GEN IV International Forum

CONCEPT OF EUROPEAN MOLTEN SALT FAST REACTOR (MSFR)

Prof Elsa MERLE
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May 23, 2017

With the support of the National NEEDS Program and the IN2P3 institute of CNRS, of UGA and Grenoble Institute of Technology, and of the EVOL and SAMOFAR Euratom Projects

Meet the presenter

Elsa Merle is professor in France at the PHELMA engineering school of Grenoble Institute of Technology, director of the Master's Program in Reactor Physics and Nuclear Engineering. She is also working at the Laboratory for Subatomic Physics and Cosmology of Grenoble in the research staff, in the MSFR research team. Since 2000, she has been actively involved in the CNRS (French National Center for Scientific Research) programs dedicated to the conceptual design of innovative Generation IV reactors. As such, she is contributing to various studies and validations of the concept of Molten Salt Reactors and more specifically since 2008 on the definition and optimization of the concept of Molten Salt Fast Reactor (MSFR). She is in charge of the work-package 1 “Integral safety approach and system integration” of the Euratom project SAMOFAR of Horizon2020, and she is representative of CNRS at the steering committee on Molten Salt Reactors of the GIF.

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Liquid-fueled reactors:
why "molten salt reactors"?

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Advantages of a Liquid Fuel

- ✓ Homogeneity of the fuel (no loading plan)
- ✓ Heat is produced directly in the heat transfer fluid
  - No heat transfer delay and very fast thermal feedback
- ✓ 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

Best candidates = fluoride (LiF – 99.995% of ^{7}Li) or chloride (NaCl – 99% in ^{37}Cl) salt

⇩

Molten Salt Reactors

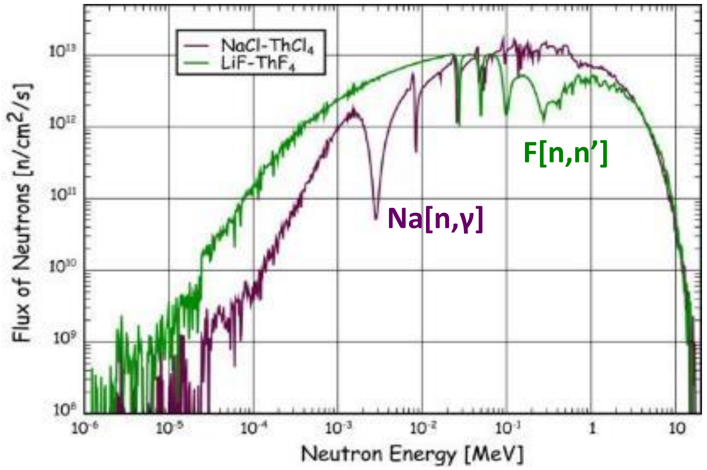
Liquid-fueled reactors: why "molten salt reactors"?

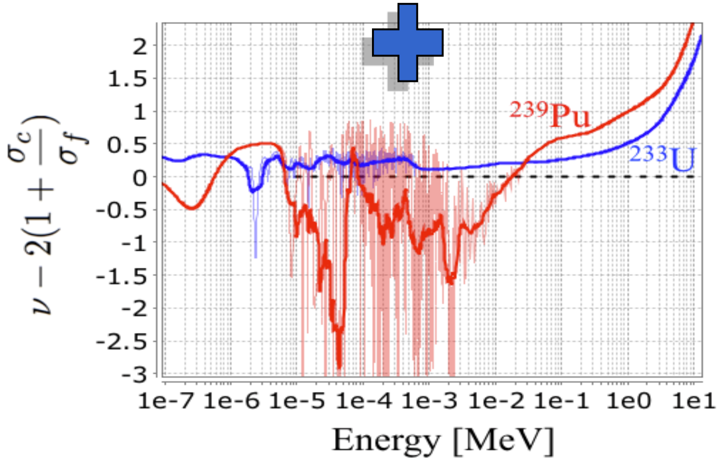
Fluoride versus chloride salt? **Thorium / ^{233}U Fuel Cycle**

Combination of both neutronic (1) and chemical (2) considerations

(1) Neutron spectrum: Breeding ratio and irradiation damages

Neutronic cross-sections of fluorine/chlorine versus neutron economy in the fuel cycle





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**

Liquid-fueled reactors: why "molten salt reactors"?

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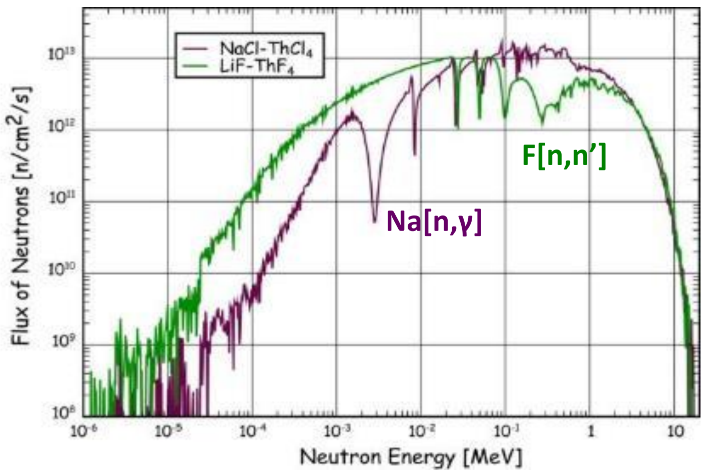
(1) Neutron spectrum: Breeding ratio and irradiation damages



Neutron spectrum less fast with fluoride salt = reduced irradiation damages (both DPA and He production) by a factor 5-7

(2) Chemical issues

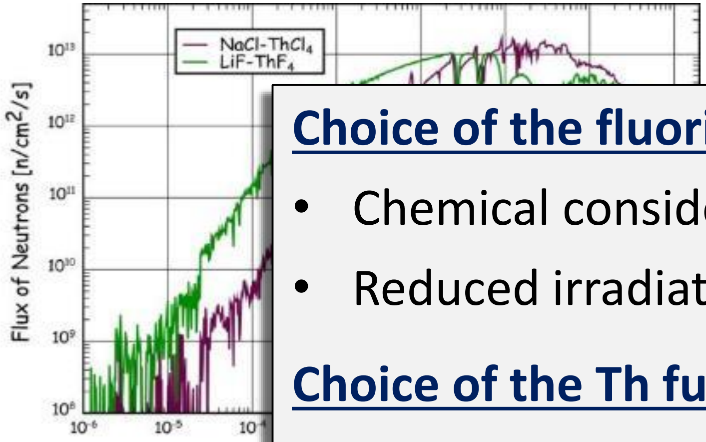
Element produced	Problem	Fluoride Salt	Chloride Salt
^{36}Cl produced via $^{35}Cl(n,\gamma)^{36}Cl$ and $^{37}Cl(n,2n)^{36}Cl$	Radioactivity - $T_{1/2}$ = 301000y		10 moles / y (373 g/y)
^{3}H produced via $^{6}Li(n,\alpha)$ t and $^{6}Li(n,t)$ α	Radioactivity - $T_{1/2}$ = 12 years	55 moles / y (166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

Liquid-fueled reactors: why "molten salt reactors"?

Fluoride versus chloride salt?

Combination of both neutronic (1) and chemical (2) considerations

(1) Neutron spectrum: Breeding ratio and irradiation damages



Neutron sp... fluoride salt... damages (both DPA and He production) by a factor 5-7

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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

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

MSR - Renewal of the concept – CNRS studies

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- ✓ Homogeneity of the fuel (no loading plan)
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- ✓ Possibility to reconfigure quickly and passively the geometry of the fuel (gravitational draining)
- ✓ Possibility to reprocess the fuel without stopping the reactor

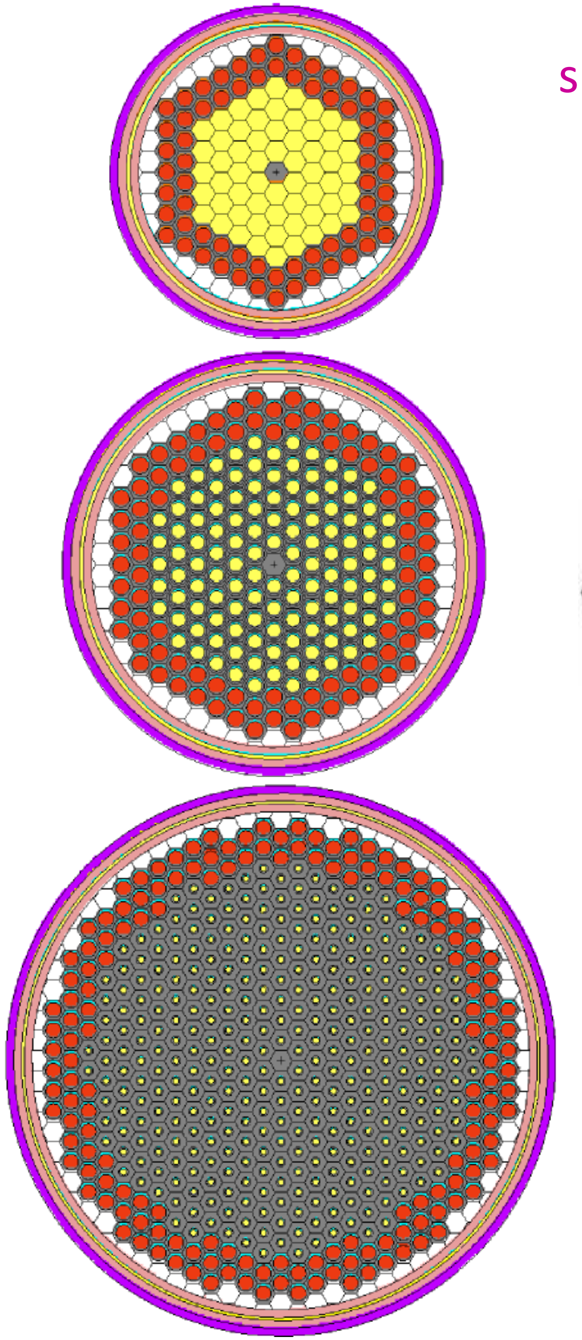
\+

Neutronic Optimization of MSR (Gen4 criteria) :

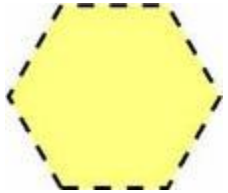
- **Safety: negative feedback coefficients**
- **Sustainability: reduce irradiation damages in the core**
- **Deployment: good breeding of the fuel + reduced initial fissile inventory**

Historical MSR Studies at CNRS

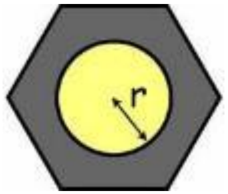
Influence of the channel radius (moderation ratio)



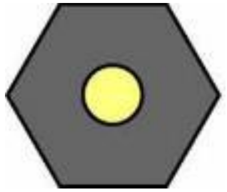
single channel



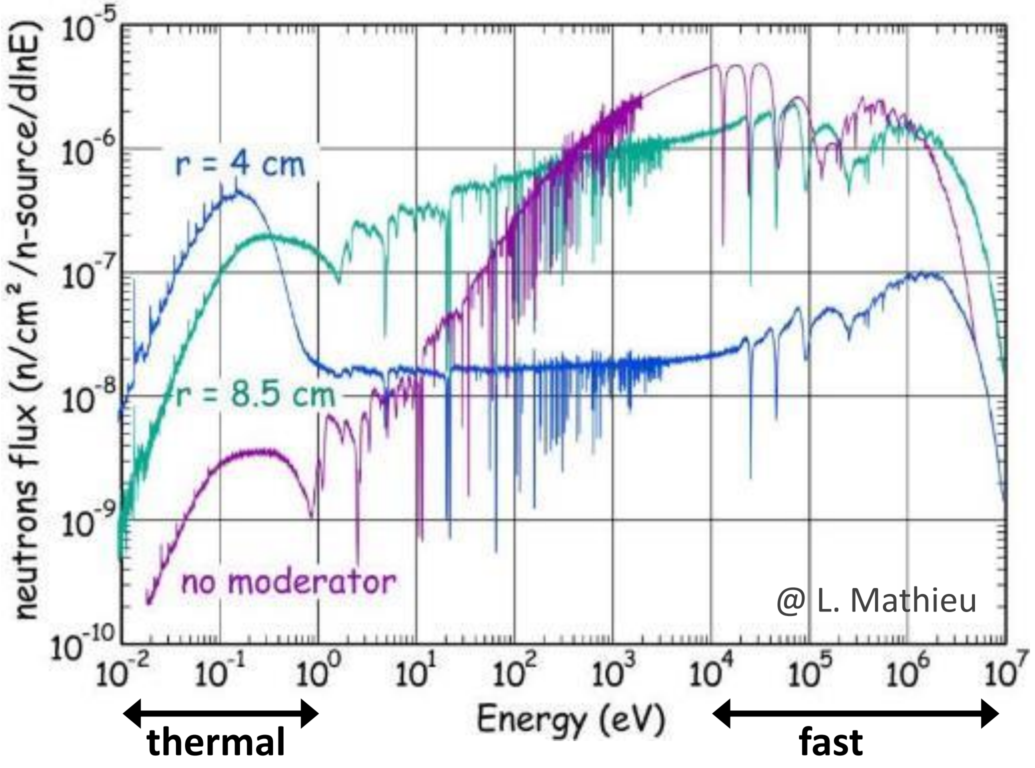
r = 8.5 cm



r = 4 cm



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

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Thermal spectrum configurations

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The Molten Salt Fast Reactor - MSFR

MSFR: Design and Fissile Inventory Optimization

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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:

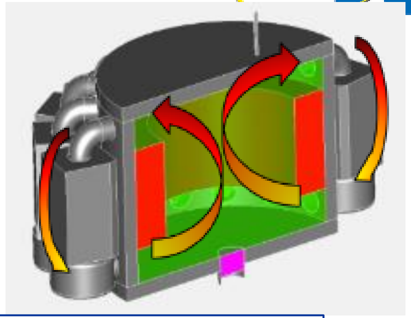
- The capacities of the heat exchangers in terms of heat extraction and the associated pressure drops (pumps) → *large fuel salt volume and small specific power*

- 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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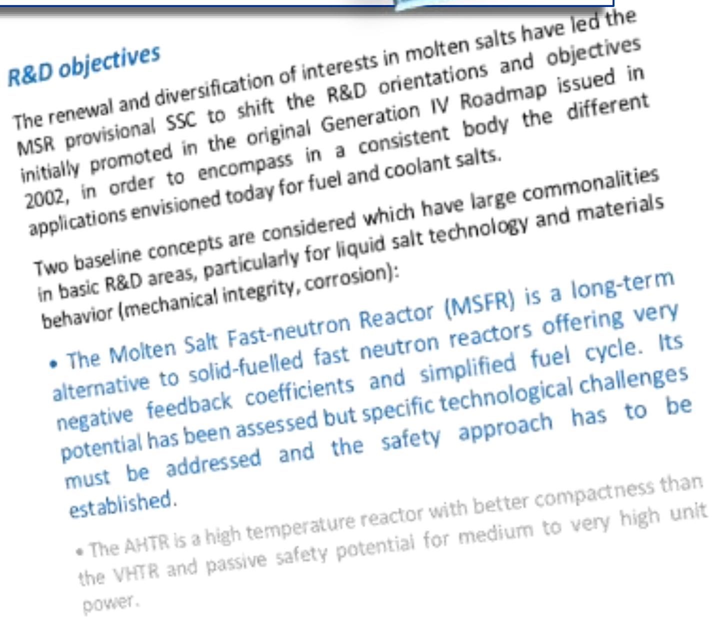
Neutronic Optimization of MSR (Gen4 criteria) :

- **Safety: negative feedback coefficients**
- **Sustainability: reduce irradiation damages in the core**
- **Deployment: good breeding of th[e] 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):

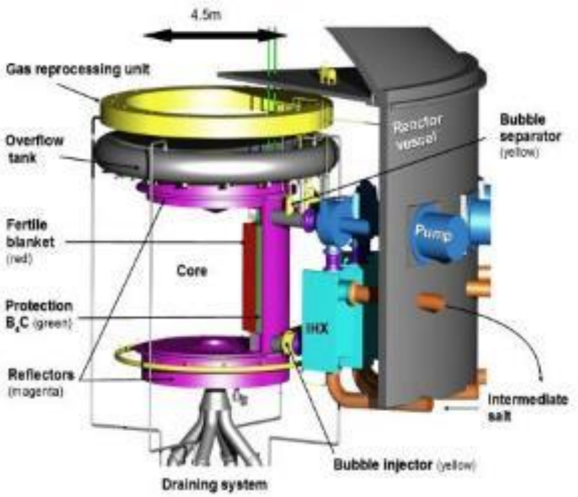
- The Molten Salt Fast-neutron Reactor (MSFR) is a long-term alternative to solid-fuelled fast neutron reactors offering very negative feedback coefficients and simplified fuel cycle. Its potential has been assessed but specific technological challenges must be addressed and the safety approach has to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

MSFR and the European project EVOL

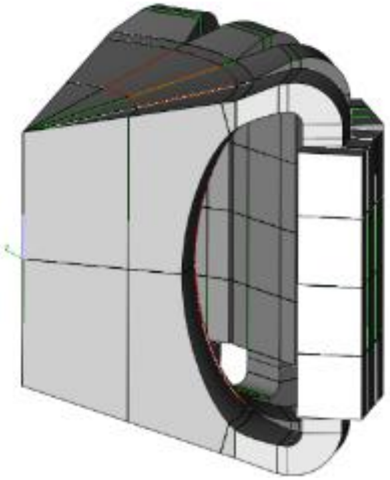
European Project "EVOL" Evaluation and Viability Of Liquid fuel fast reactor -
FP7 (2011-2013): Euratom/Rosatom cooperation

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

- **WP2: Design and Safety**
- **WP3: Fuel Salt Chemistry and Reprocessing**
- **WP4: Structural Materials**



Examples of outputs of the project:
- Optimized toroidal shape of the core
- Proposal for an optimized initial fuel salt composition
- Neutronic benchmark (comparison tools/ nuclear databases)
- First developments of a safety assessment method for MSR
- Recommendations for the choice of the core structural materials



12 European Partners: France (CNRS: Coordinator, Grenoble INP , INOPRO, Aubert&Duval), Netherlands (Technical Univ Delft), Germany (ITU, KIT-G, HZDR), Italy (Politecnico di Torino), UK (Oxford), Hungary (Tech Univ Budapest)
+ 2 observers since 2012: Politecnico di Milano and 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

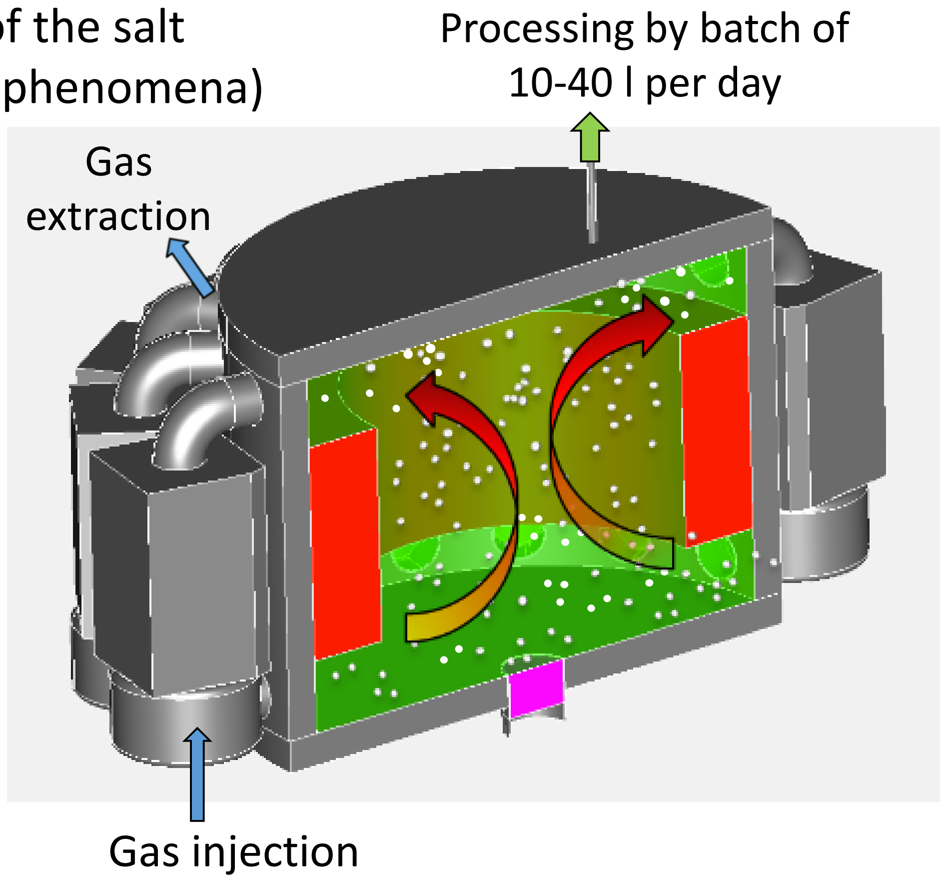
4th Generation reactors => Breeder reactors

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

Fission Products Extraction: Motivations

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

✓ Keep good neutronic properties



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

✓ Keep good neutronic properties

Physical Separation (in the core?)

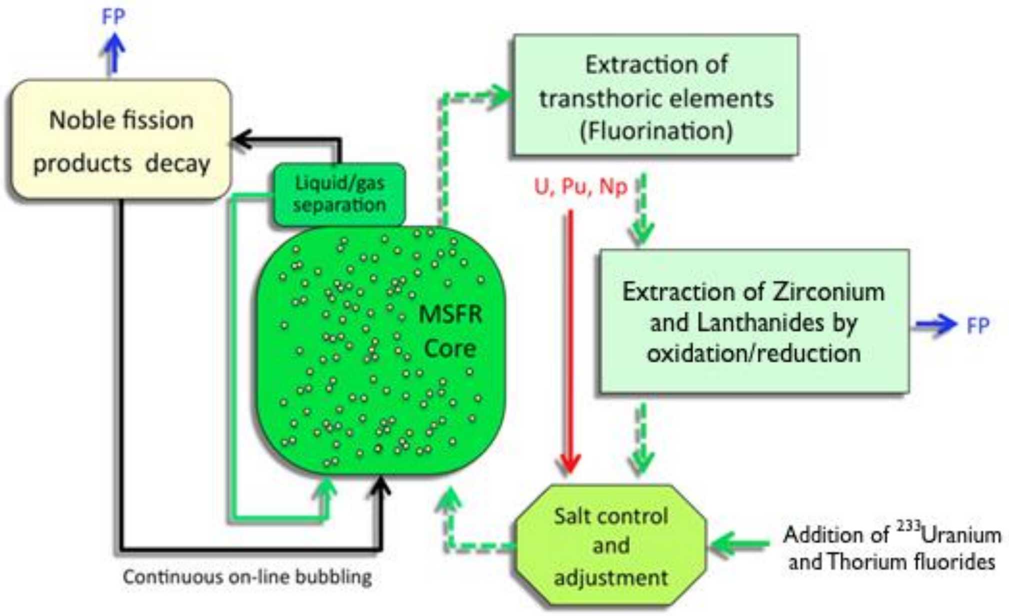
➢ Gas Processing Unit involving bubbling extraction

➢ Extract Kr, Xe, He and particles in suspension

Chemical Separation (by batch)

➢ Pyrochemical processing Unit

➢ Located on-site, but outside the reactor vessel

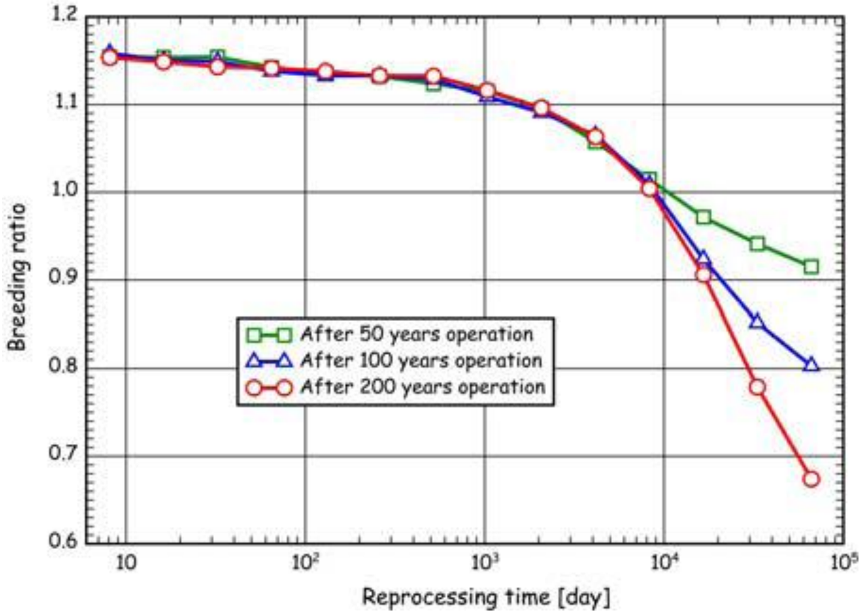


S. Delpech, E. Merle-Lucotte, D. Heuer, M. Allibert, V. Ghetta, C. Le-Brun, L. Mathieu, G. Picard, *"Reactor physics and reprocessing scheme for innovative molten salt reactor system",* J. of Fluorine Chemistry, 130 Issue 1, p. 11-17 (2009)

Concept of MSFR: Fuel processing

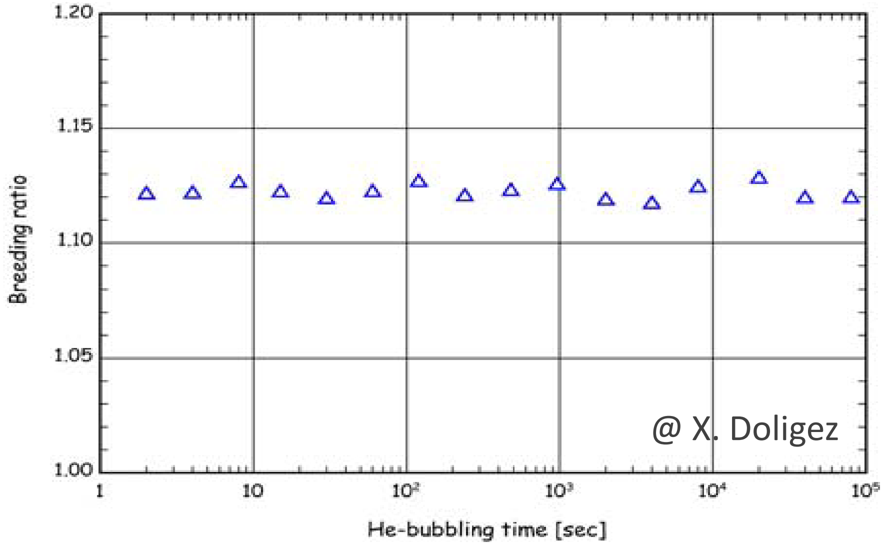
Batch chemical processing:

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

On-line (bubbling) processing:



Fast neutron spectrum

⇒ very low capture cross-sections

⇒ low impact of the processing (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 +

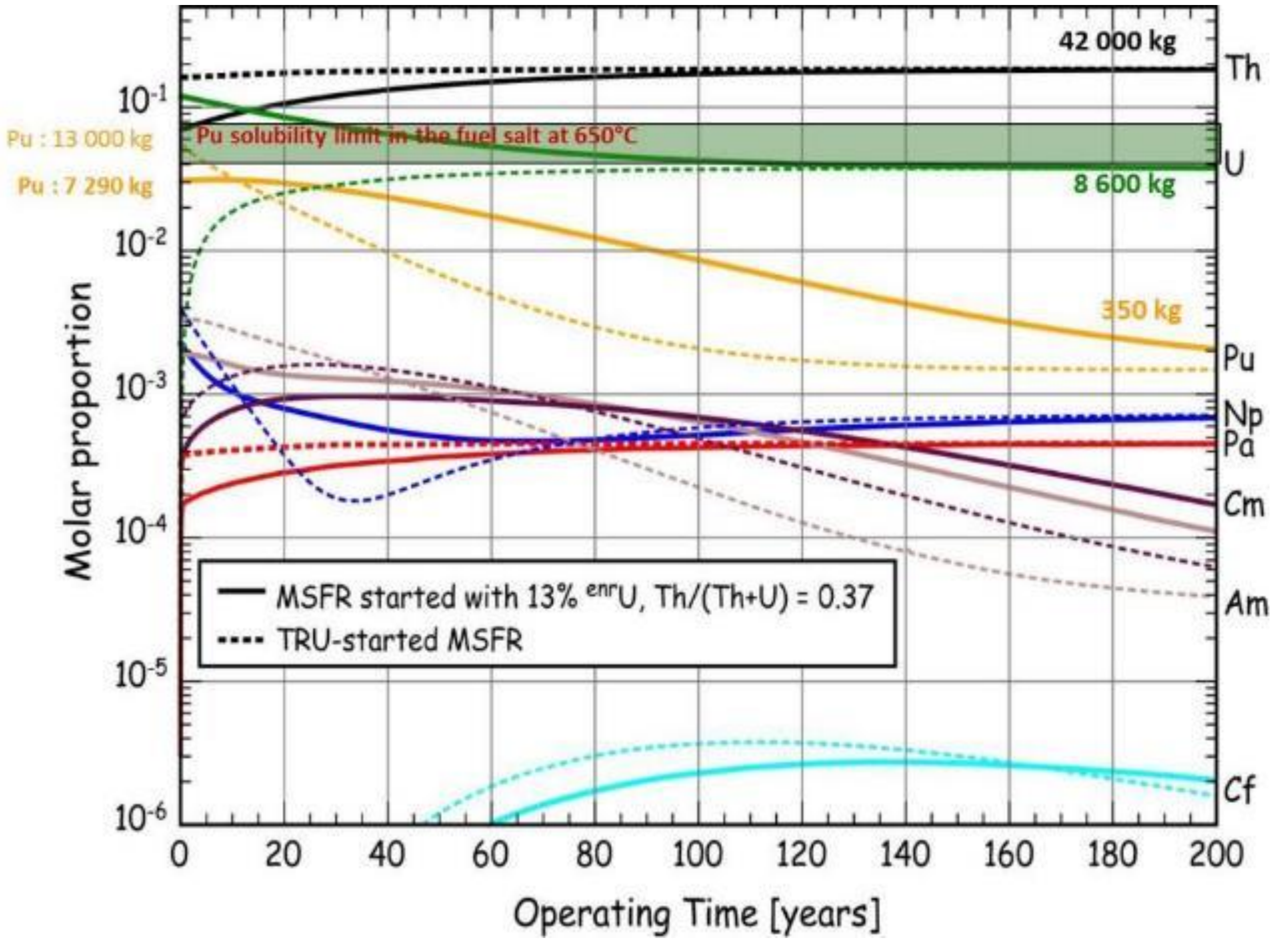
  - ➢ ^{233}U + TRU produced in LWRs
  - ➢ MOx-Th in Gen3+ / other Gen4
  - ➢ Uranium enriched (e.g. 13%) + TRU currently produced

[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

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 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)

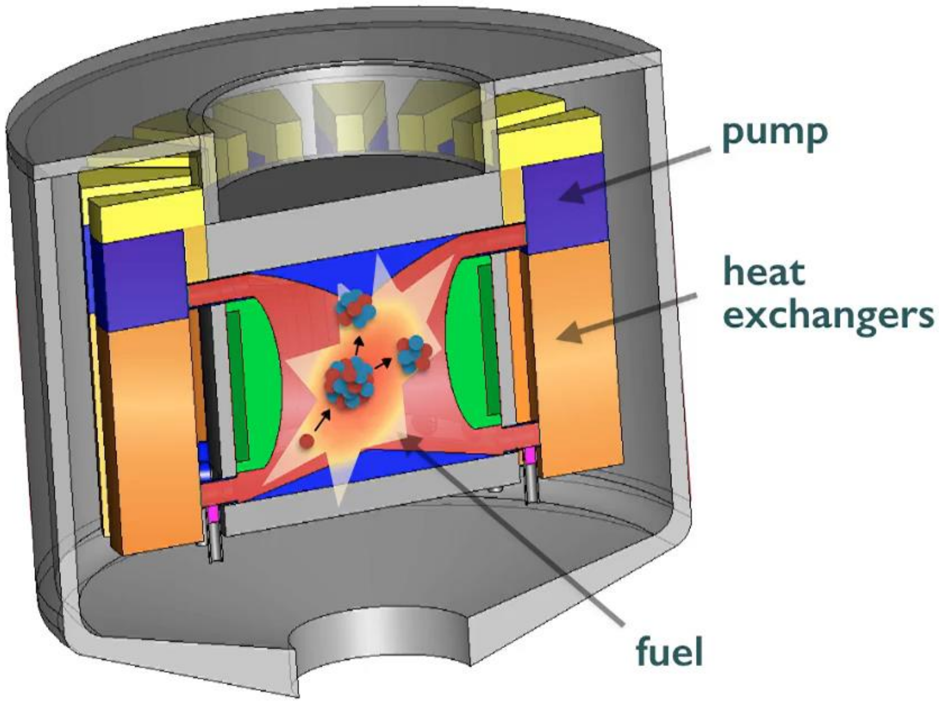
Description of the Molten Salt Fast Reactor (MSFR) system

General characteristics:

- Liquid circulating fuel
- Fuel = coolant
- Power: 3 GW_{th}
- Thermal yield: 45%
- Mean fuel temperature: 725°C
- Fast neutron spectrum
- Thorium fuel cycle

Three circuits:

Fuel salt circuit



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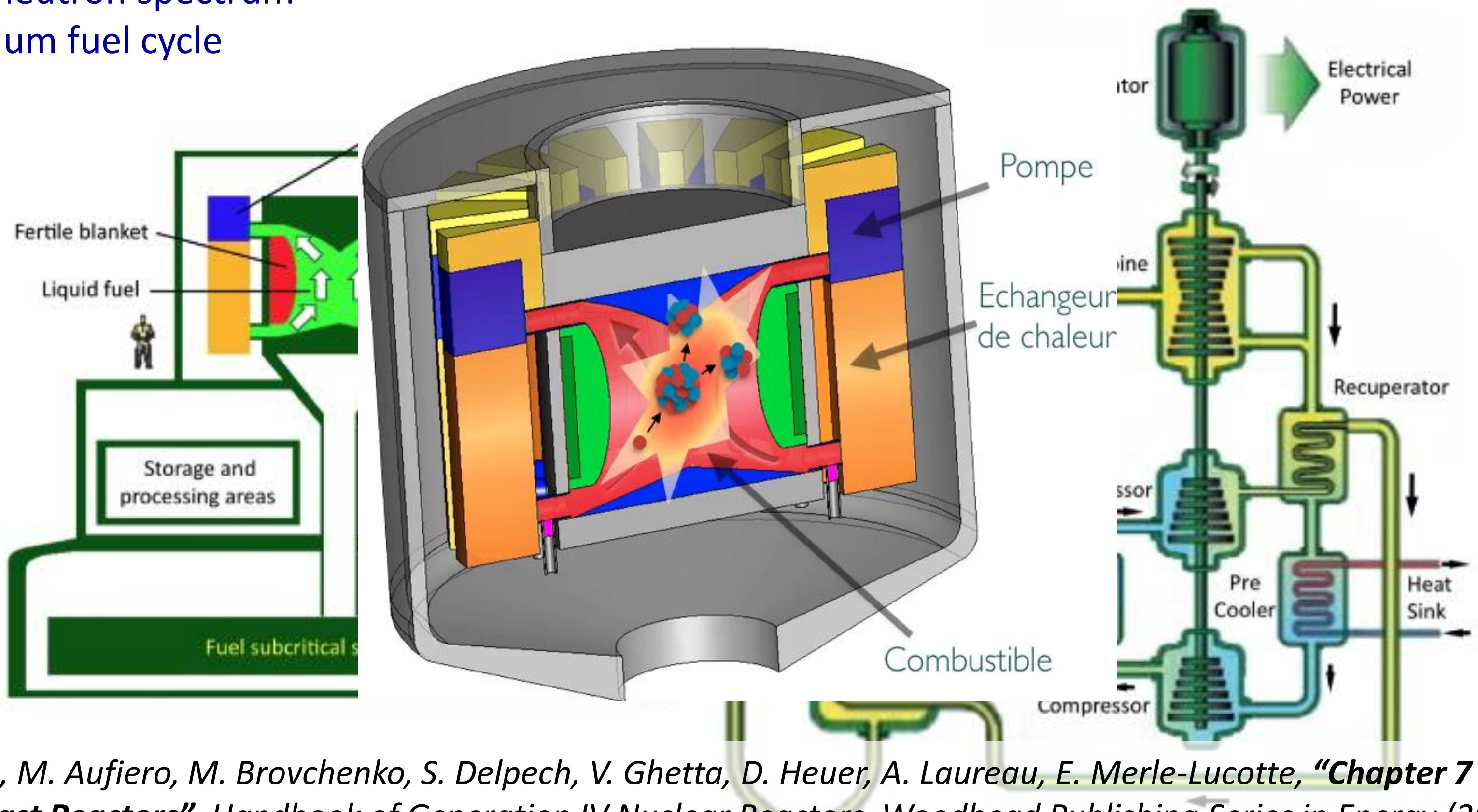
Three circuits:

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)*

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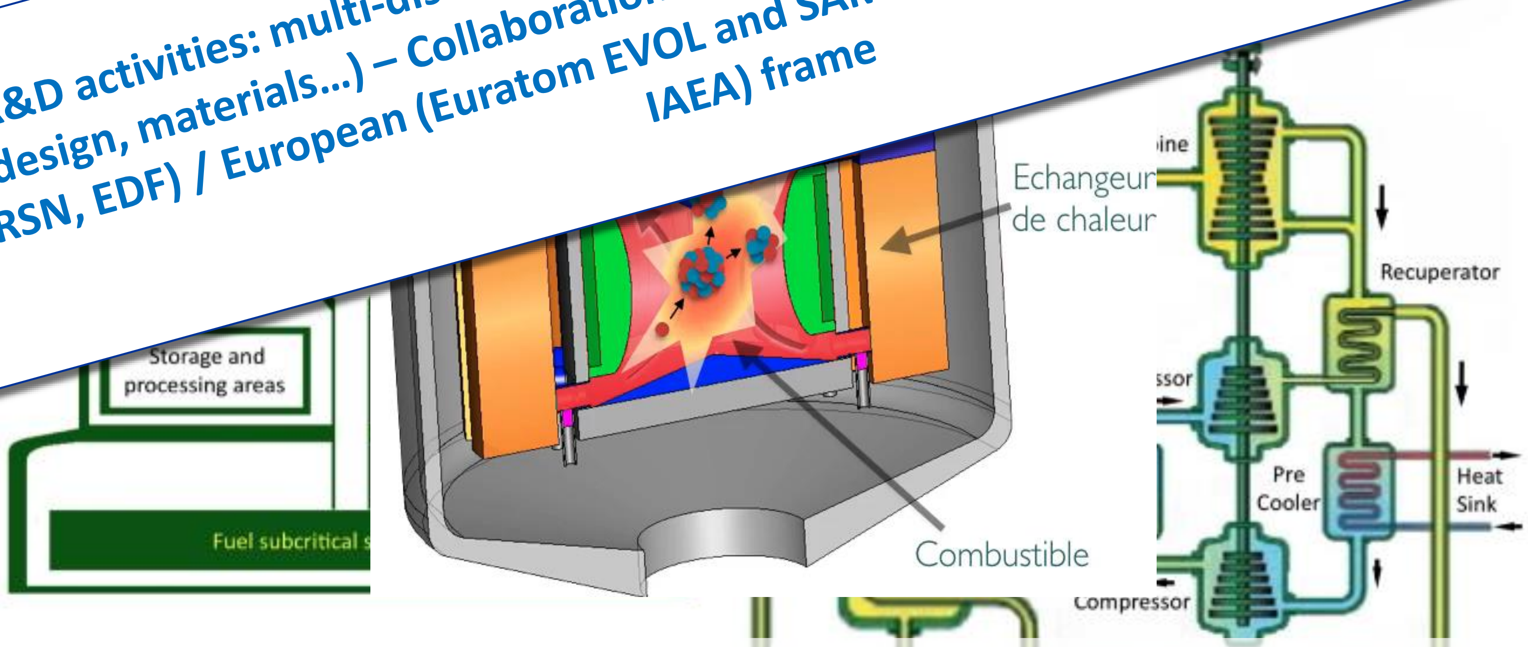
Intermediate circuit

Thermal conv

+ Dra

R&D activities: multi-disciplinary expertise (reactor physics, chemistry, safety, design, materials…) – Collaborations in a national (CNRS, Universities, AREVA, IRSN, EDF) / European (Euratom EVOL and SAMOFAR projects) / worldwide (GIF, IAEA) frame



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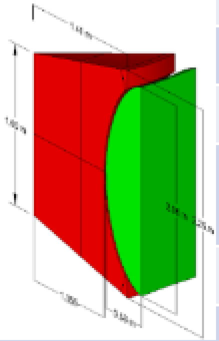
MSFR fuel circuit: characteristics of the reference configuration

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/cm³)	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 (m³)	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



SAMOFAR

MSFR design characteristics impacting strongly the reactor operation: fuel = coolant + no control rod foreseen in the core & reactor driven by the heat extraction…
⇨ Require the definition and assessment of the normal operation procedures and of a safety approach dedicated to the MSFR (liquid circulating fuel reactor)

Concept of Molten Salt Fast Reactor (MSFR)

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

4 years (2015-2019), 3,5 M€

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

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

5 technical work-packages:

WP1 Integral safety approach and system integration

WP2 Physical and chemical properties required for safety analysis

WP3 Proof of concept of key safety features

WP4 Numerical assessment of accidents and transients

WP5 Safety evaluation of the chemical processes and plant

Concept of MSFR: Safety & Fuel processing

SAMOFAR

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)

Nuclear safety: fundamentals

Specificities of a nuclear reactor:

- Huge energy reserve concentrated in the fuel
- Accumulation of radioactive elements (dangerous + produce heat)
- Large release of energy even after the reactor shutdown

Bases of the nuclear safety = control the reactor – 3 safety functions:

- Heat evacuation even after the chain reaction stops (residual heat management)
- Control of the chain reaction at any time = drive the reactor
- Confinement of the radioactive elements (= 3 barriers in LWRs)

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
  - ✓ F…
- No …
  - ✓ … …ass
  - ✓
- Fue…
  - ✓ Cold shutdown is obtained by draining the molten salt from the fuel circuit
  - ✓ Changing the fuel geometry allows for adequate shutdown margin and cooling
  - ✓ Fuel draining can be done passively or by operator action in 2 dedicated systems (normal operation storage system and emergency draining system)

❖ 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)

Concept of MSFR: SAMOFAR WP1 ”Integral safety approach and system integration”

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
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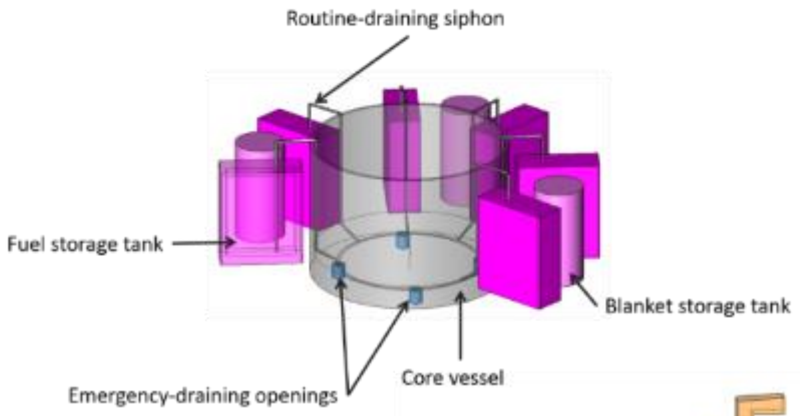
D1.7	Improved Integral power plant design (reactor core and chemical plant) to maximize safety and proposal for safety demonstrator	CNRS	Month 48

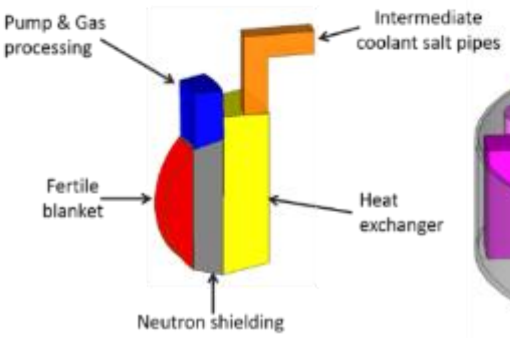
Design aspects impacting the MSFR safety analysis

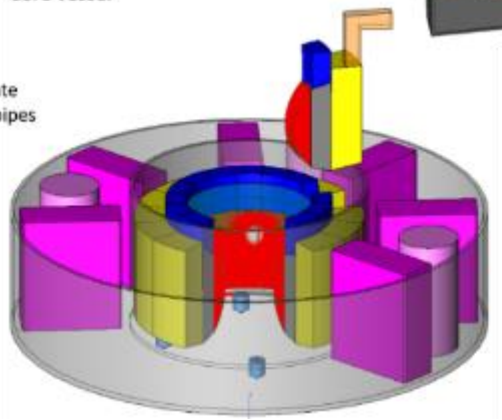
LOLF accident (Loss of Liquid Fuel) → no tools available for quantitative analysis but qualitatively:

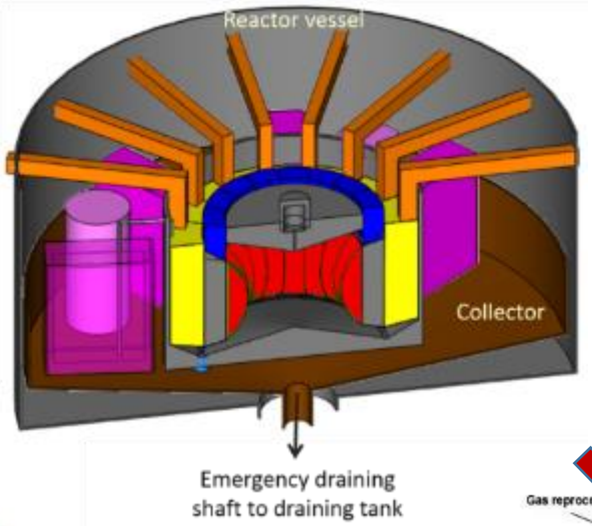
- Fuel circuit: complex structure, multiple connections
- Potential leakage: collectors connected to draining tank

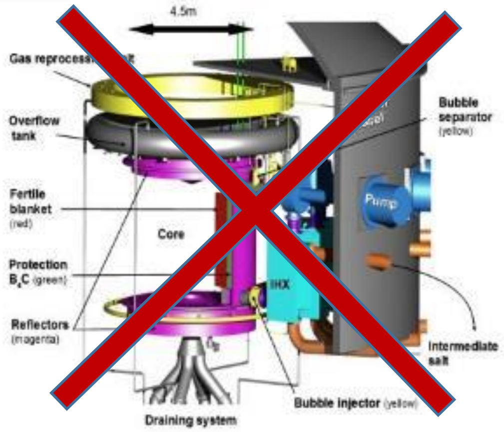
→ Proposition of an 'Integrated MSFR design' to suppress pipes/leaks











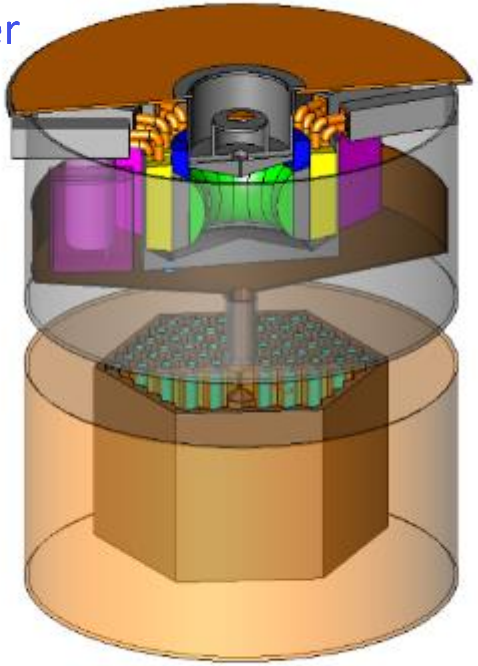
Concept of MSFR: Emergency Draining System

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) and no criticality, in any circumstances: geometry and composition
  - Passive decay heat extraction, in any circumstances: heat transfer

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



D. Gérardin, M. Allibert, D. Heuer, A. Laureau, E. Merle-Lucotte et C. Seuvre, "Design Evolutions of the Molten Salt Fast Reactor", FR17 International Conference, Yekaterinburg, Russie, 2017

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Operation aspects impacting the MSFR safety analysis

MSFR characteristics ⇨ Require the definition and assessment of the normal operation procedures dedicated to the MSFR (liquid circulating fuel reactor)

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

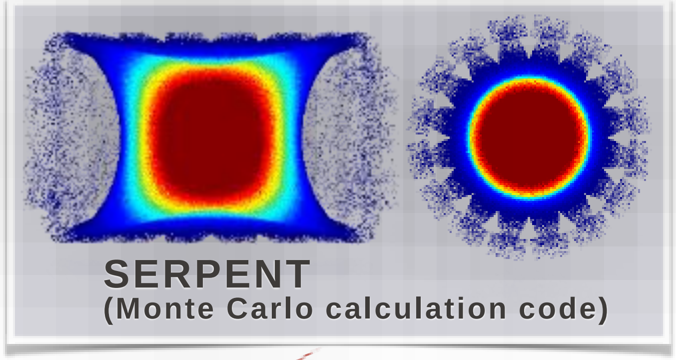
A. Laureau et al, ***“Transient Fission Matrix: kinetic calculation and kinetic parameters βeff and Λeff calculation”,*** Annals of Nuclear Energy, vol 85, p.1035–1044 (2015)

A. Laureau et al, ***“Local correlated sampling Monte Carlo calculations in the TFM neutronics approach for spatial and point kinetics applications”,*** accepted in EPJ-N (2017)

TFM kinetic equations (prompt/delayed neutrons):

$$\frac{dN_p}{dt} = \underline{\underline{G_{\chi_p \nu_p}}} \frac{1}{l_{eff}} \boldsymbol{N_p} + \underline{\underline{G_{\chi_d \nu_p}}} \sum_i \lambda_i \boldsymbol{P_i} - \frac{1}{l_{eff}} \boldsymbol{N_p}$$

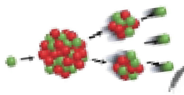
$$\frac{d\boldsymbol{P_i}}{dt} = \frac{\beta_i}{\beta_0} \left(\underline{\underline{G_{\chi_p \nu_d}}} \frac{1}{l_{eff}} \boldsymbol{N_p} + \underline{\underline{G_{\chi_d \nu_d}}} \sum_i \lambda_i \boldsymbol{P_i} \right) - \lambda_i \boldsymbol{P_i}$$



Fission matrices + Time matrix calculation

TFM
(new model)

power → **temperature**, **buoyancy effect**, **precursor production**



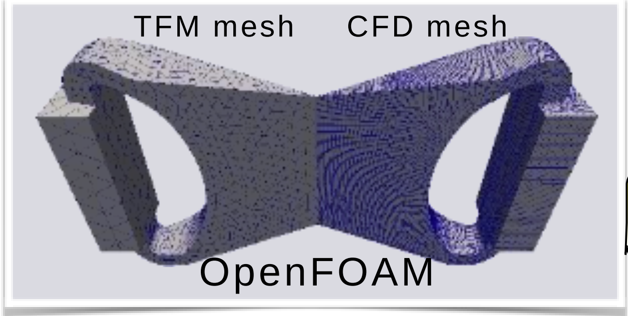
neutronics

thermal-hydraulics

CFD
k-ε realizable turbulence model

temperature field, **precursor decay position** → **delayed neutron source**, **Doppler feedback effect**, **density feedback effect**

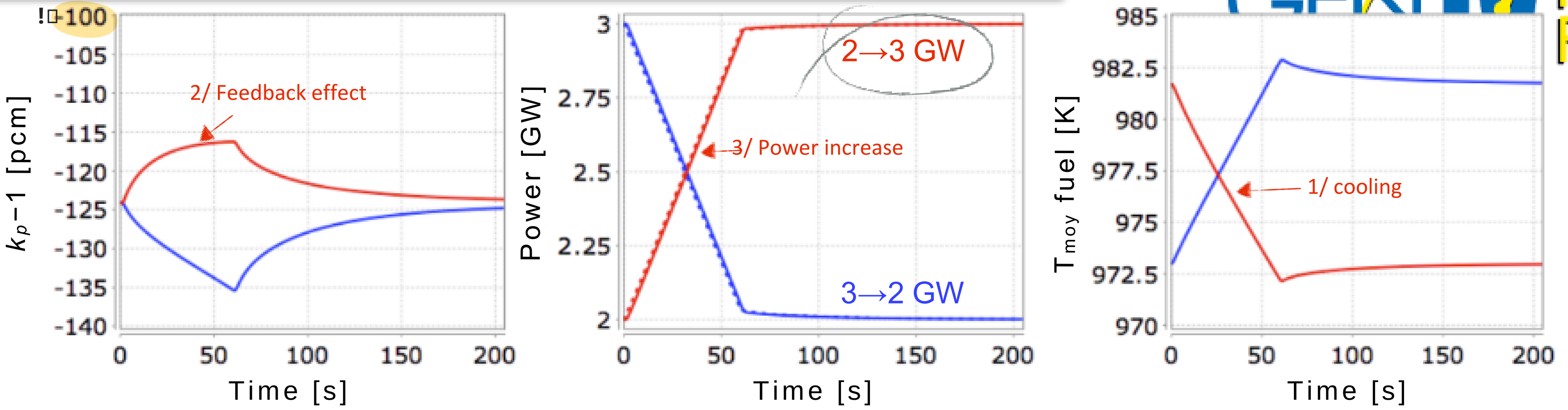
TFM kinetic equations directly implemented and solved in

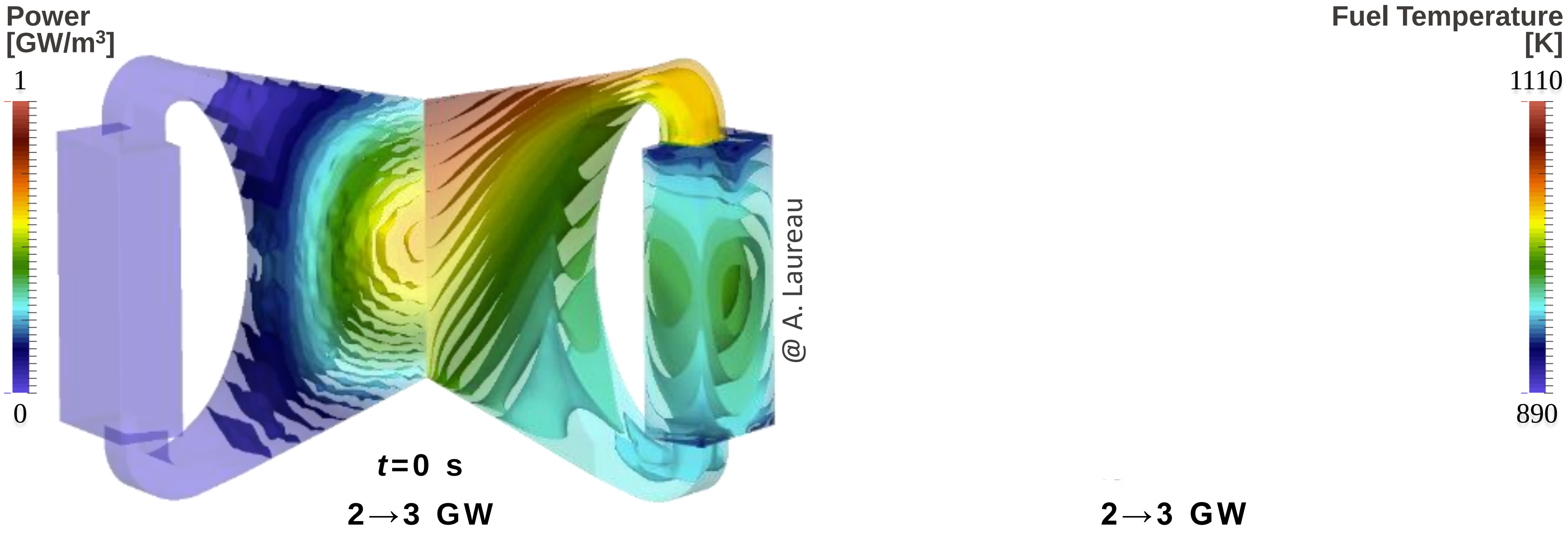


performed by

PhD thesis of Axel LAUREAU, Grenoble Alpes University, France (2012-2015)

Concept of MSFR: the TFM approach – Application to transient calculations (load following of 33% in 60s)





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)

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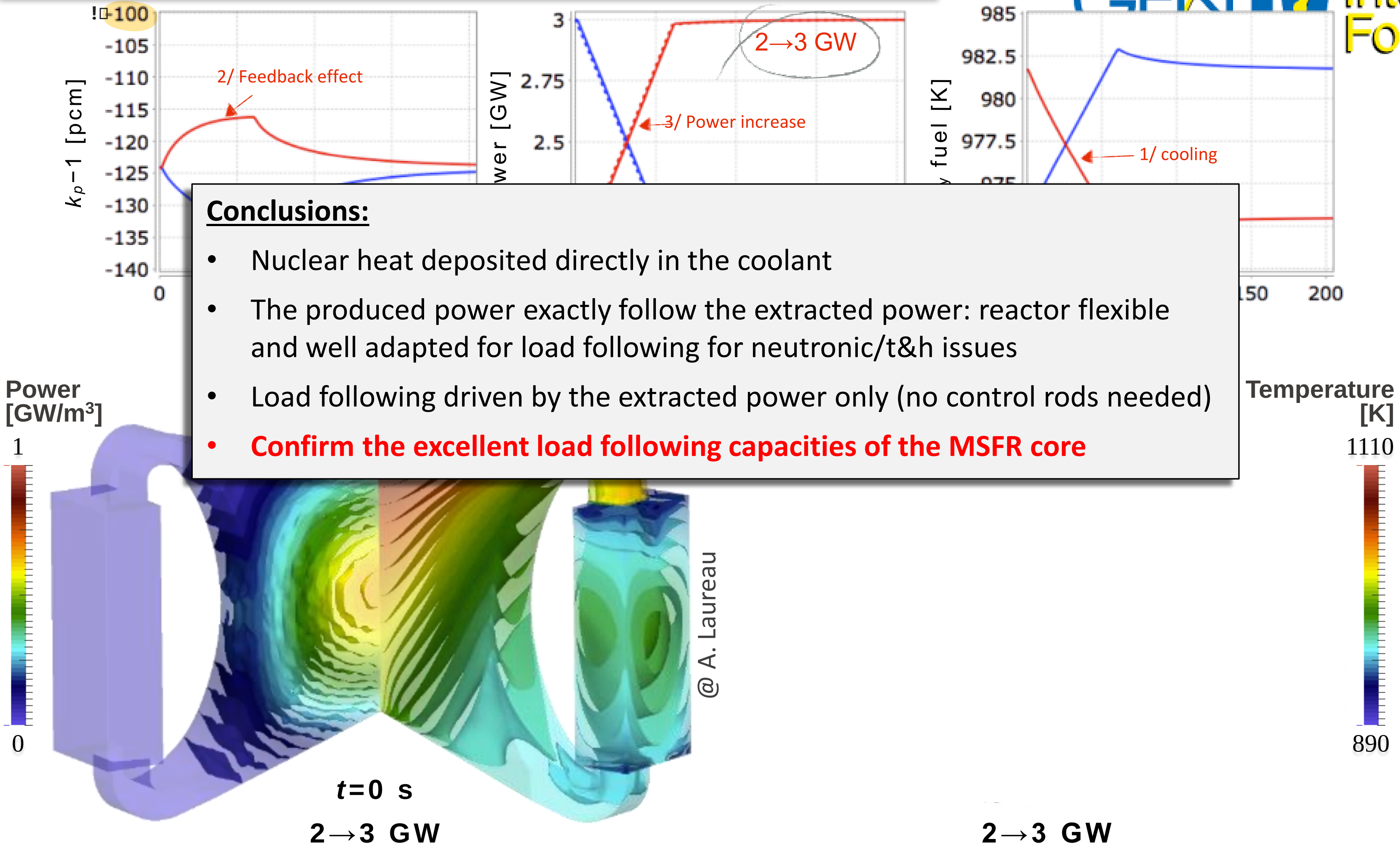

Conclusions:

- 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)

Concept of MSFR: SAMOFAR WP1 "Integral safety approach and system integration"

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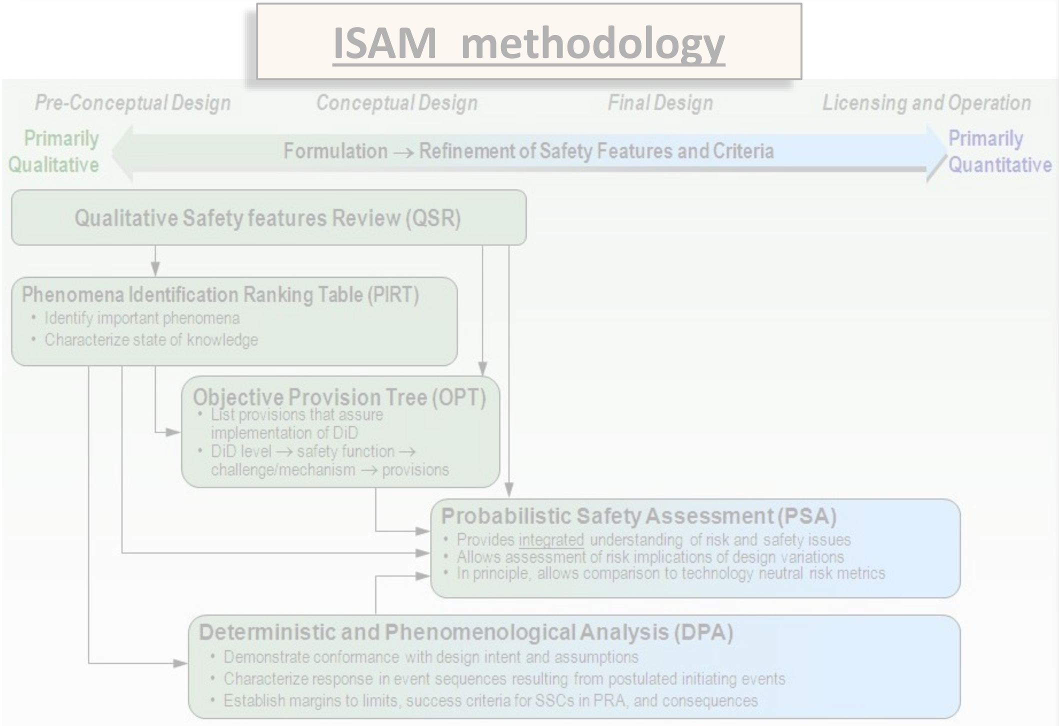
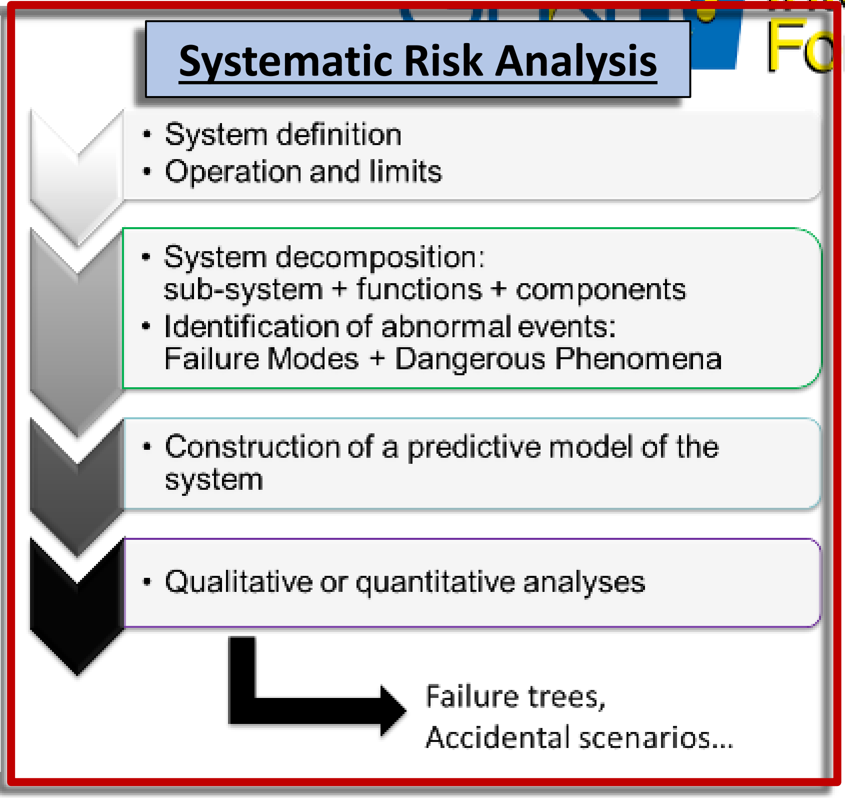
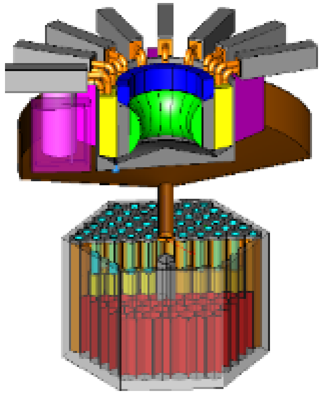
Safety Evaluation of the MSFR: ISAM + Systematic Risk Analysis







Preliminary list MSFR main accident types identified from:

- 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

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Preliminary MSFR accident list

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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

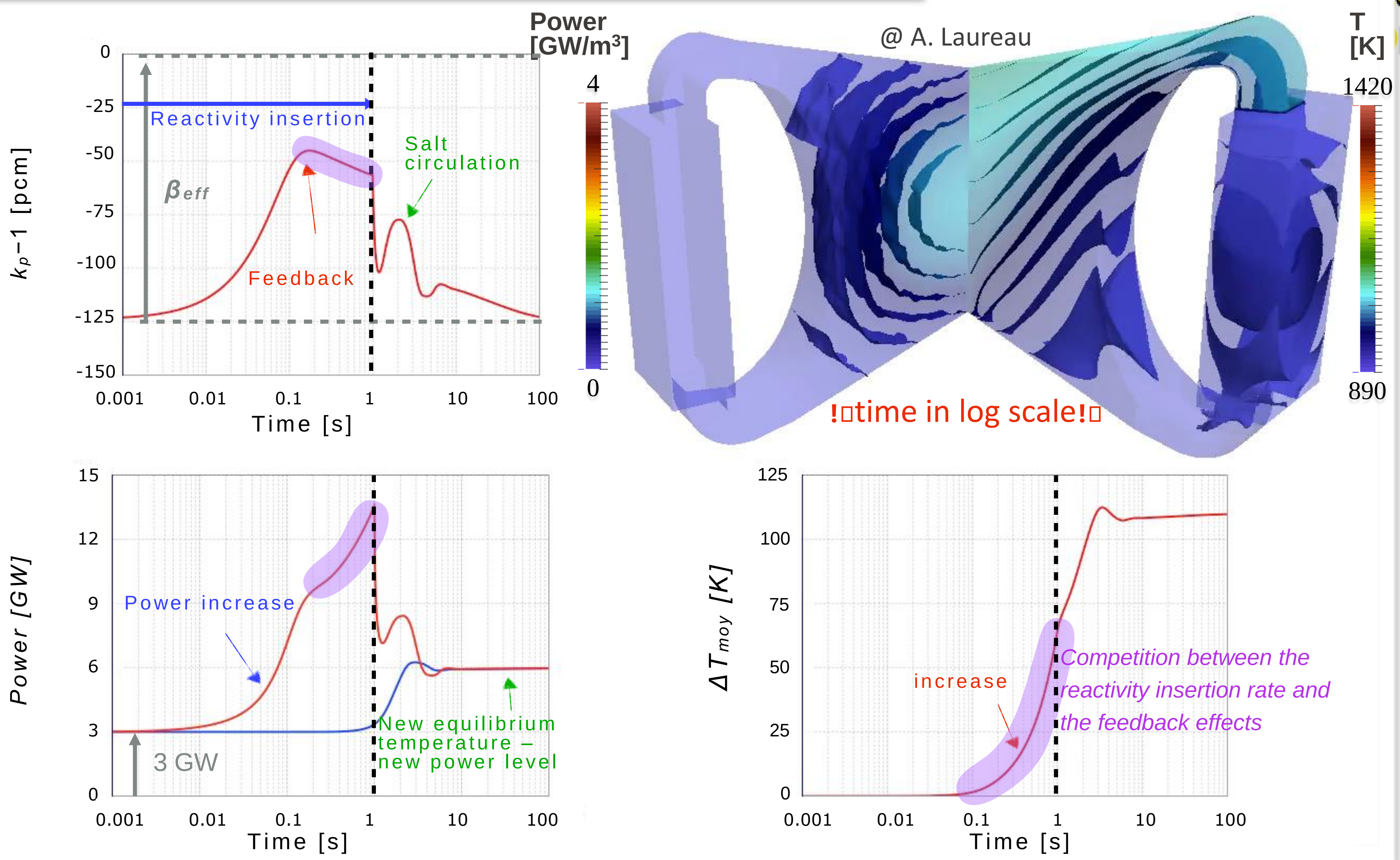
Draining system accidents

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

Design Extension Conditions

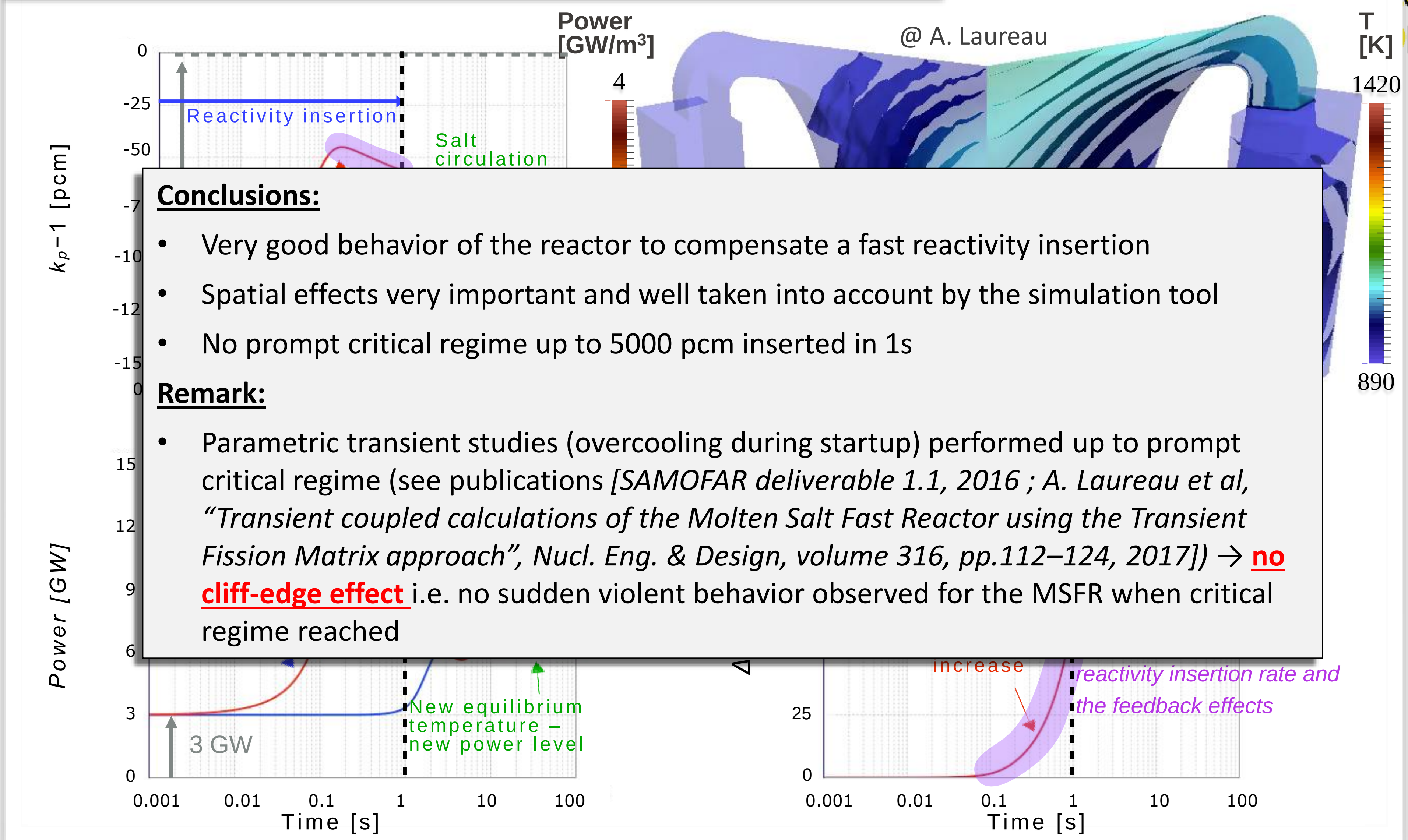
- Steam pressurization accident
- Beyond design reactivity accident

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



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)

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



Conclusions:

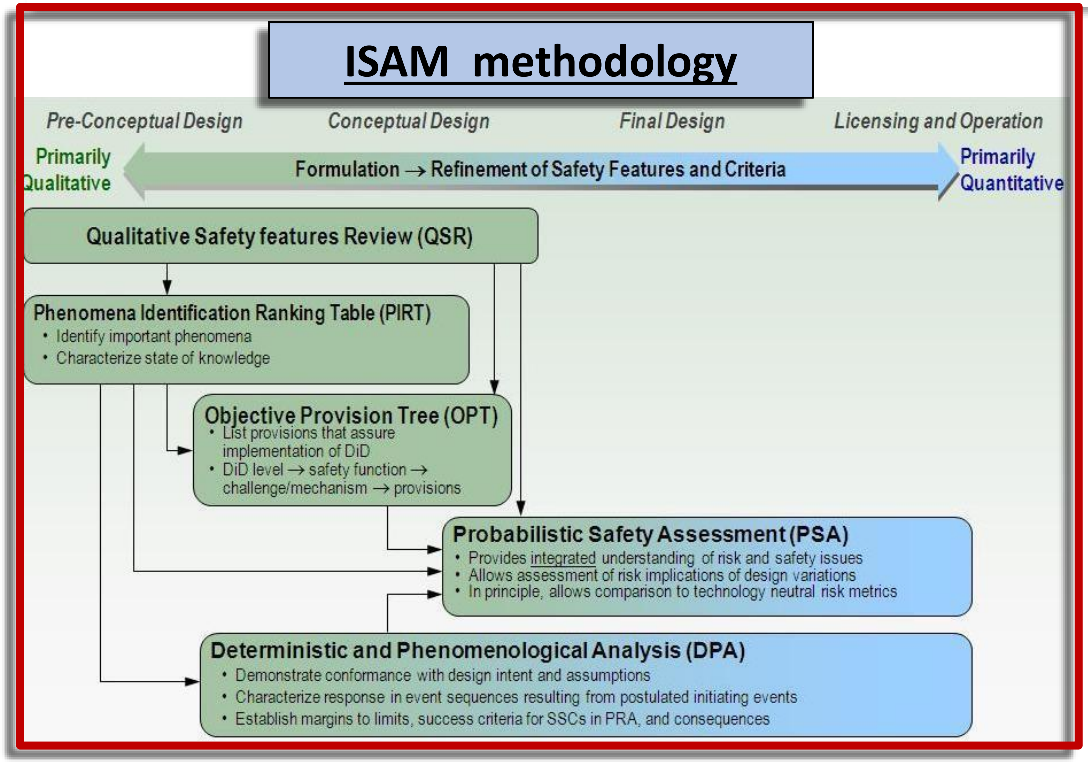
- Very good behavior of the reactor to compensate a fast reactivity insertion
- Spatial effects very important and well taken into account by the simulation tool
- No prompt critical regime up to 5000 pcm inserted in 1s

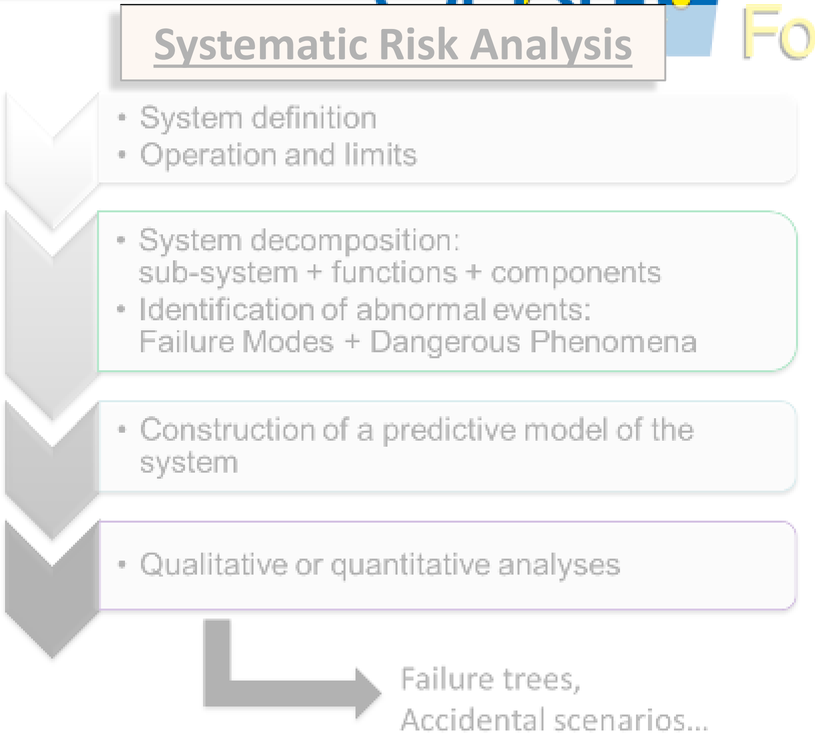
Remark:

- Parametric transient studies (overcooling during startup) performed up to prompt critical regime (see publications *[SAMOFAR deliverable 1.1, 2016 ; A. Laureau et al, "Transient coupled calculations of the Molten Salt Fast Reactor using the Transient Fission Matrix approach", Nucl. Eng. & Design, volume 316, pp.112–124, 2017])* → **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)

Safety Evaluation of the MSFR: ISAM + Systematic Risk Analysis

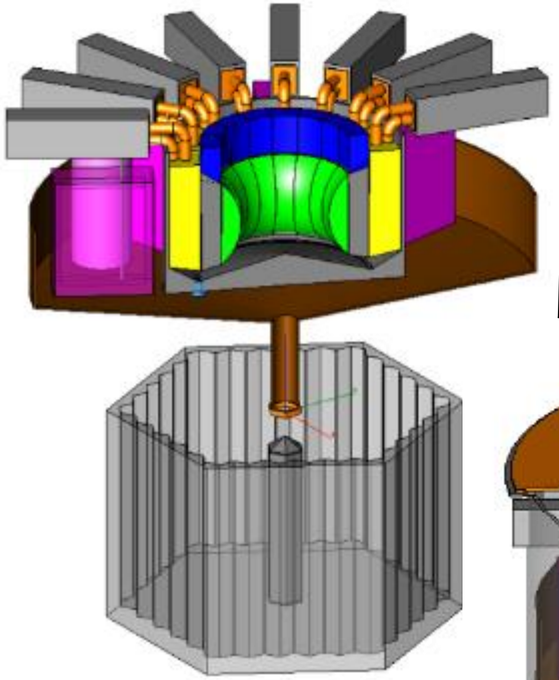




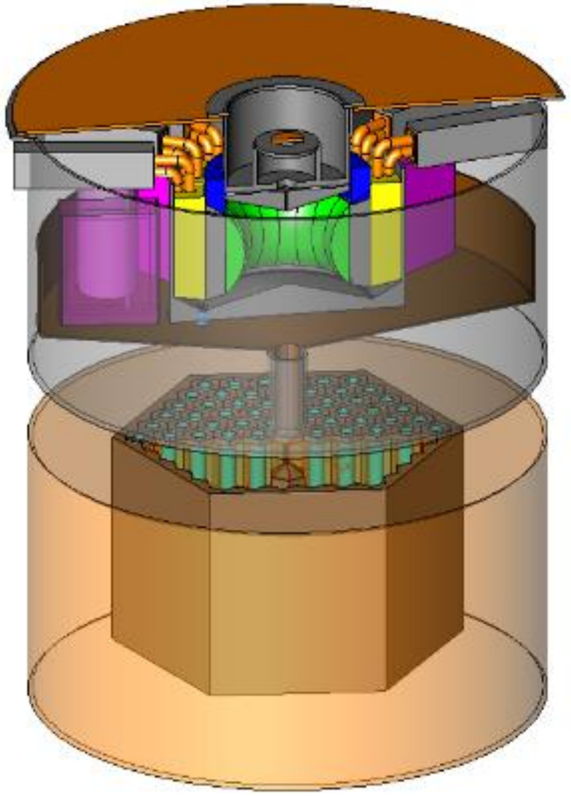
Review of the MSR Safety White Paper + Exchanges with the RSWG of the Gen4 International Forum (MSFR presentation during the RSWG meeting of October 2016)

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

Safety Evaluation of the MSFR: barrier definition



PhD theses of Delphine Gérardin and Anna-Chiara Uggenti



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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 an 'Integrated MSFR design'**

Proposed Confinement barriers:

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

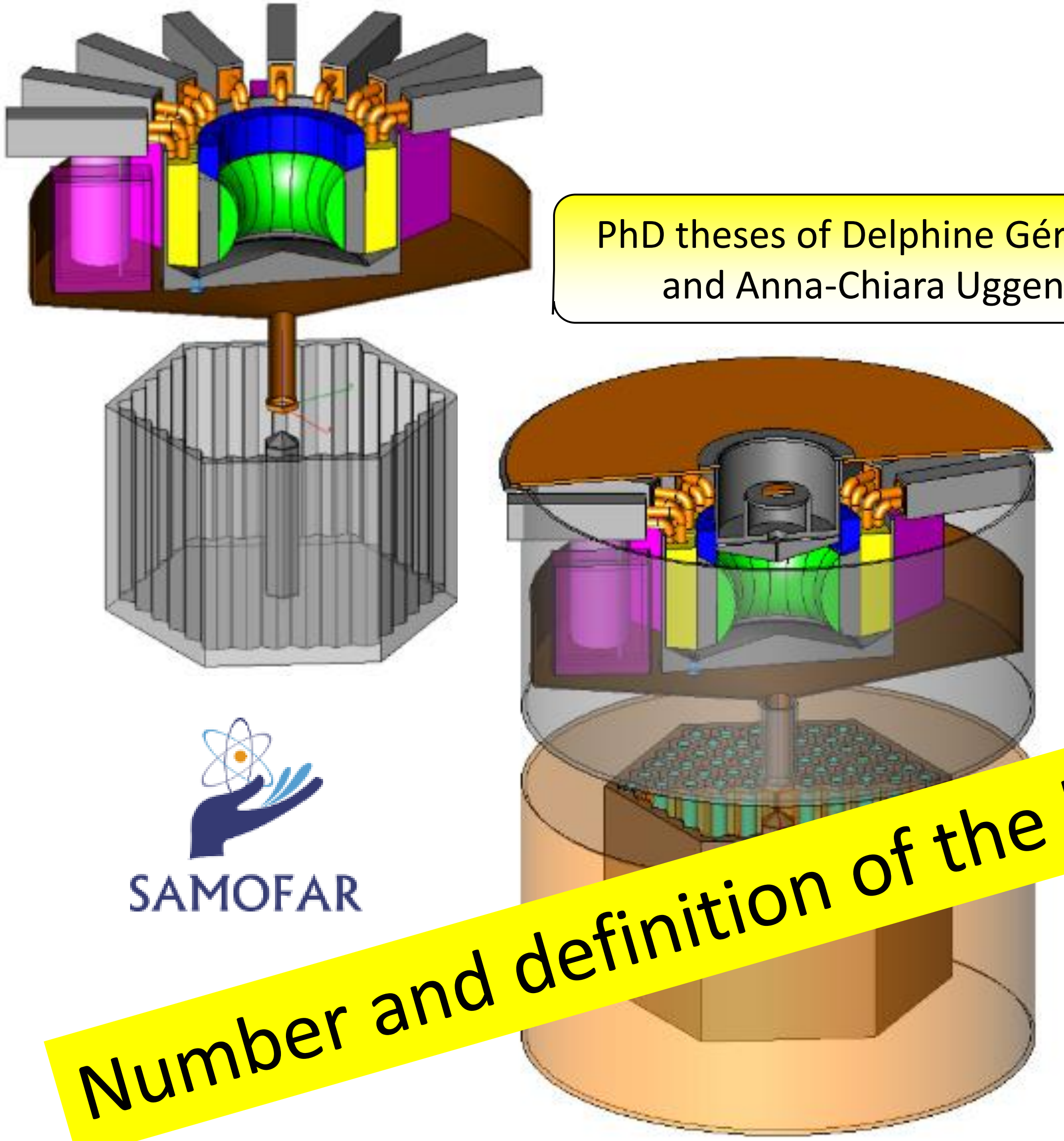
Second barrier: reactor vessel, also including the reprocessing and storage units

Third barrier: reactor wall, corresponding to the reactor building

Safety Evaluation of the MSFR: barrier definition

GEN IV International Forum

PhD theses of Delphine Gérardin and Anna-Chiara Uggenti



SAMOFAR

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

→ **Proposition of an 'Integrated MSFR design'**

Number and definition of the barriers under study

…ed Confinement barriers:

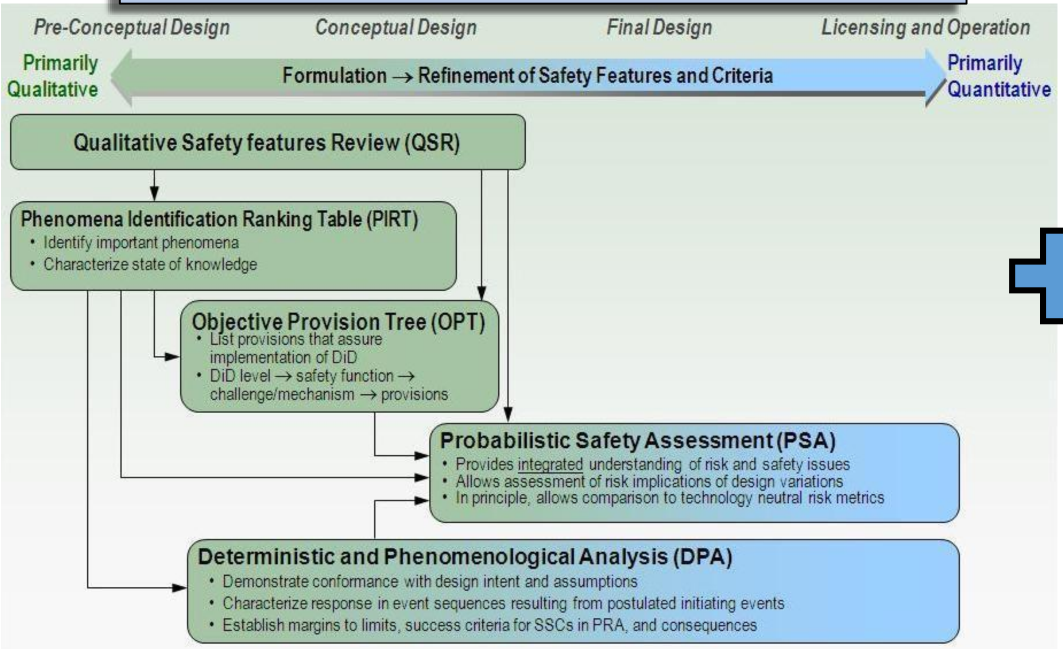
First barrier: fuel envelop, composed of two areas: critical and sub-critical areas

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

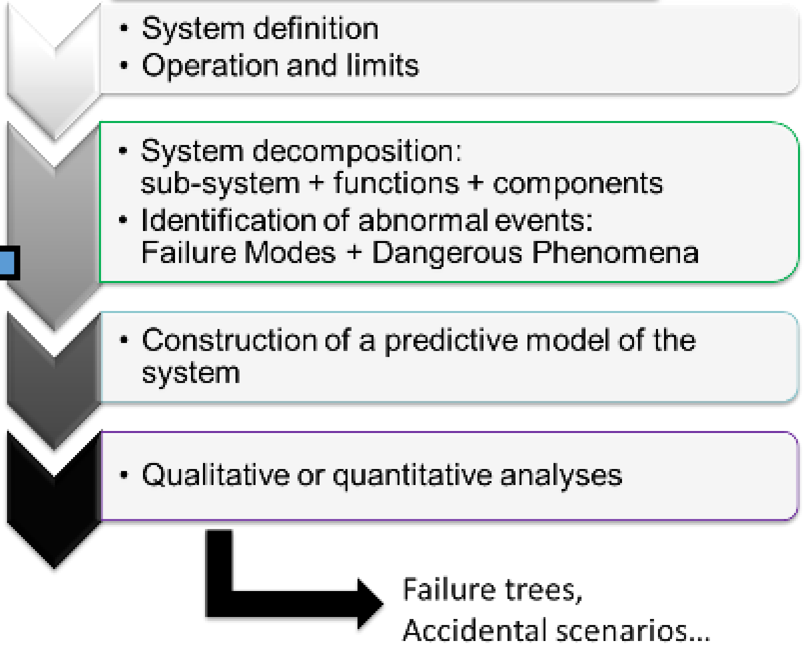
Third barrier: reactor wall, corresponding to the reactor building

Safety 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***)

Preliminary analysis of the MSFR Proliferation Resistance

in view of future collaboration

Michel Allibert, Delphine Gérardin, Daniel Heuer, Axel Laureau (CNRS-LPSC),
Elsa Merle (Prof. Grenoble INP-LPSC),

(Launched by the GIF's PR&PP Working Group in 2014)

To introduce PR&PP* features into the design process at the earliest possible stage of concept development

- *To incorporate PR&PP risk reduction into consideration of the design and use the PR&PP methodology to manage risk reduction:*
  as the design matures, increasing detail can be incorporated in the PR&PP evaluation model of the system

*PR&PP: Proliferation Resistance and Physical Protection

Application to the MSFR concept

- Application of the Proliferation Resistance methodology on the threat “fissile diversion” for the whole MSFR system (reactor and processing units)

	Proliferation resistance
Actor type	Host state
Actor capability	Unlimited
Objectives	Weapon grade ^{233}U a few SQ (as given by IAEA)
Strategy	Concealed diversion & remote clandestine facility

MSFR Pu contains 8% to 70% ^{238}Pu

MSFR U contains ^{232}U (the reason why the Th-U cycle is said PR)→2.6MeV
(suitable for nuclear explosive but detectable and detrimental to electronic devices and humans)

Concept of MSFR: proliferation issues

Preliminary conclusions

Case studied: fissile diversion

- Analysis
  - Fuel salt diversion is not possible because of radiation level
  - Pu contains too much ^{238}Pu to be weapon grade
  - Diversion of Bi from the pyrochemical unit allows Pa use to get weapon grade U in clandestine facility
  - Bi diversion has to be carried out soon after reduction to minimize 2.6MeV ɣ detection
  - Th reduction is still unknown but would seriously impede diversion if significant (measurements are needed)
- Levers available:
  - 2.6 MeV radiation detection capabilities (inside pyro unit and plant exit)
  - Detection by mass balance (maximum diversion rate?)

NEXT to come:

- Identify and analyze other PR threats related to the MSFR system
- Need for interactions with the PR&PP WG (GIF) and with IAEA

Demonstration steps and Demonstrator for the 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

Demonstration steps and Demonstrator for the MSFR

GEN IV International Forum[SM]

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- ✓ 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

GEN IV International Forum

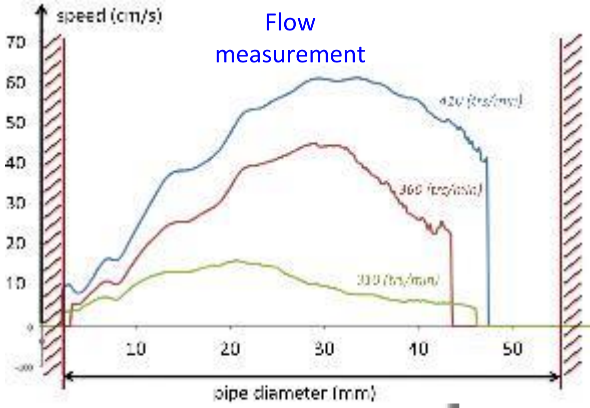
The Forced Fluoride Flow Experiment

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

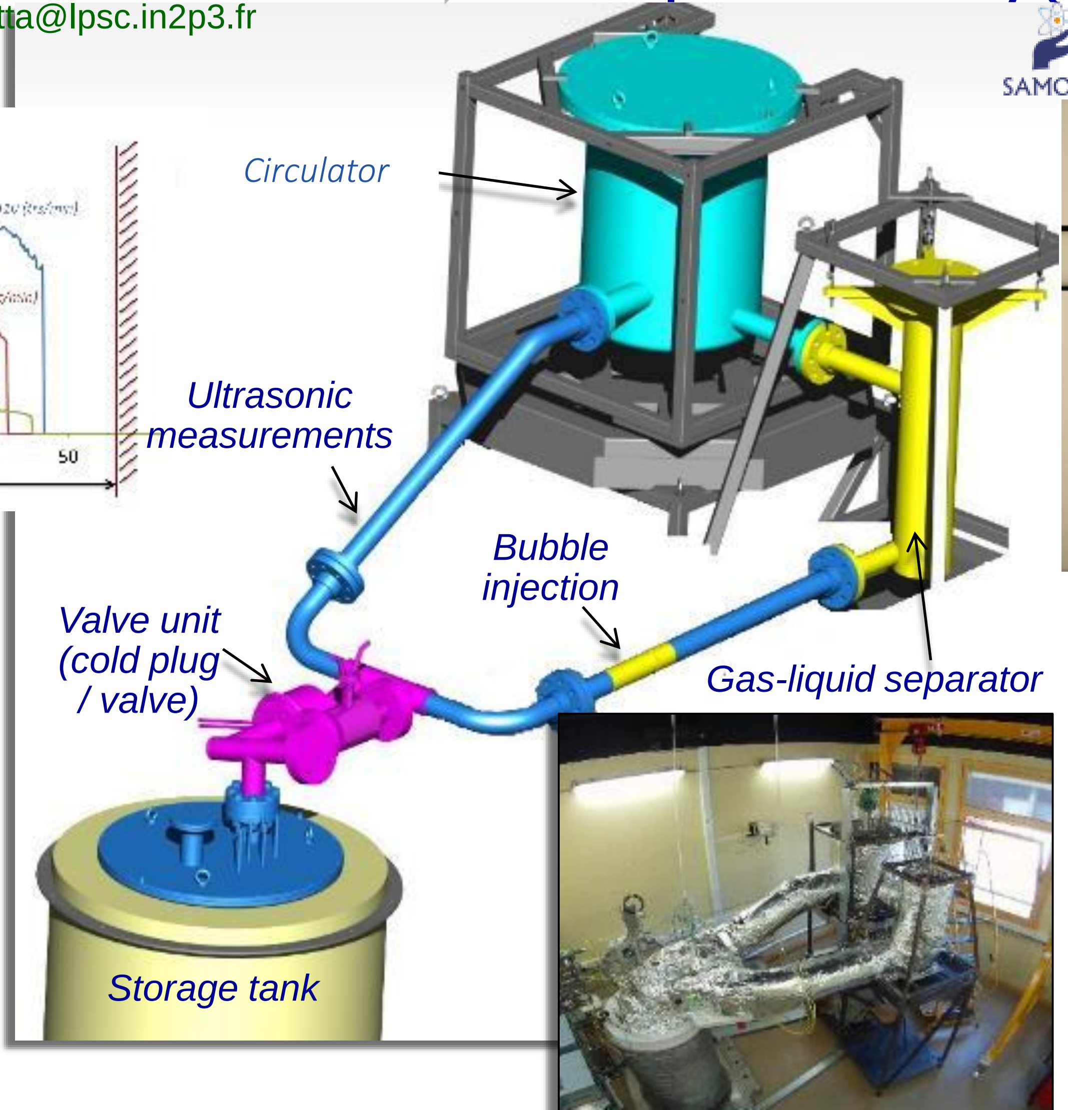
Veronique.Ghetta@lpsc.in2p3.fr

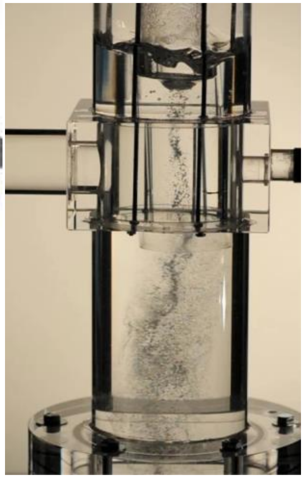
⇨ **Next step: SWATH facility (SAMOFAR project)**

SAMOFAR



@ V. Ghetta





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Demonstration steps and Demonstrator for the MSFR

GEN IV International Forum℠

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:

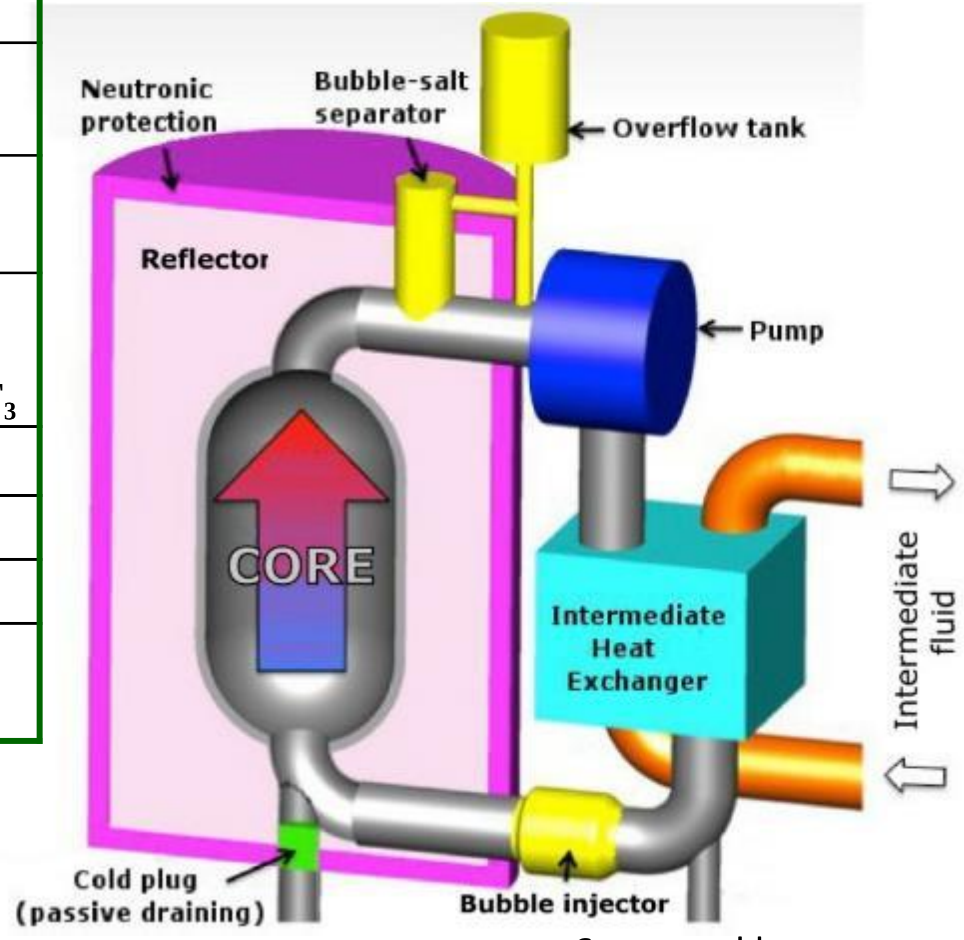
- ✓ Inactive simulant salt ⇨ Standard laboratory
  Hydrodynamics, material, measurements, model validation
- ✓ Low activity level (Th, depleted U) ⇨ Standard lab + radio protect
  Pyrochemistry, corrosion, chemical monitoring
- ✓ High activity level ($^{enriched}U$, ^{233}U, Pu, MA) ⇨ Nuclear facility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

Power Demonstrator of the MSFR

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

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



6 external loops

From Power Demonstrator of the MSFR to a SMR-MSFR or S-MSFR

GEN IV International Forum[SM]

	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 processing 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 processing 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)

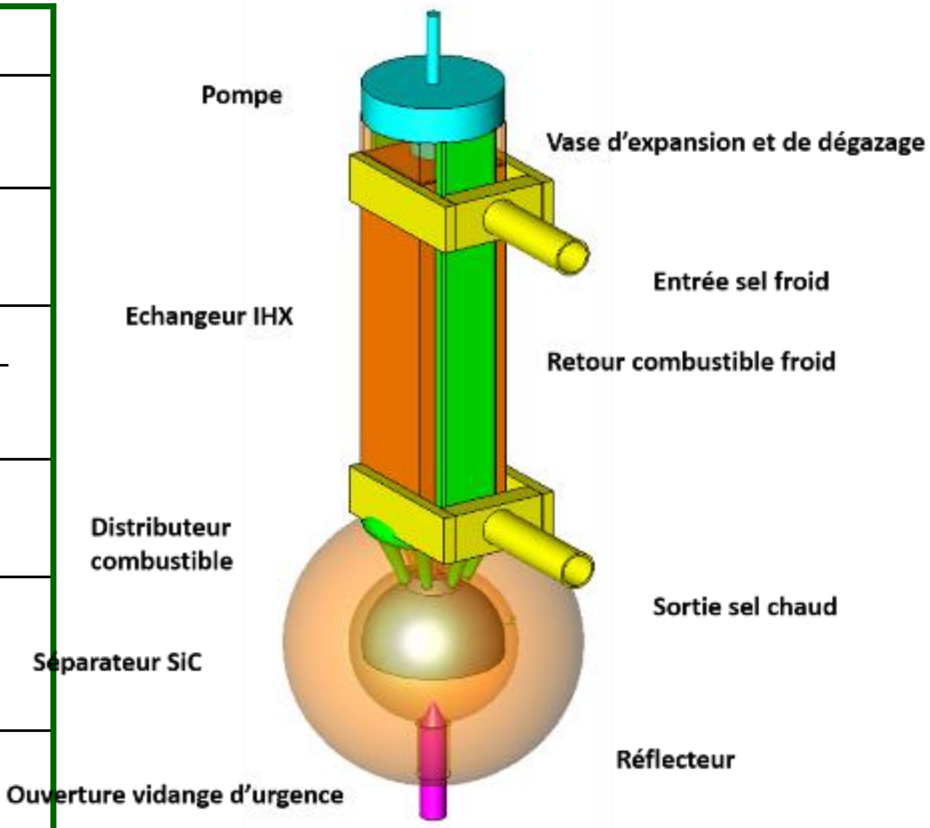
From Power Demonstrator of the MSFR to a SMR-MSFR or S-MSFR

	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 processing 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 processing 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 – S-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 fuel and only salt control + bubbling but no chemical processing (stable physico-chemical characteristics of the salt)

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)

Davide RODRIGUES, ***"Solvatation du thorium par les fluorures en milieu sel fondu à haute température : application au procédé d'extraction réductrice pour le concept MSFR"***, PhD Thesis, Paris Sud University (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)

David LECARPENTIER, ***"Le concept AMSTER, aspects physiques et sûreté"***, EDF and CNAM, Paris, France (2001)

Thesis and Papers on MSFR Reactor Physics & Safety 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

Other MSR publications

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 7 - 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)

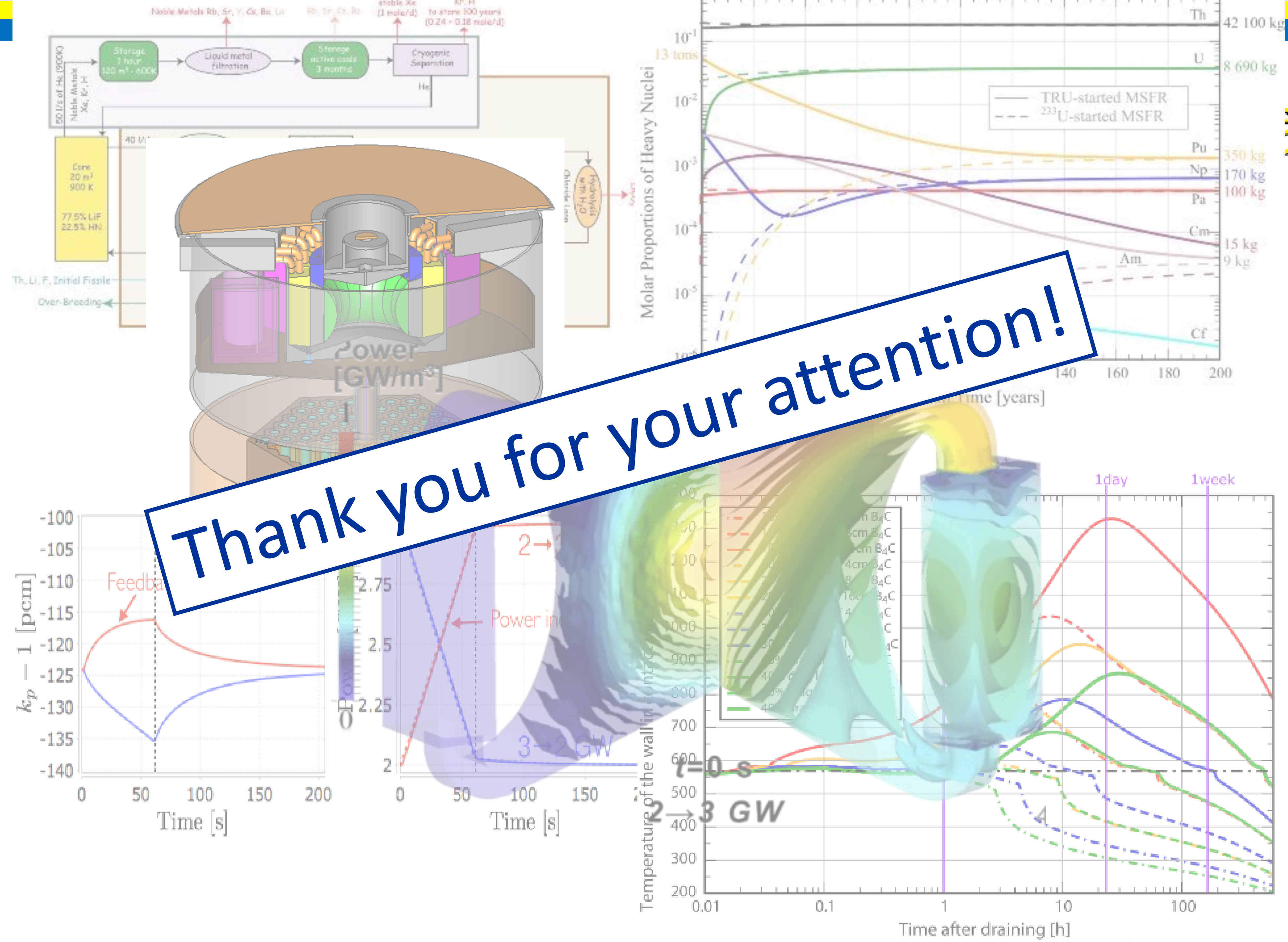
H. Boussier, S. Delpech, V. Ghetta, D. Heuer, D.E. Holcomb, V. Ignatiev, E. Merle-Lucotte, J. Serp, ***"The Molten Salt Reactor in Generation IV: Overview and Perspectives"***, Proceedings of the Generation4 International Forum Symposium, San Diego, USA (2012)

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)

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):
http://*www.snetp.eu/www/snetp/.../sra_annex-MSRS.pdf*

Thank you for your attention!



UPCOMING WEBINARS

June 12, 2017	Lead Fast Reactor, Dr. Craig Smith	US Naval Graduate School, USA
July 12, 2017	Thorium Fuel Cycle, Dr. Franco Michel-Sendis	NEA/OECD, France
August 22, 2017	Metallic Fuel for SFRs, Dr. Steven Hayes	Idaho National Laboratory, USA