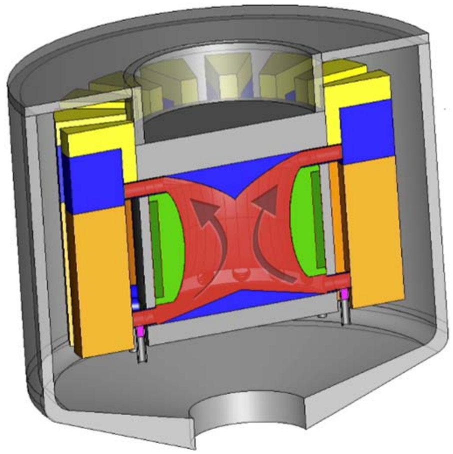
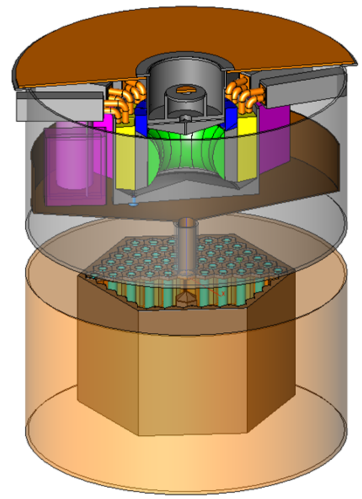
Concept of Molten Salt Fast Reactor





Prof. Elsa MERLE – merle@lpsc.in2p3.fr

For the MSFR Team – FRANCE - LPSC Grenoble (CNRS-IN2P3 / Grenoble INP – PHELMA / Grenoble Alpes University) and IPN Orsay (CNRS-IN2P3)

With the support of the IN2P3 institute and the PACEN and NEEDS Programs of CNRS, Grenoble Institute of Technology, and of the EVOL and SAMOFAR Euratom Projects

Liquid-fueled reactors: why “molten salt reactors”?

Advantages of a Liquid Fuel

✓ Homogeneity of the fuel (no loading plan)

✓ Heat is produced directly in the heat transfer fluid

✓ Possibility to reconfigure passively the geometry of the fuel:

- One configuration optimizes the electricity production managing the criticality
- An other configuration allows a long term storage with a passive cooling system

✓ Possibility to reprocess the fuel without stopping the reactor:

- Better management of the fission products that damage the neutronic and physicochemical characteristics
- No reactivity reserve (fertile/fissile matter adjusted during reactor operation)

Which constraints for a liquid fuel?

- Melting temperature not too high
- High boiling temperature
- Low vapor pressure
- Transparent to neutrons
- Good thermal and hydraulic properties (fuel = coolant)
- Stability under irradiation
- Good solubility of fissile and fertile matters
- No production of radio-isotopes hardly manageable
- Solutions to reprocess/control the fuel salt

Lithium fluorides fulfill all constraints

⇩

Molten Salt Reactors

Liquid-fueled reactors: why “molten salt reactors”?

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- High boiling temperature, Low vapor pressure
- Transparent to neutrons
- Good thermal and hydraulic properties (fuel = coolant)
- Stability un
- Good solub
- No product
- Solutions to

Lithium fluorides fulfill
all constraints

Molten Salt Reactors

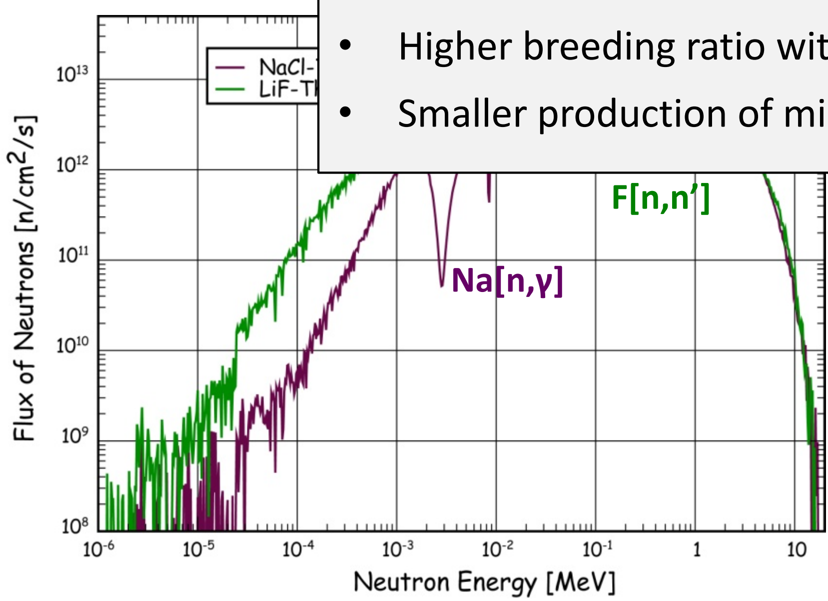
cross-sections of
versus neutron
in the fuel cycle

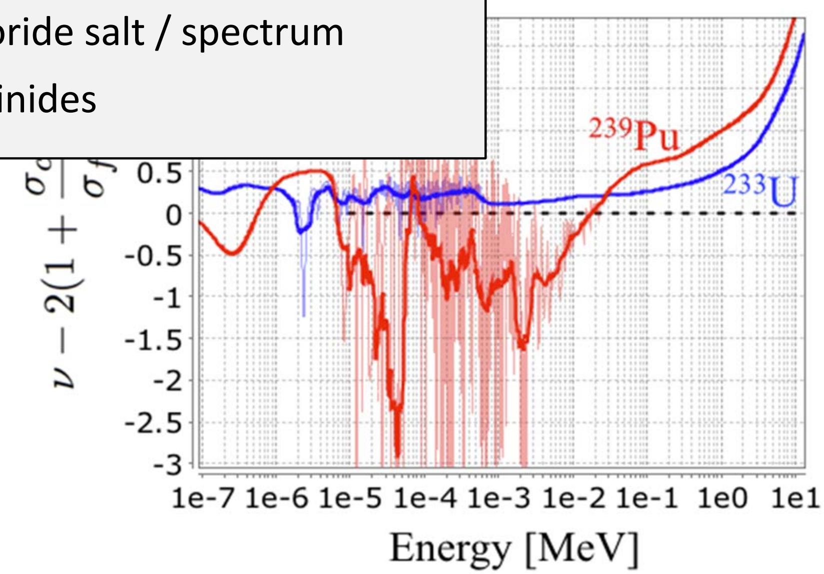
Choice of the fluoride salt:

- Chemical considerations (production of ^{36}Cl with chloride)
- Reduced irradiation damages (spectrum less fast)

Choice of the Th fuel cycle:

- Higher breeding ratio with a fluoride salt / spectrum
- Smaller production of minor actinides





MSR - Renewal of the concept – CNRS studies

- ✓ Homogeneity of the fuel (no loading plan)
- ✓ 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

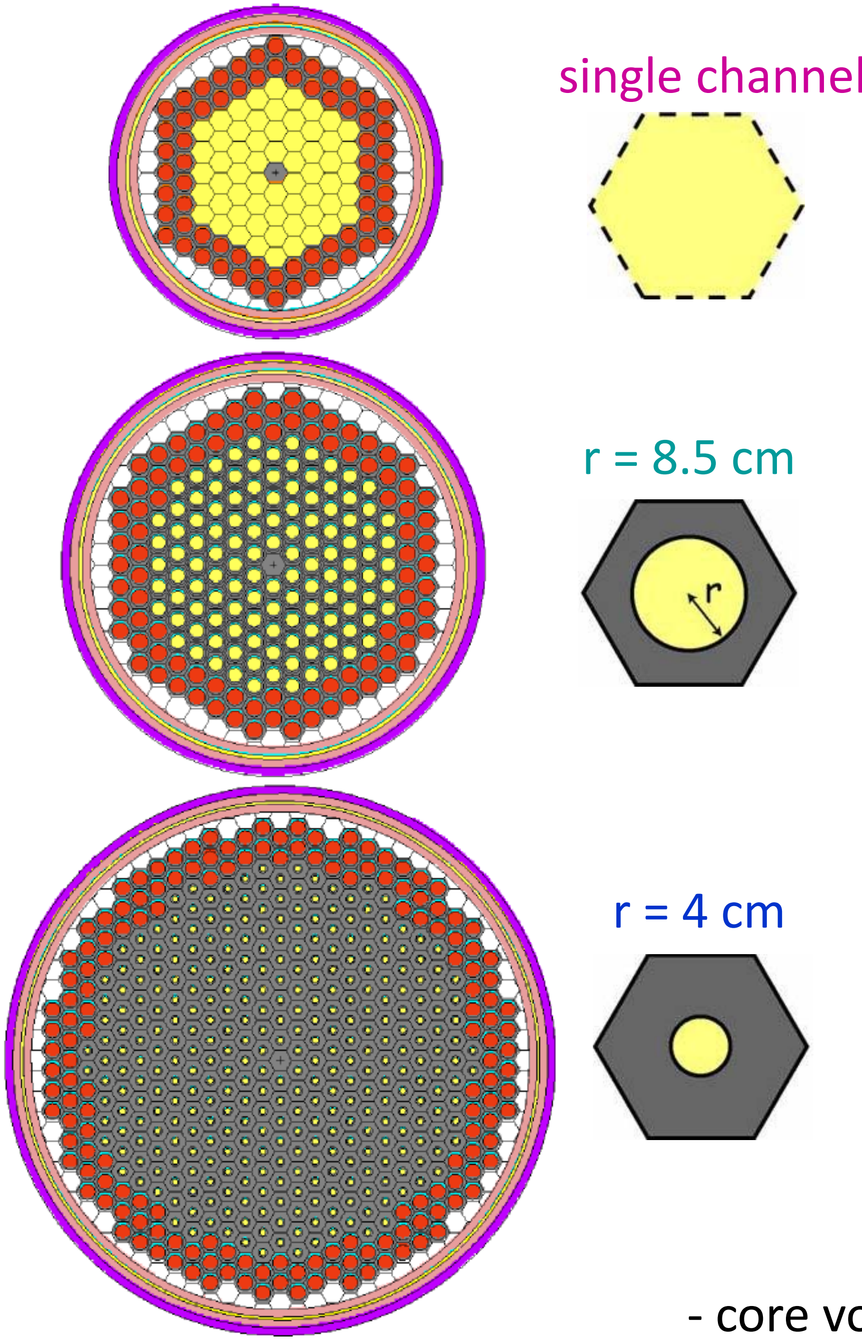
+

Neutronic Optimization of MSR (Gen4 criteria) :

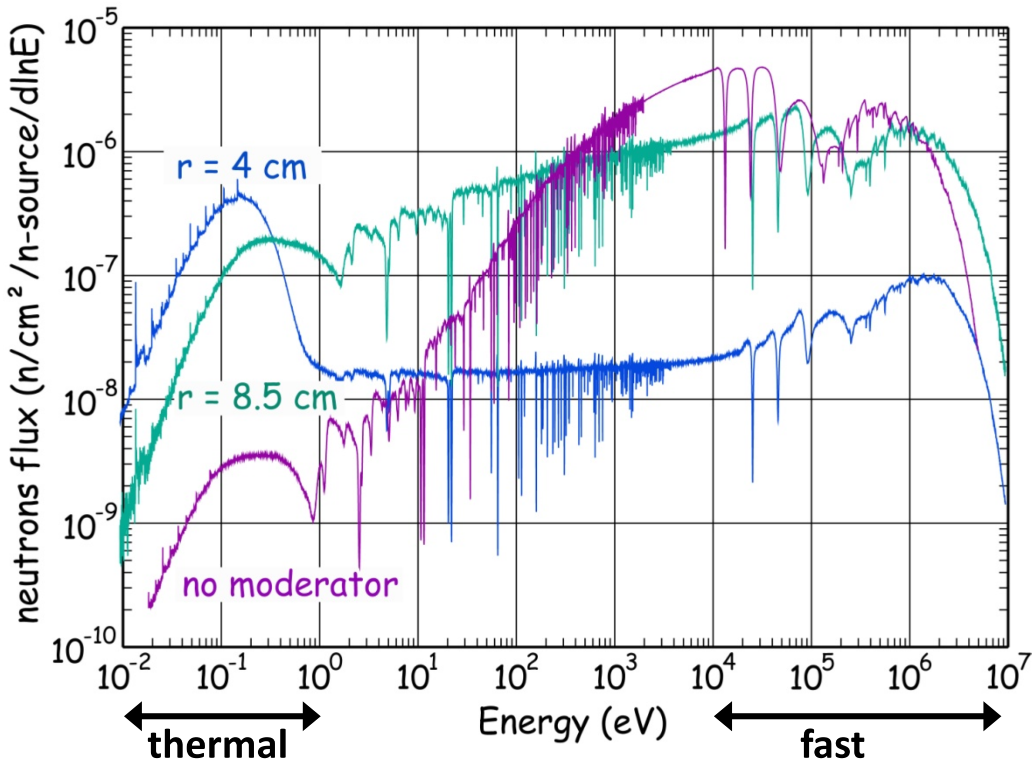
- **Safety: negative feedback coefficients**
- **Sustainability: reduce irradiation damages in the core**
- **Deployment: good breeding of the fuel + reduced initial fissile inventory**

Historical MSR Studies at CNRS

Influence of the channel radius (moderation ratio)



3 different moderation ratios:



- core volume adjusted to keep the same salt volume -

Historical MSR Studies at CNRS

PhD thesis of Ludovic MATHIEU

Thermal spectrum configurations

- **positive feedback coefficient**
- iso-breeder
- quite long graphite life-span
- **low ^{233}U initial inventory**

Epithermal spectrum configurations

- quite negative feedback coefficient
- iso-breeder
- **very short graphite life-span**
- **quite low ^{233}U initial inventory**

Fast spectrum configurations (no moderator)

- **very negative feedback coefficients**
- **very good breeding ratio**
- **no problem of graphite life-span**
- large ^{233}U initial inventory

Historical MSR Studies at CNRS

Thermal spectrum configurations

- positive feedback coefficient
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The Molten Salt Fast Reactor - MSFR

MSFR: Design and Fissile Inventory Optimization

Reactor Design and Fissile Inventory Optimization = Specific Power Optimization

2 parameters:
- The produced power
- The fuel salt volume and the core geometry

Liquid fuel and no solid matter inside the core ⇒ possibility to reach specific power much higher than in a solid fuel

3 limiting factors:

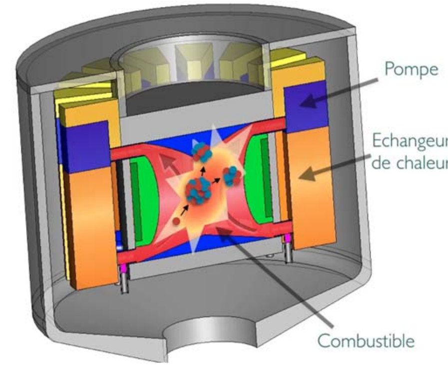
- The capacities of the heat exchangers in terms of heat extraction and the associated pressure drops (pumps) → *large fuel salt volume and small specific power*

- The neutronic irradiation damages to the structural materials (in Ni-Cr-W alloy) which modify their physicochemical properties. Three effects: displacements per atom, production of Helium gas, transmutation of Tungsten in Osmium → *large fuel salt volume and small specific power*

- The neutronic characteristics of the reactor in terms of burning efficiencies → *small fuel salt volume and large specific power* and of deployment capacities, i.e. breeding ratio (= ^{233}U production) versus fissile inventory → *optimum near 15-20 m^3 and 300-400 W/cm^3*

⇒ Reference MSFR configuration with 18 m^3 and 330 W/cm^3 corresponding to an initial fissile inventory of 3.5 tons per GWe

Concept of Molten Salt Fast Reactor (MSFR)



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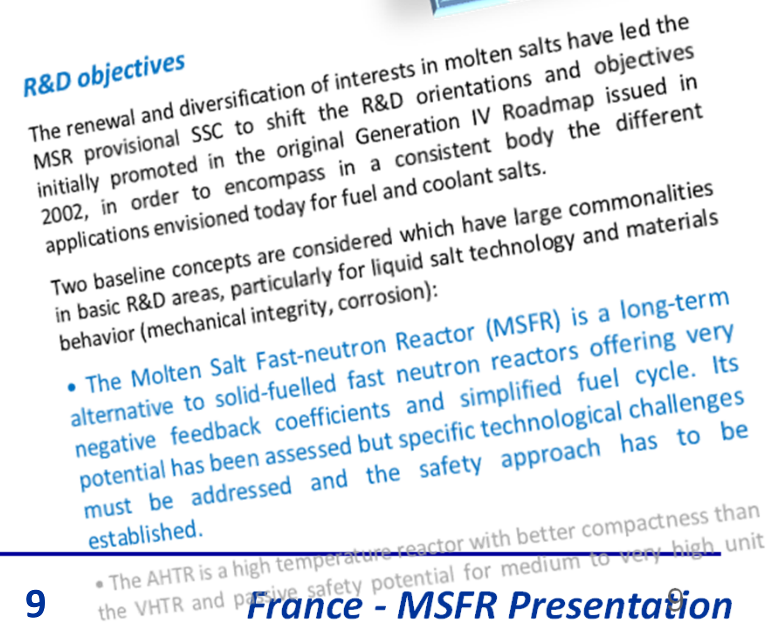
Neutronic Optimization of MSR (Gen4 criteria) :

- **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)** by the GIF Policy Group

- **All feedback thermal 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

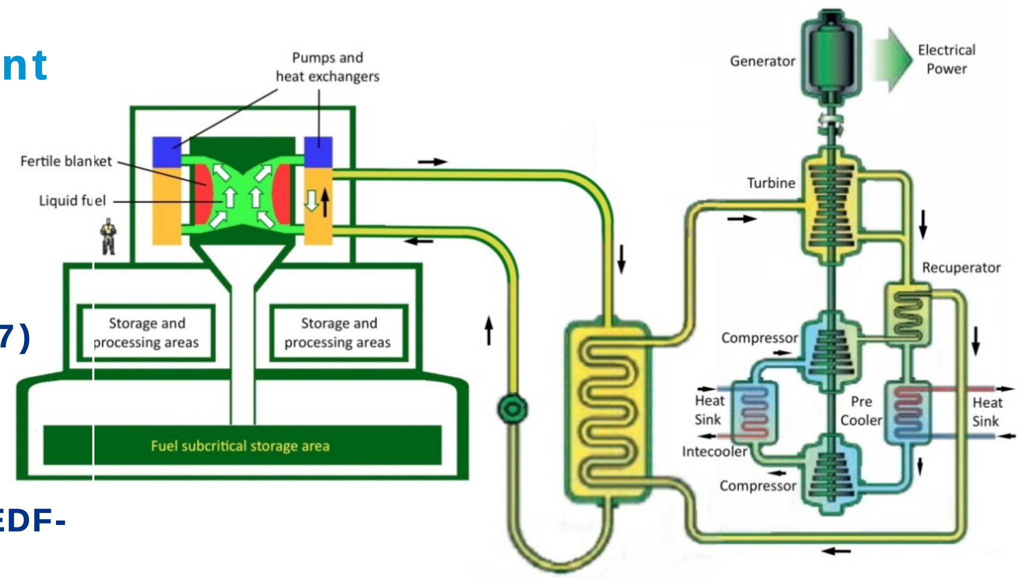
France - MSFR Presentation 9

Concept of Molten Salt Fast Reactor (MSFR)

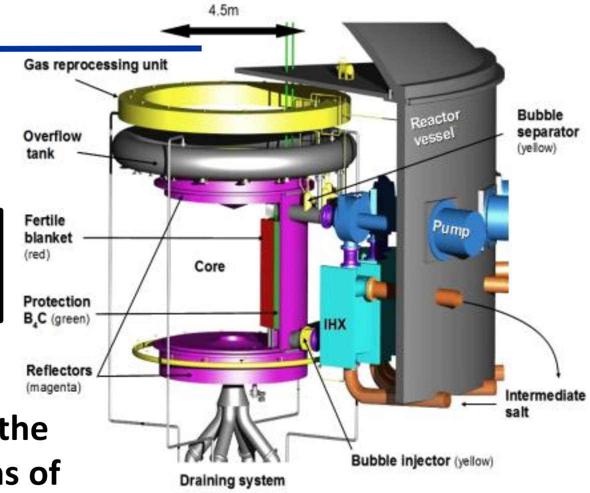
Now: R&D studies requiring multi-disciplinary expertise (reactor physics, chemistry, safety, materials, design…) from academic and industrial worlds

Collaboration Frameworks at different levels:

- **World:** Generation 4 International Forum(GIF)
- **Europe:** SAMOFAR project (H2020) - EVOL collaborative project - Euratom/Rosatom (FP7)
- **National:**
  - French inter-disciplinary programs - former PACEN (PCR-ANSF, GNR GEDEPEON) then NEEDS (since 2012 with AREVA-CEA-CNRS-EDF-IRSN)
  - project TSF (Molten Salt Technology) of the Carnot Energy Institute
  - structuring project CLEF (Liquid Fuel for the Future of Energy) of Grenoble Institute of Technology
  - collaborations with Rhodia and AREVA on reprocessing issues (funding of PhD theses) and with Aubert&Duval for material issues



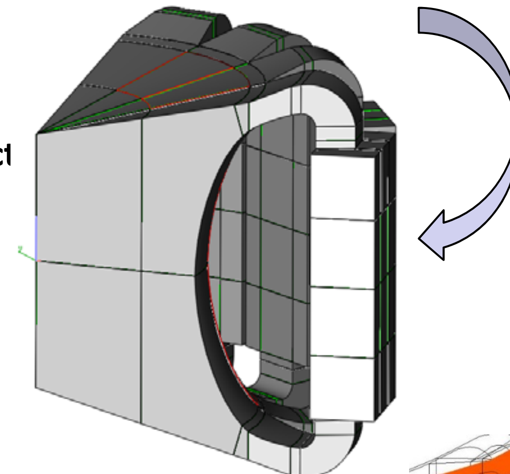
MSFR and the European project EVOL



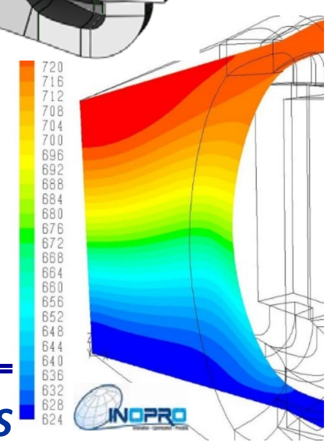
European Project "EVOL" Evaluation and Viability Of Liquid fuel fast reactor - *FP7 (2011-2013): Euratom/Rosatom cooperation*

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**



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)

Concept of MSFR: Fuel processing

4th Generation reactors => Breeder reactors

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

Fission Products Extraction: Motivations

✓ Control physicochemical properties of the salt (control deposit, erosion and corrosion phenomena's)

✓ Keep good neutronic properties

Physical Separation (in the core?)

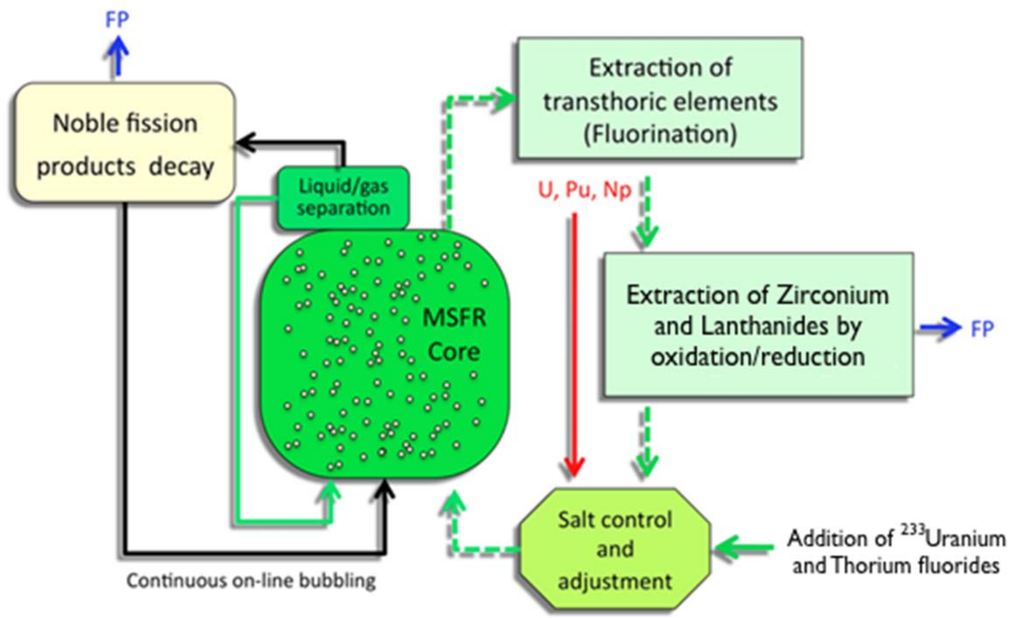
➢ Gas Processing Unit through bubbling extraction

➢ Extract Kr, Xe, He and particles in suspension

Chemical Separation (by batch)

➢ Pyrochemical processing Unit

➢ Located on-site, but outside the reactor vessel

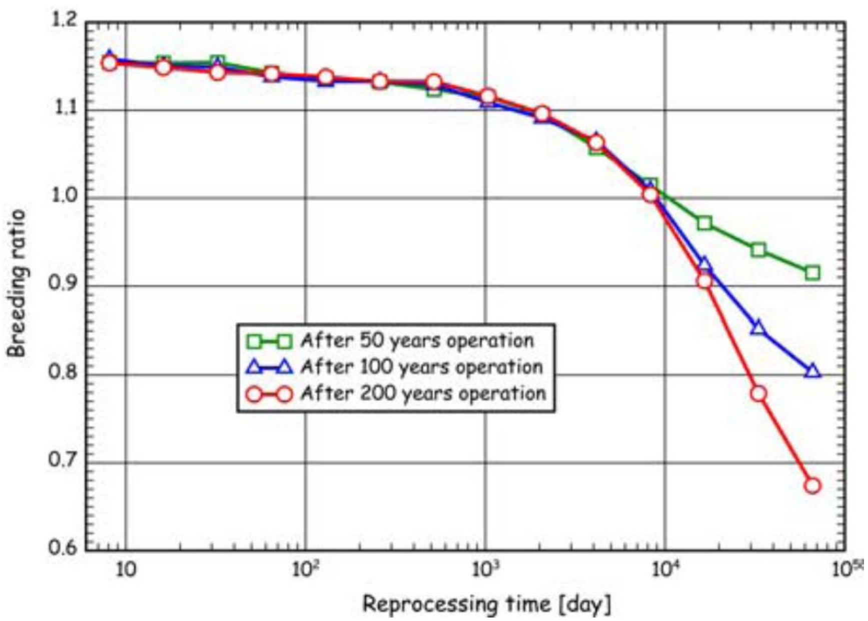


S. Delpech, E. Merle-Lucotte, D. Heuer, M. Allibert, V. Ghetta, C. Le-Brun, L. Mathieu, G. Picard, *"Reactor physics and reprocessing scheme for innovative molten salt reactor system",* J. of Fluorine Chemistry, 130 Issue 1, p. 11-17 (2009)

Concept of MSFR: Fuel processing

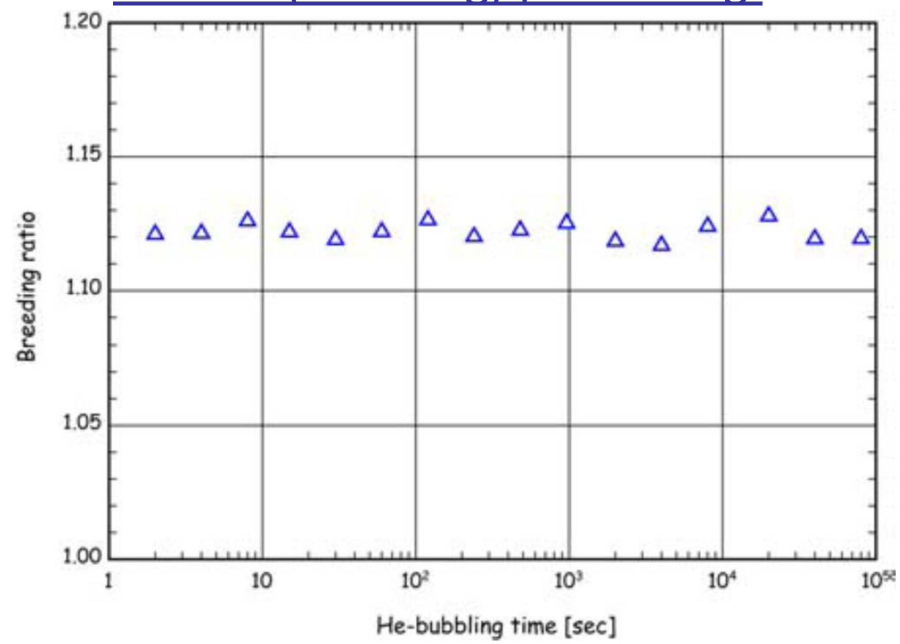
<u>Batch chemical processing:</u>

Element	Absorption (per fission neutron)
Heavy Nuclei	**0.9**
Alkalines	$< 10^{-4}$
Metals	0.0014
Lanthanides	0.006
Total FPs	**0.0075**



PhD thesis of Xavier DOLIGEZ

<u>On-line (bubbling) processing:</u>



Fast neutron spectrum

⇒ very low capture cross-sections

⇒ low impact of the reprocessing (chemical and bubbling) on neutronics

⇒ Parallel studies of chemical and neutronic issues possible

Concept of MSFR: Starting modes and deployment capacities

Which initial fissile load to start a MSFR?

- Start directly ^{233}U produced in Gen3+ or Gen4 (included MSFR) reactors

- Start directly with enriched U: U enrichment < 20% (prolif. Issues)

- Start with the Pu of current LWRs mixed with other TRU elements: solubility limit of valence-III elements in LiF

- Mix of these solutions: Thorium as fertile matter +
  - ➢ ^{233}U + TRU produced in LWRs
  - ➢ MOx-Th in Gen3+ / other Gen4
  - ➢ Uranium enriched (e.g. 13%) + TRU currently produced

[kg per GWe]	^{233}U started MSFR	TRU (Pu UOx) started MSFR	Enriched U (13%) + TRU started MSFR	Th Pu-MOx started MSFR
Th 232	25 553	20 396	10 135	18 301
Pa 231				20
U 232				1
U 233	3 260			2 308
U 234				317
U 235			1 735	45
U 236				13
U 238			11 758	
Np 237		531	335	54
Pu 238		229	144	315
Pu 239		3 902	2 464	1 390
Pu 240		1 835	1 159	2 643
Pu 241		917	579	297
Pu 242		577	364	1 389
Am 241		291	184	1 423
Am 243		164	104	354
Cm 244		69	44	54
Cm 245		6	4	

Concept of MSFR: Starting modes and deployment capacities

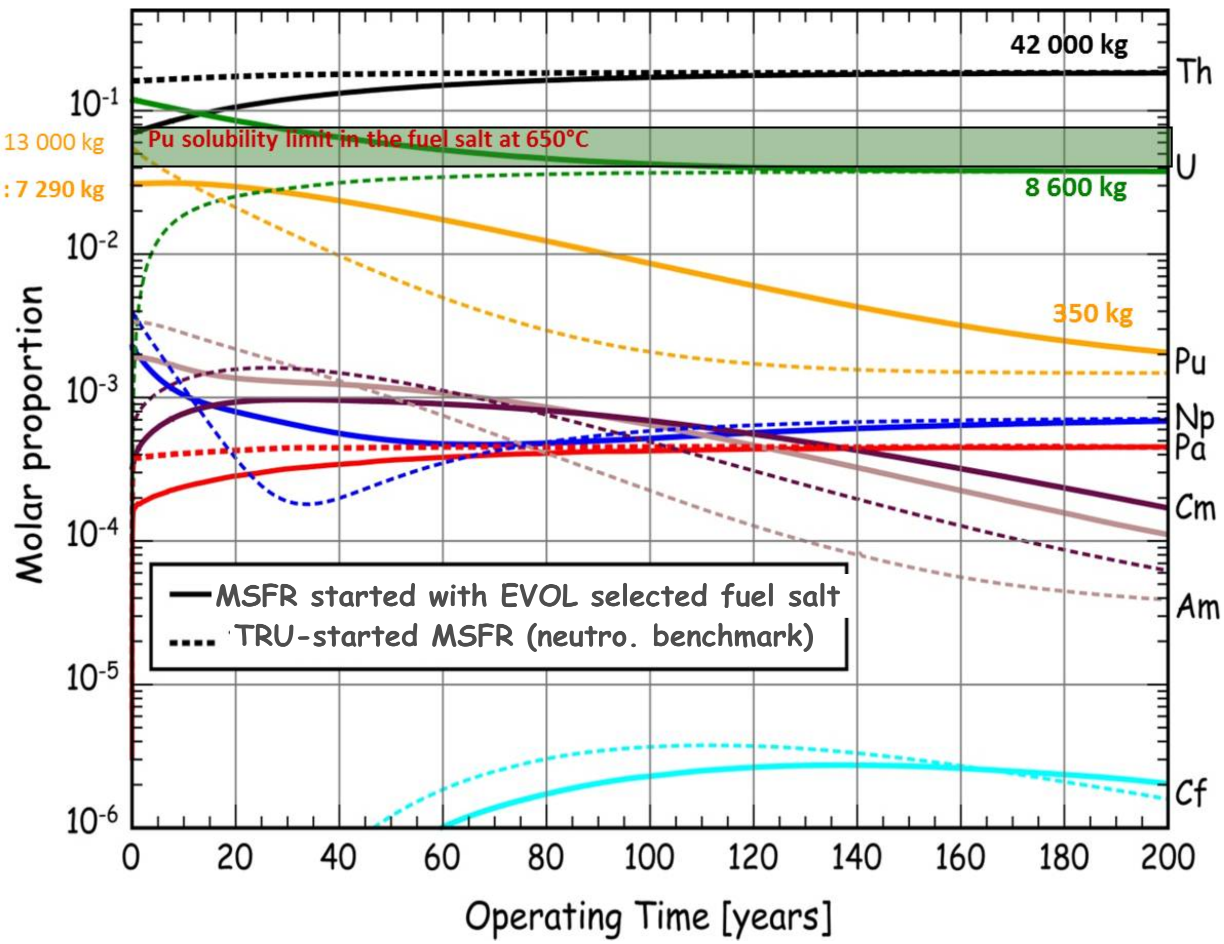
EVOL : Selection of the optimized fuel salt composition (deliverable 3.7)

Optimized initial composition of the fuel salt:

LiF-ThF_4-UF_4-$(TRU)F_3$ with (77.7-6.7-12.3-3.3 mol%) and U enriched at 13%

Density = 5085.6 - 0.8198*(T/K) - T(solid.) = 867 K

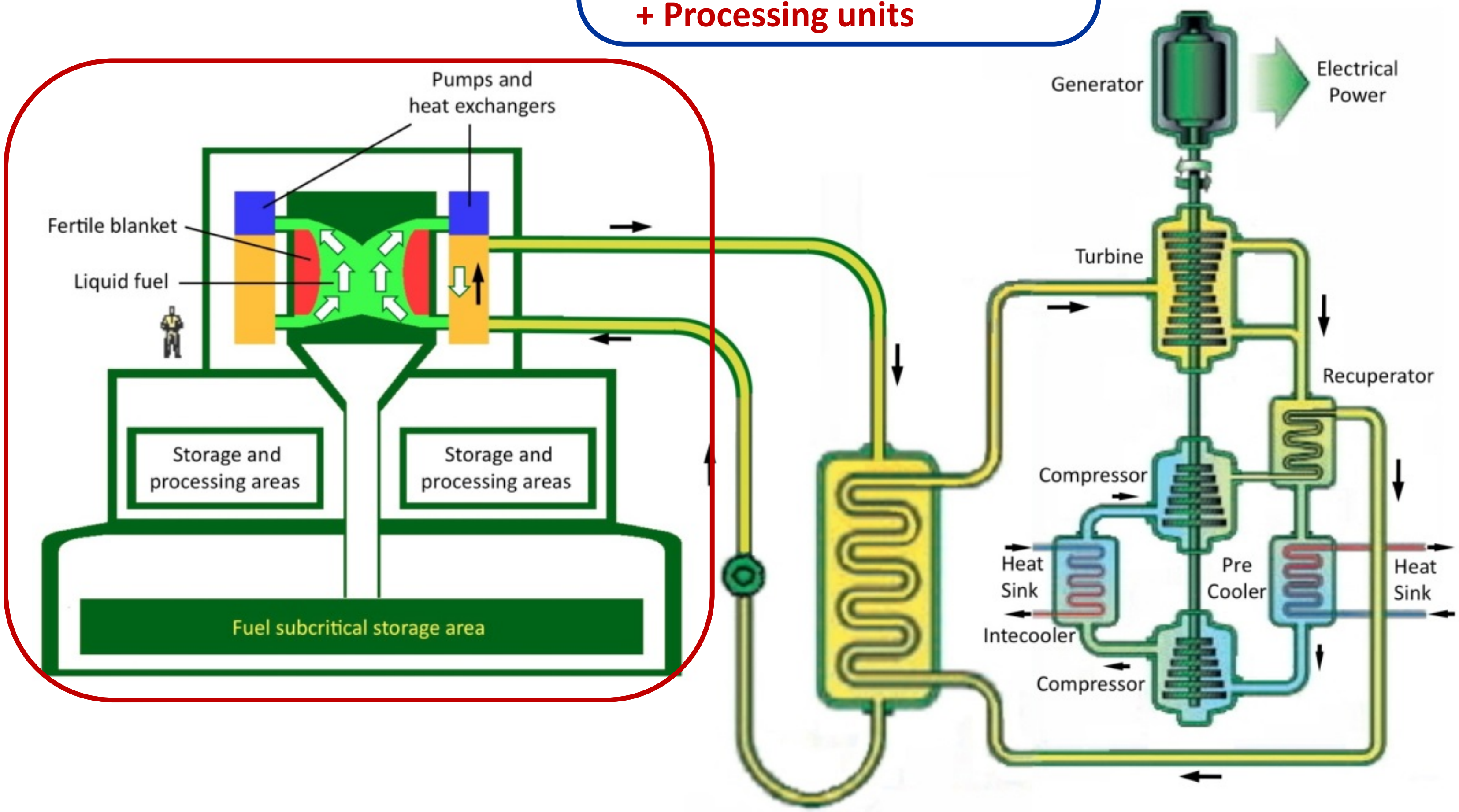
Neutronics, chemical and material behavior very satisfying



Concept of Molten Salt Fast Reactor (MSFR)

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

+ Draining / storage tanks
+ Processing units

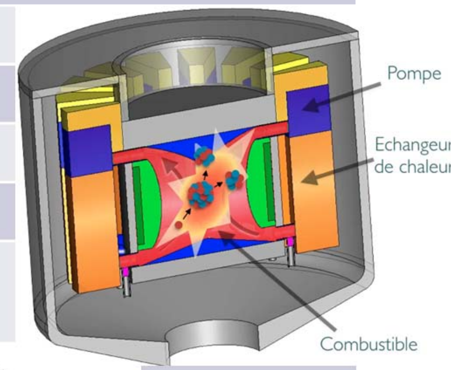


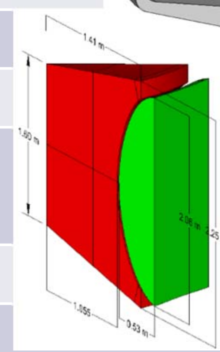
*M. Allibert, M. Aufiero, M. Brovchenko, S. Delpech, V. Ghetta, D. Heuer, A. Laureau, E. Merle-Lucotte, **"Chapter 7 - Molten Salt Fast Reactors"**, Handbook of Generation IV Nuclear Reactors, Woodhead Publishing Series in Energy (2015)*

MSFR neutronic characteristics: from EVOL to SAMOFAR

Review of previous studies ⇨ list of constraints leading to the following proposal:

Parameter	Value
Thermal/electric power	3000 MWth / ~1300 MWe
Fuel salt temperature rise in the core (°C)	100
Fuel molten salt - Initial composition	LiF-ThF_4-$^{233}UF_4$ or LiF-ThF_4-$^{enr}UF_4$-(Pu-MA)F_3 with 77.5 mol% LiF
Fuel salt melting point (°C)	585
Mean fuel salt temperature (°C)	725
Fuel salt density (g/cm^3)	4.1
Fuel salt dilation coefficient (g.cm^{-3}/°C)	8.82 10^{-4}
Fertile blanket salt - Initial composition (mol%)	LiF-ThF_4 (77.5%-22.5%)
Breeding ratio (steady-state)	1.1
Total feedback coefficient (pcm/°C)	-8
Toroidal core dimensions (m)	Radius: 1.06 to 1.41 Height: 1.6 to 2.26
Fuel salt volume (m^3)	18 (1/2 in the core)
Total fuel salt cycle in the fuel circuit	3.9 s
Intermediate fluid	fluoroborate (8NaF-92$NaBF_4$), FLiNaK, LiF-ZrF_4, FLiBe





Concept of Molten Salt Fast Reactor (MSFR)

SAMOFAR Project – Horizon2020
Safety Assessment of a MOlten salt FAst Reactor

SAMOFAR

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

+ See presentation by Jan-Leen Kloosterman

Concept of MSFR: Fuel processing

SAMOFAR project (WP5) + NEEDS French program
Chemistry and materials

State and amount of the elements at each step of the reprocessing (reactivity, chemical state, extraction efficiency)

Experimental validation of the reductive extraction

Material corrosion resistance

Contact person: Dr Sylvie Delpech – IPNO / IN2P3 / CNRS
(delpech@ipno.in2p3.fr)

WP1: Tasks and Deliverables

Del. n°	Deliverable title	Lead benef.	Delivery date
D1.1	Description of initial reference design and identification of safety aspects	CNRS	Month 6
D1.2	Identifying safety related physico-chemical and material data	JRC	Month 6
D1.3	Development of a power plant simulator	CNRS	Month 24
D1.4	Safety issues of normal operation conditions, including start, shut-down and load-following	CIRTEN	Month 30
D1.5	Development on an integral safety assessment methodology for MSR	IRSN	Month 36
D1.6	Identification of risks and phenomena involved, identification of accident initiators and accident scenarios	CIRTEN	Month 36
D1.7	Improved Integral power plant design (reactor core and chemical plant) to maximize safety and proposal for safety demonstrator	CNRS	Month 48

Design aspects impacting the MSFR safety analysis

PhD theses of Mariya Brovchenko and Delphine Gérardin

- 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
  - ✓ …ass
  - ✓
- Fue
  - ✓
  - ✓ Changing the fuel geometry allows for adequate shutdown margin and cooling
  - ✓ Fuel draining can be done passively or by operator action in 2 dedicated systems (normal operation and emergency draining systems)

❖ Design definition (core and draining system at least)

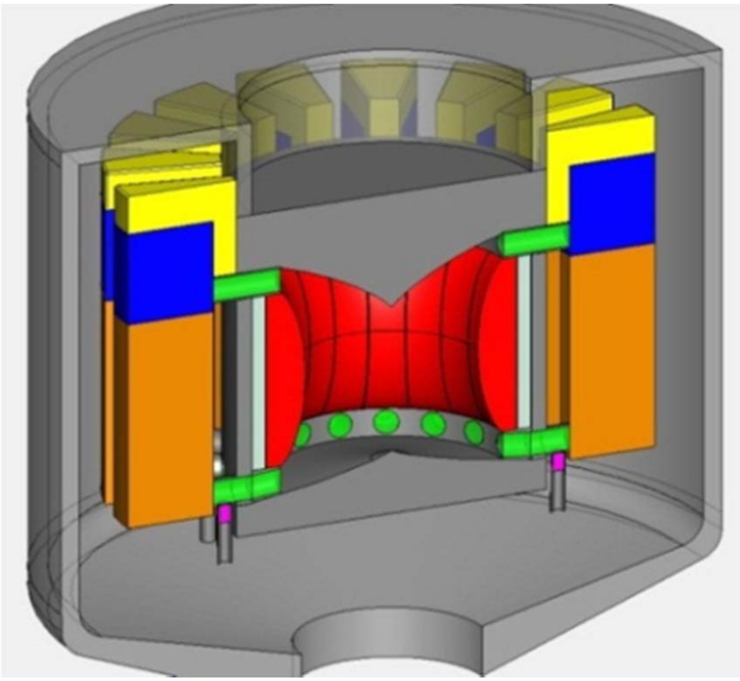
❖ Definition of the normal operation procedures

❖ Safety evaluation: accident initiators? Accident scenarios?

❖ Safety approach: severe accident? Barriers? Reactivity control?

M. Brovchenko, D. Heuer, E. Merle-Lucotte, M. Allibert, V. Ghetta, A. Laureau, P. Rubiolo, *"Design-related Studies for the Preliminary Safety Assessment of the Molten Salt Fast Reactor",* Nuclear Science and Engineering,**175**, 329–339 (2013)

Design aspects impacting the MSFR safety analysis

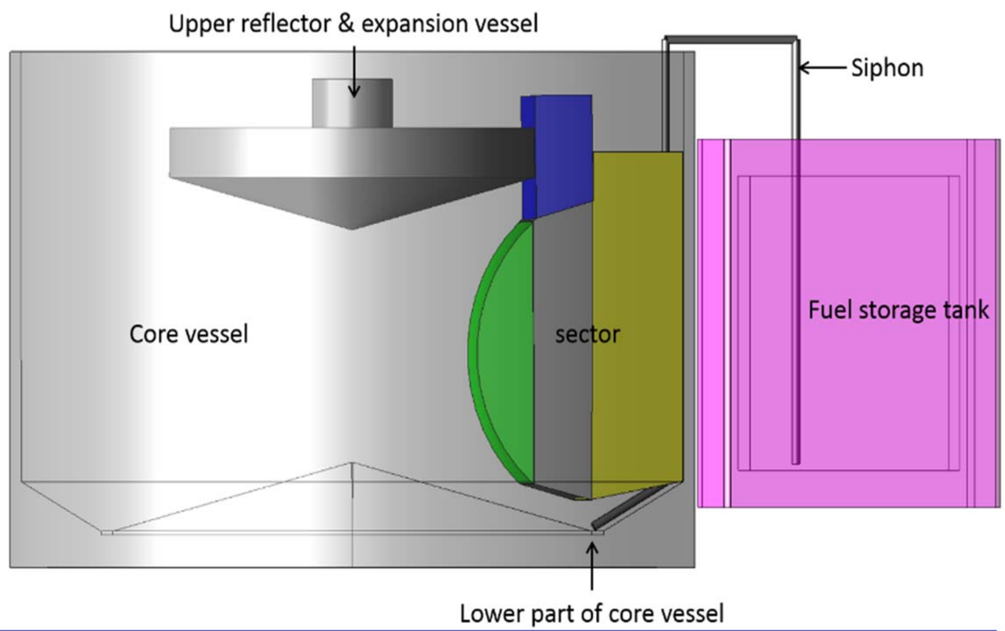


LOLF accident (Loss of Liquid Fuel)

→ no tools available for quantitative analysis but qualitatively:

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

→ Proposition of a 'segmented MSFR design' to suppress pipes/leaks



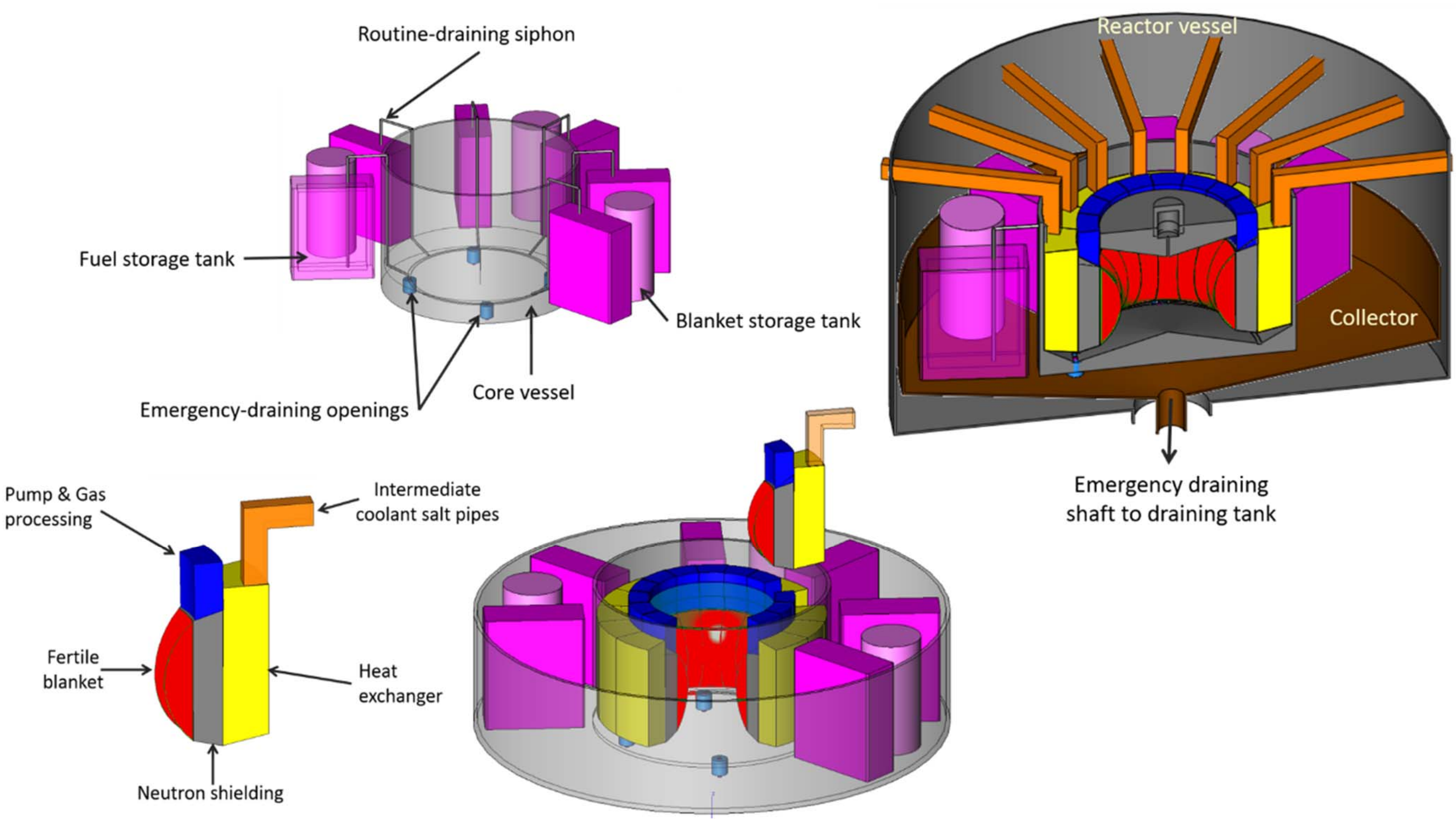
<u>3 circuits:</u>

- **Fuel circuit**
- Intermediate circuit
- Energy conversion system

+ Draining tanks

Concept of MSFR: Fuel salt loop (fuel circuit)

Segmented core geometry (SAMOFAR proposal):



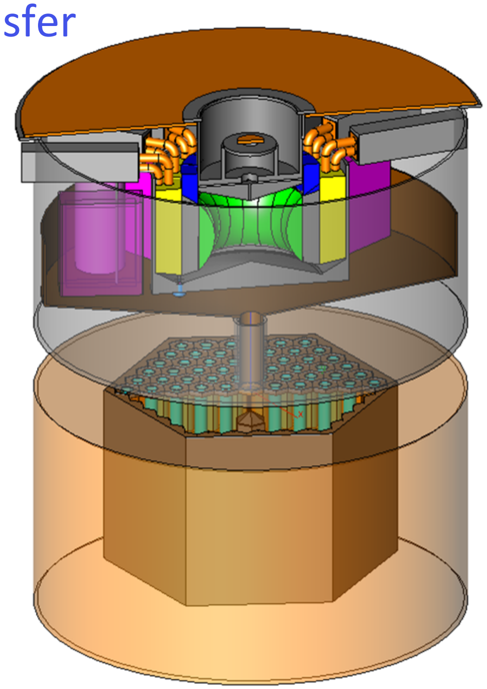
Concept of MSFR: Emergency Draining System

Emergency Draining System = vessel containing the fuel salt + cooling rods

- Emergency draining triggered and achieved by redundant and reliable devices (detection & opening): technology

- Maintain the fuel salt in a passively safe situation for long periods of time (months, years):
  - Resilient to high T° fuel: material
  - Large usable volume (>18m^3) but no criticallity, in any circumstances: geometry
  - Passive decay heat extraction, in any circumstances: heat transfer

- *Potential advantages:*
  Large grace periods (margins) before taking action such as:
  - cooling
  - fuel solidification (with and without cooling)
  - external heating (in absence of cooling) to recover liquid fuel



Operation aspects impacting the MSFR safety analysis

SAMOFAR

Normal operation modes: load following

Idea = accomplish **load following without using control rods**, by varying the power extracted from the core while keeping the structure materials temperature as constant as possible

For this, several levers available, among which:

•The **fuel salt circulation speed** which can be adjusted by controlling the power of the pumps in each sector

•The **intermediate fluid circulation speed** which can be adjusted by controlling the power of the intermediate circuit pumps

•The **temperature of the intermediate fluid** in the intermediate exchangers. This temperature can be controlled by means of a double bypass. With this procedure, the temperature of the intermediate fluid at the conversion exchanger inlet can be kept constant while its temperature is increased in a controlled manner at the inlet of the intermediate exchangers.

•If necessary the temperature in the core may also be adjusted by varying the proportion of bubbles injected in the core. The injection of bubbles reduces the salt density and, as a consequence, reduces the mean temperature of the fuel salt. Typically, a 3% proportion of bubbles lowers the fuel salt temperature by 100°C.

- Precise transient calculations (*core scale*) performed → development and validation of dedicated simulation tools (see TFM-OpenFOAM coupling)
- System code (*plant simulator*) under development to study and define more precisely these operation procedures

Concept of MSFR: transient calculations – the Transient Fission Matrix (TFM) approach

A. Laureau et al, ***"Transient Fission Matrix: kinetic calculation and kinetic parameters βeff and Λeff calculation",*** Annals of Nuclear Energy, volume 85, p. 1035–1044 (2015)

Molten Salt Fast Reactor (MSFR)

- Liquid fuel (precursor motion)
- Fuel = coolant
- Circulation time ~ 4 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

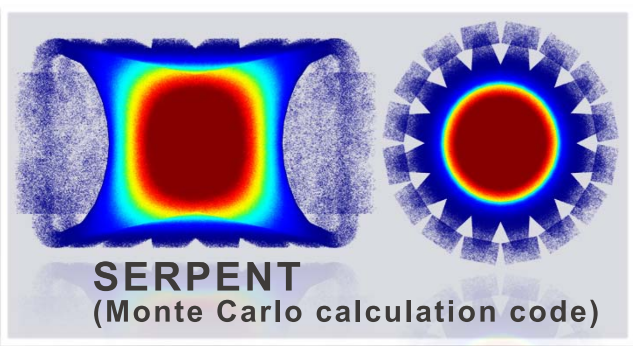
Objective : multiphysics simulations of liquid-fuelled reactors – here optimized coupling of neutronics + thermal-hydraulics:

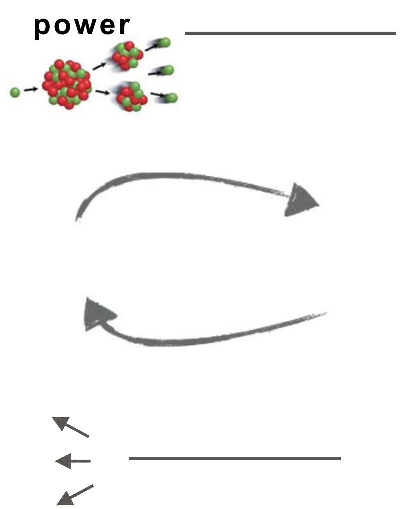
- high precision of the T&H modeling (flow distribution)
  → CFD code OpenFOAM

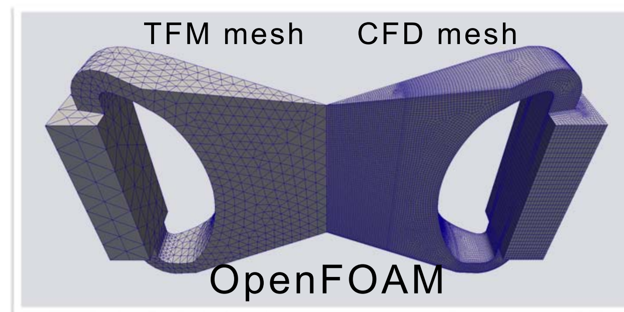
PhD thesis of Axel LAUREAU

- 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

Transient Fission Matrix
(neutronic model)

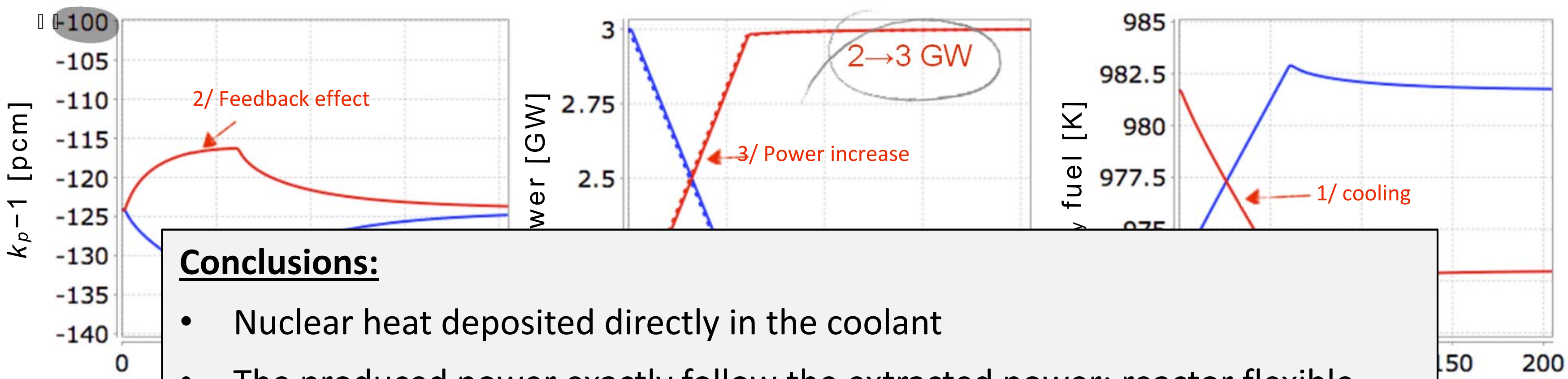






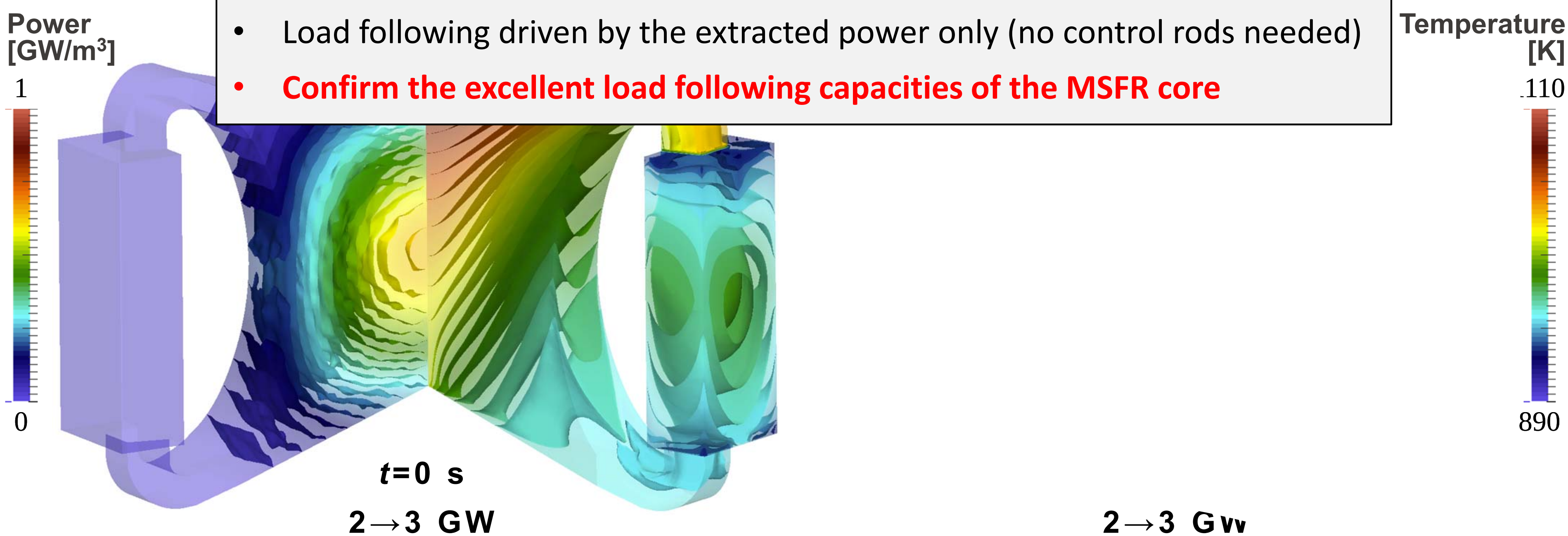
Concept of MSFR: Definition of the operation procedures

Application to transient calculations   (load following of 33% in 60s)



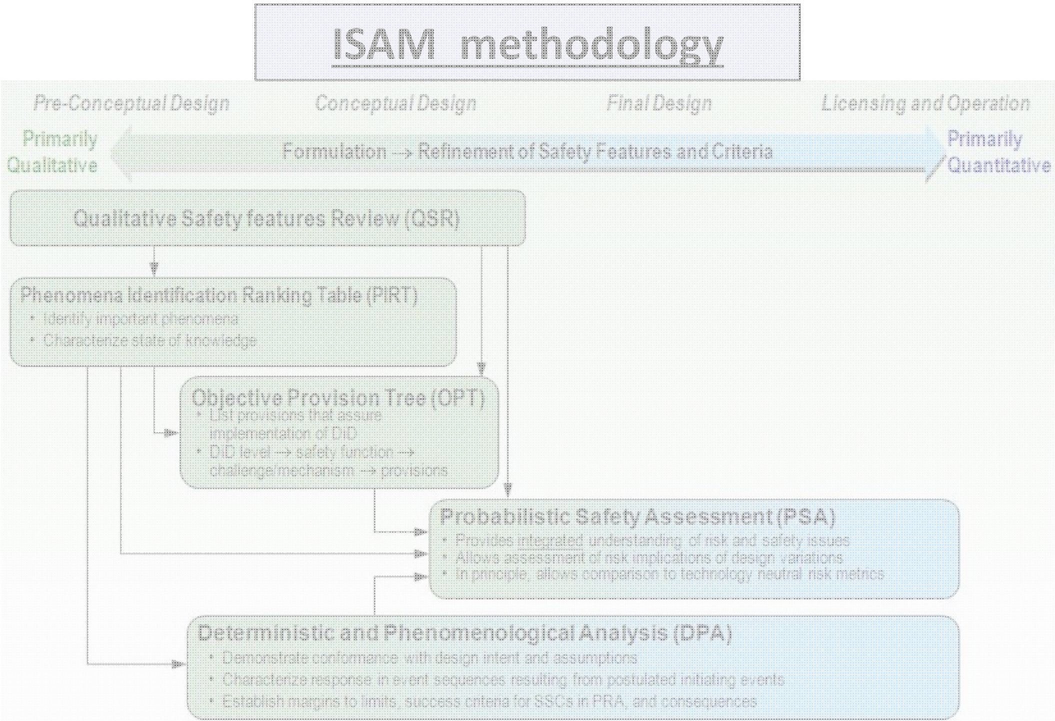
Conclusions:

- Nuclear heat deposited directly in the coolant
- The produced power exactly follow the extracted power: reactor flexible and well adapted for load following for neutronic/t&h issues
- Load following driven by the extracted power only (no control rods needed)
- **Confirm the excellent load following capacities of the MSFR core**



Axel LAUREAU, ***"Développement de modèles neutroniques pour le couplage thermohydraulique du MSFR et le calcul de paramètres cinétiques effectifs"***, PhD Thesis, Grenoble Alpes University, France (2015)

Safety Evaluation of the MSFR: ISAM + Systematic Risk Analysis



Systematic Risk Analysis

- System definition
- Operation and limits

- System decomposition:
  sub-system + functions + components
- Identification of abnormal events:
  Failure Modes + Dangerous Phenomena

- Construction of a predictive model of the system

- Qualitative or quantitative analyses

→ Failure trees,
Accidental scenarios…

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- Operation and limits

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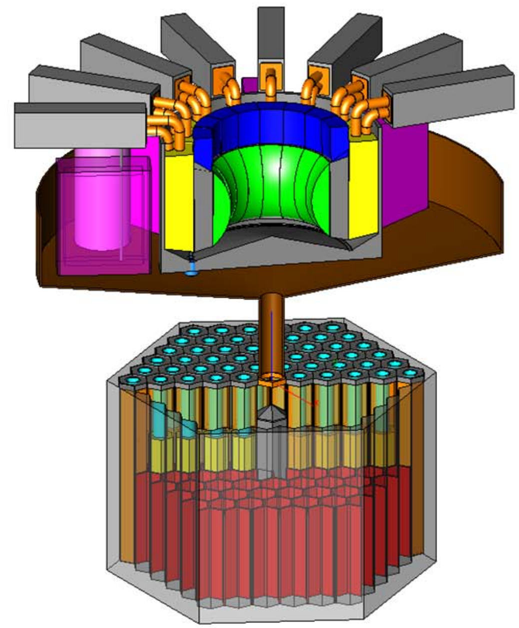
Accidental scenarios…



<u>Preliminary list MSFR main accident types identified from:</u>

- Knowledge on PWR
- Deliverables EVOL 2.5 & 2.6 + PhD thesis of M. Brovchenko
- Preliminary systemic risk analysis
- Qualitative reevaluation to take account for the new design

SAMOFAR

Preliminary MSFR accident list

PhD thesis of
Delphine Gérardin

Fuel circuit accidents

- LOHS - Loss Of Heat Sink
- LOFF - Loss Of Fuel Flow
- TLOP - Total Loss Of Power
- OVC - OVer-Cooling
- LOLF - Loss Of Liquid Fuel
- RAA - Reactivity Anomalies Accident

Draining system accidents

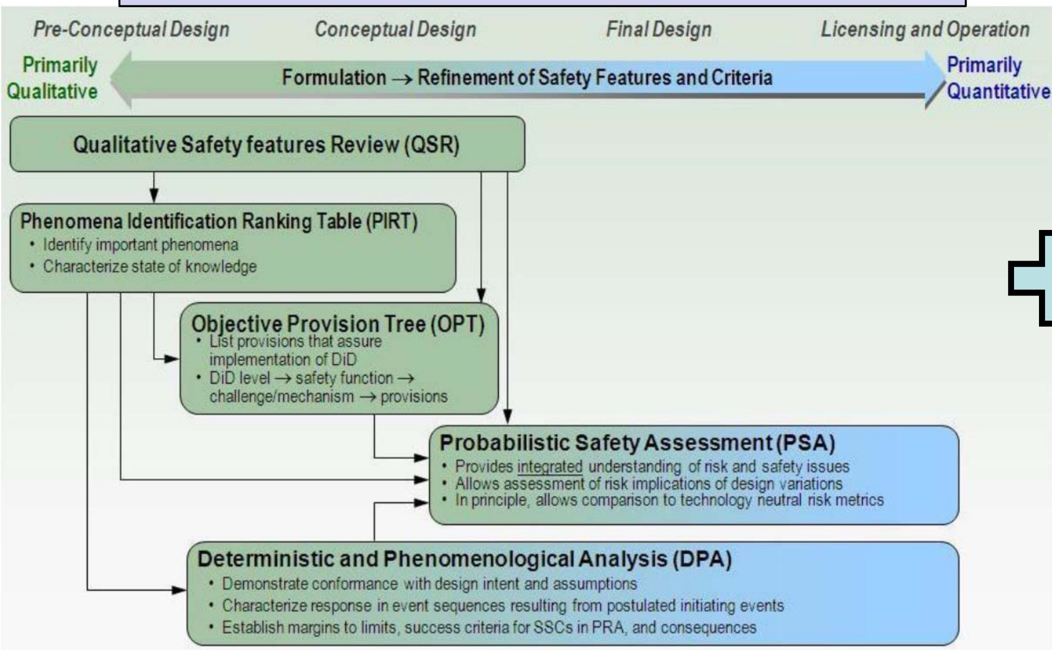
- LOHS - Loss Of Heat Sink
- LOLF - Loss Of Liquid Fuel
- DIA – Draining Interruption Accidents

Design Extension Conditions

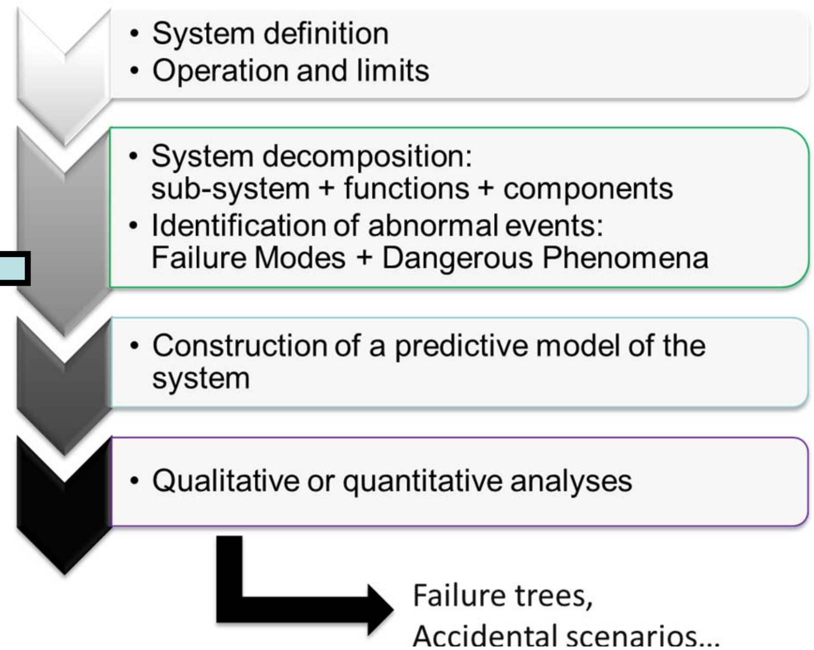
- Steam pressurization accident
- Beyond design reactivity accident

Safety Evaluation of the MSFR: ISAM + Systematic Risk Analysis

Methodology: ISAM + INPRO / WENRA



Systematic Risk Analysis



- **Develop a safety approach dedicated to a fast spectrum MSR with a circulating fuel, with both deterministic and probabilistic approaches** - **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 characteristics: definition of severe accident, of the barriers, practical elimination…**

- **Build a reactor risk analysis model**
  - Identify the **initiators (Postulated Initiated Events, hazards) and high risk scenarios**
  - Evaluate the risk due to the **residual heat and the radioactive inventory**
  - Evaluate some potential design solutions (**barriers**)
  - Allow reactor designer to estimate impact of design changes (***design by safety***)

SAMOFAR

Demonstration steps and Demonstrator of MSFR

Sizing of the facilities:

Small size: ~1liter - chemistry and corrosion – off-line processing

Pyrochemistry: basic chemical data, processing, monitoring

Medium size: ~100 liters – hydrodynamics, noble FP extraction, heat exchanges

Process analysis, modeling, technology tests

Full size experiment: ~1 m^3 salt / loop – validation at loop scale

Validation of technology integration and hydrodynamics models

3 levels of radio protection:

✓ Inactive simulant salt ⇨ Standard laboratory

Hydrodynamics, material, measurements, model validation

✓ Low activity level (Th, depleted U) ⇨ Standard lab + radio protect

Pyrochemistry, corrosion, chemical monitoring

✓ High activity level ($^{enriched}U$, ^{233}U, Pu, MA) ⇨ Nuclear facility

Fuel salt processing: Pyrochemistry, , Actinides recycling

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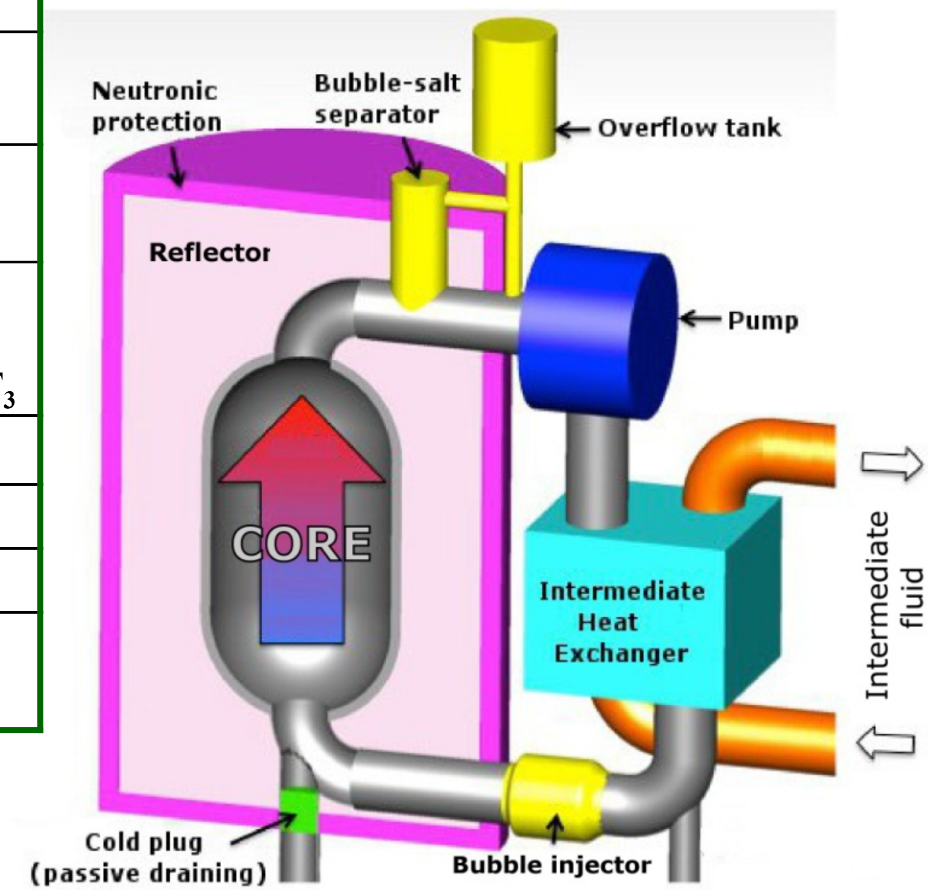
Power Demonstrator of the MSFR

Thermal power	**100 MWth**
Mean fuel salt temperature	**725 °C**
Fuel salt temperature rise in the core	**30 °C**
Fuel Molten salt initial composition	**75% LiF-ThF$_4$-^{233}UF$_4$ (~660 kg of ^{233}U) or LiF-ThF$_4$-(^{enriched}U+MOx-Th)F$_3$**
Fuel salt melting point	**565 °C**
Fuel salt density	**4.1 g/cm^3**
Fuel salt volume	**1.8 m^3**
Total fuel salt cycle in the fuel circuit	**3.5 s**

Demonstrator characteristics representative of the MSFR

From the power reactor to the demonstrator:
Power / 30 and Volume / 10



6 external loops

E. Merle-Lucotte, D. Heuer, M. Allibert, M. Brovchenko, V. Ghetta, A. Laureau, P. Rubiolo, ***"Recommandations for a demonstrator of Molten Salt Fast Reactor"***, Proceedings of the International Conference FR13, Paris, France (2013)

From Power Demonstrator of the MSFR to SMR-MSFR

	No radial blanket and H/D=1	No radial blanket and H/D=1
Power [MW_{th}]	**100**	**200**
Initial ^{233}U load [kg]	654	654
Fuel reprocessing of 1l/day		
Feeding in ^{233}U [kg/an]	**11.38**	**23.38**
Breeding ratio	-29.83%	-30.64%
Total ^{233}U needed [kg]	**1013.87**	**1388.37**

Around 650kg of ^{233}U to start

Under-breeder reactor

Fuel reprocessing of 4l/day		
Feeding in ^{233}U [kg/an]	**11.20**	**22.58**
Breeding ratio	-29.37%	-29.59%
Total ^{233}U needed [kg]	**1001.86**	**1353.13**

Low impact of the chemical reprocessing rate (not mandatory for the demonstrator / SMR)

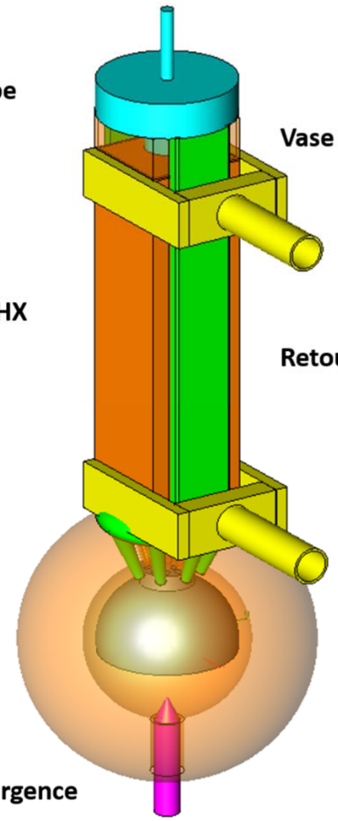
From Power Demonstrator of the MSFR to SMR-MSFR

	No radial blanket and H/D=1	No radial blanket and H/D=1	Radial blanket and H/D=1	Radial blanket and H/D=1
Power [MW_{th}]	**100**	**200**	**100**	**200**
Initial ^{233}U load [kg]	654	654	667	667
Fuel reprocessing of 1l/day				
Feeding in ^{233}U [kg/an]	11.38	23.38	1.72	4.70
Breeding ratio	**-29.83%**	**-30.64%**	**-4.52%**	**-6.16%**
Total ^{233}U needed [kg]	1013.87	1388.37	738.83	835.16
Breeding ratio (radial + axial fertile blankets)			***1.81%***	***-0.04%***
Fuel reprocessing of 4l/day				
Feeding in ^{233}U [kg/an]	11.20	22.58	1. 48	3.58
Breeding ratio	**-29.37%**	**-29.59%**	**-3.88%**	**-4.69%**
Total ^{233}U needed [kg]	1001.86	1353.13	722.50	794.21
Breeding ratio (radial + axial fertile blankets)			***2.49%***	***1.54%***

Addition of axial + radial fertile blankets ⇨ small modular breeder MSFR

Small Modular Reactor - MSFR

Thermal power	**100 MWth to 300 MWth**
Mean fuel salt temperature	**675 °C**
Fuel salt temperature rise in the core	**30 °C**
Fuel Molten salt initial composition	**75% LiF-(Heavy Nuclei)F_4 – in Th/U or U/Pu fuel cycle**
Core dimensions	**Int. Diameter ~1.3 m** **Ext. Diameter ~2.3 m**
Fuel Salt Volume	**2 m^3** **1.1 in core** **0.9 in external circuits**
Total fuel salt cycle in the fuel circuit	**3.5 s**



May be operated 30 years with the same salt and only salt control + bubbling but no chemical processing (stable physico-chemical characteristics of the salt)

Some documents mentioning the MSRF

MSR-Safety White Paper, Gen4 International Forum, SSC-MSR, under review (2016)

M. Allibert, M. Aufiero, M. Brovchenko, S. Delpech, V. Ghetta, D. Heuer, A. Laureau, E. Merle-Lucotte, ***"Chapter X - Molten Salt Fast Reactors",*** Handbook of Generation IV Nuclear Reactors, Woodhead Publishing Series in Energy (2015)

"Introduction of Thorium in the Nuclear Fuel Cycle", Nuclear Science 2015, NEA website https://www.oecd-nea.org/science/pubs/2015/7224-thorium.pdf (2015)

J. Serp, M. Allibert, O. Beneš, S. Delpech, O. Feynberg, V. Ghetta, D. Heuer, D. Holcomb, V. Ignatiev, J.L. Kloosterman, L. Luzzi, E. Merle-Lucotte, J. Uhlíř, R. Yoshioka, D. Zhimin, ***"The molten salt reactor (MSR) in generation IV: Overview and Perspectives",*** Prog. Nucl. Energy, 1-12 (2014)

H. Boussier, S. Delpech, V. Ghetta, D. Heuer, D.E. Holcomb, V. Ignatiev, E. Merle-Lucotte, J. Serp, ***"The Molten Salt Reactor in Generation IV: Overview and Perspectives"***, Proceedings of the Generation4 International Forum Symposium, San Diego, USA (2012)

CEA, Rapport sur la gestion durable des matières nucléaires - Tome 4 : Les autres filières à neutrons rapides de 4ème génération (2012)

C. Renault, S. Delpech, E. Merle-Lucotte, R. Konings, M. Hron, V. Ignatiev, ***"The molten salt reactor: R&D status and perspectives in Europe"***, Poceedings of FISA2009: 7th European Commission conference on EURATOM research and training in reactor systems, Prague, Tchéquie (2009)

SNETP
Sustainable Nuclear Energy Technology Platform

See also the annex on Molten Salt Reactor Systems of the Strategic Research Agenda (published in January 2012) Agenda of the SNETP (Sustainable Nuclear Energy Technology Platform of Europe) here: http://*www.snetp.eu/www/snetp/.../sra_annex-MSRS.pdf*

Some PhD Thesis in France on MSR

Axel LAUREAU, ***"Développement de modèles neutroniques pour le couplage thermohydraulique du MSFR et le calcul de paramètres cinétiques effectifs"***, PhD Thesis, Grenoble Alpes University, France (2015)

Mariya BROVCHENKO, ***"Etudes préliminaires de sûreté du réacteur à sels fondus MSFR"***, PhD Thesis, Grenoble Institute of Technology, France (2013)

Xavier DOLIGEZ, ***"Influence du retraitement physico-chimique du sel combustible sur le comportement du MSFR et sur le dimensionnement de son unité de retraitement",*** PhD Thesis, Grenoble Institute of Technology and EDF, France (2010)

Elsa MERLE-LUCOTTE, ***"Le cycle Thorium en réacteurs à sels fondus peut-il être une solution au problème énergétique du XXIème siècle ? Le concept de TMSR-NM",*** Habilitation à Diriger les Recherches, Grenoble Institute of Technology, France (2008)

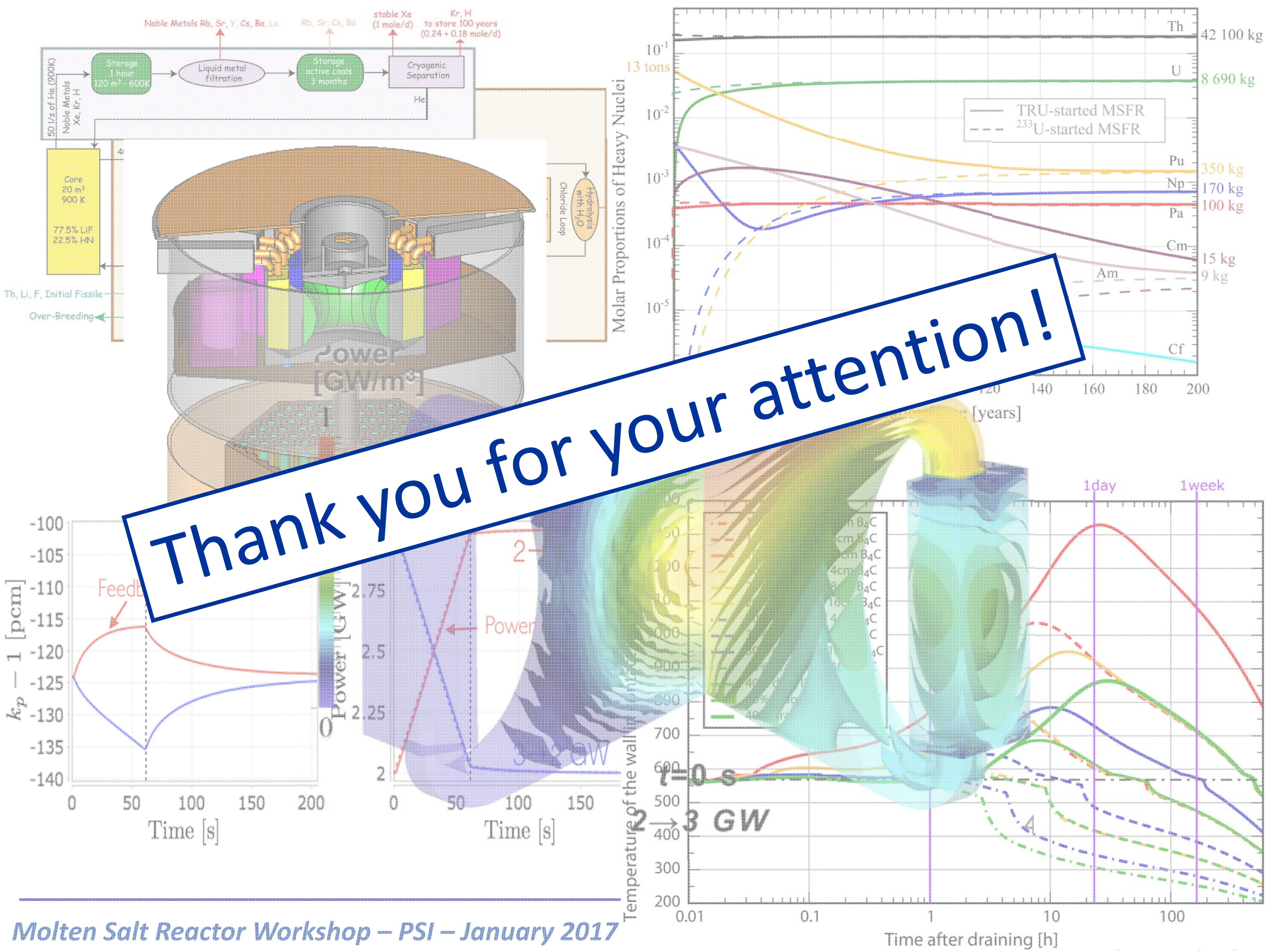
Ludovic MATHIEU, ***"Cycle Thorium et Réacteurs à Sel Fondu: Exploration du champ des Paramètres et des Contraintes définissant le Thorium Molten Salt Reactor",*** PhD Thesis, Grenoble Institute of Technology and EDF, France (2005)

Jorgen FINNE, ***"Chimie des mélanges de sels fondus - Application à l'extraction réductrice d'actinides et de lanthanides par un métal liquide"***, PhD Thesis, EDF-CEA-ENSCP, Paris, France (2005)

Fabien PERDU, ***"Contributions aux études de sûreté pour des filières innovantes de réacteurs nucléaires",*** PhD Thesis, Grenoble Institute of Technology, France (2003)

Alexis NUTTIN, ***"Potentialités du concept de réacteur à sels fondus pour une production durable d'énergie nucléaire basée sur le cycle thorium en spectre épithermique",*** PhD Thesis, Grenoble I University and EDF, France (2002)

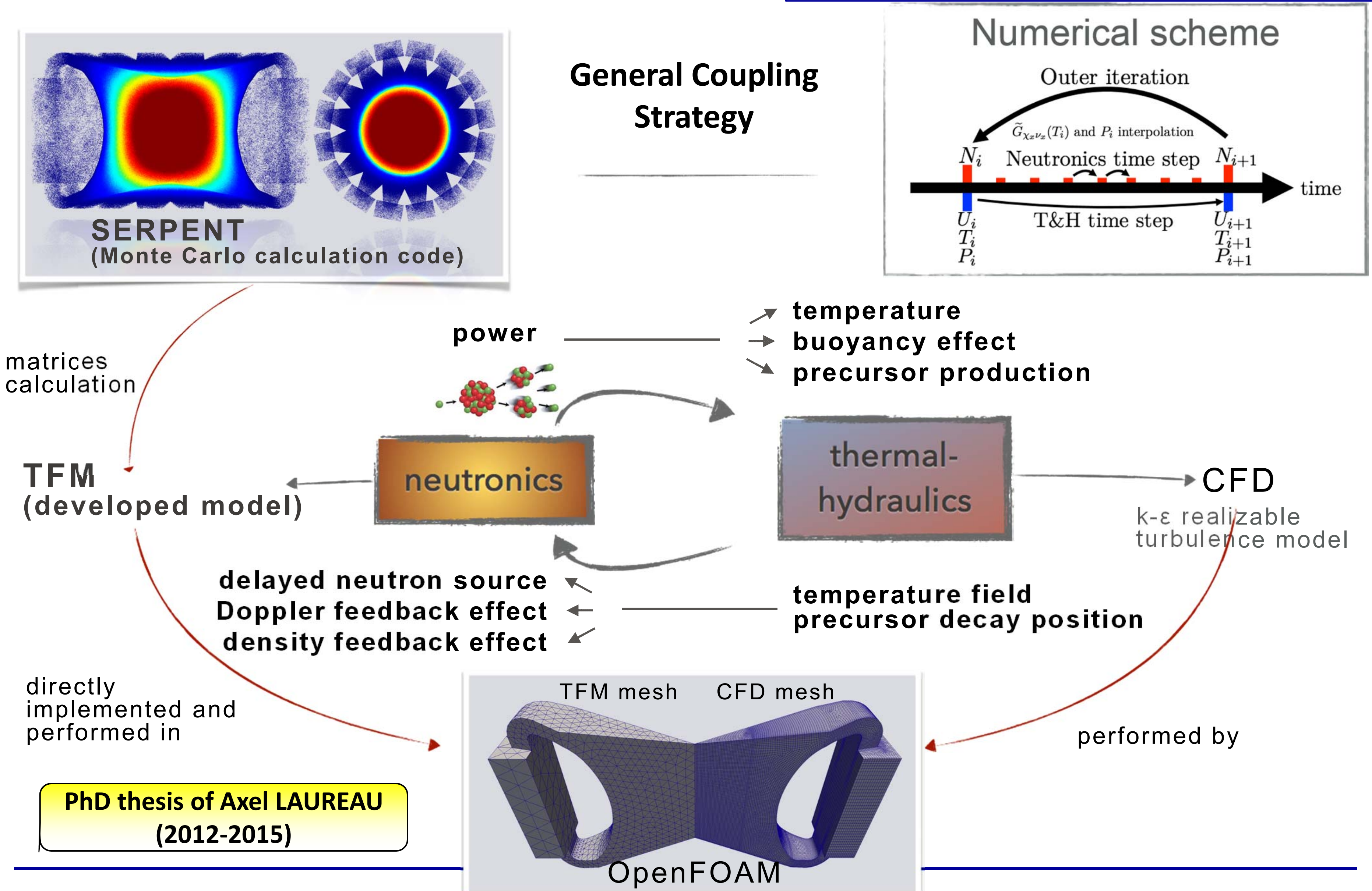
Available on http://lpsc.in2p3.fr/index.php/fr/38-activites-scientifiques/physique-des-reacteurs-nucleaires/183-msfr-bibliographie or 'MSFR LPSC' in google search



Thank you for your attention!

Concept of MSFR: transient calculations – the Transient Fission Matrix (TFM) approach

A. Laureau et al, ***"Transient Fission Matrix: kinetic calculation and kinetic parameters βeff and Λeff calculation",*** Annals of Nuclear Energy, volume 85, p. 1035–1044 (2015)

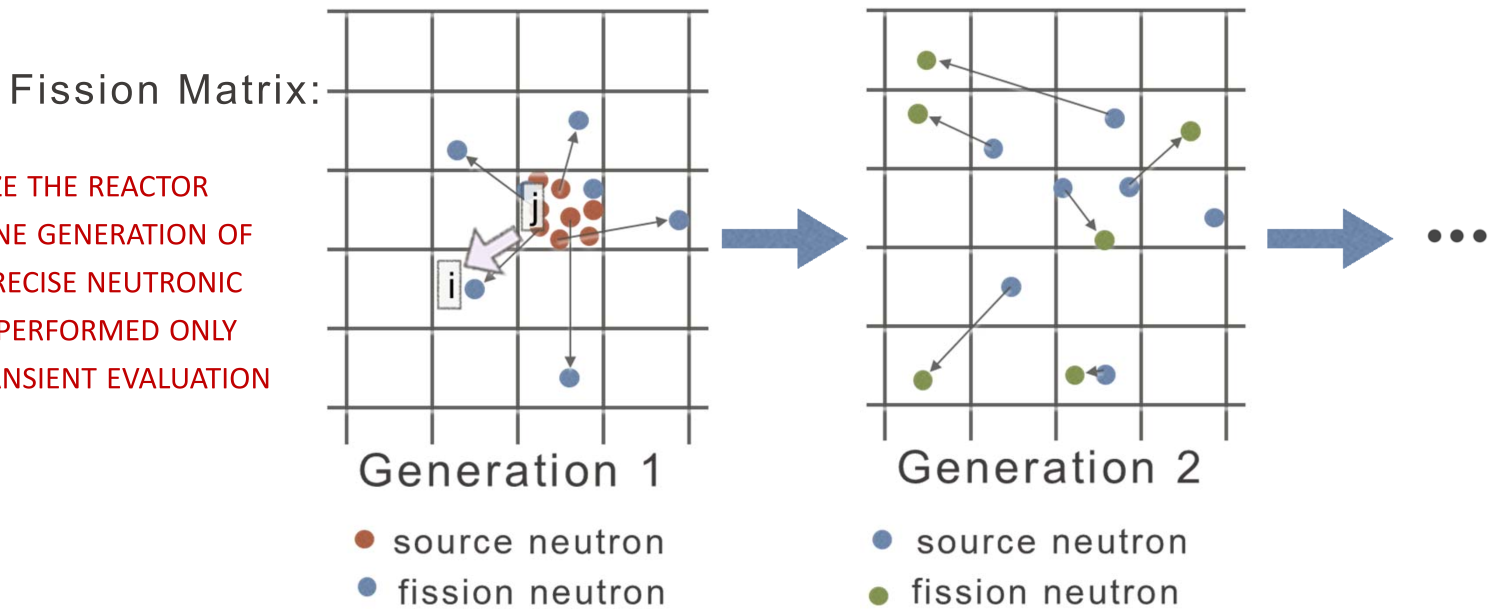


PhD thesis of Axel LAUREAU (2012-2015)

Concept of MSFR: transient calculations – the Transient Fission Matrix (TFM) approach

neutron kinetic model - Transient Fission Matrix (TFM) Approach

CHARACTERIZE THE REACTOR RESPONSE ON ONE GENERATION OF NEUTRONS = PRECISE NEUTRONIC CALCULATIONS PERFORMED ONLY ONCE BEFORE TRANSIENT EVALUATION



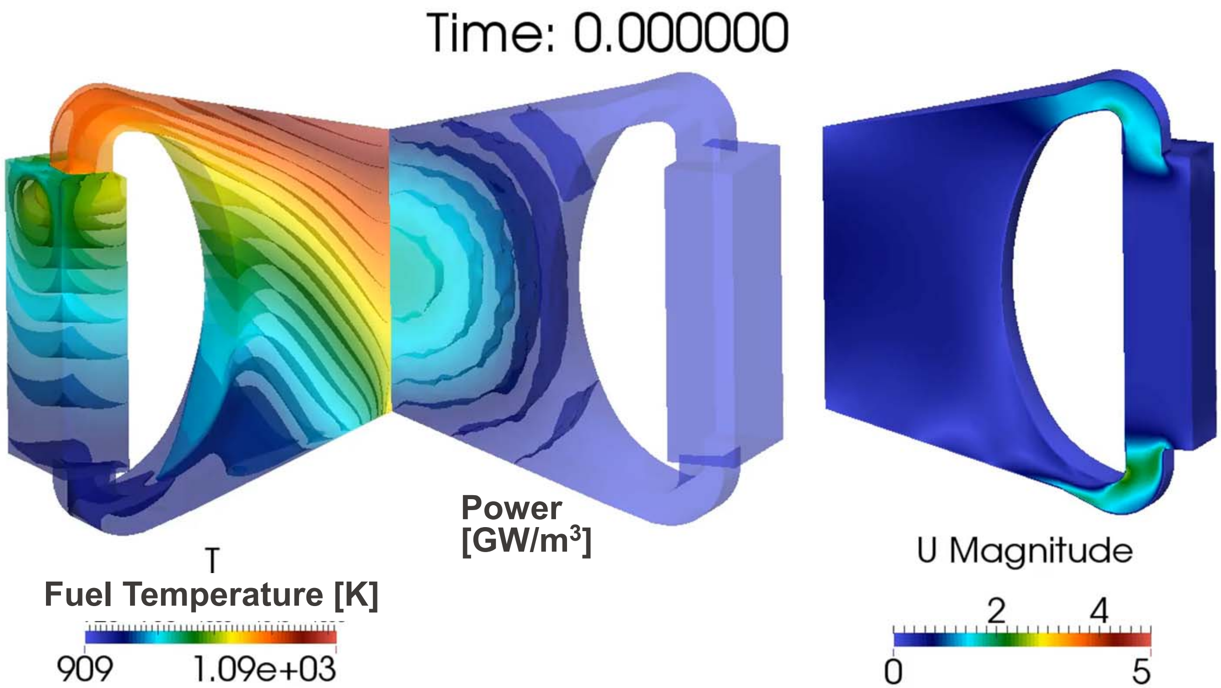
Step 1: Matrix element *ij* = volume *i* neutron production probability induced by an incoming source neutron injected in *j*

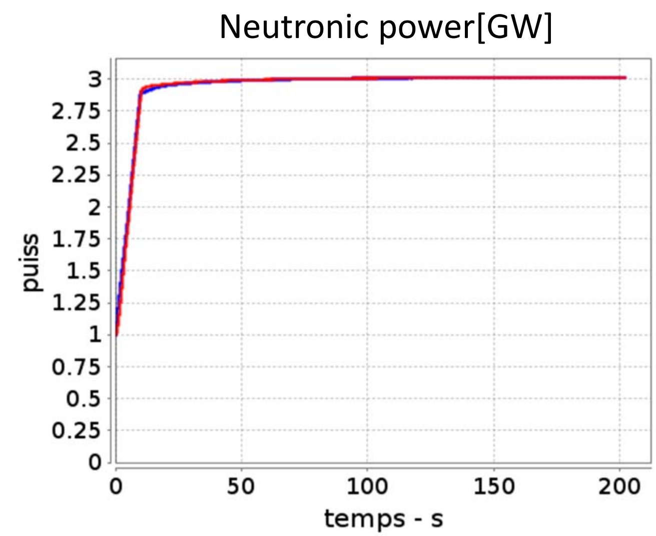
Step 2: Matrix time response - Transient Fission Matrix TFM approach -
A. Laureau et al, "Transient Fission Matrix: Kinetic calculation and kinetic parameters βeff and Λeff Calculation", Annals of Nuclear Energy, Vol. 85, p. 1035-1044 (2015)

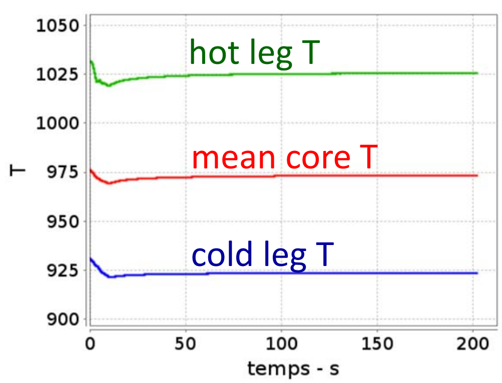
Step 3: Matrix interpolation (temperature variation during the transient – feedback effects)

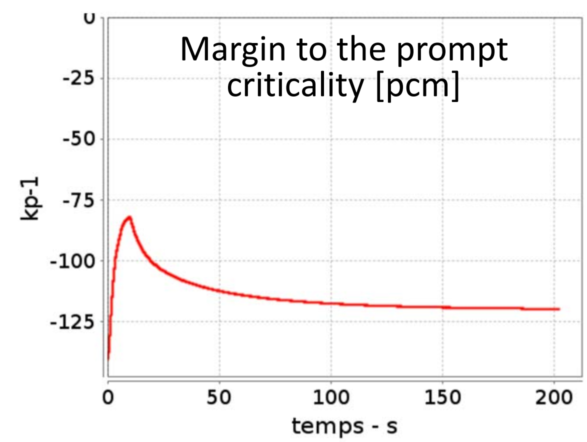
Transient calculations: load following from 1 → 3 GW in 10s with a variable fuel flow

Proportional variation of the power and of the fuel flow to keep the temperature field constant in core **→ Very stable and flexible behavior of the MSFR (temperature field stable / quasi stationary regime)**

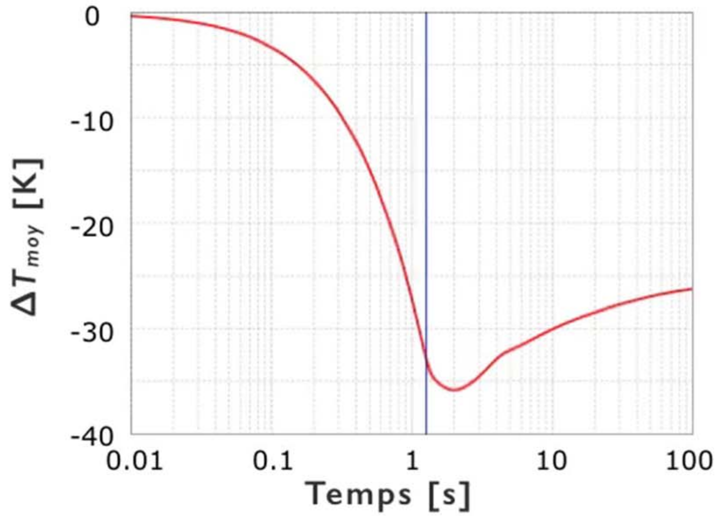


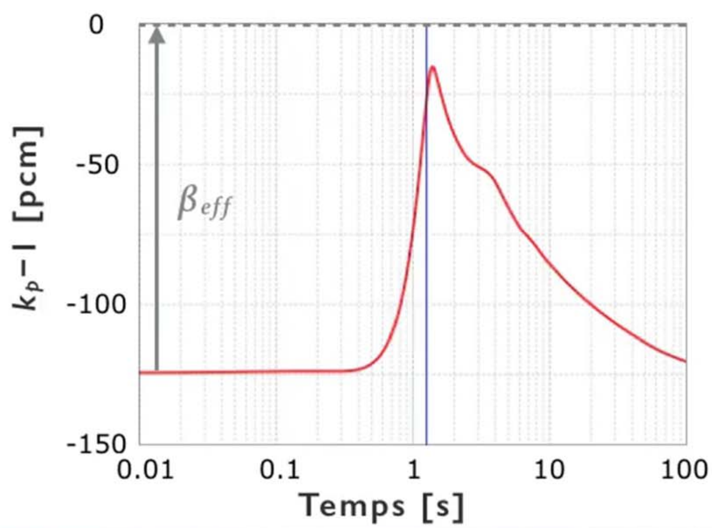


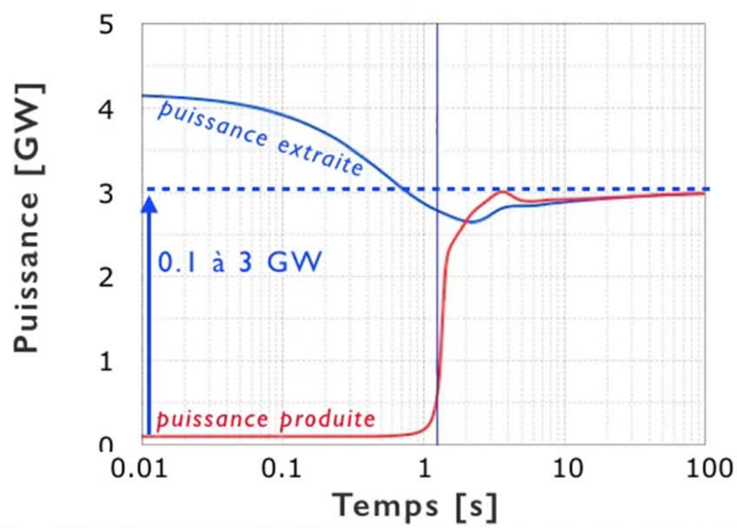




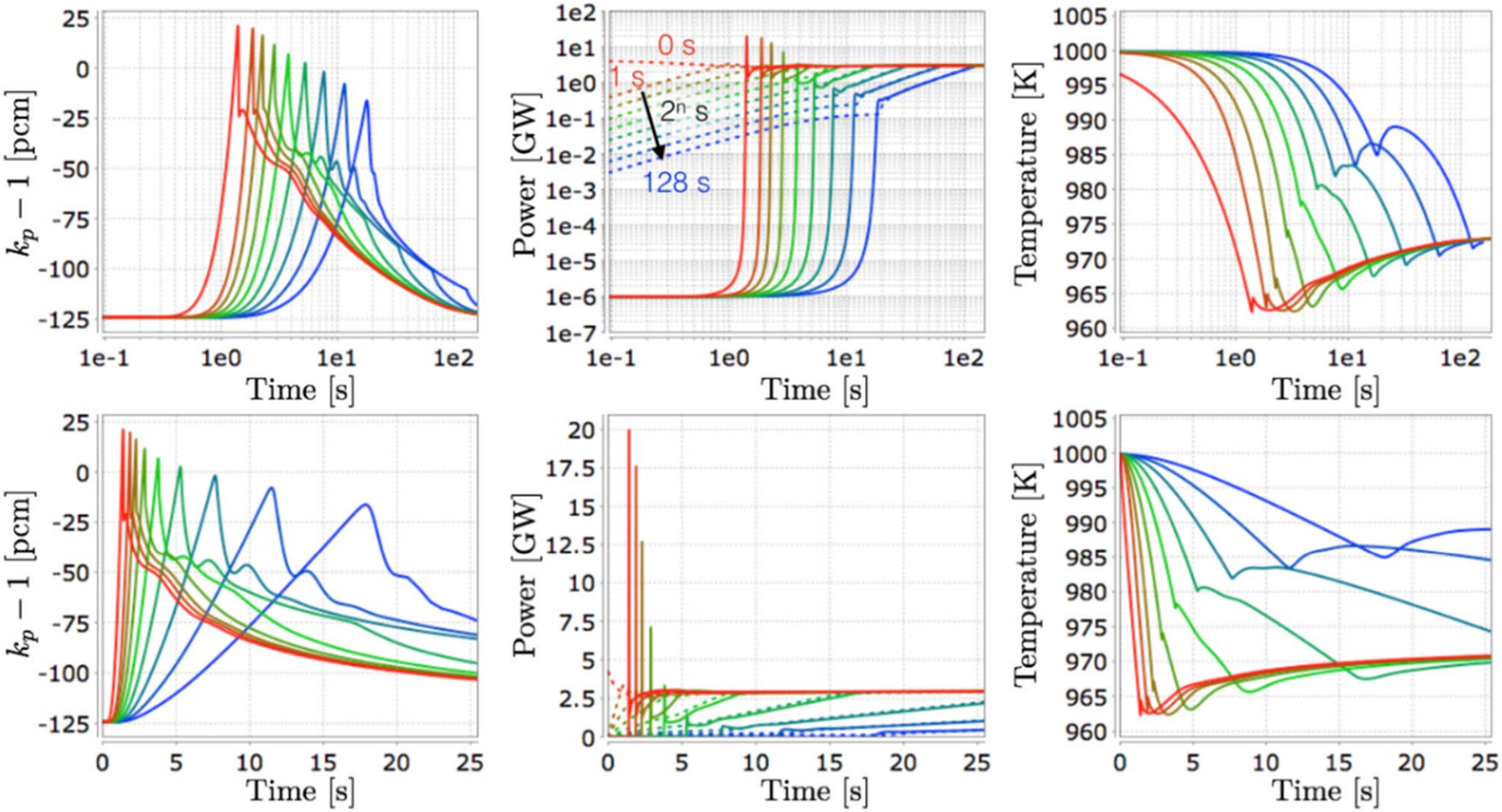
incident de sur-refroidissement : de 0.1 à 3 GW



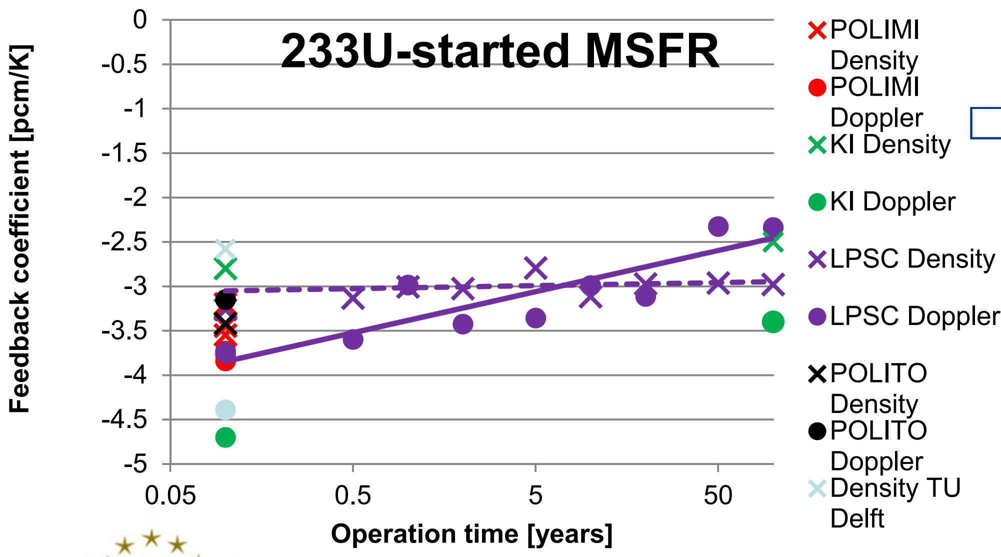




Evolution of margin to prompt criticality (k_p-1), of the power and of the mean fuel salt temperature for a 1 kW up to 3 GW overcooling transient with a time constant between 0 and 128s

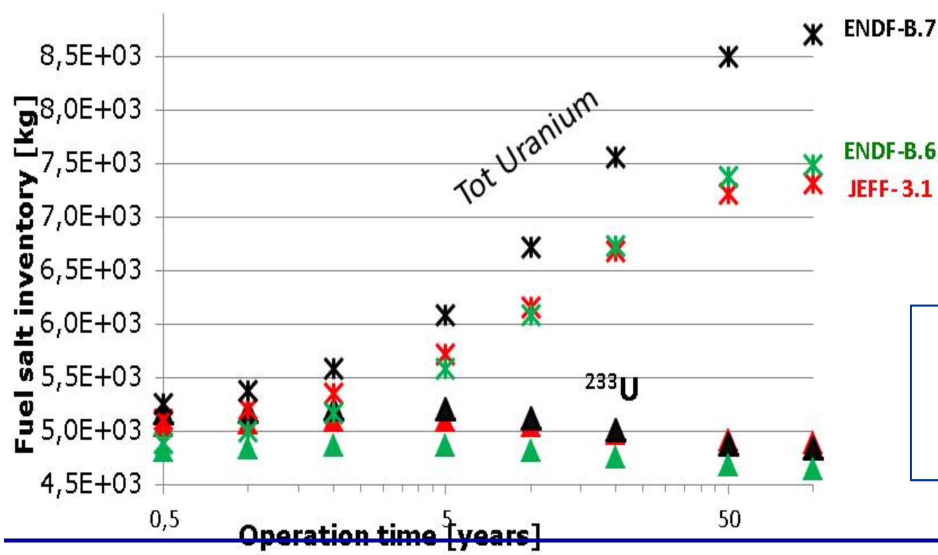


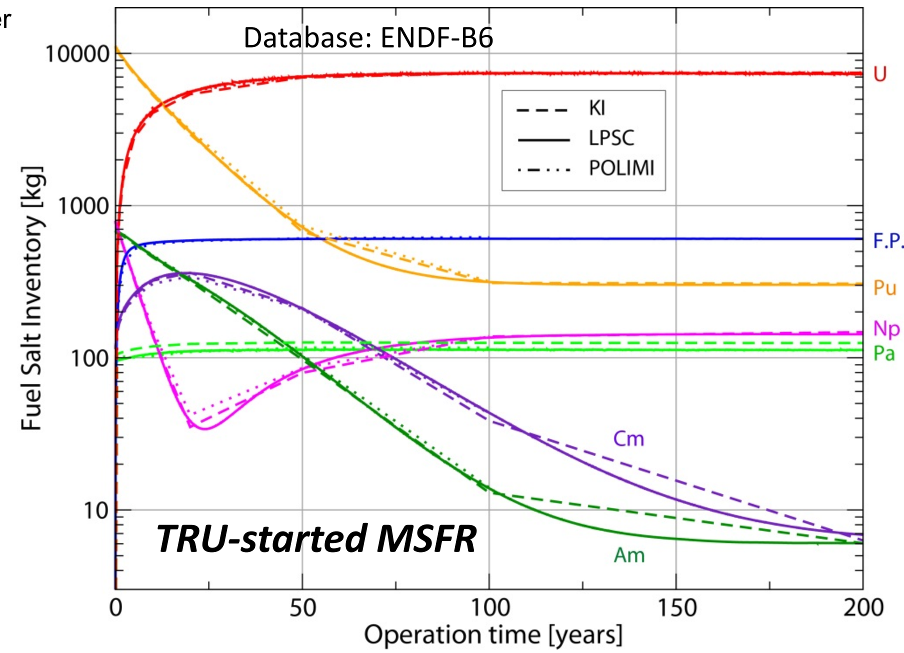
MSFR optimization: neutronic benchmark (EVOL)



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

PhD Thesis of M. Brovchenko





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

Concept of Molten Salt Fast Reactor (MSFR)

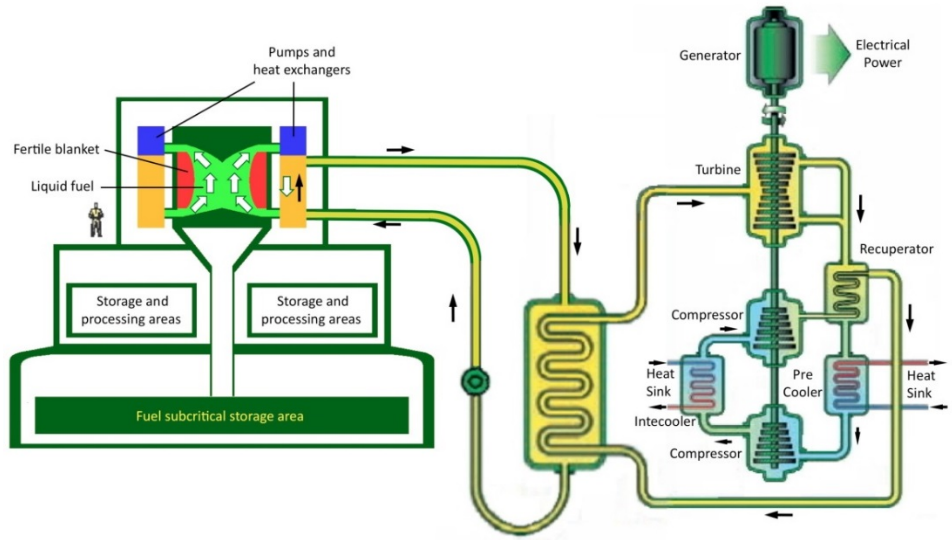
MSFR

Molten Salt

(fission fuel + coolant)

flowing through the core and the heat exchangers

Nuclear Core



associated to

Processing Units of the fuel located on-site

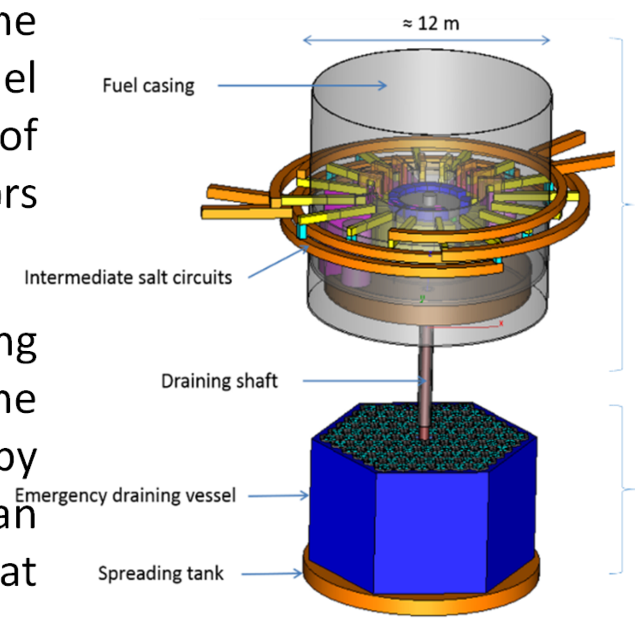
Concept of MSFR: Fuel salt loop (fuel circuit)

Draining systems

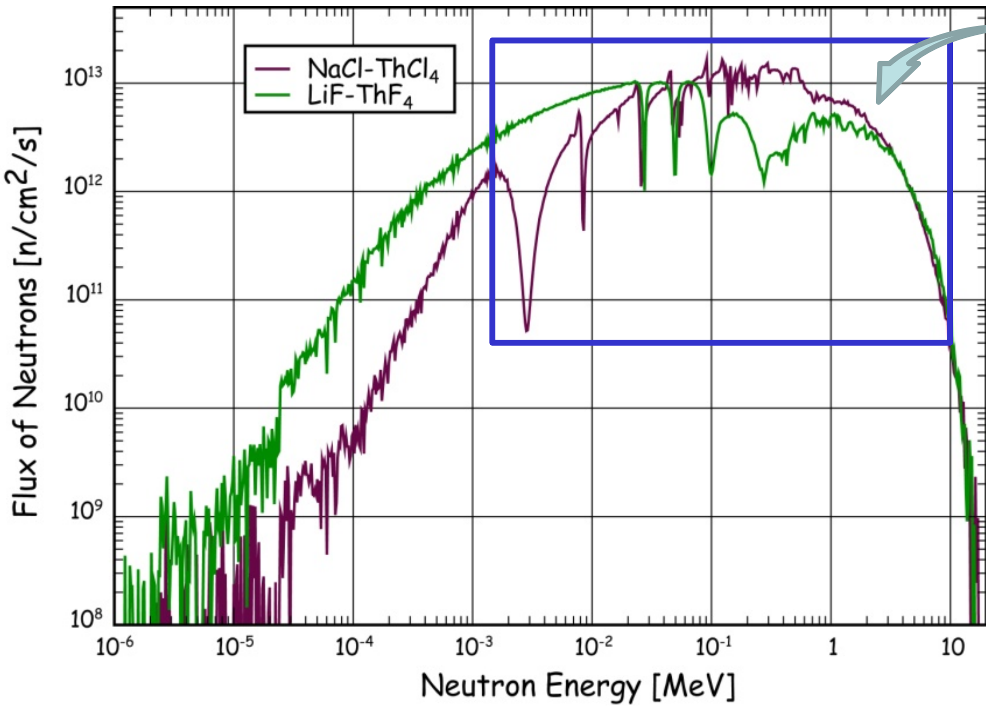
There are two draining modes with its associated system:

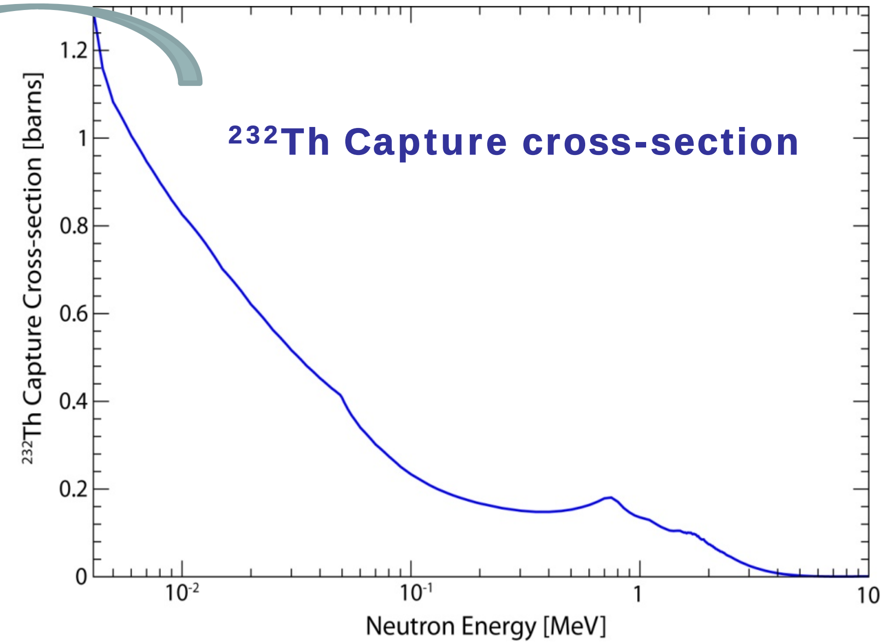
- Controlled routine draining: fuel salt transfer to actively cooled storage tanks, in view of short duration maintenance procedures (a few days to a few weeks). These routine draining tanks, called the storage tanks, also ensure the fuel salt heating and control prior to core filling. The routine draining can be rather slow (e.g., one hour) because the fuel temperature can be lowered prior to draining. This type of draining could be done every 1 to 5 years, when the sectors are replaced.

- Emergency draining: in the event of an anomaly during operation, the fuel salt can be drained directly in the emergency draining tank, either by active devices, or by passive means. This draining must be rapid (e.g., less than 10 minutes) to limit the fuel salt heating in a loss of heat removal event.



MSFR: choice of the liquid fluid





Parameter	Fluoride Salt	Chloride Salt
Thorium capture cross-section in core (barn)	0.61	0.315
Thorium amount in core (kg)	42 340	47 160
Thorium capture rate in core (mole/day)	11.03	8.48
Thorium capture cross-section in blanket (barn)	0.91	0.48
Thorium amount in the blanket (kg)	25 930	36 400
Thorium capture rate in the blanket (mole/day)	1.37	2.86
^{233}U initial inventory (kg)	5720	6867
Neutrons per fission ν in core	2.50	2.51
^{233}U capture cross-section in core (barn)	0.495	0.273
^{233}U fission cross-section in core (barn)	4.17	2.76
Capture/fission ratio α (spectrum-dependent)	0.119	0.099
Total breeding ratio	1.126	1.040

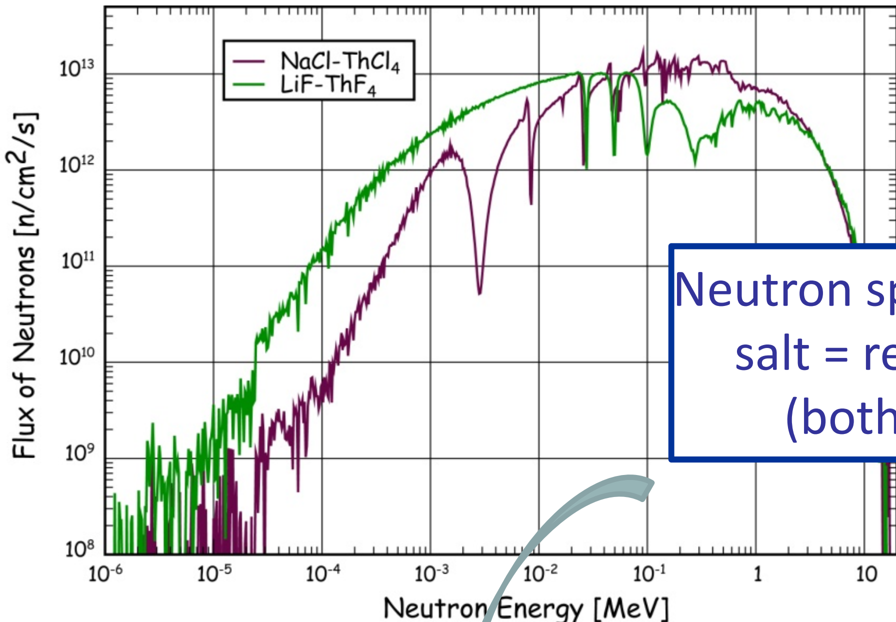
MSFR: choice of the liquid fluid

Element produced	Problem	Fluoride Salt	Chloride Salt
^{36}Cl produced via ^{35}Cl(n,γ)^{36}Cl and ^{37}Cl(n,2n)^{36}Cl	Radioactivity - $T_{1/2}$ = 301000y		10 moles / y (373 g/year)
^{3}H produced via ^{6}Li(n,α) t and ^{6}Li(n,t) α	Radioactivity - $T_{1/2}$ = 12 years	55 moles / y (166 g/y)	
Sulphur produced via ^{37}Cl(n,α)^{34}P(β-[12.34s])^{34}S and ^{35}Cl(n,α)^{32}P(β-[14.262 days])^{32}S	Corrosion (located in the grain boundaries)		10 moles / year
Oxygen produced via ^{19}F(n,α)^{16}O	Corrosion (surface of metals)	88.6 moles/year	
Tellurium produced via fissions and extracted by the on-line bubbling	Corrosion (cf. Sulphur)	200 moles/year	200 moles/year

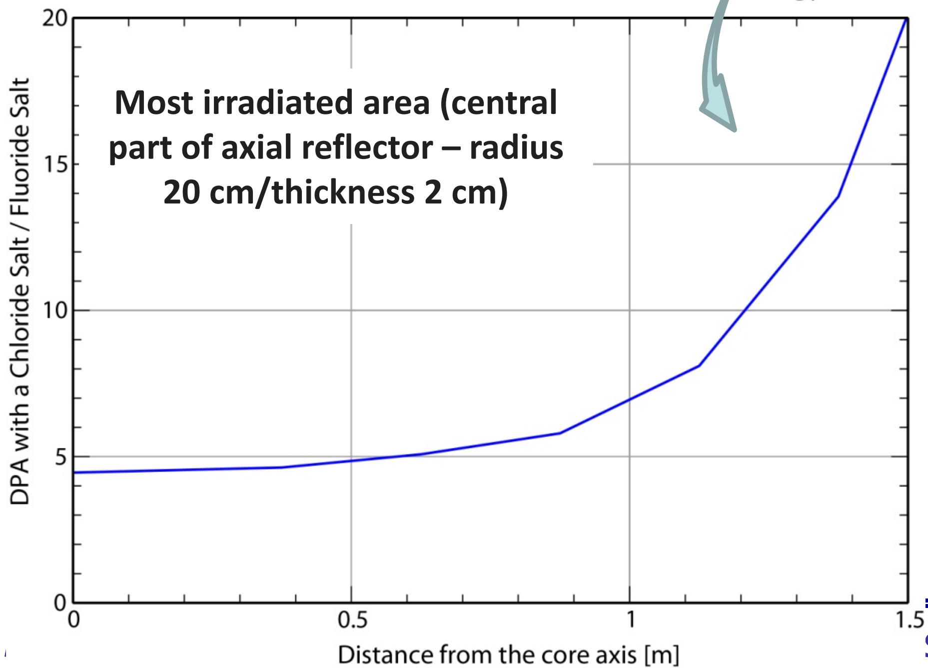
Combination of both neutronic and chemical considerations

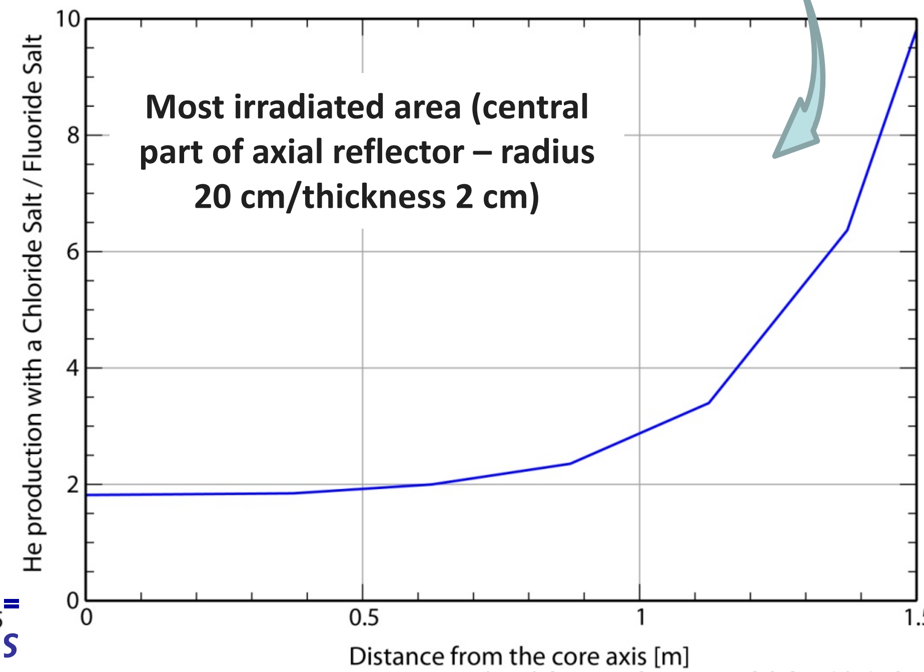
MSFR based on a molten LiF fuel salt

MSFR: choice of the liquid fluid



Neutron spectrum less fast with fluoride salt = reduced irradiation damages (both DPA and He production)





Demonstration steps and Demonstrator of MSFR

Sizing of the facilities:

Small size: ~1liter - chemistry and corrosion – off-line processing
Pyrochemistry: basic chemical data, processing, monitoring

Medium size: ~100 liters – hydrodynamics, noble FP extraction, heat exchanges
Process analysis, modeling, technology tests

Full size experiment: ~1 m^3 salt / loop – validation at loop scale
Validation of technology integration and hydrodynamics models

3 levels of radio protection:

- ✓ Inactive simulant salt ⇨ Standard laboratory
  Hydrodynamics, material, measurements, model validation
- ✓ Low activity level (Th, depleted U) ⇨ Standard lab + radio protect
  Pyrochemistry, corrosion, chemical monitoring
- ✓ High activity level ($^{enriched}U$, ^{233}U, Pu, MA) ⇨ Nuclear facility
  Fuel salt processing: Pyrochemistry, , Actinides recycling

First steps toward a demonstration of MSFR: the FFFER loop at LPSC Grenoble – FLiNaK salt – Technological aspects

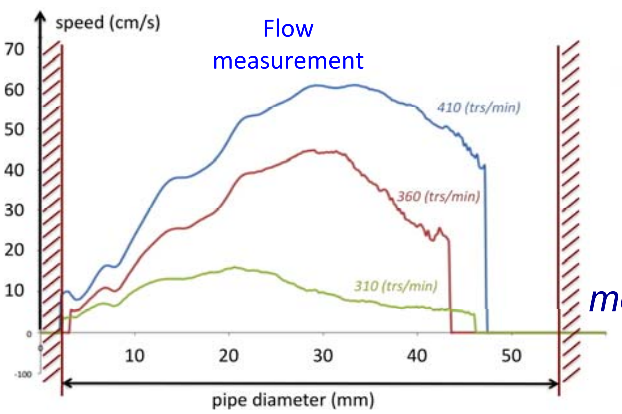
The Forced Fluoride Flow Experiment

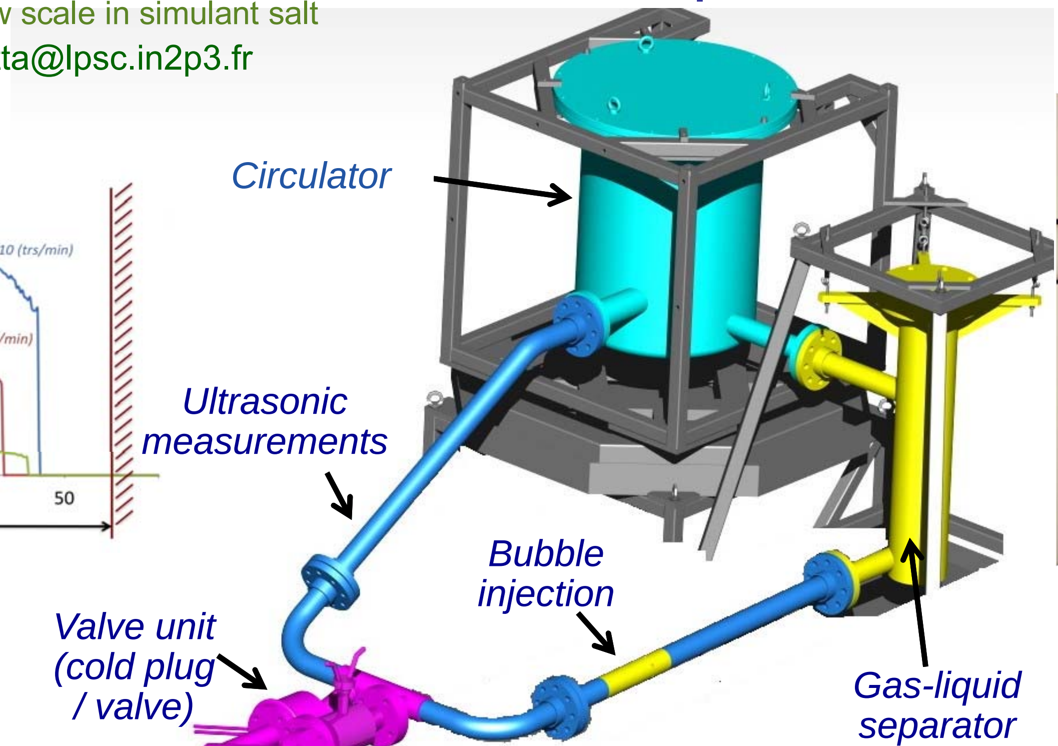
Reproduces the gases and particles extractions at 1/10th flow scale in simulant salt

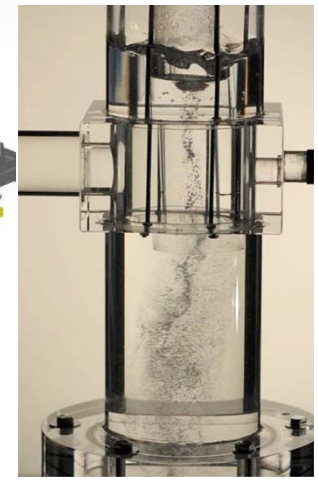
Veronique.Ghetta@lpsc.in2p3.fr

Next step: SWATH facility (SAMOFAR project, WP3, see presentation of J.L. Kloosterman)

SAMOFAR







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LPSC Grenoble

Concept of MSFR: Fuel processing

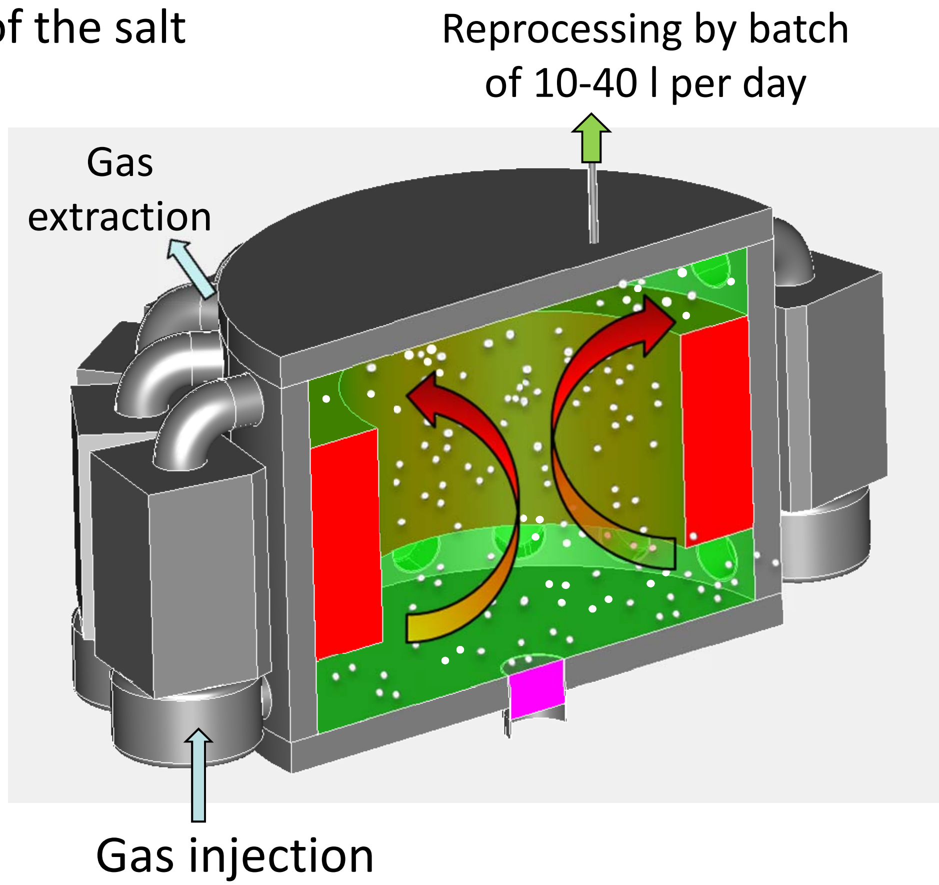
4th Generation reactors => Breeder reactors

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

Fission Products Extraction: Motivations

✓ Control physicochemical properties of the salt (control deposit, erosion and corrosion phenomena's)

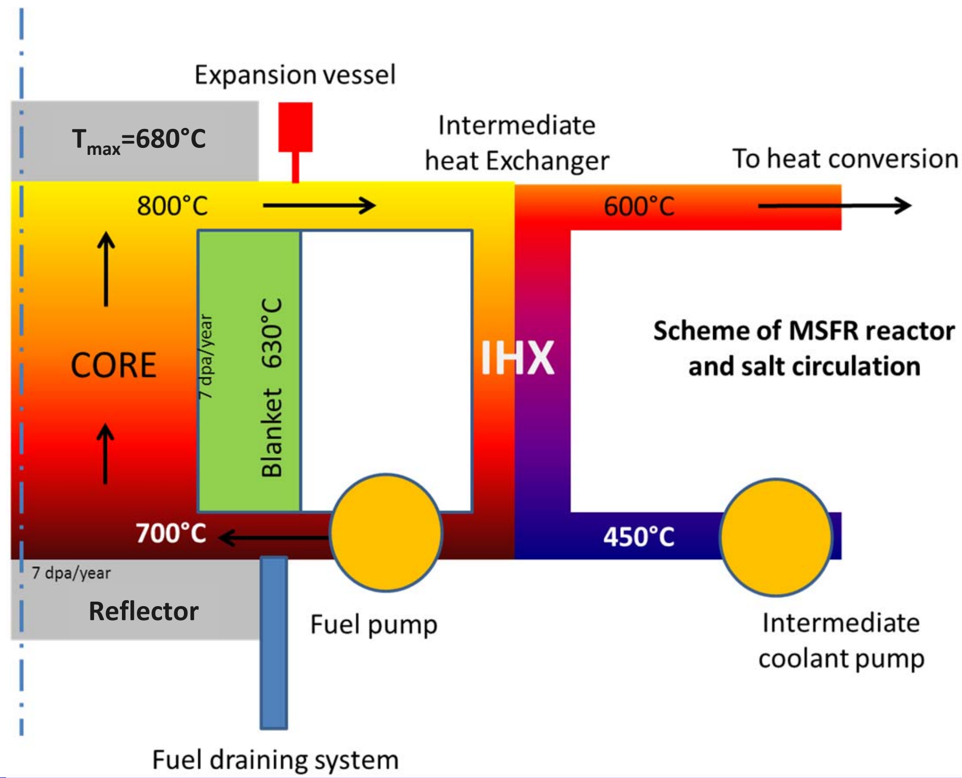
✓ Keep good neutronic properties



Concept of MSFR: structural materials (Ni-based alloys) resistance

Ni	W	Cr	Mo	Fe	Ti	C	Mn	Si	Al	B	P	S
79.432	9.976	8.014	0.736	0.632	0.295	0.294	0.257	0.252	0.052	0.033	0.023	0.004

Neutronic irradiation damages to the structural materials (modify their physicochemical properties) = displacements per atom, production of Helium gas, transmutation of Tungsten in Osmium, activation – At high temperatures



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Neutronic irradiation damages to the structural materials (modify their physicochemical properties) = displacements per atom, production of Helium gas, transmutation of Tungsten in Osmium, activation

Structural elements: layers	Displacements per atom	He production	Tungsten transmutation
0-2.5 cm	6.8 dpa/year	12 ppm / year	0.11 at% /year
2.5-7.5 cm	3.5 dpa/year	6 ppm / year	0.07 at% /year

To be experimentally studied: He production (maximal acceptable amount, diffusion effects?) + Effects on the long-term resistance of structural materials due to W transmutation + Effects of high temperature on structural materials

Conclusions:

- Irradiation damages low + Limits unknown
- Irradiation damages limited to the first 10 cm (replaced 3-4 times or use a thin layer of SiC for example as thermal protection)
- Materials not under large mechanical stress

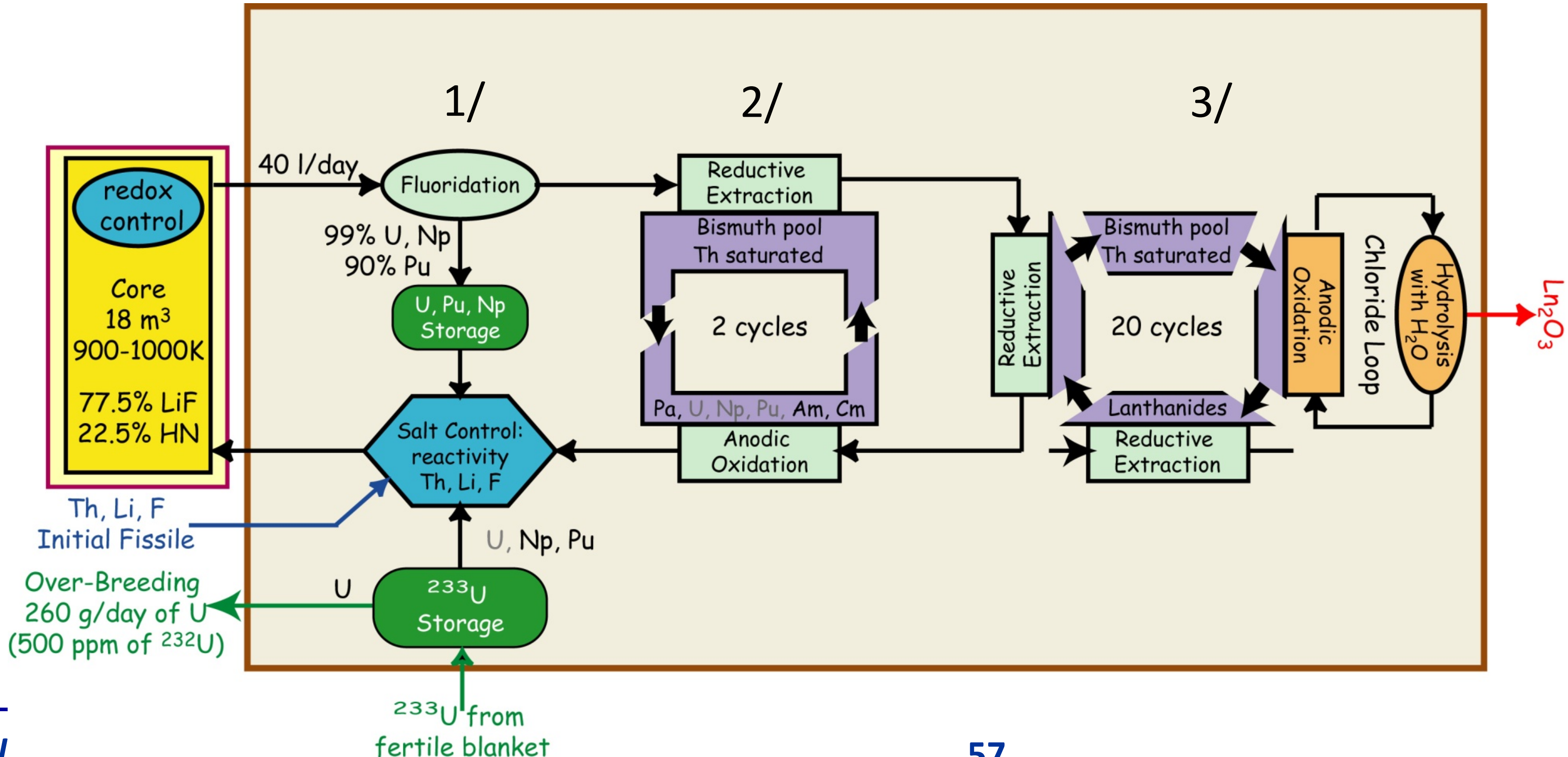
Concept of MSFR: Fuel processing

On-site Chemical Processing Unit

1/ Salt Control + Fluorination to extract U, Np, Pu + few FPs - Expected efficiency of 99% for U/Np and 90% for Pu – Extracted elements re-injected in core

2/ Reductive extraction to remove actinides (except Th) from the salt – MA re-injected by anodic oxidation in the salt at the core entrance

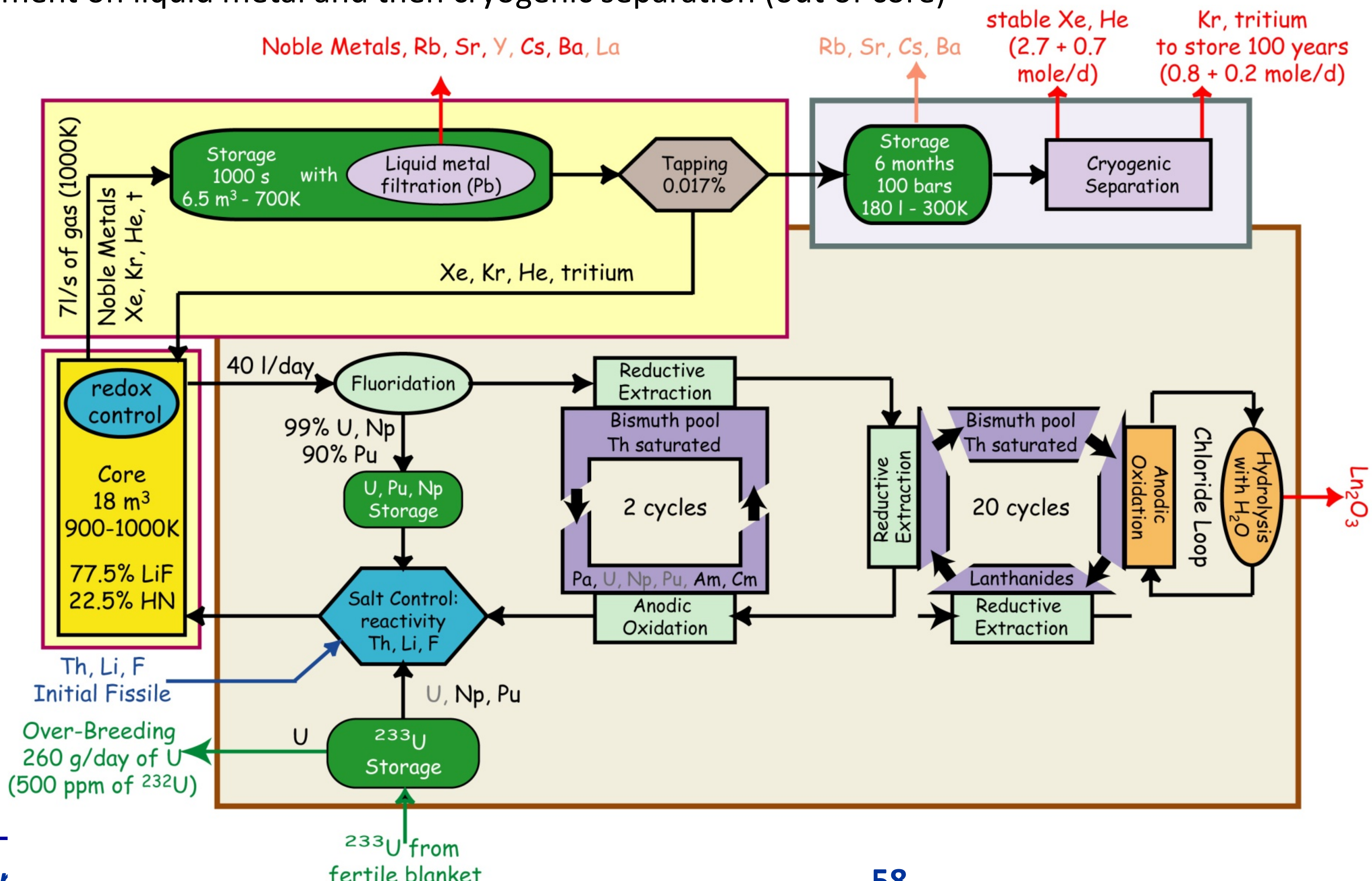
3/ Second reductive extraction to remove all the elements other than the solvent - lanthanides transferred to a chloride salt before being precipitated



Concept of MSFR: Fuel processing

Noble gazes bubbling in the core (within the fuel salt loop)

To remove all insoluble fission products (mostly noble metals) and rare gases, helium bubbles are voluntary injected in the flowing liquid salt (bottom of the core) → Separation salt / bubbles → Treatment on liquid metal and then cryogenic separation (out of core)



Concept of MSFR: Starting modes and deployment capacities

"Incinerator MSR" identical to MSFR except for the fuel salt composition + suppression of the fertile blanket

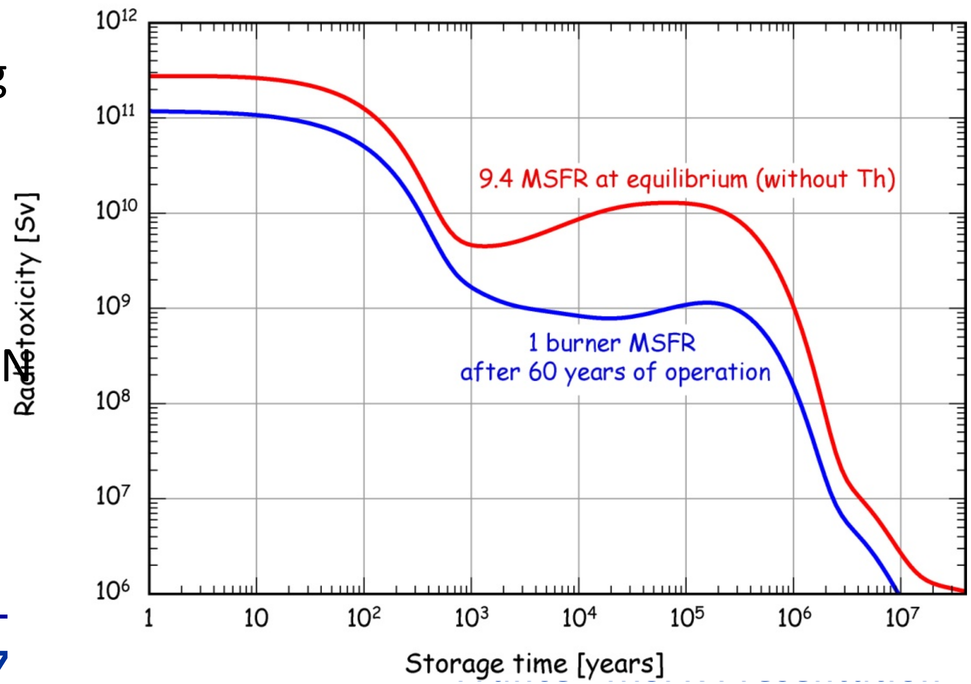
Fuel salt: FLiNaK with 46.5% ^{7}LiF, 11.5% NaF, 41.7% KF, $(HN)F_4$

- Melting point correctly low even with small HN proportion (no Th) in the salt
- Neutron spectrum not too thermalized

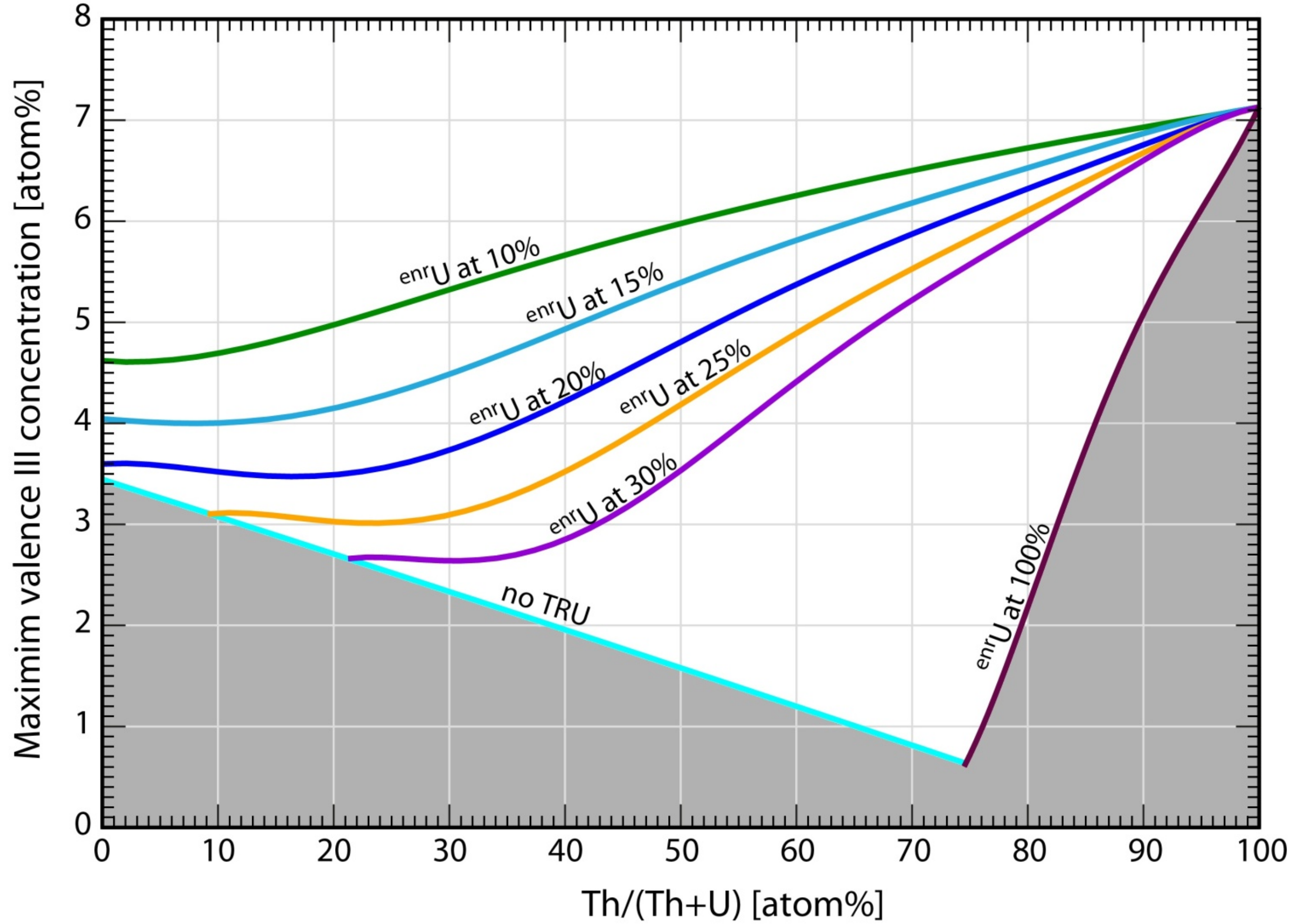
Incinerator operation:

- Initial HN load to reach criticality: 685 kg of transTh from MSFR
- Fueled with transTh from MSFR to maintain reactivity
- Shutdown after 60 years of operation: HN burning equivalent to 9.4 MSFR inventories

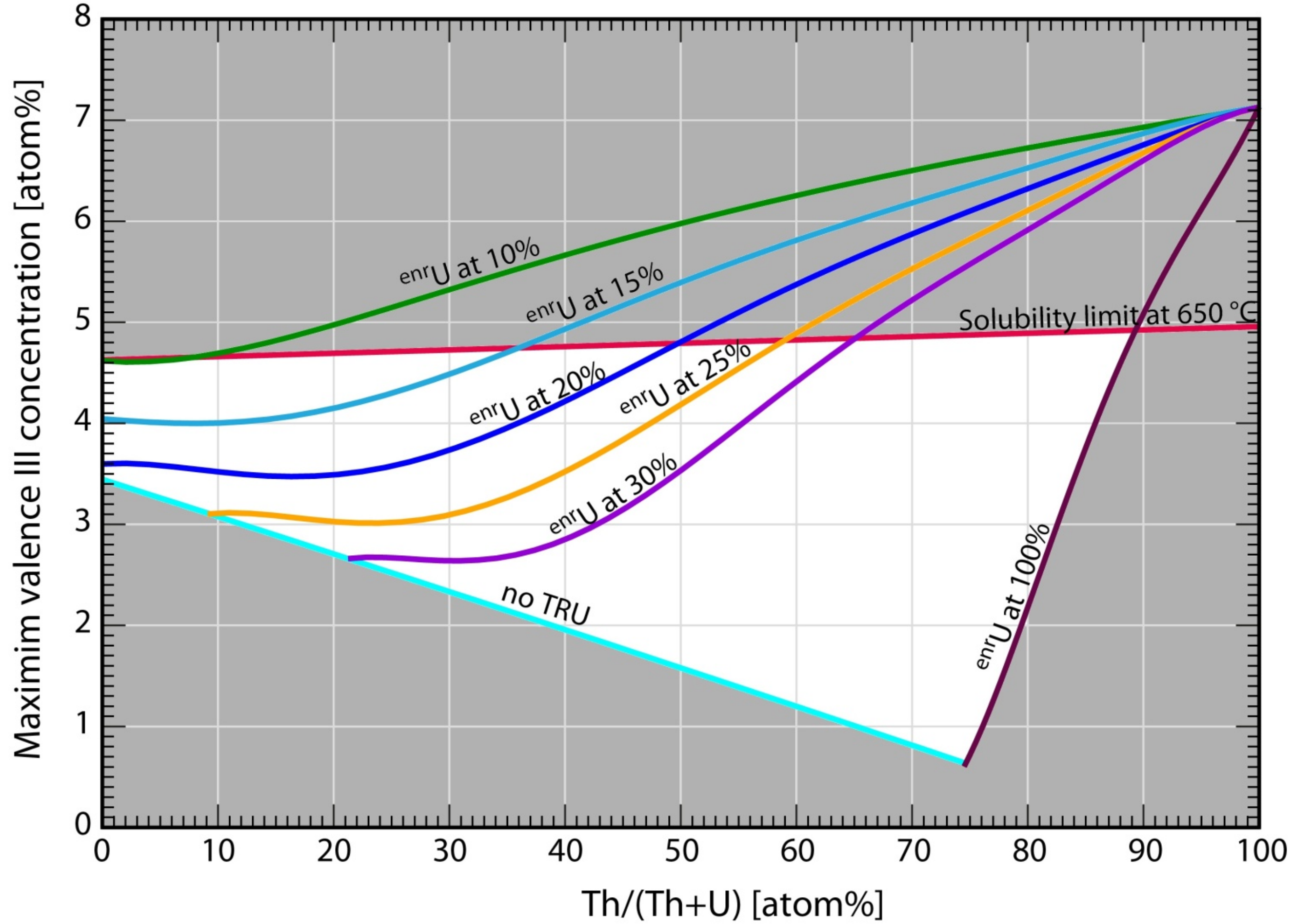
[kg]	9.4 MSFR (input)	Inventory at 60 yrs	Burning efficiency
U	72 751	6 407	11.5
Np	1 381	506	2.8
Pu	2 768	1 530	1.8
Am	72	39	1.8
Cm	33	64	0.5
HN	77 005	8 550	9.1



Power Demonstrator of the MSFR: initial fissile load

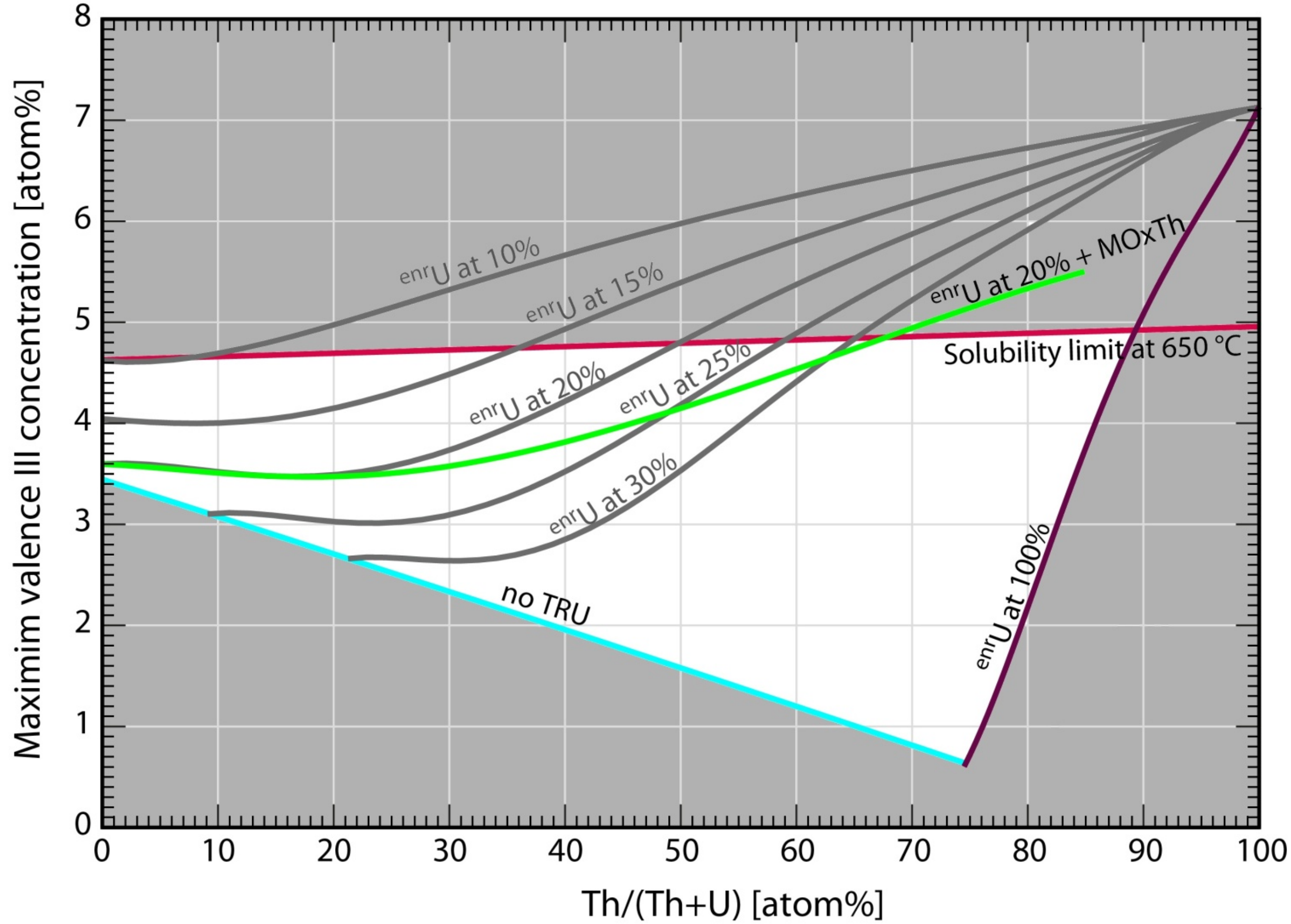


Power Demonstrator of the MSFR: initial fissile load



✓ enrichedU mixed with transuranic elements possible with U enrichment of 15% - 20%

Power Demonstrator of the MSFR: initial fissile load



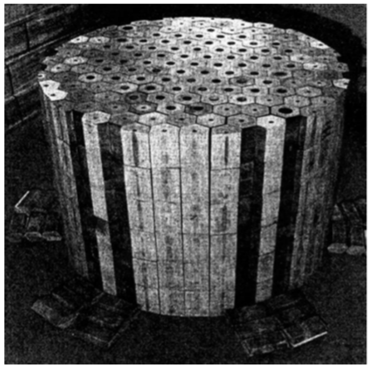
- ✓ enrichedU mixed with transuranic elements possible with U enrichment of 15% - 20%
- ✓ Uranium enriched at 20% mixed with irradiated MOx-Th with a ratio of Th/(Th+U) = 20 to 65%

Molten Salt Reactors - Renewal of the concept

- Thorims-NES5 then FUJI-AMSB in Japan since the 80's
  Reactor of very low specific power fed with ^{233}U produced in sub-critical reactors
- Resumption of the MSBR's studies by CEA and EDF since the 90's
- TIER-1 project of C. Bowman in the 90's
  Pu burner (LWR's spent fuel assemblies dissolved in liquid fuel) in sub-critical reactors
- TASSE (CEA) project in the 90's
  Plutonium burner (liquid fuel) in sub-critical reactors
- AMSTER (EDF) project in the 90's
  Plutonium burner then breeder reactor in Thorium cycle
- REBUS (EDF), MOSART (Kurchakov Institute), SPHINX (Czech Republic)
  Projects of actinide burners
- MOST Network, FP5, 2001-2004
  European network having assessed the studies, the experiments and the state of knowledge concerning molten salt reactors
- ALISIA (Assessment of Liquid Salts for Innovative Applications), FP6, 2007-2008
  European Action - Lead authors : O.Bene C. Cabet, S. Delpech, P. Hosnedl, V. Ignatiev, R. Konings, D. Lecarpentier, O. Matal, E. Merle-Lucotte, C. Renault, J. Uhlir, 6st Euratom Framework Prog.

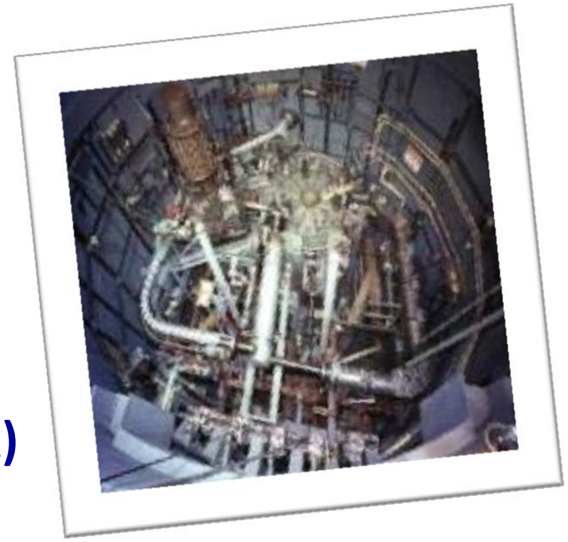
Molten Salt Reactors – Historical Studies

Historical studies of MSR: Oak Ridge Nat. Lab. - USA



- 1954 : **Aircraft Reactor Experiment (ARE)**
  Operated during 1000 hours
  Power = 2.5 MWth

- 1964 – 1969: **Molten Salt Reactor Experiment (MSRE)**
  Experimental Reactor
  Power: 7.4 MWth
  Temperature: 650°C
  U enriched 30% (1966 - 1968)
  ^{233}U (1968 – 1969) - ^{239}Pu (1969)
  No Thorium inside



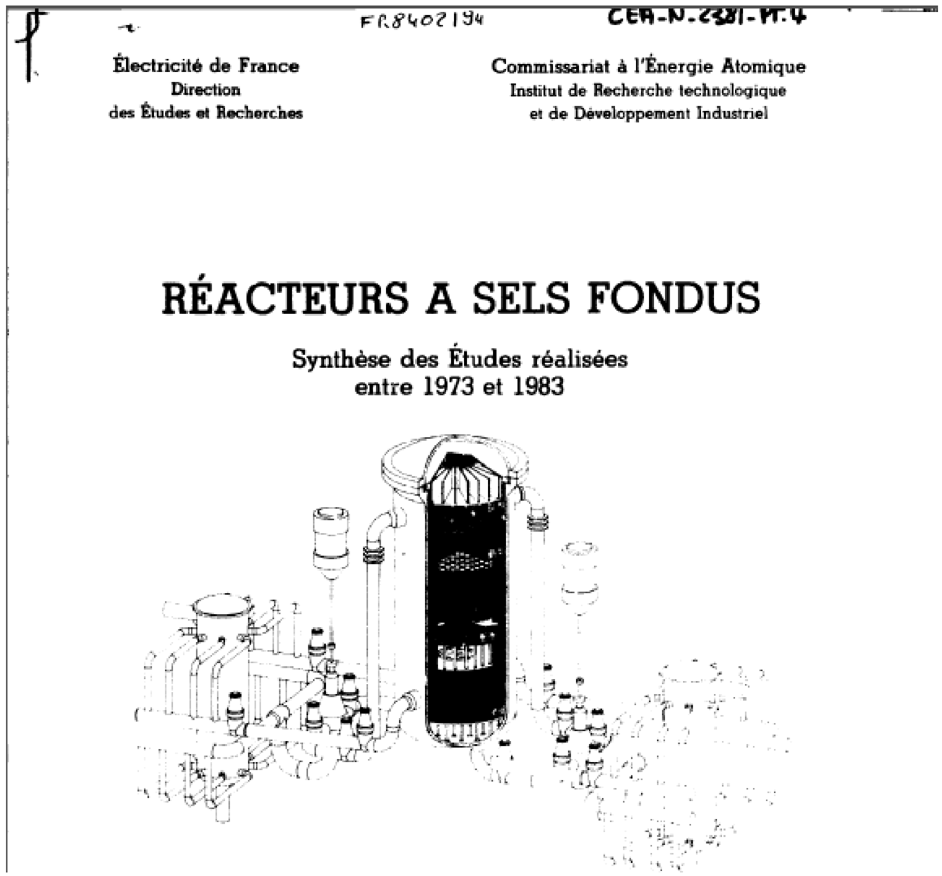
- 1970 - 1976: **Molten Salt Breeder Reactor (MSBR)**
  Never built
  Power: 2500 MWth
  Thermal neutron spectrum

Molten Salt Reactors - Renewal of the concept

- Thorims-NES5 then FUJI-AMSB in Japan since the 80's

  Reactor of very low specific power fed with ^{233}U produced in sub-critical reactors

- Resumption of the MSBR's studies by CEA and EDF – 70's to 80's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Électricité de France
Direction
des Études et Recherches

Commissariat à l'Énergie Atomique
Institut de Recherche technologique
et de Développement Industriel

RÉACTEURS A SELS FONDUS

Synthèse des Études réalisées
entre 1973 et 1983

Molten Salt Reactors - Renewal of the concept

Past studies on Molten Salt Reactors at EDF R&D
since 2000

At the begining of the 2000'

1. Study of actinide Burner on thorium support AMSTER (adaptation of the MSBR) – 2001

From 2001 to 2005 Thorium breeder in thermal spectrum considered as a better option for sustainalitity.

1. In-house research : neutronic / processing / corrosion
2. Support to CNRS and CEA research
3. Contribution to European projects
   MOST (2001), ALISIA (2007), SAMOFAR (2015)

Since 2005 non moderated Thorium breeder as most promizing option for sustainability

Contact person: David LECARPENTIER, EDF R&D

MSR - Renewal of the concept – CNRS studies

- Participation to the project TIER I of C. Bowman (1998)

- Re-evaluation of the MSBR from 1999 to 2002

  PhD thesis of Alexis NUTTIN

  Use of a probabilistic neutronic code (MCNP)

  Development of an in-house evolution code for materials (REM)

  Coupling of the neutronic code with the evolution code

- From the Thorium Molten Salt Reactor to the Molten Salt Fast Reactor

  Breeder in the Thorium fuel cycle and Actinide Burner Reactor

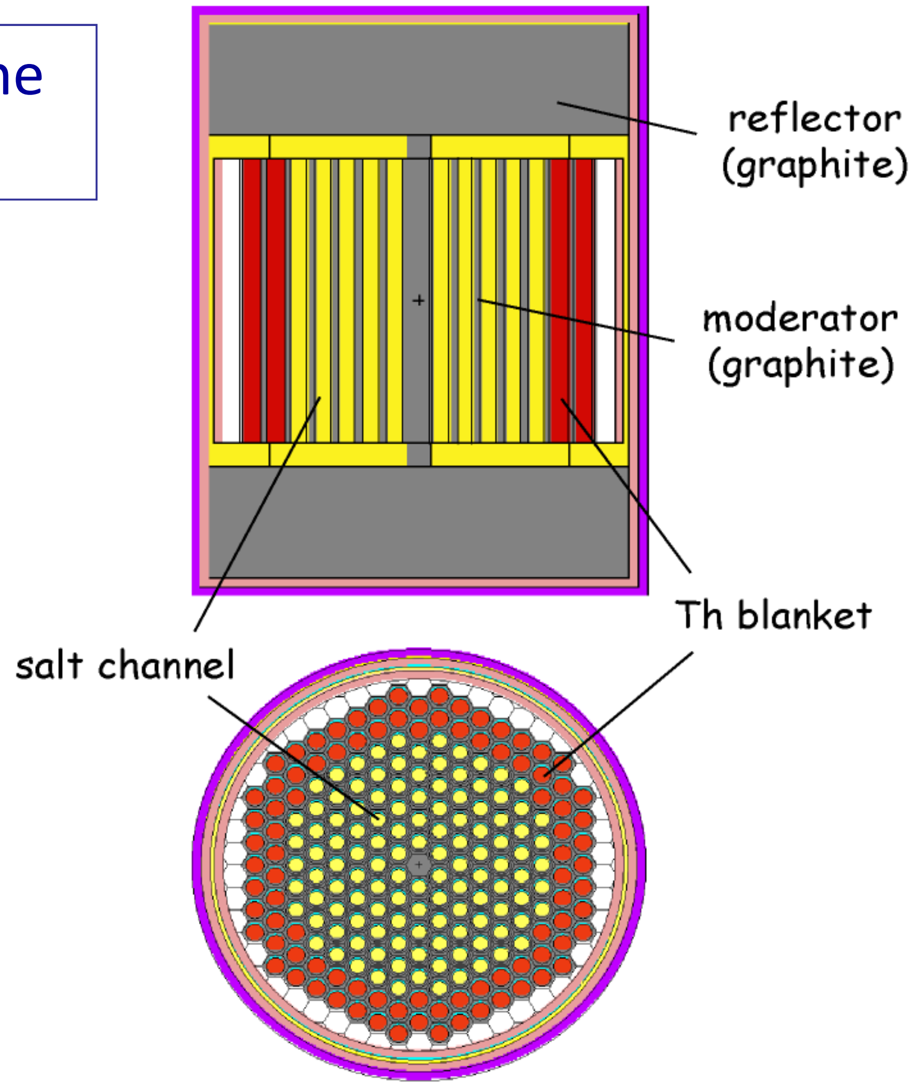
  Developed to solve the problems of the MSBR project

  - Bad (null to positive) feedback coefficients
  - Positive void coefficient
  - Unrealistic reprocessing
  - Problems specific to the graphite moderator
    - Lifespan
    - Reprocessing and storage
    - Fire risk

Historical MSR Studies at CNRS

Systematic studies (PhD thesis L. Mathieu)

Molten Salt Reactor operated in the Thorium Fuel Cycle



TMSR general parameters:

- total power: 2500 MWth (1000 MWe)
- salt composition:

78% LiF – 22% (HN)F_4 (21.4% ThF_4 – 0.6% UF_4)

- mean temperature: 630 °C (900 K)

TMSR geometrical parameters:

- core shape: cylindrical (H=D)
- salt volume: 20 m^3
- fertile blanket: Thorium
- hexagon size (moderator): 15 cm
- channel radius (fuel salt): varying

Safety Evaluation of the MSFR: Other tools

- An **identification of main risks and possible accidents** should be performed before starting PIRT and OPT. This task will be achieved by applying both top-down and bottom-up methods

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- Top-down approaches:
  - **Master Logic Diagram (MLD)**
    - Identify top events to be prevented, build-up detailed sub-events and then look for all possible causes for these events, considering all phenomena physically possible
    - *application to the MSFR initiated at CNRS*

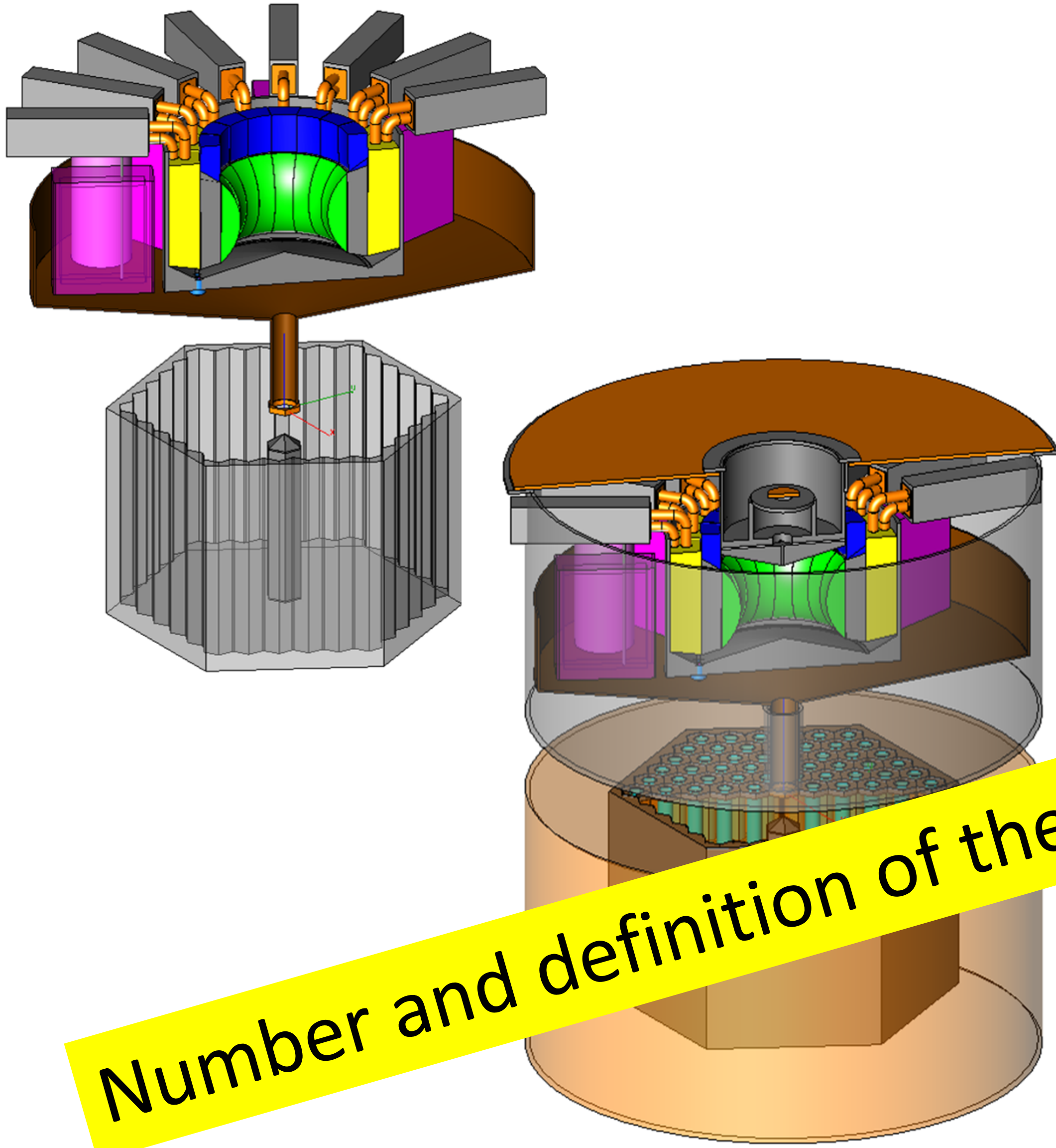
PhD thesis of Delphine Gérardin

  - **Lines Of Defense (LoD)**
    - Ensure that every accidental evolution of the reactor state is always prevented by a minimum set of homogenous (in number and quality) safety features

PhD thesis of Anna-Chiara Uggenti

- Bottom-up approaches:
  - **Functional Failure Mode and Effect Analysis (FFMEA)**
    - *application to MSFR initiated at Polito*

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

→ Proposition of a 'segmented MSFR design'

\+

Propo... ...arriers:

...uel envelop, ...sed 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

Number and definition of the barriers to be done

Concept of MSFR: Starting modes and deployment capacities

MSFR configurations considered in this deployment scenario:
3 kinds of ^{233}U-TRU started MSFR + "incinerator" MSFR (end-of-game studies)

MSFR started with U-Pu-AM + Mox-Th Compositions [kg/GW_{el}]		
Z	Initial	60 years
90	18301	22817
91	20	81
92	2684	4992
93	54	71
94	6034	490
95	1779	72
96	54	178

MSFR started with 1,5% ^{233}U + Pu-AM Uox 50 years Compositions [kg/GW_{el}]		
Z	Initial	60 years
90	21493	23109
91	0	82
92	1922	5083
93	372	72
94	4305	298
95	778	33
96	13	72

MSFR started with ^{enri}U + TRU (ref EVOL composition) Compositions [kg/GW_{el}]		
Z	Initial	60 years
90	9944	21851
91	0	56
92	17341	7457
93	324	69
94	4552	2389
95	278	153
96	47	133

MSFR "incinerator" started with transTh from previous MSFR Compositions [kg/GW_{el}]		
Z	Initial	60 years
90	0	0,3
91	1.2	1,8
92	872	4232
93	13	309
94	81	1376
95	15	122
96	23	398

Very good deployment capacities -
Transition to the Thorium fuel cycle achieved
+ Close the current fuel cycle (reduce the stockpiles of produced transuranic elements)

D. Heuer, E. Merle-Lucotte, M. Allibert, M. Brovchenko, V. Ghetta, P. Rubiolo , *"Towards the Thorium Fuel Cycle with Molten Salt Fast Reactors"*, Annals of Nuclear Energy 64, 421–429 (2014)

Concept of MSFR: safety issues

REPORT

IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Review of Generation IV Nuclear Energy Systems

6.7 CONCLUSION REGARDING REACTORS OPERATING WITH FUEL SALT

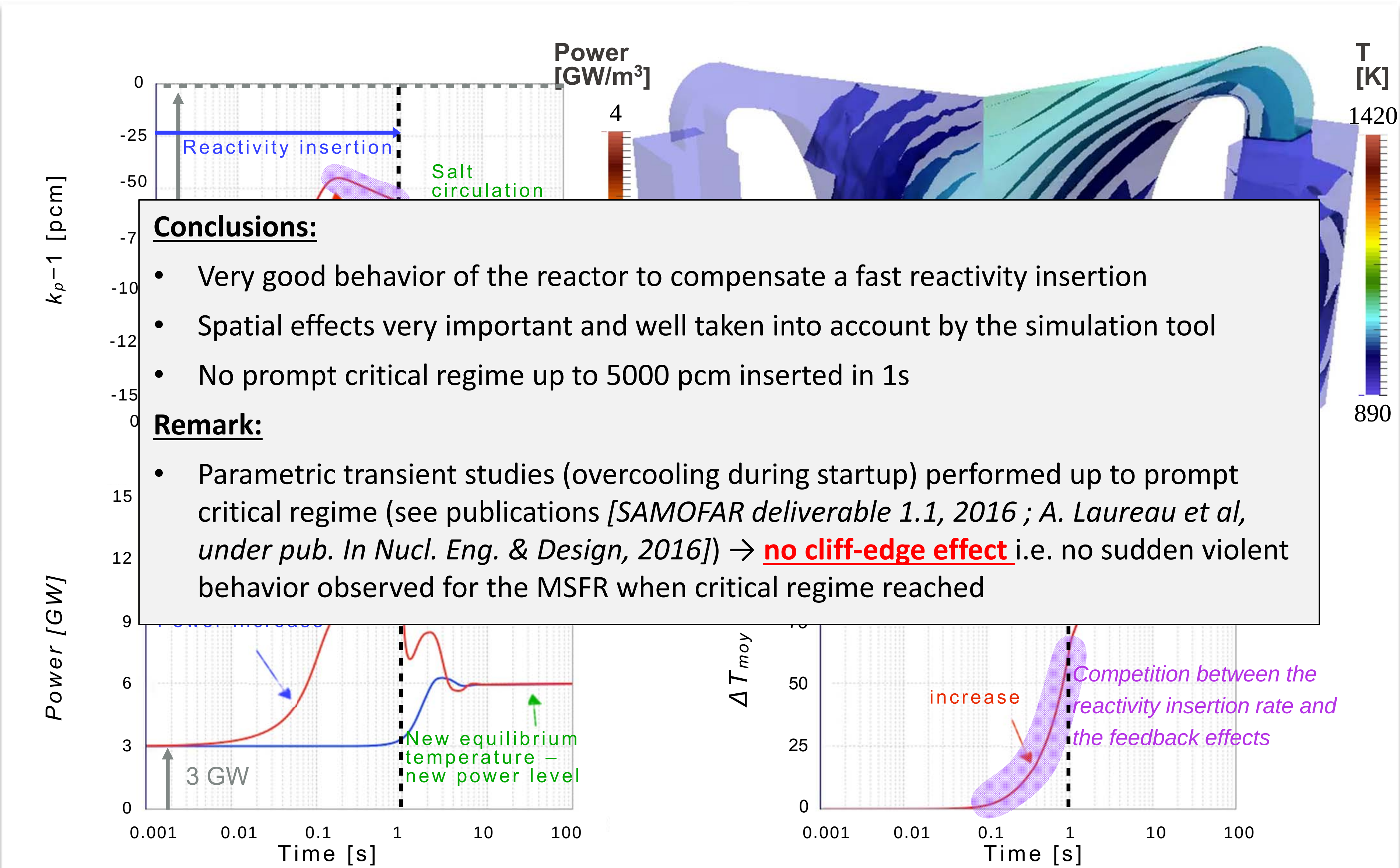
The fuel salt-based MSR concept is very different to the other concepts selected by GIF, owing in particular to the fact that the fuel is in liquid form and combined with the coolant. These characteristics give it interesting intrinsic nuclear properties, in theory enabling very stable reactor operation: the neutron feedback coefficients are strongly negative, even for a large power fast-spectrum reactor. This behaviour poses a problem, however, in terms of the approach to criticality during reactor startup, particularly with the MSFR concept, which does not feature control rods.

A time-dependent linear reactivity insertion of 500 pcm for insertion time from 1s to 500 s was studied. This approach appears to adequately cover the various reactivity insertion conditions described previously.

Analysing the transient using a zone-based point kinetics model in the fuel system revealed that no power surges liable to damage reactor internals occur when the insertion time is longer than approximately 1 second.

Furthermore, the designers indicate that despite the low proportion of delayed neutrons, the reactor would be able to tolerate reactivity insertions of up to 1000 pcm in 1 second, at which level the core would reach prompt criticality (taking feedback into consideration).

Concept of MSFR: the TFM approach – Application to transient calculations (reactivity insertion – 1000 pcm in 1s)



Conclusions:

- Very good behavior of the reactor to compensate a fast reactivity insertion
- Spatial effects very important and well taken into account by the simulation tool
- No prompt critical regime up to 5000 pcm inserted in 1s

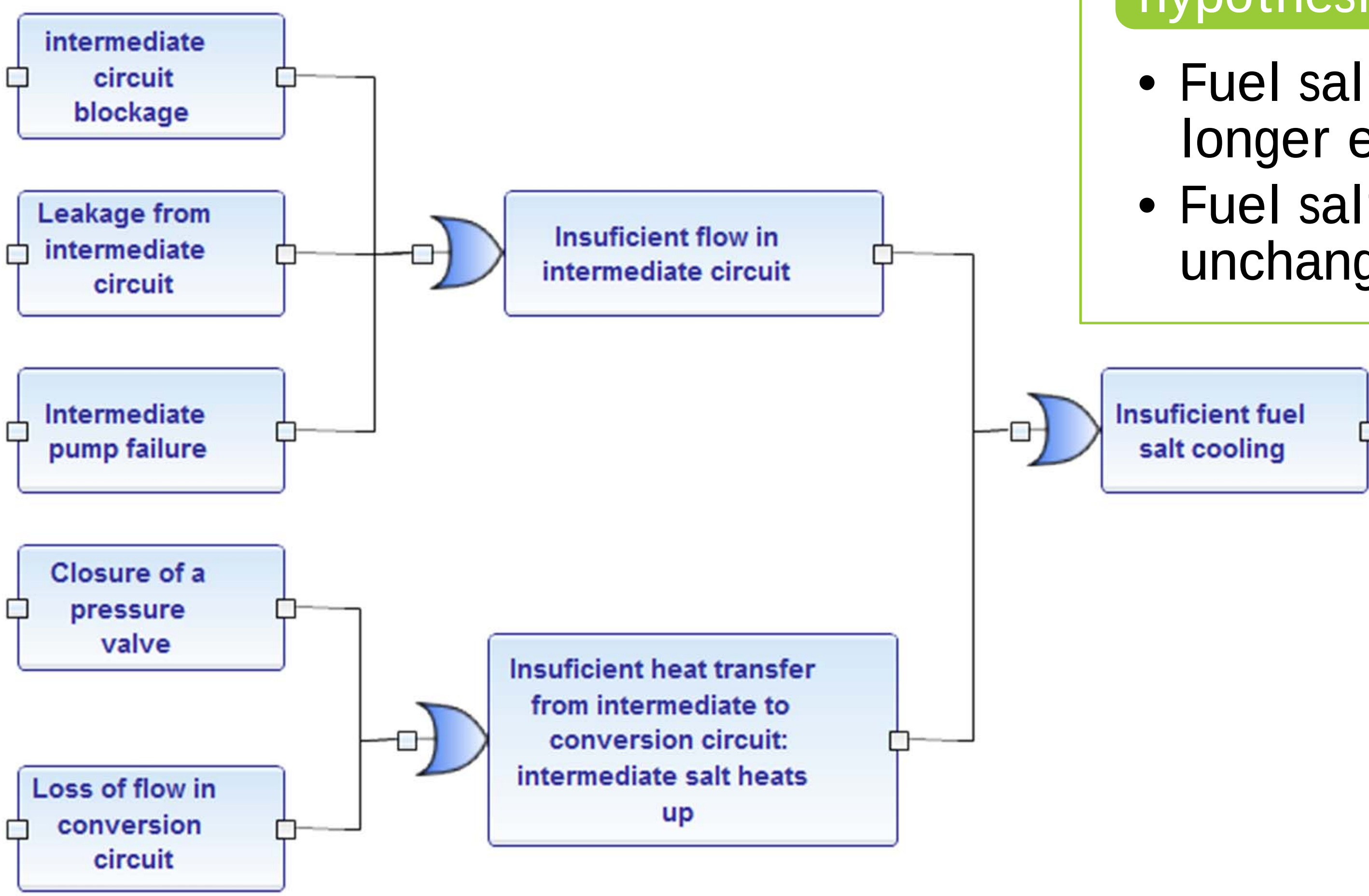
Remark:

- Parametric transient studies (overcooling during startup) performed up to prompt critical regime (see publications *[SAMOFAR deliverable 1.1, 2016 ; A. Laureau et al, under pub. In Nucl. Eng. & Design, 2016]*) → **no cliff-edge effect** i.e. no sudden violent behavior observed for the MSFR when critical regime reached

A. Laureau et al, "Coupled Neutronics and Thermal-hydraulics Transient Calculations based on a Fission Matrix Approach: M&C, SNA and MC Method International Conference, Nashville, USA (2015)

Fuel circuit accidents: examples

LOHS - Loss Of Heat Sink



Accident hypothesis

- Fuel salt cooling no longer ensured
- Fuel salt circulation unchanged

Fuel circuit accidents: examples

LOHS - Loss Of Heat Sink

Phenomena

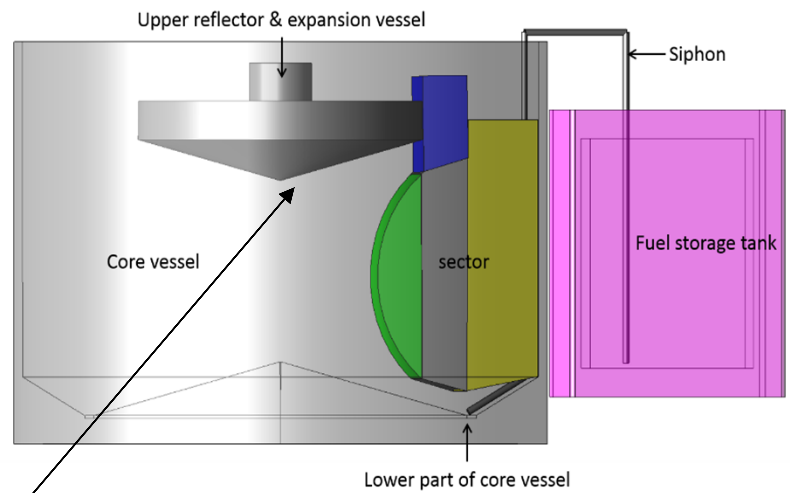
- Reactor power shutdown because of neutronic feedbacks
- Fuel salt heating because of residual heat

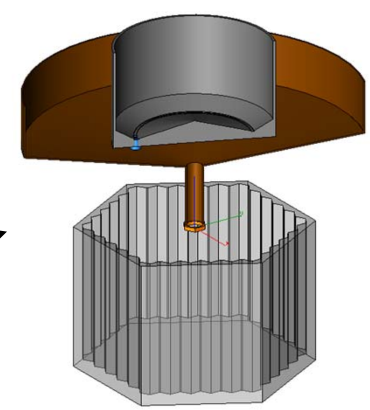
Risks

- Damage to the structure due to high temperature or salt expansion

Provisions

- In case of loss of intermediate flow
  - Natural convection in intermediate circuit
  - Intermediate fluid thermal inertia
  - In case of pump failure in intermediate circuit:
    - Intermediate pump inertia
- Overflow system to prevent fuel salt dilation consequences
- Draining system to prevent too high fuel temperature consequences
- Thermal resistant structural materials





Fuel circuit accidents: examples

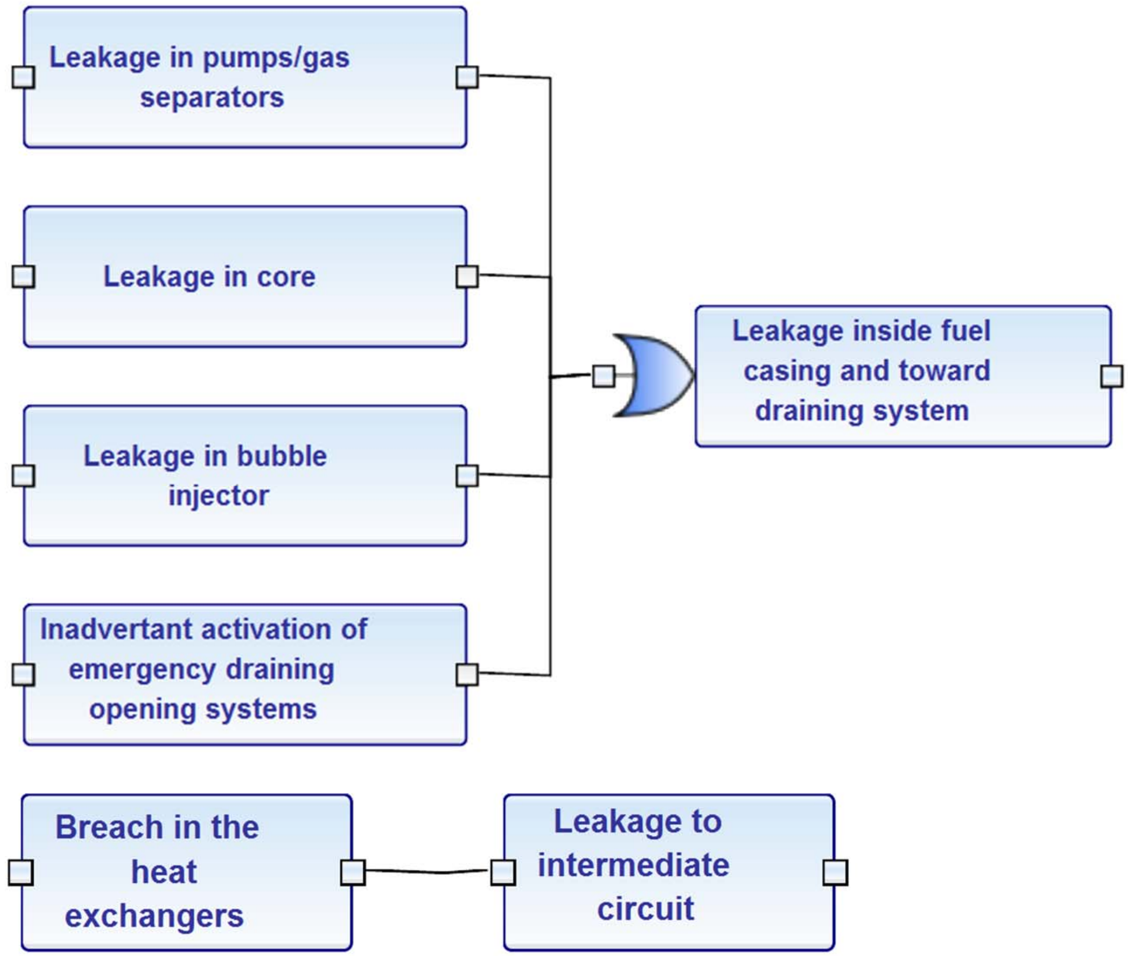
LOLF - Loss Of Liquid Fuel

Accident hypothesis

- significant leak of the fuel salt outside the fuel circuit.

Note

- Accident particularly important in liquid fuel reactor for design optimization



Fuel circuit accidents: examples

LOLF - Loss Of Liquid Fuel

Phenomena

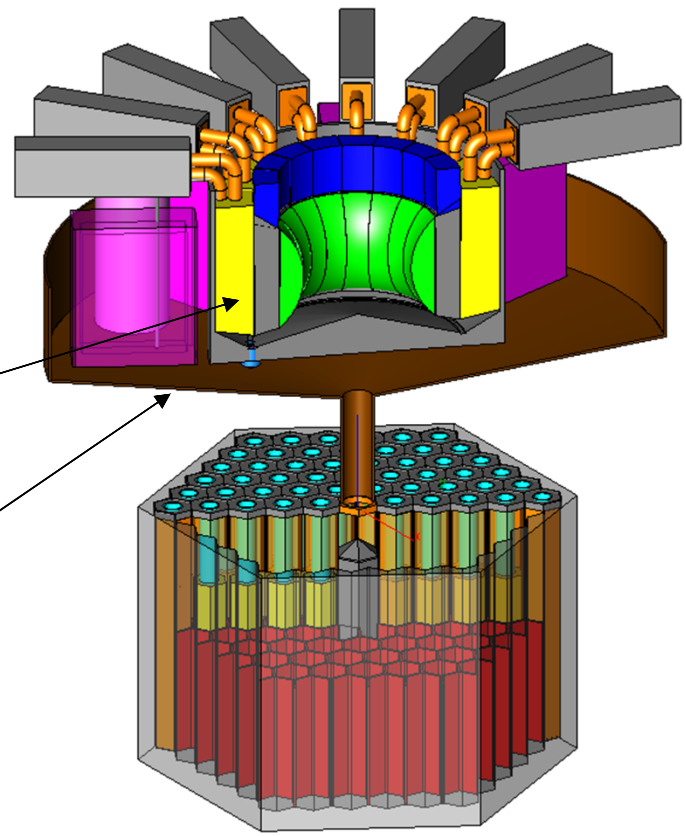
- Interruption of fuel flow and cooling
- Reactor shutdown

Risks

- Contamination of other parts of the reactor

Provisions

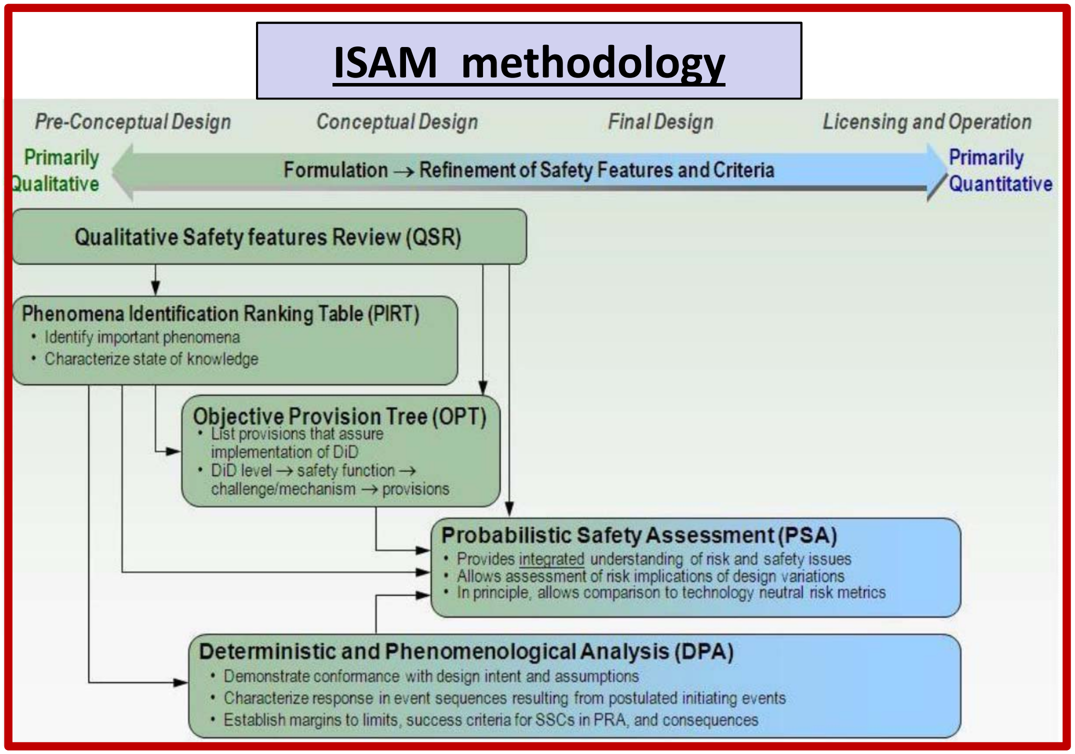
- Design optimized to reduce risk of leakage (segmented geometry)
- Early leakage detection (to be defined)
- Collector position beside the fuel casing in order to recover the fuel
- Higher pressure in the intermediate circuit than in the fuel circuit

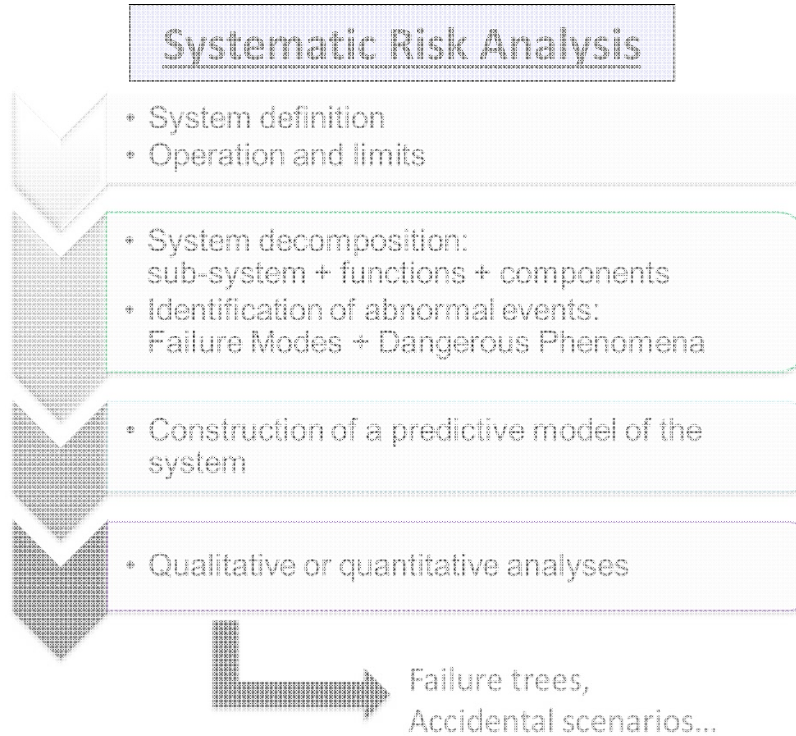


Complementary studies proposal

- Definition of inspection and control devices and procedures

Safety Evaluation of the MSFR: ISAM + Systematic Risk Analysis





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Application of GIF methodology: ISAM (QSR) & MSFR

Preliminary results of the QSR application to the fuel circuit of the MSFR (2014) = list of a few significant points that need to be covered, for example:

✓Analyze the **non stationary thermal-hydraulic behavior in the fuel circuit** for a operational/incidental/accidental transient (impact of natural convection; detailed design of the heat exchangers) – Utility of a **redundant safety system for the residual heat removal?**

✓Specify the **reactor normal operation procedures** (start-up , follow-up and shut-down) to identify safety issues

✓Add one or several **temperature and/or reactivity control systems** dedicated to the start or shut-down, transients (filling or draining procedures)

✓ **Select the intermediate fluid and subsequently design the intermediate circuit** and the heat exchangers

✓ Large number of **passive systems and procedures** included in the MSFR design, some **used for both normal operation and incidental/accidental conditions**: positive or not for safety issues?

PRELIMINARY

Other sub-systems of the MSFR to be analyzed: fertile blanket, gas processing system, processing and radioactive material storage systems, intermediate circuit, thermal conversion circuit

Exchanges with the RSWG of the Gen4 International Forum
(MSFR presentation during the last RSWG meeting mid-october 2016)