature and of precursor abundance in the salt exiting and re-entering the core after a short interval (circulation time of ~4s)

MSFR: good behavior thanks to the large negative thermal feedback coefficients



MSFR: Physical Analysis of Load-Following – Neutronics calculations

Load following transients (IPK model):
exponential decrease of the extracted power from 100% to 50% /25%



Fission power produced in the core follows the extracted power
⇨ MSFR core driven by the extracted power thanks to its large negative feedback coefficients + energy deposited directly in the coolant

Small variations (< 23 K) of the average fuel temperature evaluated

⇨ **Satisfactory behavior of the MSFR for load following**

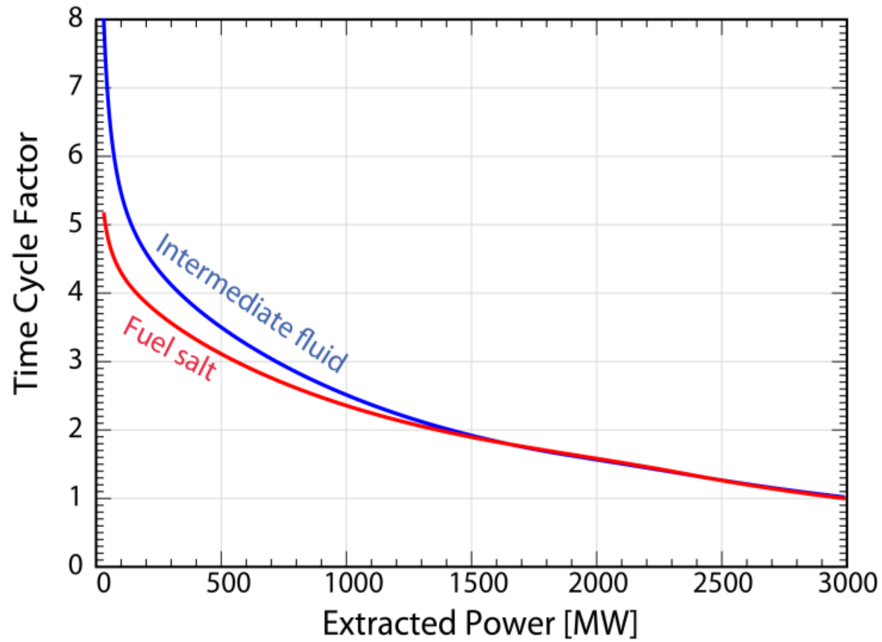
MSFR: Physical Analysis of Load-Following – Thermal calculations

Case studied here with a simple quasi-stationary model to optimize the heat transfers: thermal issues in the fuel circuit for a grid load following of around 50% in 10 minutes

Strong coupling between thermal hydraulics and neutronics (feedback coefficients)
⇨ crucial role of the pumps and heat exchangers for the definition and evaluation of the operating procedures

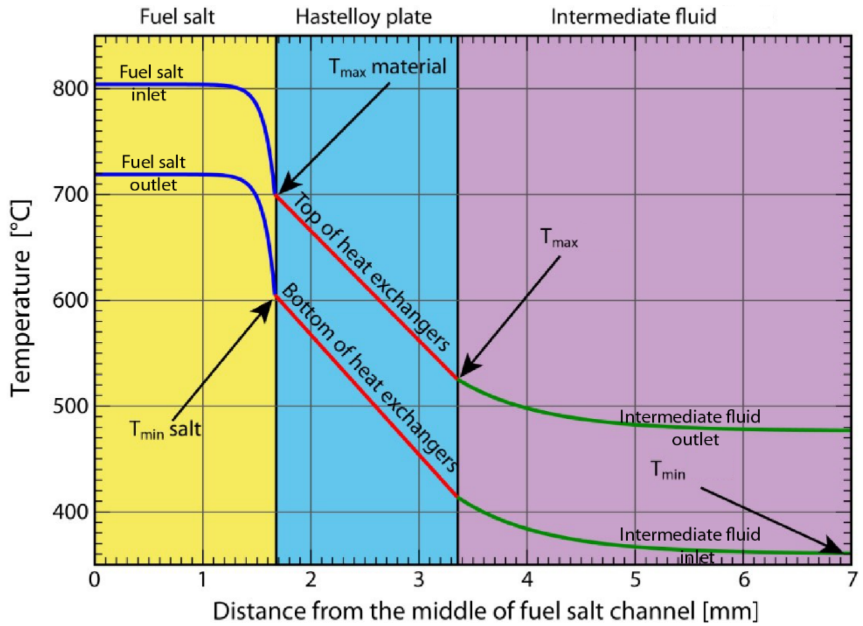
Parameters available to drive the power variation

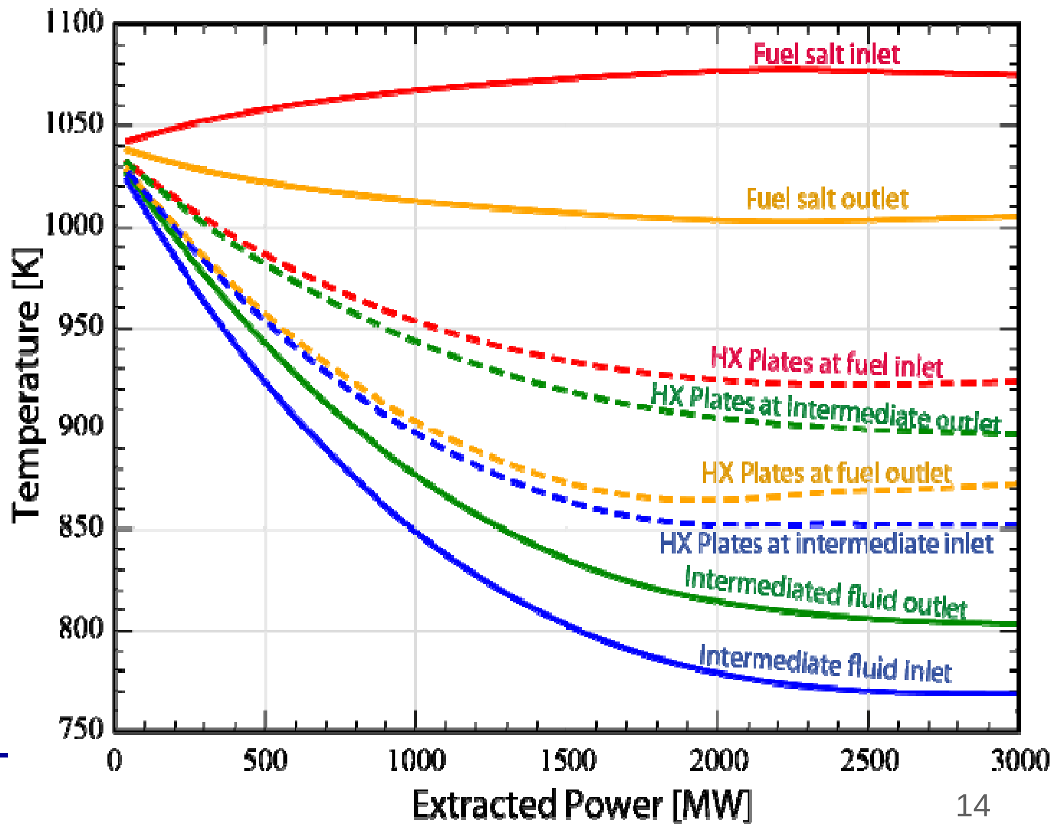
- flow velocity of the fuel salt controlled by the pumping power in the fuel circuit
- flow velocity of the intermediate fluid controlled by the pumping power in the intermediate circuit
- input temperature of the intermediate fluid in the heat exchangers which may be adjusted thanks to a by-pass bringing a fraction of the outlet flow to the inlet flow



MSFR: Physical Analysis of Load-Following – Thermal calculations

Case studied here with a simple quasi-stationary model to optimize the heat transfers: thermal issues in the fuel circuit for a grid load following of around 50% in 10 minutes





⇨ Power excursion from 3 GWth to 1.5 GWth in some minutes results in a mean temperature variation of less than 10 degrees for the heat exchanger plates

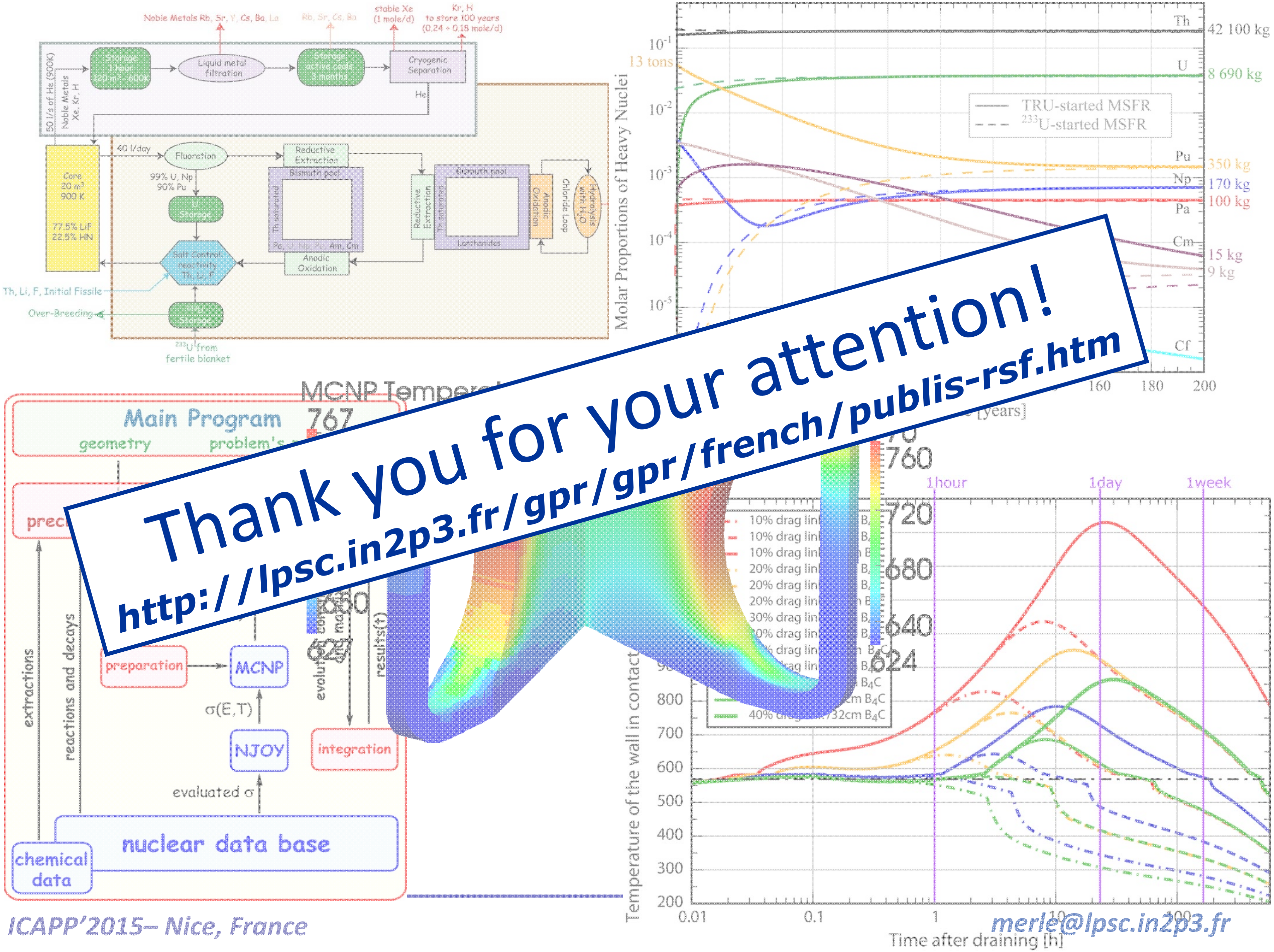
Conclusions and Perspectives

⇨ Flexibility of the liquid-circulating fuel MSFR during normal operation: very promising for load-following

⇨ Improved Point-Kinetic (IPK) model: very fast calculations – preliminary validation with the COUPLE code developed at KIT in the frame of the EVOL FP7 project

⇨ More complete tool based on a stochastic code for neutronics (Transient Fission Matrix (TFM) method) coupled to a CFD code for thermal-hydraulics, dedicated to transient calculations and currently developed at CNRS: see A. Laureau et al, "Coupled Neutronics and Thermal-hydraulics Transient Calculations based on a Fission Matrix Approach: Application to the Molten Salt Fast Reactor", Proceed. of the Joint International Conference on M&C, SNA and MC Method, Nashville, USA (2015)

⇨ In the frame of the SAMOFAR ("A Paradigm Shift in Nuclear Reactor Safety with the Molten Salt Fast Reactor" – 2015-2019) project of H2020: development of a MSFR power plant simulator based on the IPK model for the kinetics calculations and adjusted to the TFM+CFD tool – to assess the dynamic behavior of the overall plant, define the operation procedures of the reactor and determine the associated controls and safety margins

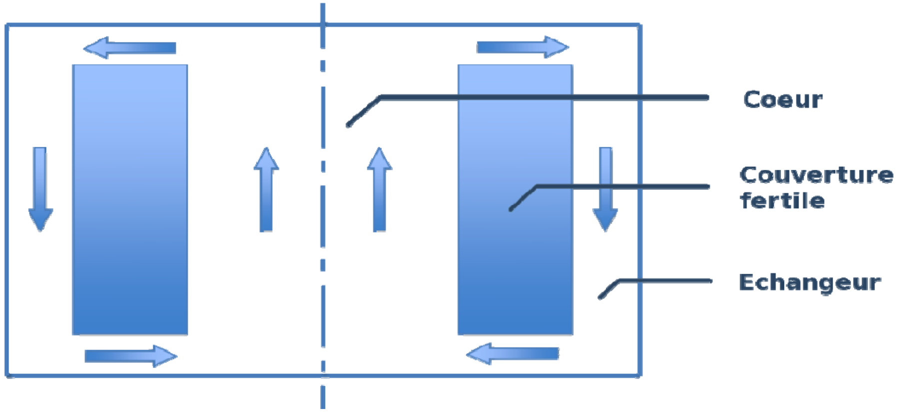


Thank you for your attention!

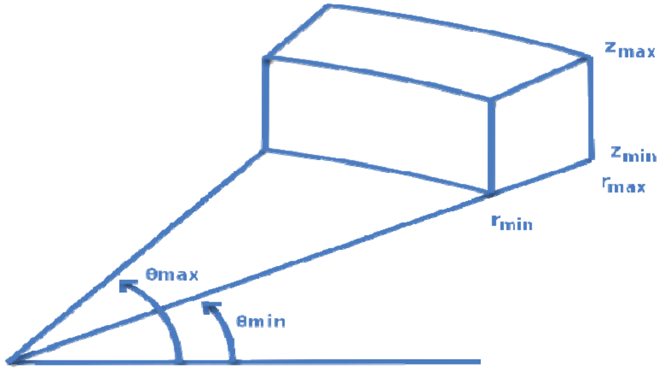
http://lpsc.in2p3.fr/gpr/gpr/french/publis-rsf.htm

merle@lpsc.in2p3.fr

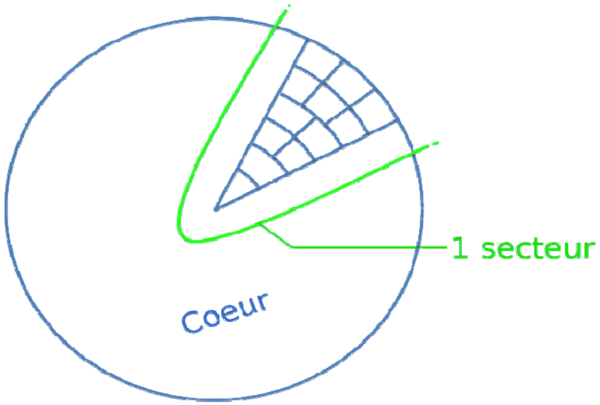
Improved Point-Kinetic (IPK)(*) model implementation:



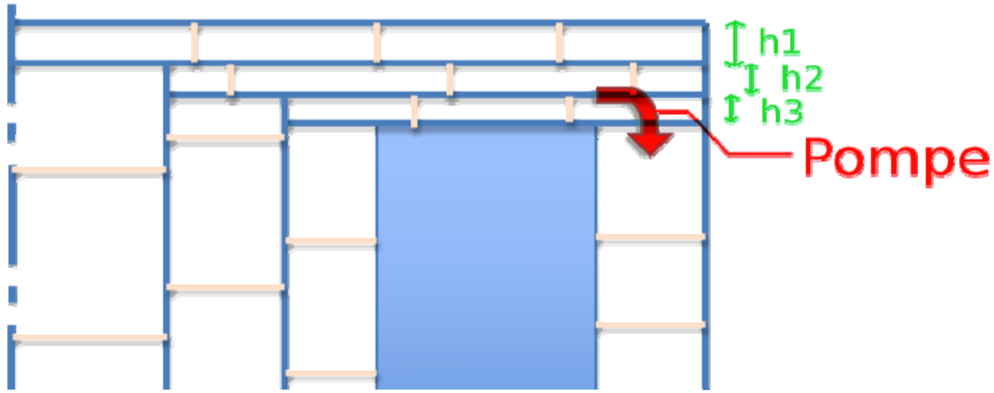
Salt circulation in the MSFR



Elementary cell



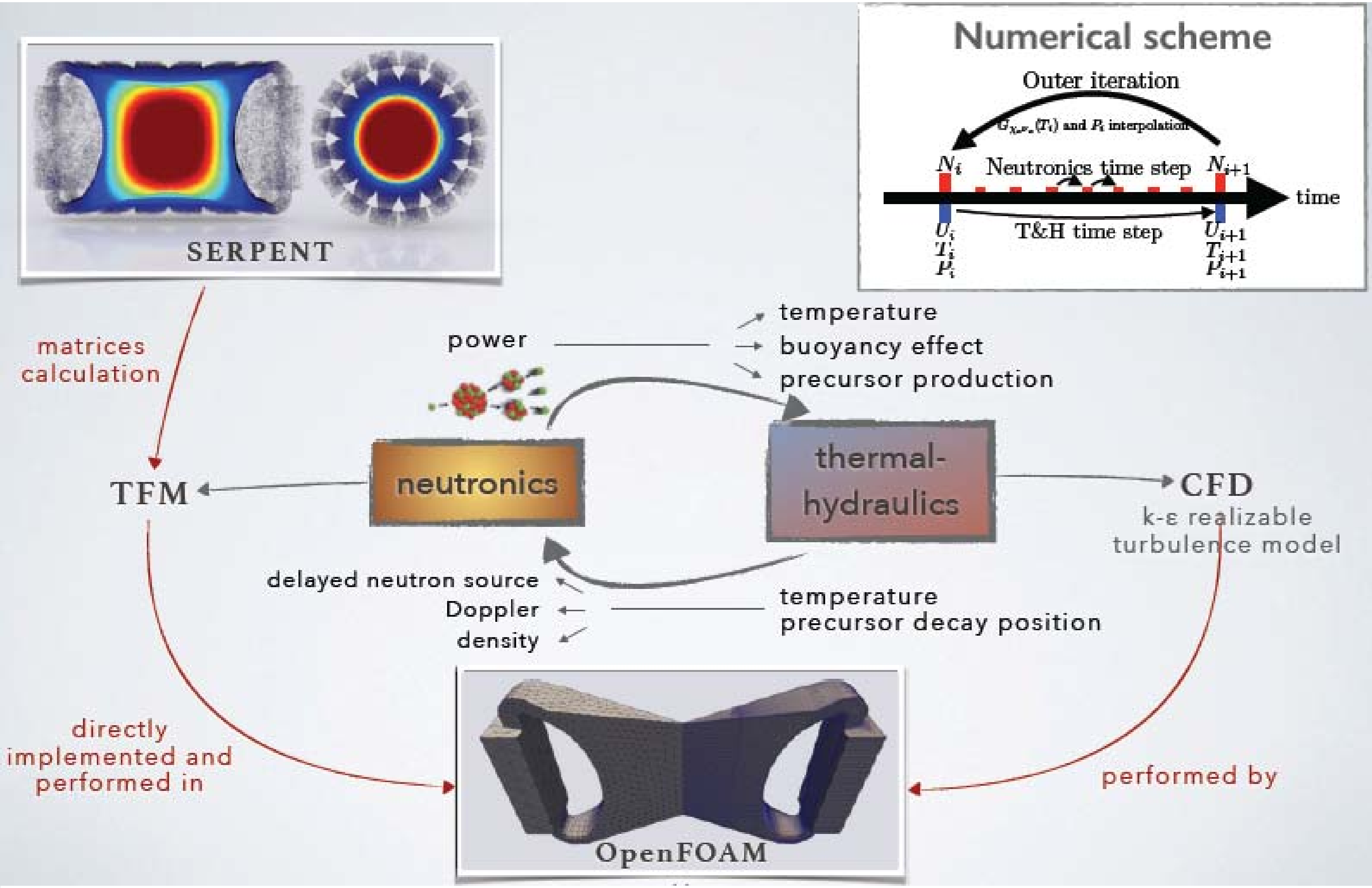
Mesh in the horizontal plan



Mesh in the vertical plan

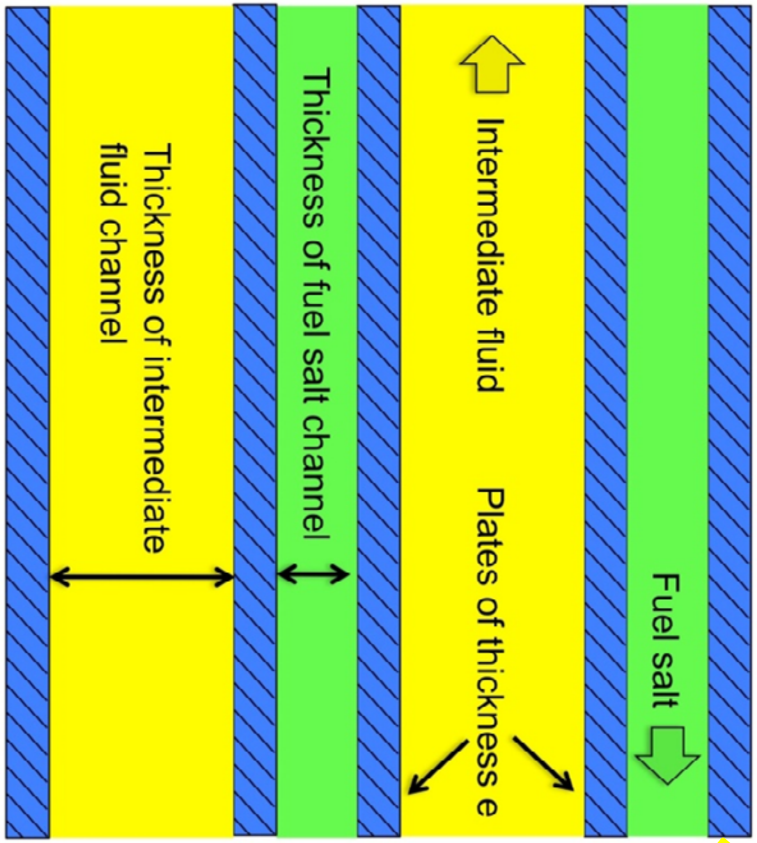
(*) A. Laureau. "MSFR - Etude des transitoires Cinétique point par zone", *Master Internship, Grenoble Institute of Technology/LPSC-IN2P3-CNRS* France (2011)

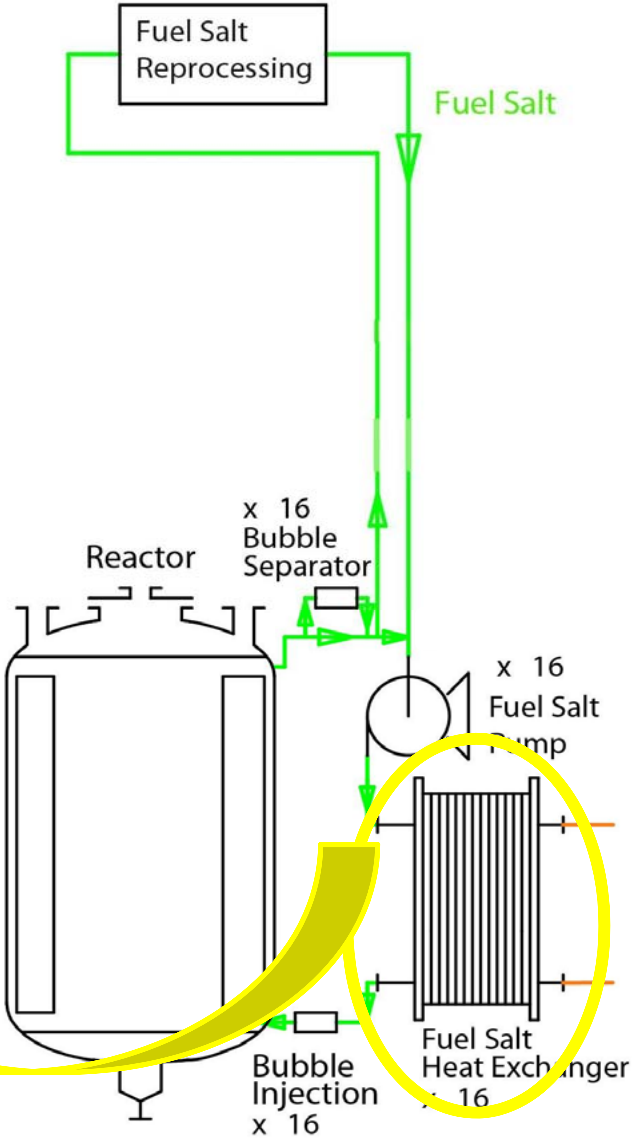
Coupling Strategy: Transient Fission Matrix & CFD codes



A. Laureau et al, "Coupled Neutronics and Thermal-hydraulics Transient Calculations based on a Fission Matrix Approach: Application to the Molten Salt Fast Reactor", Proceed. of the Joint International Conference on M&C, SNA and MC Method, Nashville, USA (2015)

MSFR: conceptual design of the salt heat exchangers





Two kind of intermediate fluid considered in this study: liquid metal or fluoride salt

MSFR: conceptual design of the salt heat exchangers

Constrained Parameter	Limiting value (P_{0i})	Acceptable deviation (σ_i)
Minimum thickness of the fuel salt channel	2.5 mm	0.05 mm
Minimum thickness of the plate	1.75 mm	0.035 mm
Maximum speed of the fuel salt	3.5 m/s	0.07 m/s
Maximum speed of the intermediate fluid (liquid lead)	1.75 m/s	0.035 m/s
Maximum speed of the intermediate fluid (salt)	5.5 m/s	0.11 m/s
Maximum temperature of the materials	700 °C	1 °C
Minimum margin to solidification of the fuel salt	50 °C	1 °C
Minimum margin to solidification of the intermediate fluid	40 °C	1 °C

Each set of values of the variable parameters evaluated with the quality function:

$$\prod_i exp\left(\frac{P_i - P_{0i}}{\sigma_i}\right)$$

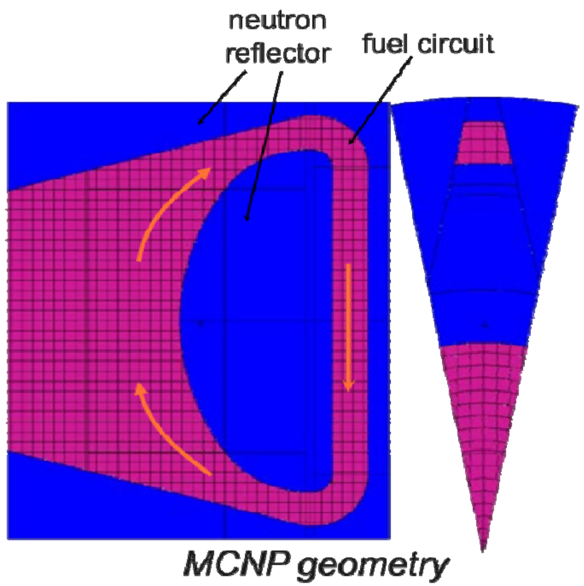
Variables of the study:

- ✓ the diameter of the pipes
- ✓ the thickness of the plates
- ✓ the gap between the plates on the intermediate fluid side (or “thickness of the intermediate fluid channel”)
- ✓ the fuel salt temperature at core entrance
- ✓ the fuel salt temperature increase within the core
- ✓ the temperature increase of the intermediate fluid in the heat exchangers
- ✓ the mean temperature difference between the two fluids within the heat exchangers

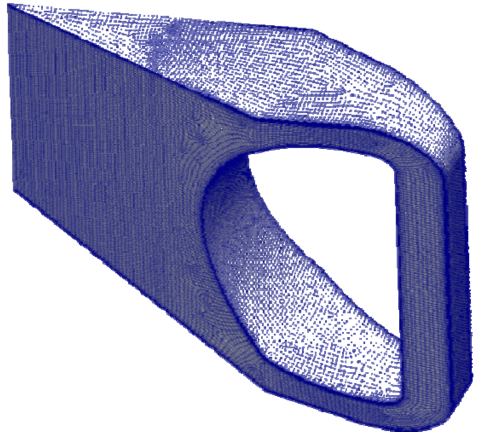
MSFR optimization: thermal-hydraulic studies

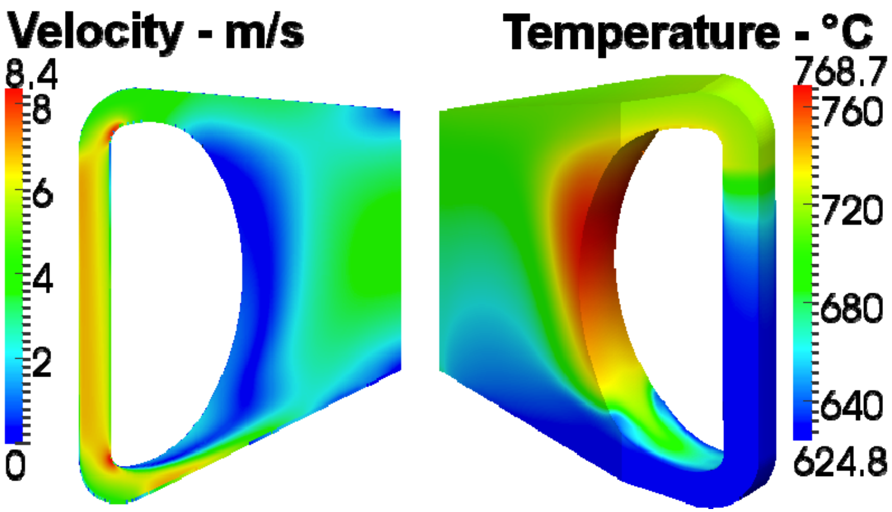
PhD Thesis of A. Laureau

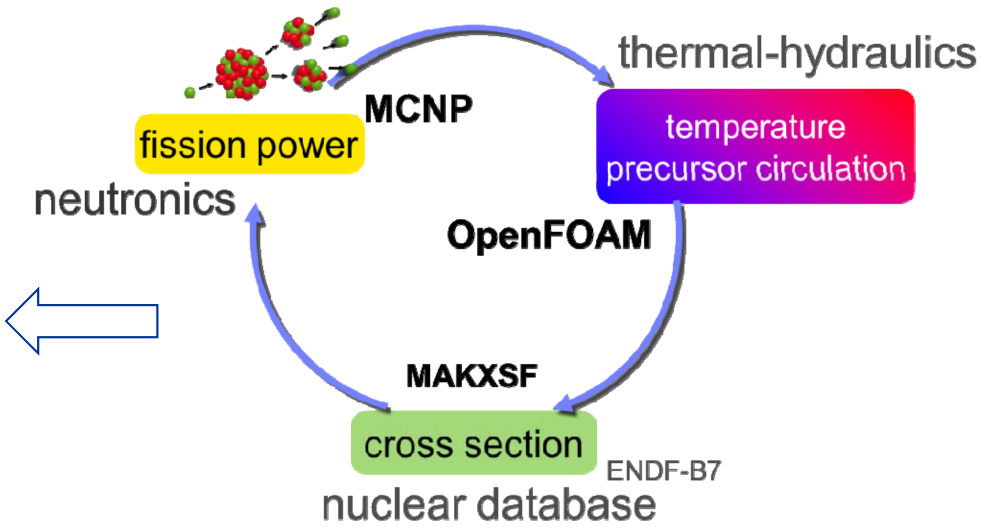
Steady state neutronic / thermal-hydraulic coupling dedicated to liquid fuel reactor



CFD mesh - 1/16 core 300 k cells







Thermo-hydraulic model

The control equations for the liquid-fuel in the COUPLE code are written as following:

Mass conversation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$$

Momentum conversation equation:

$$\frac{\partial \rho u_i}{\partial t} + \nabla \cdot (\rho U u_i + p) = \nabla \cdot \eta \nabla u_i$$

Energy conversation equation:

$$\frac{\partial \rho T}{\partial t} + \nabla \cdot (\rho U T) = \nabla \cdot \frac{\lambda}{C_p} \nabla T + \frac{S_T}{C_p}$$

See ANS-2013 Meeting presentation :
ZHANG D., ZHAI Z.-G., CHEN X.-N., WANG S., RINEISKI A., “COUPLE, a coupled neutronics and thermal-hydraulics code for transient analyses of molten salt reactors”

COUPLE code

Neutronics model

- based on the multi-group (here 2) diffusion theory while considering flow effects of the liquid-fuel

Diffusion equation for the neutron flux of group g:

$$\frac{1}{v_g}\frac{\partial \phi_g}{\partial t} = S_g + \chi_{p,g}(1-\beta)\sum_{g'=1}^{G}(\nu\Sigma)_{f,g'}(r)\phi_{g'}(r,t) + \sum_{i=1}^{I}\chi_{d,i,g}\lambda_i C_i(r,t)$$
$$+\sum_{g'=1}^{G}\Sigma_{g'\to g}(r)\phi_{g'}(r,t) - \Sigma_{t,g}\,\phi_g(r,t) + \nabla\cdot D_g(r)\nabla\phi_g(r,t) - \frac{1}{v_g}\nabla\cdot[U\phi_g(r,t)]$$

The balance equation for the delayed neutron precursor of family i:

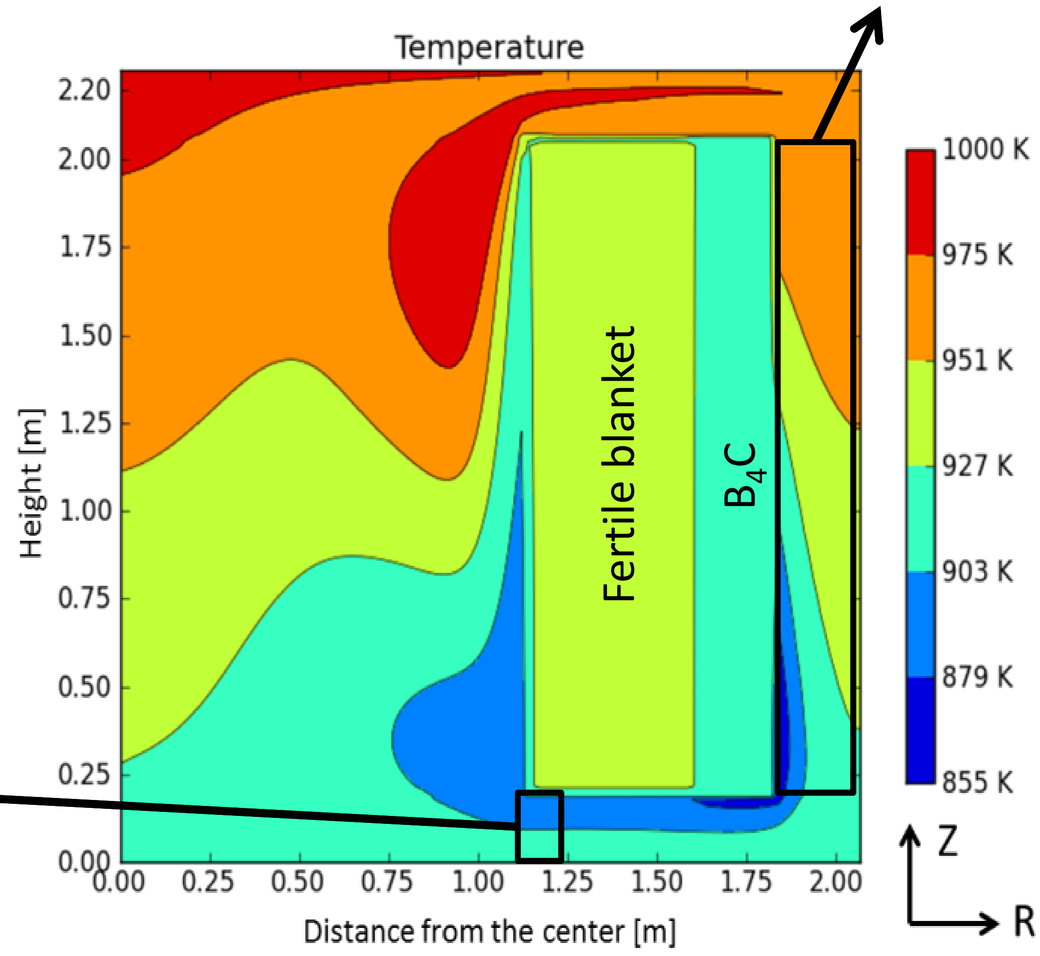
$$\frac{\partial C_i(r,t)}{\partial t} = \beta_i\sum_{g'=1}^{G}(\nu\Sigma)_{f,g'}(r)\phi_{g'}(r,t) - \lambda_i C_i(r,t) - \nabla\cdot[UC_i(r,t)]$$

MSFR model

Steady state calculation

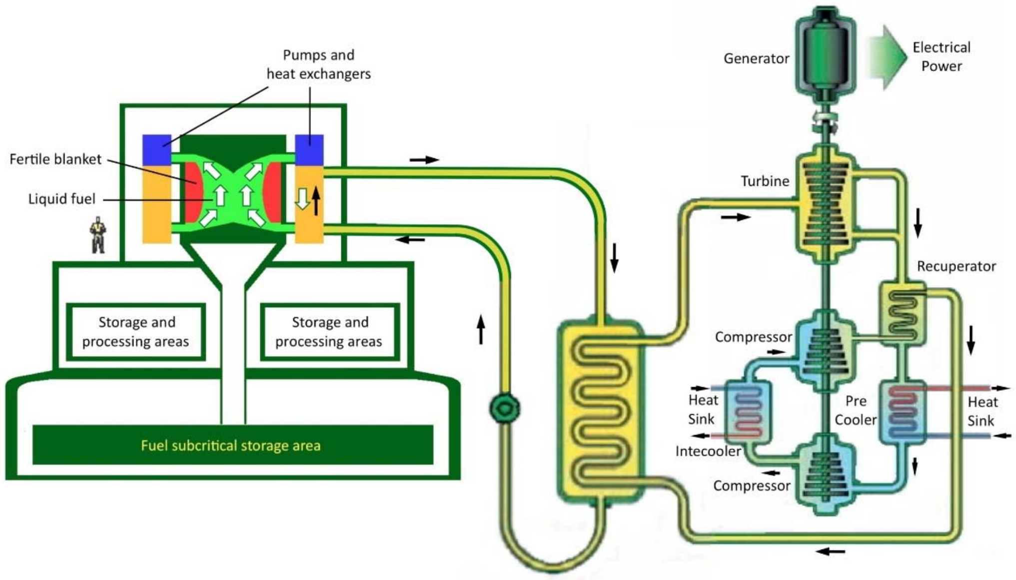
- Half of the core model
- with 112/130 cells in the R/Z directions

Heat exchanger model:
Negative heat source



Pump model:
injection velocity
profile adjusted to
avoid recirculation

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:

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

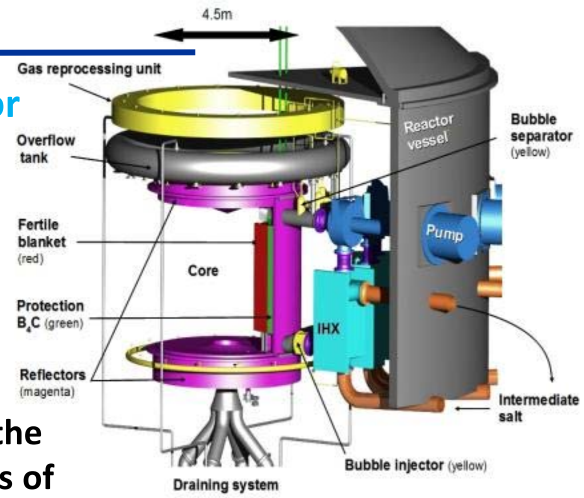
R&D objectives

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)

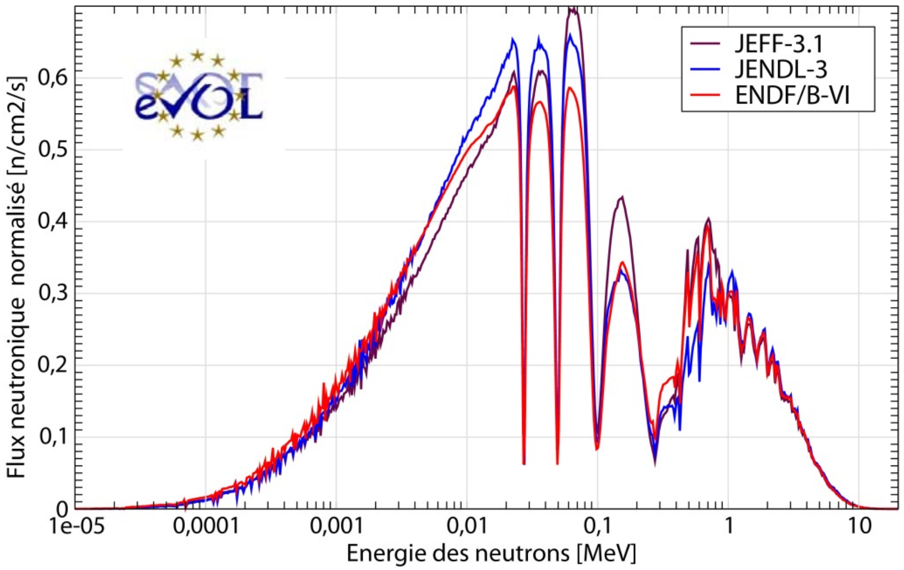
Partners: RIAR (Dimitrovgrad), KI (Moscow), VNIITF (Snezinsk), IHTE (Ekateriburg), VNIKHT (Moscow) et MUCATEX (Moscow)

MSFR optimization: neutronic benchmark (EVOL)

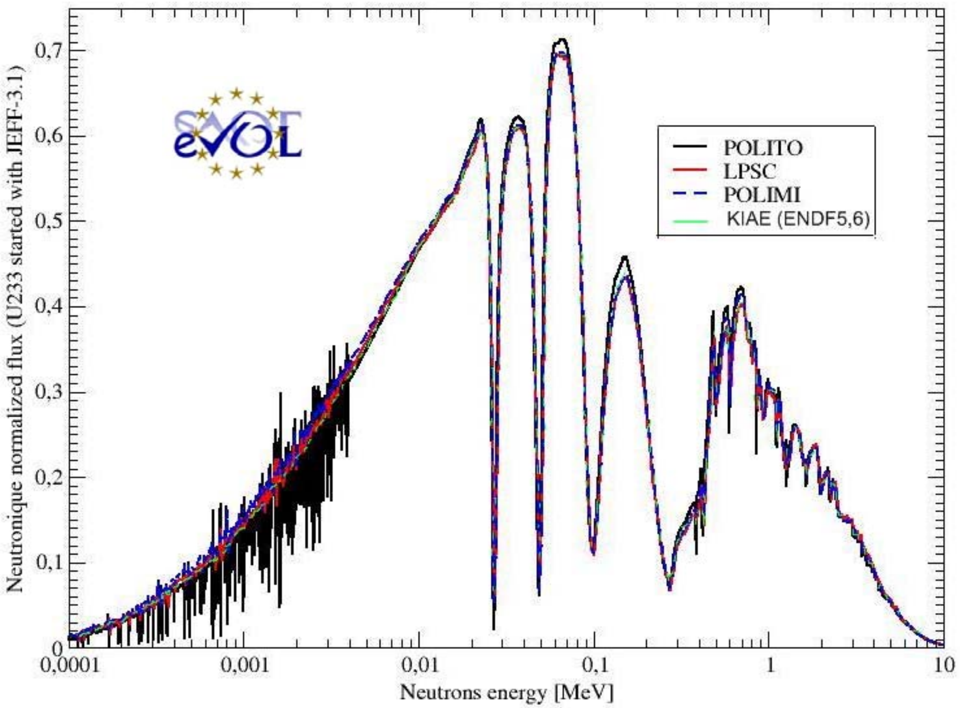
POLIMI calculations performed with SERPENT

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

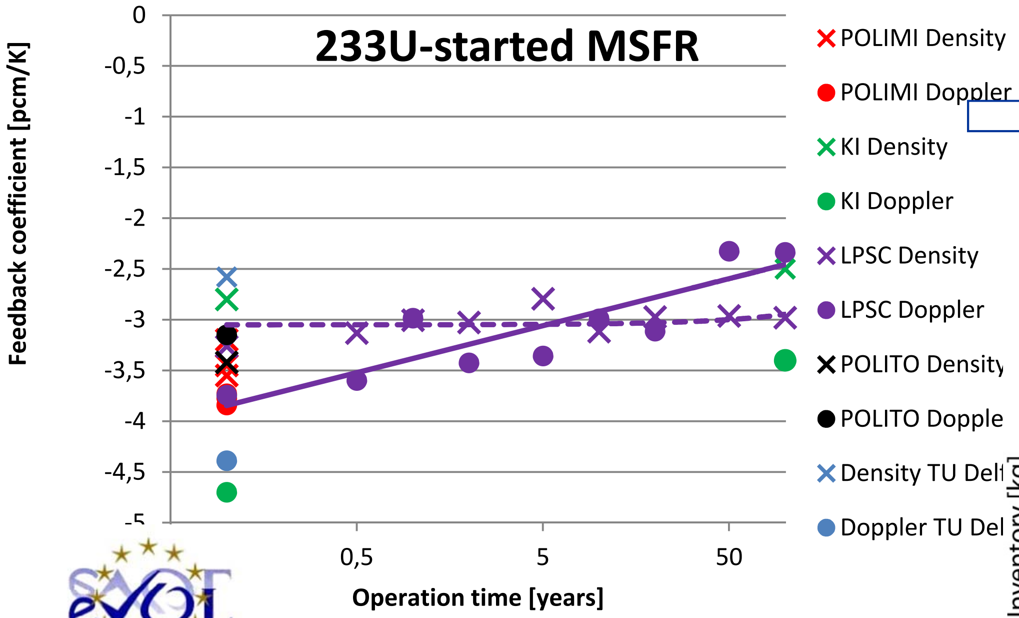


LPSC-IN2P3 calculations performed with MCNP
(coupled to in-house material evolution code REM)

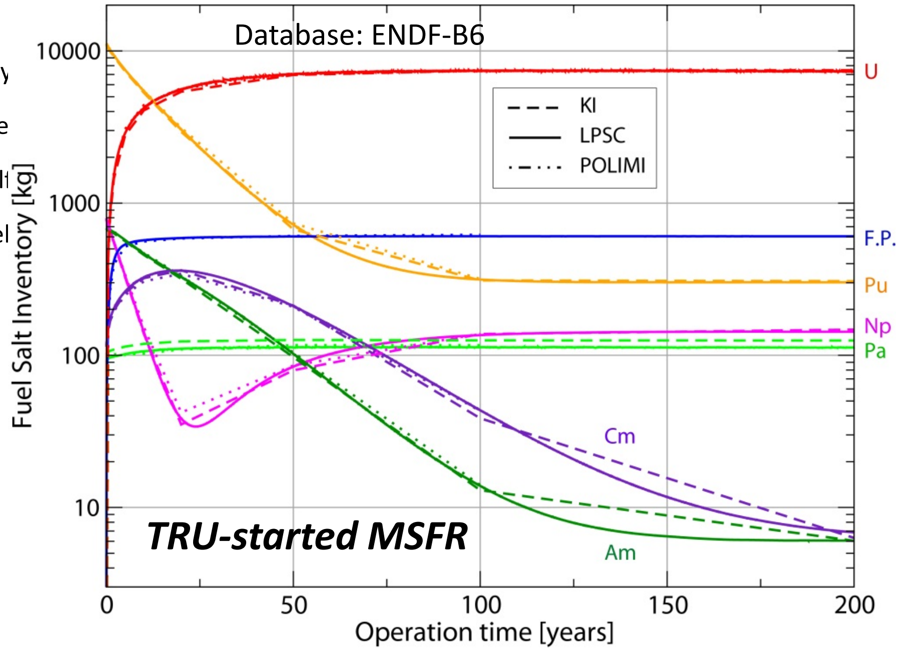


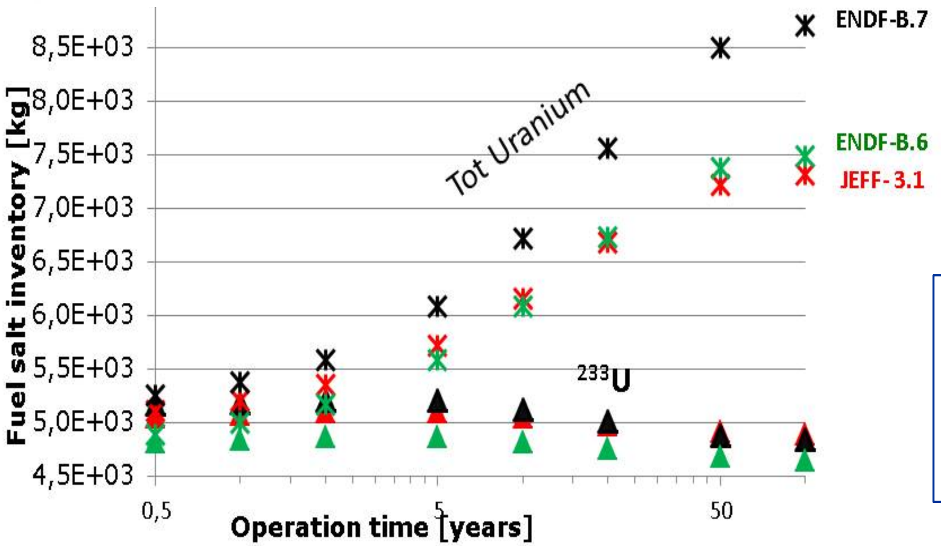
<u>Static calculations (BOL here):</u>
Good agreement between the different simulation tools – High impact of the nuclear database

MSFR optimization: neutronic benchmark (EVOL)

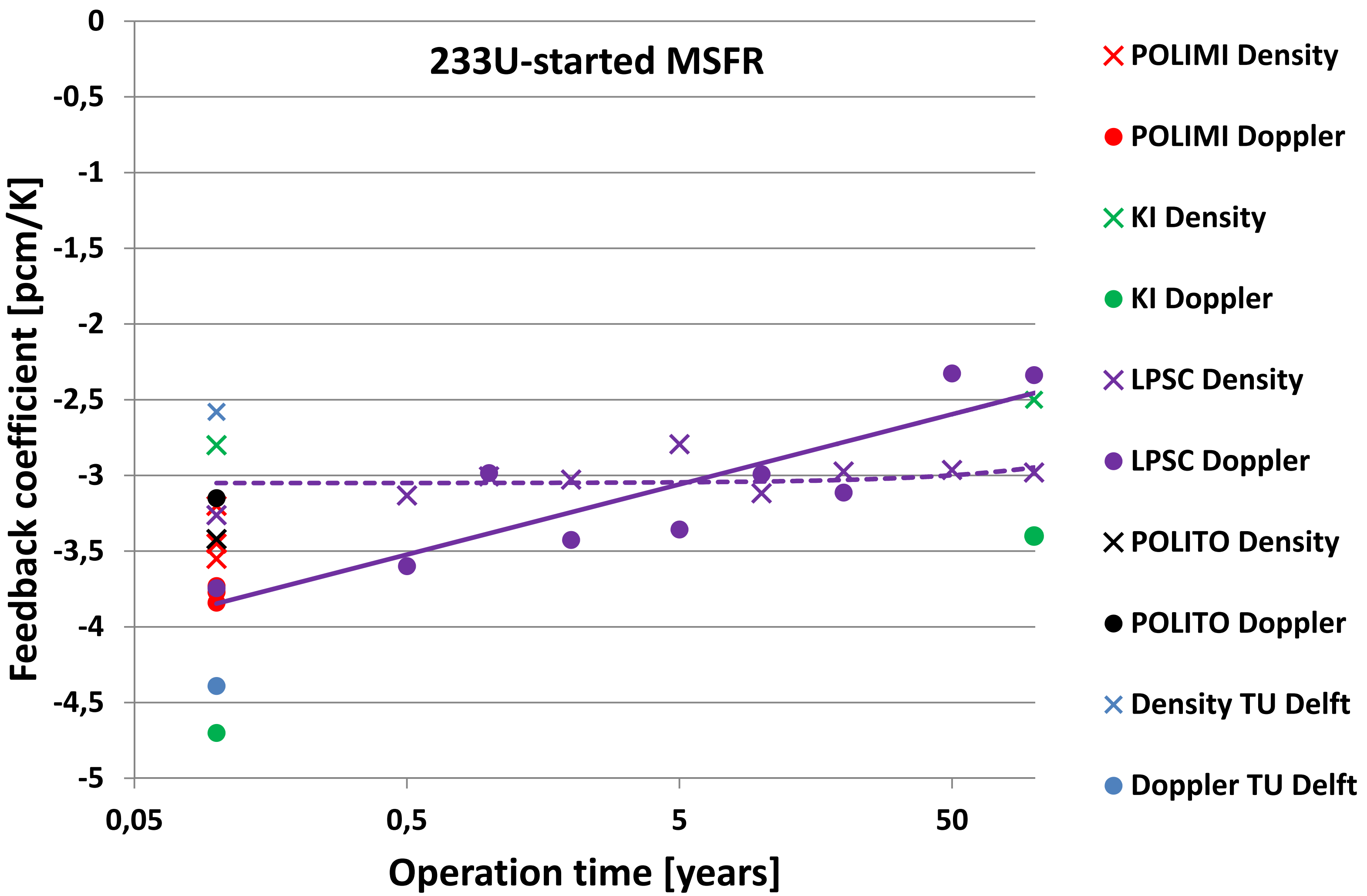


Largely negative feedback coefficients, ∀ the simulation tool or the database used





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



233U-started MSFR
Feedback coefficient [pcm/K]
0
-0,5
-1
-1,5
-2
-2,5
-3
-3,5
-4
-4,5
-5
0,05
0,5
5
50
Operation time [years]
POLIMI Density
POLIMI Doppler
KI Density
KI Doppler
LPSC Density
LPSC Doppler
POLITO Density
POLITO Doppler
Density TU Delft
Doppler TU Delft

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

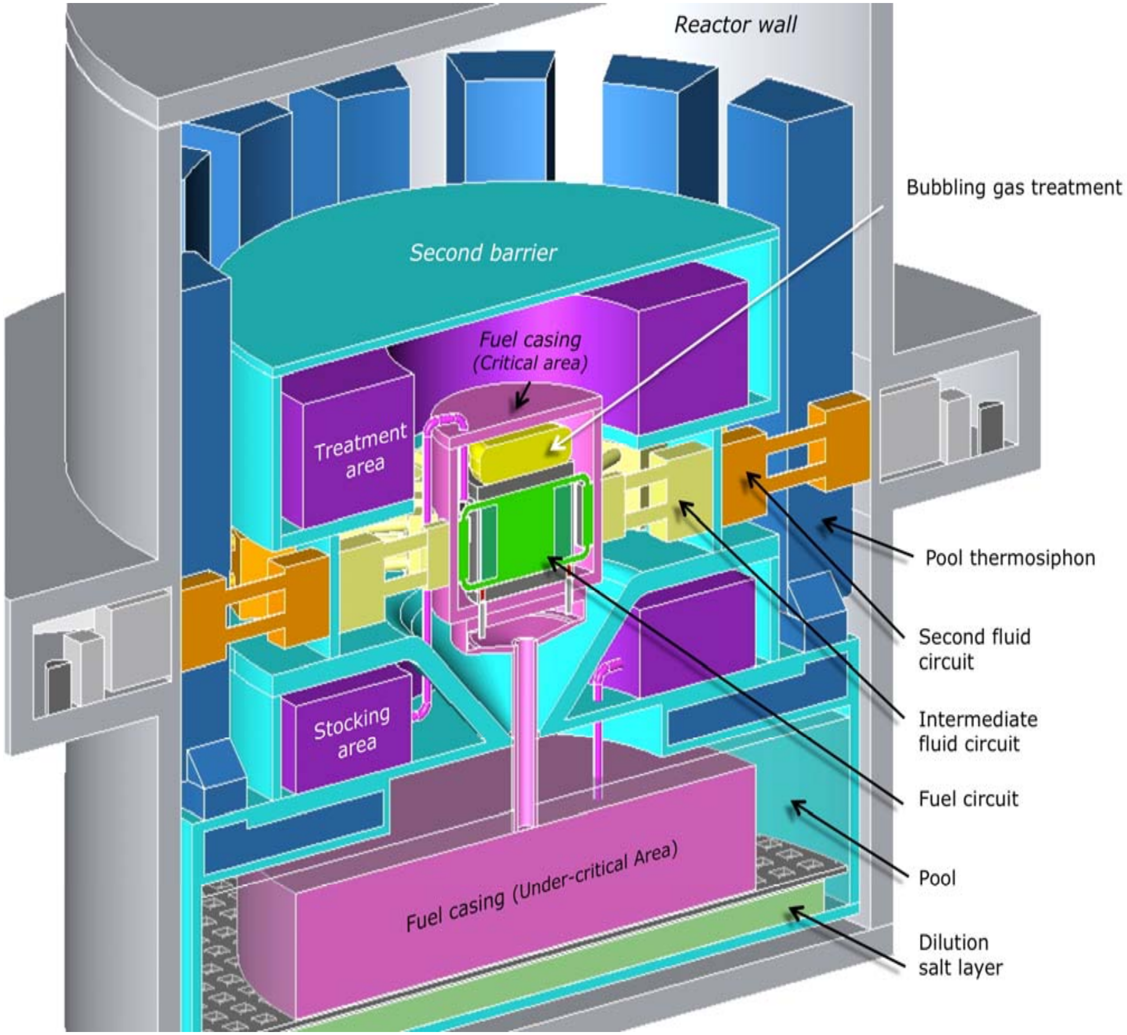
THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020

SAMOFAR

HORIZON 2020

MSFR: draining system



Three 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

Design of the Draining Tanks=

to keep the liquid fuel for long durations in a sub-critical geometry and at a controlled temperature

Poor thermal conductivity of the molten salts combined with criticality issues

⇒ salt layer thickness limited in the draining tank

⇒ Flat draining tanks with a large surface and a small thickness, immersed in a pool of water for cooling

Draining tanks of the MSFR (ENC2014 conference)

MSFR = liquid circulating fuel ⇒ dedicated safety approach required

Draining system = protection system for the MSFR (no safety rods)

↳ Main safety issue

Objective of the present study: **find simple (even if not optimal) solutions to manage the heat extraction of the fuel salt in the draining system and give an idea of the characteristic phenomena and time periods for this safety system**

Fuel position	System failure	Associated grace period
Core	After fuel circulation instant stop - without core damaging)	30 minutes
Core	After fuel circulation stop with inertia - without core damaging)	1 hour
Core	Extra draining delay - with core destruction	+20 minutes
Draining tank	Absence of water - no tank damaging	30 minutes to 1 hour
Draining tank	Absence of water - tank damaging	6 hours
Draining tank	Absence of heat extraction from water remaining liquid and unpressurized	12 hours
Draining tank	Absence of heat extraction from water - vaporization into the third barrier	23 days

Perspectives: **Improve the thermal calculations to be more realistic (incl. convection) + Evaluation of other cooling modes (e.g. using an inert salt) in the draining system + Coupled safety and design studies (MSFR simulator)**