CS IN2P3 – 3-4/02/2022

Molten Salt Reactor project at IN2P3

Elsa Merle

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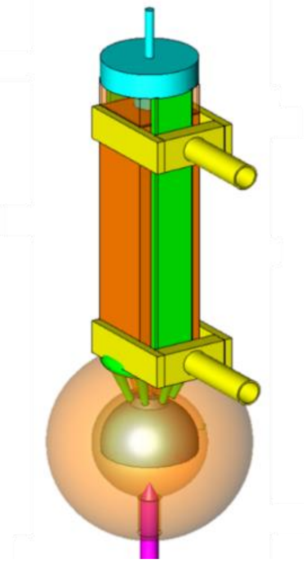
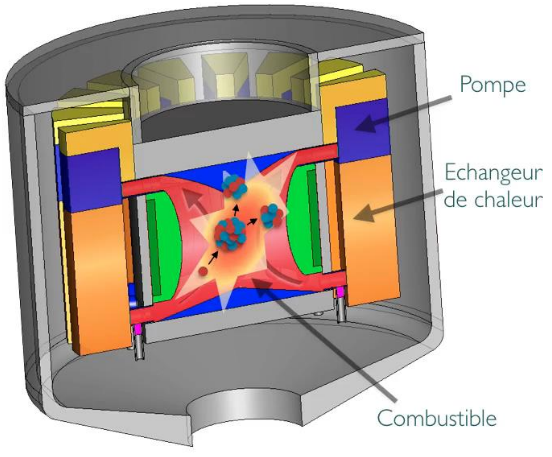
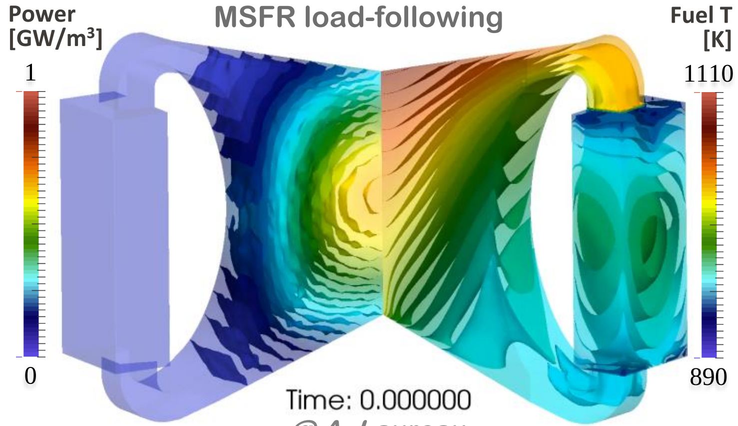
On behalf and with the help of the colleagues of the 'CNRS French Team MSFR'



Small Modular Reactor
@ M. Allibert



MSFR – Molten Salt Fast Reactor



@ A. Laureau

financé par IDEX Université Grenoble Alpes

MSR project @ IN2P3: researchers and laboratories involved (physics side)

3 permanents :

- **Lydie GIOT** (Maître assistante – IMT Atlantique) – 25%
- **Axel LAUREAU** (Chargé de recherche – CNRS) – 10 to 60%
- **Elsa MERLE** (Professeur – Grenoble INP) – 50%

LPSC GRENOBLE | MODANE / Equipe MSFR

Subatech / Equipe SEN

1 émérite :

- **Daniel HEUER** (DR CNRS émérite – départ à la retraite obligatoire au 01/01/2022)

1 bénévole :

- **Michel ALLIBERT** (DR CNRS retraité – expert en physico-chimie)

5 doctorants dans nos équipes (7 thèses soutenues depuis 2003) :

- **Thibault LE MEUTE** : *Modélisation d'un scénario d'insertion de réactivité dans un réacteur à sels fondus de génération IV* – Co-financement 2/3 **CEA Cadarache** et 1/3 **équipe MSFR/LPSC** (ressources propres) – Début 10/2019 (LPSC)
- **Laura MESTHIVIERS** : *Capacité de conversion des transuraniens en Réacteurs à Sels Fondus* – Co-financement **ORANO** et **équipe MSFR/LPSC** – Début 11/2019 (LPSC)
- **Hugo PITOIS** : *Simulation et sûreté du réacteur à sels fondus MSFR dans le cadre du projet européen SAMOSAFER* – **Financement projet SAMOSAFER** – Début 11/2020 (LPSC)
- **Yohannes MOLLA** : *Quantification des incertitudes pour la puissance résiduelle, impact des données nucléaires* – Financement **IMT Atlantique et université de Nantes** – Début 10/2021 (Subatech)
- **Thomas SORNAY** : *Etude des effets de seuil en termes de sûreté/fonctionnement, de conception et de gestion de la matière d'un réacteur à sels fondus de type SMR en cycle U/Pu* – Co-financement **Framatome Lyon** et **équipe MSFR/LPSC** – Début 11/2021 (LPSC)

MSR project @ IN2P3: scientific issues and some achievements

Advantages of a liquid fuel (molten salt)

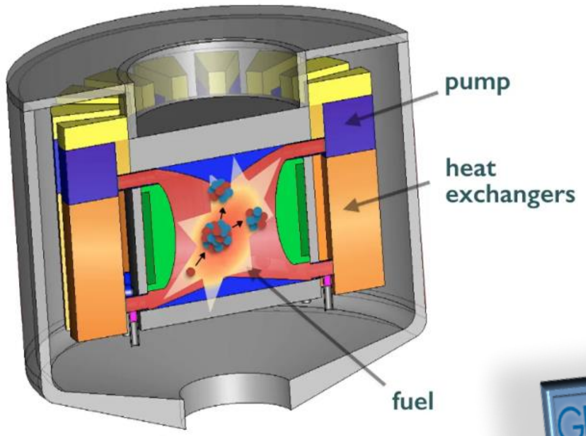
- Heat is produced directly in the heat transfer fluid
- Homogeneity of the fuel (no loading plan)
- No classic fuel fabrication (pellet / cladding / assembly)
- Possibility to reconfigure passively the fuel geometry in some mn
  - One configuration optimized for electricity production managing the criticality
  - One sub-critical configuration for a long term storage with a passive cooling system
- Possibility to reprocess the fuel without stopping the reactor
  - No reactivity reserve
  - Better management of the fission products that damage the neutronic and physicochemical characteristics

+

Neutronic optimization of MSR ('Gen4 reactors' criteria) :
- Safety
- Sustainability
- Deployment

2008: Selection by the **Generation 4 International Forum** of the IN2P3 innovative MSR concept based on a fast neutron spectrum, and called **MSFR (Molten Salt Fast Reactor)**

+ Registered as the **'CNRS reactor'** in the **official IAEA database ARIS**



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.

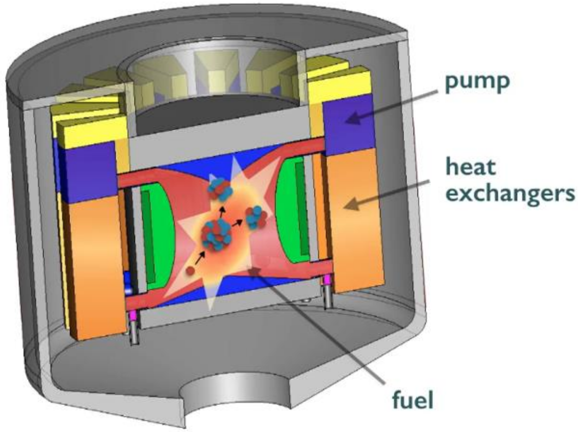
Two baseline concepts are considered which have large commonalities in basic R&D areas, particularly for liquid salt technology and materials behavior (mechanical integrity, corrosion):

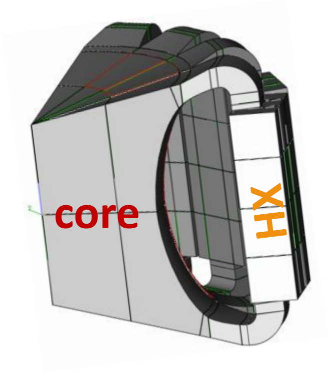
- The Molten Salt Fast-neutron Reactor (MSFR) is a long-term alternative to solid-fuelled fast neutron reactors offering very negative feedback coefficients and simplified fuel cycle. Its potential has been assessed but specific technological challenges must be addressed and the safety approach has to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

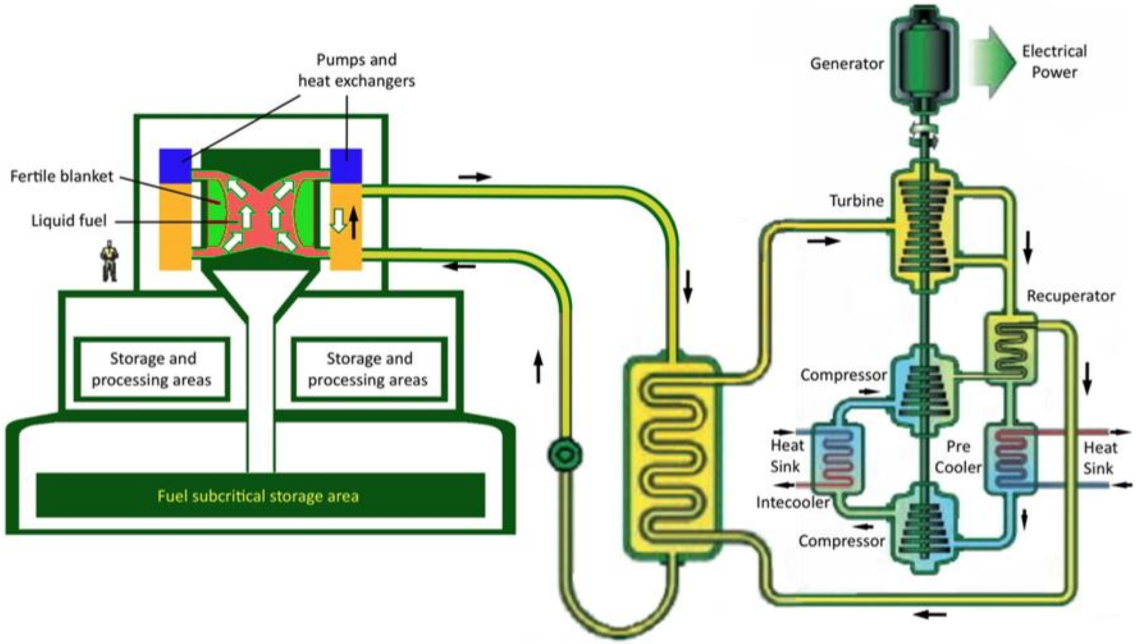
MSR project @ IN2P3: scientific issues and some achievements

➢ MSFR technical characteristics

- Reactor whose fuel is liquid and circulates to extract heat
- Reactor compact and simple core geometry, integrated design (heat exchangers in the core vessel)
- Fast neutron spectrum
- High temperature = high thermodynamic efficiency
- Excellent feedback coefficients (temperature and void)







➢ MSR innovative features compared to solid fuel reactors

- **Large flexibility in the design and operation** of the reactor in terms of fuel composition, reactor operation (load following), power level (large size reactor to SMR – micro-reactor)
- **No classical fuel fabrication** (cladding, assembly): cost reduction, easy to add waste (actinides currently produced) as fuel to burn them efficiently (continuous in-core recycling)
- **Elimination of most of accident and over-accident initiators** + safety coefficients excellent + no cliff-edge effect: reactor with high level of intrinsic safety

MSR project @ IN2P3: scientific issues and some achievements

➢ **R&D studies led at CNRS: simulations/safety/design/chemistry (LPSC, IJC Lab, SUBATECH)**

- Simulations in neutronics and reactor physics (LPSC, Subatech)
- Nuclear data, sensitivity studies, decay heat (Subatech) *+ see presentations @M. Kerveno / X. Doligez*
- Safety analyses of molten salt reactors (LPSC)
- Core and systems design studies (LPSC)
- Deployment scenario studies including MSR (LPSC)
- Chemical experimental studies of molten salts (IJCLab – *see IN2P3 SC 2016, @S. Delpech*)
- Experimental facilities FFFER and SWATH (LPSC – *see presentation @V. Ghetta*)

Academic research approach

Complementary to the R&D approach of the industry and the technological one of the CEA, starting from the knowledge of the elementary phenomena in physics and chemistry, from an analysis of the evaluated databases and the new needs, based on systematic studies of the various observables related to these phenomena, and carried by traditional approaches of the fundamental research (Monte-Carlo simulation codes, Green functions, genetic algorithms, correlated samplings, analytical resolution...)

➢ **Developments of codes specific / generic adapted to MSR modelling**

- Coupled code neutronics chemistry REM for burn-up calculations (@D. Heuer, X. Doligez, A. Nuttin)
- Cocodrilo and Coconust codes for nuclear data uncertainties propagation and assimilation respectively due to decay heat data and to neutron cross sections using a Total Monte Carlo approach (@ L. Giot and A. Laureau)
- Code coupling neutronics « Transient Fission Matrix » + CFD thermal-hydraulics (@A. Laureau)
- Power plant simulator: LiCore MSR core code (@A. Laureau) coupled to the ALICES platform of CORYS/Framatome
- Multicriteria system optimization code SONGE based on genetic algorithm (@D. Heuer)
- Innovative scenarios for the future (ISF) code (@D. Heuer)

MSR project @ IN2P3: scientific issues and some achievements

➢ Coupled neutronics chemistry REM code: Boltzmann-Bateman evolution under constraints

Bateman Equation for nucleus i (in place B of the system):

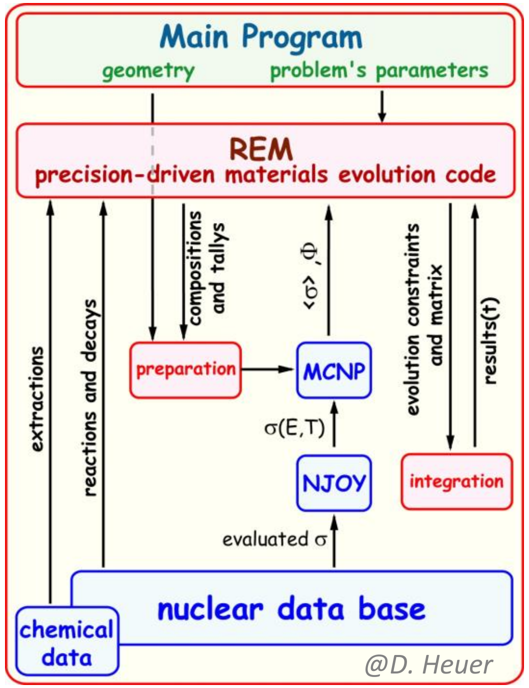
$$\frac{\partial N_i^B}{\partial t} = \sum_{j\neq i}\left\{\left(\lambda_{j\to i} + X_j <\sigma_{j\to i}\phi>\right)N_j^B\right\} + \sum_{C\neq B}\lambda_{Chem}^{C\to B}N_i^C - \lambda_i N_i^B - <\sigma_i\phi> N_i^B - \sum_{C\neq B}\lambda_{Chem}^{B\to C}N_i^B$$

production by radioactive decay — production by nuclear reaction — disappearance by radioactive decay — disappearance by nuclear reaction

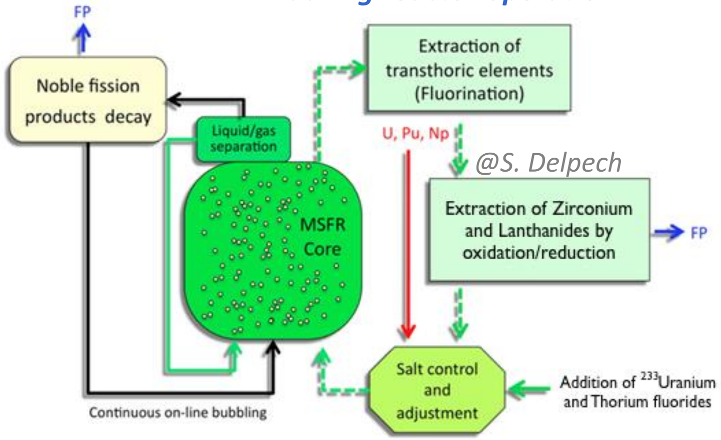
with *'B' = location of nucleus i in the sub-system B*
'B → C' = transfer from sub-system B to sub-system C

Calculation of the evolution of matter in each part of the system

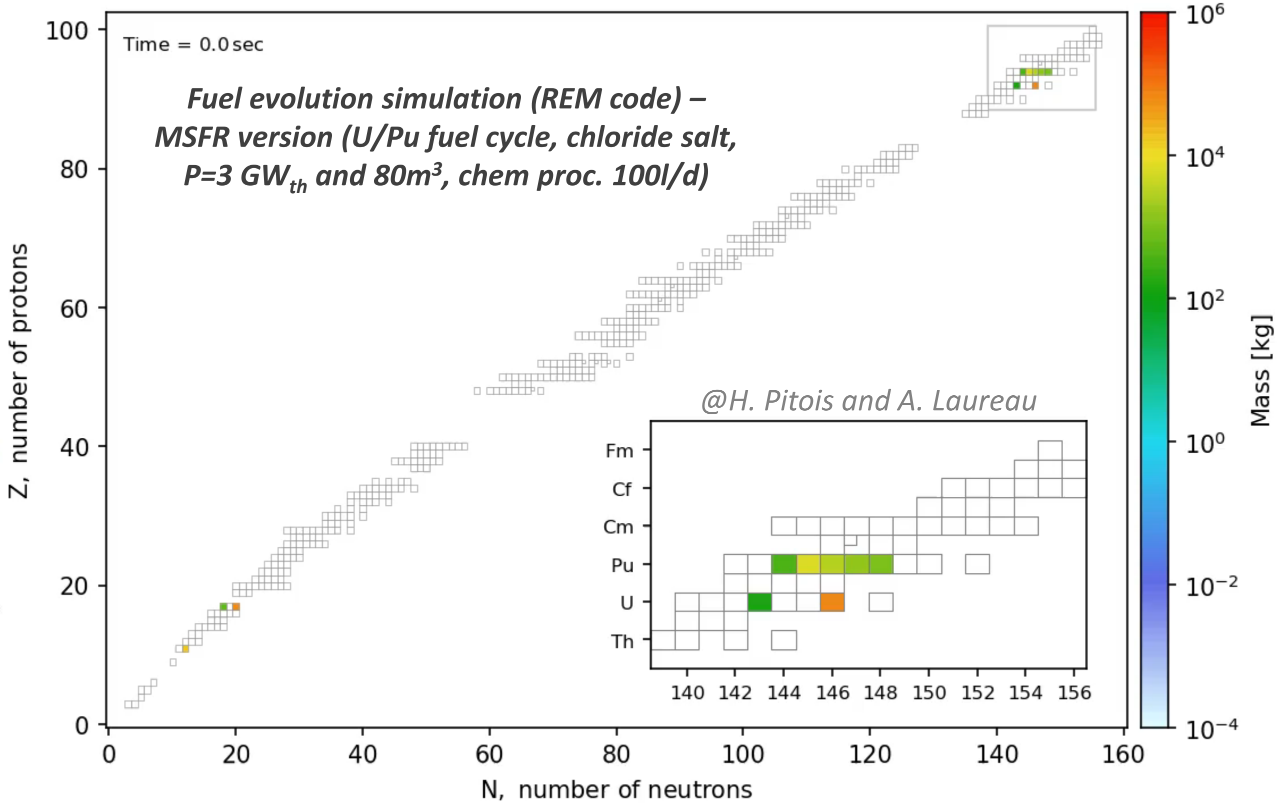
⇒ Determination of isotopes concentrations, gamma or neutron flux + residual heat (fundamental data for radioprotection) everywhere (core, reprocessing unit, bubbling system, draining tanks…) – Basis of the design and of the safety, proliferation and radioprotection assessment of the whole system



chemical processing and feeding during reactor operation



+ Mosarela code under development @CEA



MSR project @ IN2P3: scientific issues and some achievements

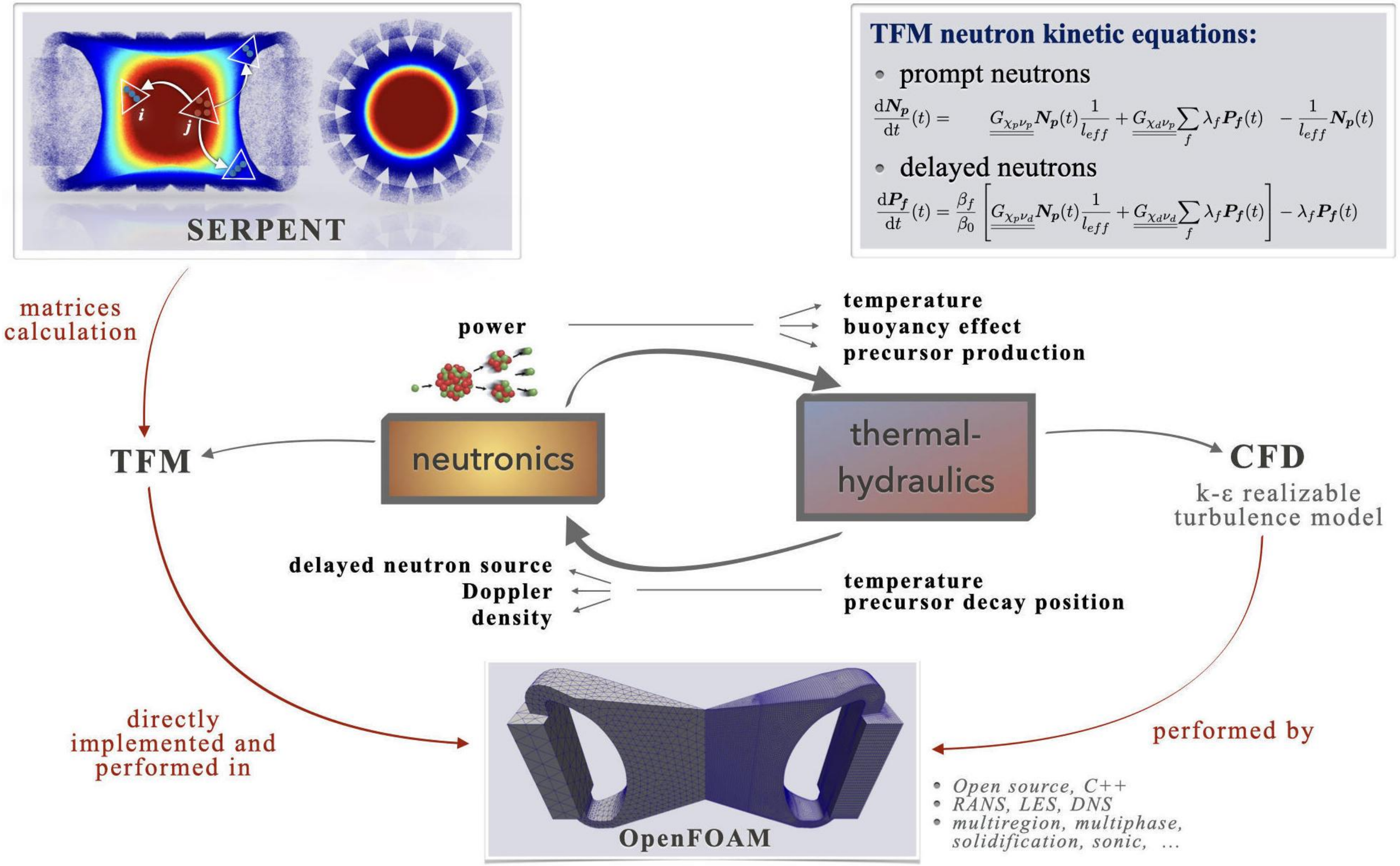
➢ Code coupling neutronics « Transient Fission Matrix » + CFD thermal-hydraulics

- **Objective:** simulate and study molten salt reactor transients, i.e. its normal (load following, start-up...) or abnormal (reactivity insertion, over-cooling...) operating state changes
- **Specificities:** turbulent liquid fuel in core (accurate 3D simulation) and circulating out of core (delayed neutrons), fuel = coolant

***+ Current collaboration CNRS-IN2P3 / Framatome to implement the TFM approach in the StarCCM+ code** (master and PhD thesis of Thomas Sornay, 2021)*

Application of the TFM approach to MSR, PWR, SFR (Astrid), research reactors (Zephyr) and provided to CEA and Framatome

+ Validated on criticality experiments (Flattop, Jezebel)



MSR project @ IN2P3: scientific issues and some achievements

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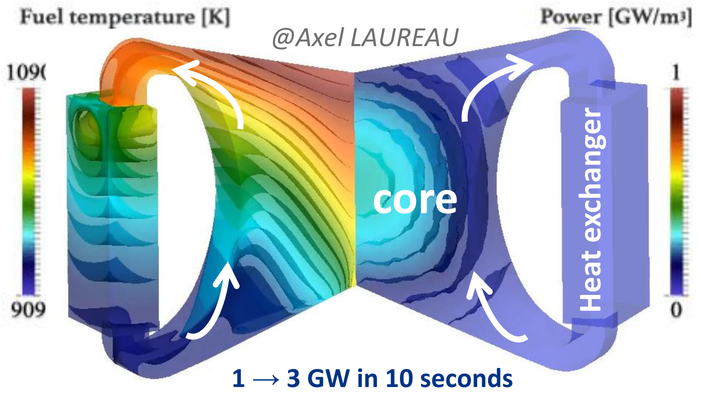
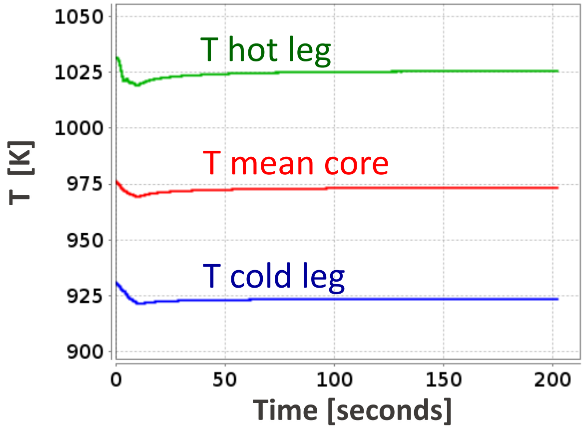
Transient studies with the TFM-OpenFoam coupled code → MSFR load following from 1 to 3 GW in 10s

- Nuclear heat deposited directly in the coolant (= fuel salt) ⇒ **large flexibility for controlling the core**, which closely follows the network demand
- Reactor control provided by the heat extracted **without requiring the action of a control rod**
- Possibility to adjust the flow of the salts ⇒ **mean core structure temperatures stable** during the load following therefore little thermal fatigue
- High intrinsic stability of the core ⇒ **relevant safety margins**





MSR project @ IN2P3: scientific issues and some achievements

➢ Nuclear safety and decay heat study

- **Objective:** never have any consequences on the off-site environment
- **Needs:** fulfill the **3 safety functions** (control of the reactivity, fuel cooling, radioactive material confinement) + **suppress by design any accident initiator** + **no risk of any over-accident**

Nuclear safety: fundamentals – Safety functions

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:

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

MSR project @ IN2P3: scientific issues and some achievements

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Control the chain reaction:

– All safety coefficients are excellent ⇒ intrinsic stability of the core

– If no control rods = suppression of the ejection risk

– Processing of the fuel during reactor operation (refueling and cleaning) = continuous control and adjustment of the fuel composition + no need of an initial reactivity reserve

Fuel cooling under any circumstances:

– Possibility for spreading the fuel by a simple gravitational draining to ensure a passive and efficient cooling (draining system)

Confinement of the radioactive material of the reactor:

– No high pressure

– No risk of state change of the fuel and no risk of violent chemical reaction with any component of the environment

– Processing of the fuel during reactor operation (cleaning) = extraction of some of the radioactive material (fission products) out of the core, reducing the core source term

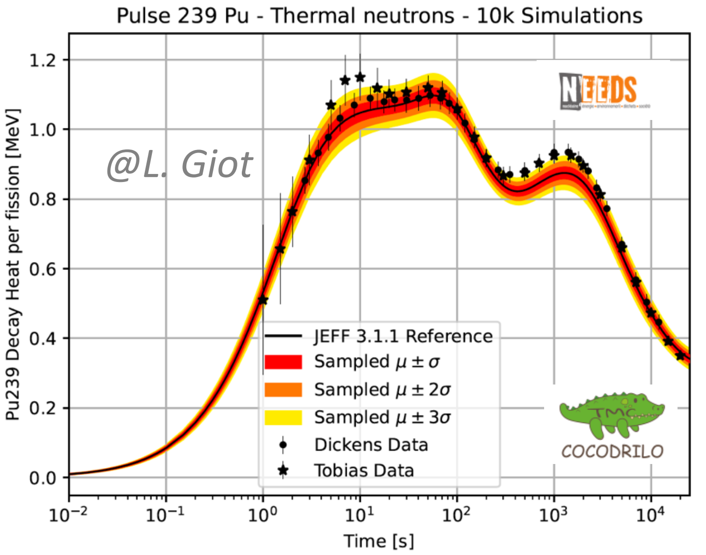
➢ Development of a safety analysis method for liquid-circulating fuel reactors (see SAMOSAFER and SAMOFAR European projects+ PhD thesis of D. Gérardin – collaboration with IRSN, Framatome and POLITO)

➢ Decay heat and nuclear data uncertainties

Cocodrilo and Coconust codes (@L. Giot and A. Laureau, Subatech)

First calculations: impact of the uncertainties of the Fission Yields

See PhD thesis of Y. Molla (Subatech) with application to the MSFR



MSR project @ IN2P3: Genesis and timeline

In2p3

GIF
- MSFR becomes the reference concept of MSR

EDF
- Funding of 3 PhD MSR (Evaluation MSR, Neutronic, neutronic-reprocessing coupling)

RHODIA-SOLVAY
- Funding of 1 PhD (Chemistry)
- Funding of 2 PhD CIFRE (Chemistry, reprocessing)

PACEN
- Unite a community
- Fund an experimental laboratory in CNRS Orsay
- Propose a concept of fast MSR in U/Th fuel cycle in fluoride salts

NEEDS
- Maintain the community
- Fund experimental studies
- Safety studies
- NEEDS 2020 : PIRT safety

FRAMATOME
- Co-funfing of 1 PhD (SMR MSR)

CORYS
- Development of MSFR operating simulator

CEA
- Funding of 2 PhD (Materials, safety)

ORANO
- Funding of 1 PhD (chloride MSR)

@ S. Delpech

1999 — 2004 — 2007 — 2008 — 2011 — 2015 — 2017 — 2019 — 2020

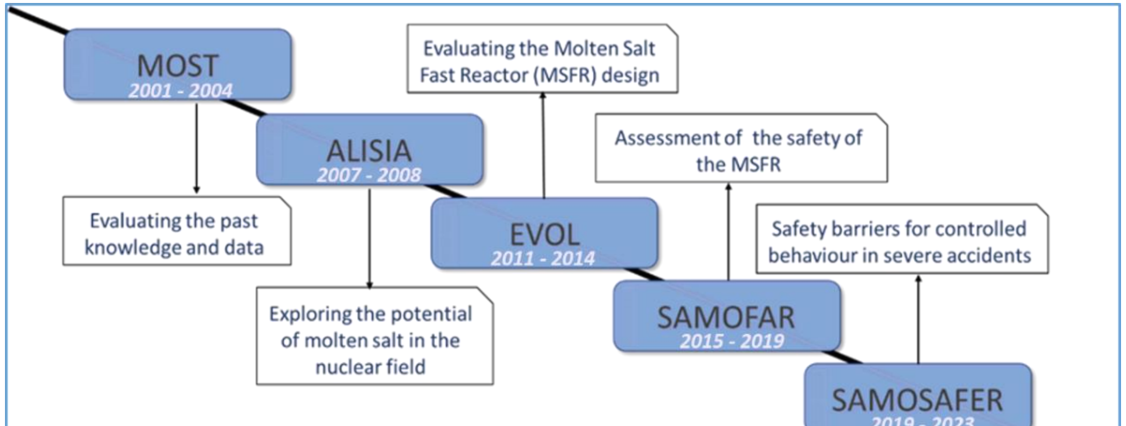
ALISIA : European project
- Development of an european community

EVOL : European project
- Funding of 2 PhD (CNRS)
- Optimization of fuel salt composition
- Proposition of a core design
- Neutronic benchmark
- Proposition of a reprocessing scheme

SAMOFAR : European project
- Funding of 1 PhD and a post-doc (CNRS)
- Reprocessing unit safety
- MSFR safety analysis
- Return on design

IN2P3 - FRAMATOME
- Signature of the MoU
- Funding of 1 PhD (SMR MSR)

SAMOSAFER : European project
- Funding of 1 PhD and a post-doc (CNRS)
- Multiphysical core calculations
- Safety
- Calculation of insertion and reactivity
- Waste management
- Reactor operation studies
- Validation of reprocessing steps



MSR European projects since 2000

MSR project @ IN2P3: projects and perspectives

➢ How to design an innovative reactor?

- **Define the use and then the related specifications of the reactor**: electricity production, waste burning, heat production, spatial propulsion, submarines, radioisotope production…
- **Select a reactor concept** with qualities coherent with the specifications, able to provide new options and flexibility, and adapt it to the specifications (studies, experiments)
  - Choice of the neutron spectrum: from thermal to fast
  - If breeder/energy production reactor: choice of the fuel cycle
  - Choice of a fluoride or chloride fuel salt
  - Choice of the reactor power and volume: from SMR (even microreactor) to large size core

Advantages of a reduced specific power reactor:

Reduced irradiation damage, less volumetric heat to be extracted (simplified exchanger design), reduced residual power (safety), possibility of operating for several decades with the same fuel salt and much lighter fuel processing, simplification of the system

➢ Evolution of the research projects since 15 years at CNRS/IN2P3 on Gen4-MSR

- **« reference MSFR » concept (breeder in Th/^{233}U cycle with fluoride salt, objectives = identification of viable configurations)** studied and optimized since 15 years at CNRS + EVOL, SAMOFAR, SAMOSAFER European projects + GIF / IAEA : **toroidal core of around 2.3mx2.3m with 18m^3 of fuel salt**
- **MSFR concept in U/Pu fuel cycle and chloride NaCl salt in a large 3 GWth version** (optimization studies, *PhD thesis of Hugo Pitois fund. Samosafer*) **and in a SMR version** (simplified concept + identify the steps to industrialization, *PhD of Thomas Sornay Framatome/CNRS-LPSC*)
- **Convertor version (fuel = Pu and/or minor actinides, chloride salt NaCl+$MgCl_2$)**, *PhD thesis CNRS-LPSC/Orano Laura Mesthiviers + ISAC project / ARAMIS concept*

MSR project @ IN2P3: projects and perspectives

➢ **SAMOSAFER European project (2019-2023):** continuation of the **neutronic benchmark and safety/operation studies of the reference MSFR** (CEA, Framatome, EDF, IRSN + POLITO, POLIMI, PSI) + PhD thesis H. Pitois (2020-2023)

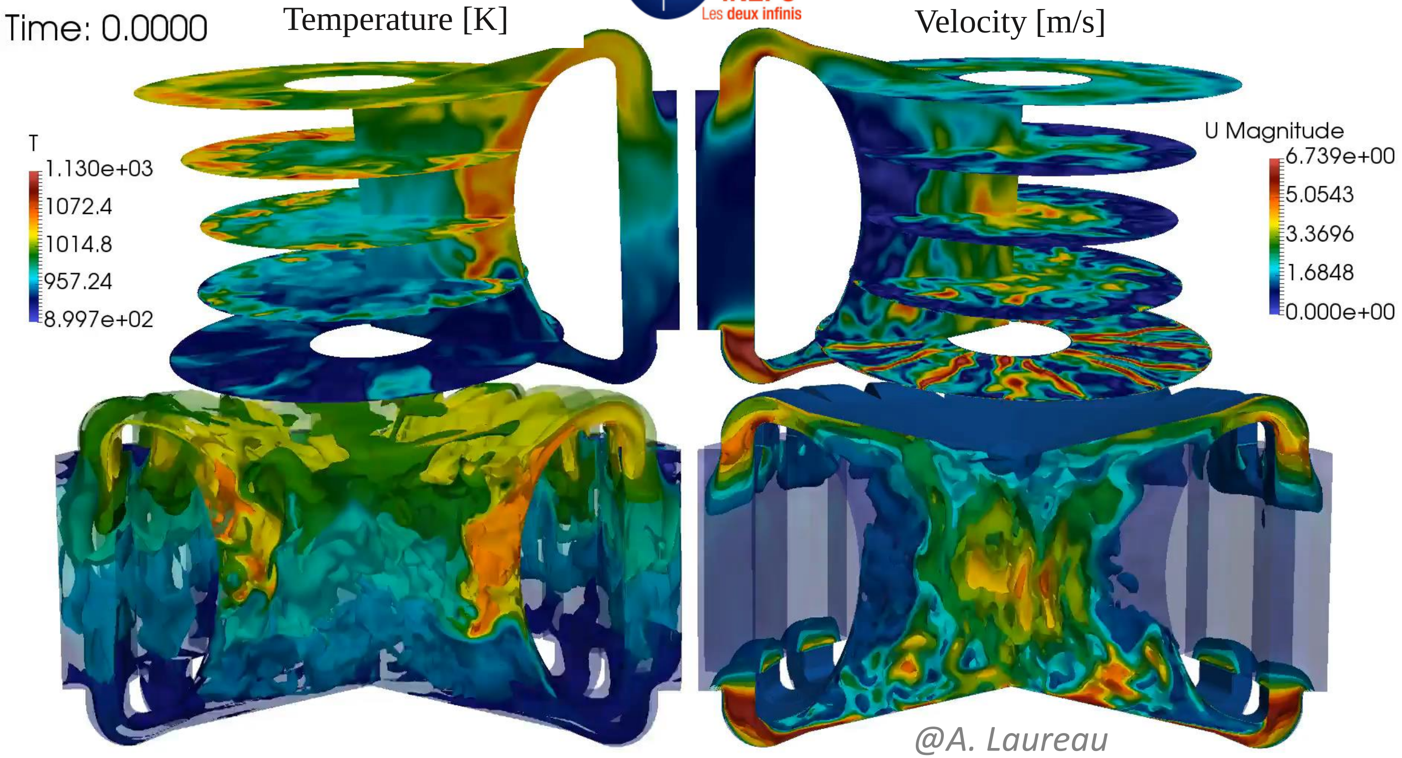
Impact of turbulent in-core temperature fluctuations on the fission power amplitude during normal operation?

Core stability according to flow turbulence

- Flow turbulence induces temperature variation/oscillation
- Temperature variation induces power variation
- *How large? Is it a problem?*

Study of this phenomenon

- DES calculation
  → Large Eddy Simulation with a RANS modeling near to the walls
- Solve the large scales of the turbulence (and Δρ fluctuations)
- ***MSFR geometry can/should be improved!***



Calculation illustration of the first 16 seconds of the starting of a DES calculation using the MSFR-EVOL geometry, TFM-OpenFOAM multiphysics calculations

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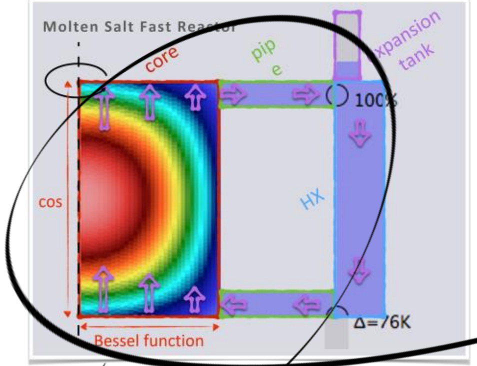
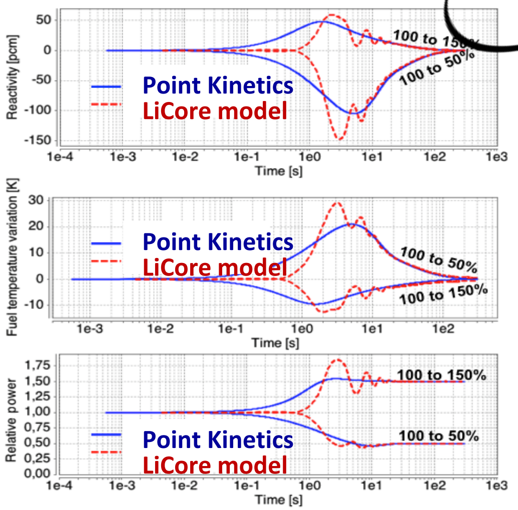
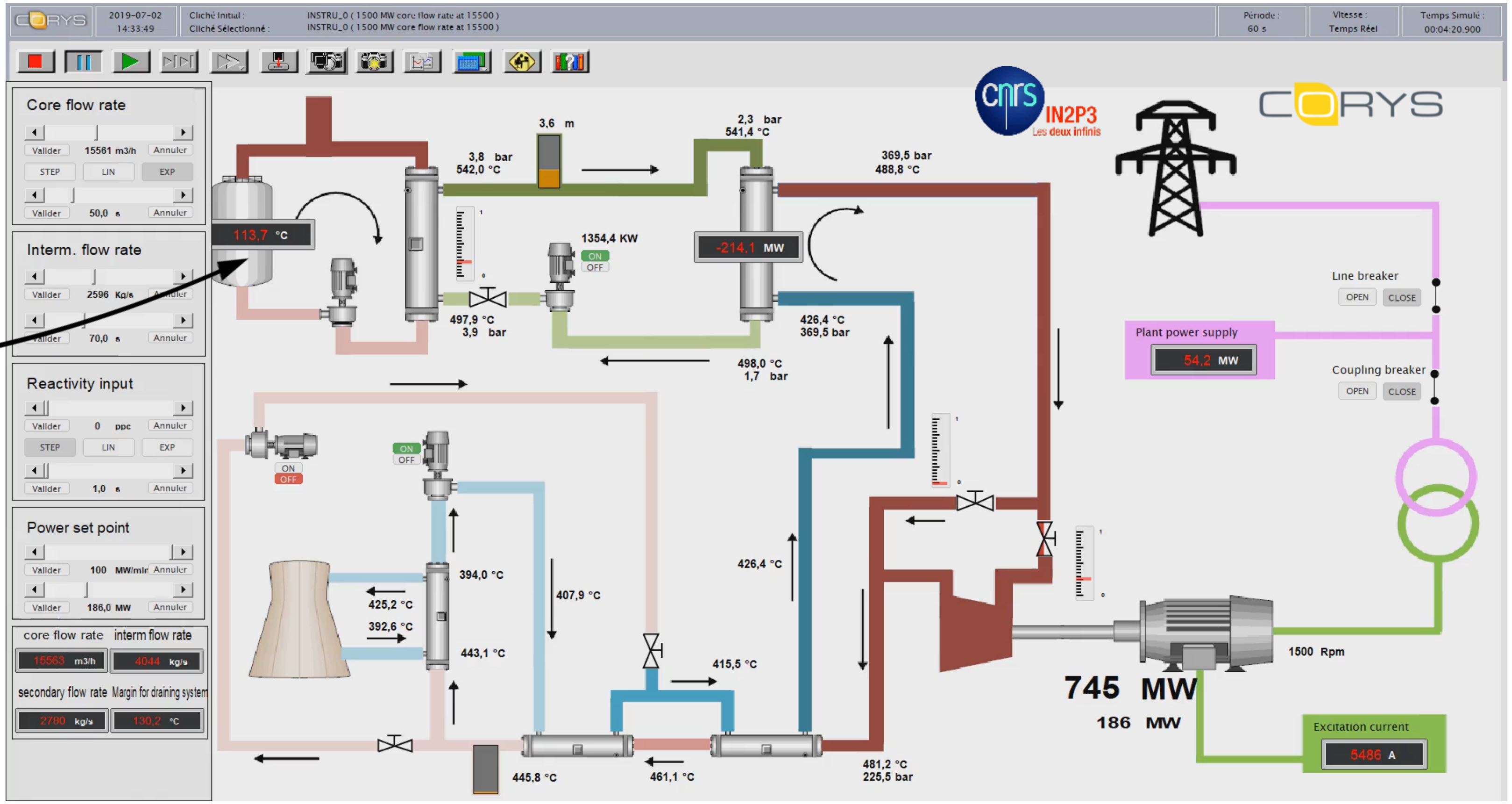
- **With the CORYS company**: continuation of the **MSFR power plant simulator development**

IN2P3 LiCore MSFR core modelling (real time calculations)







(*) CORYS: World Leader of the dynamic simulation for nuclear, transport and hydrocarbides industries / Simulators for the training of operators and for operation studies and definition of new plants during the design phase

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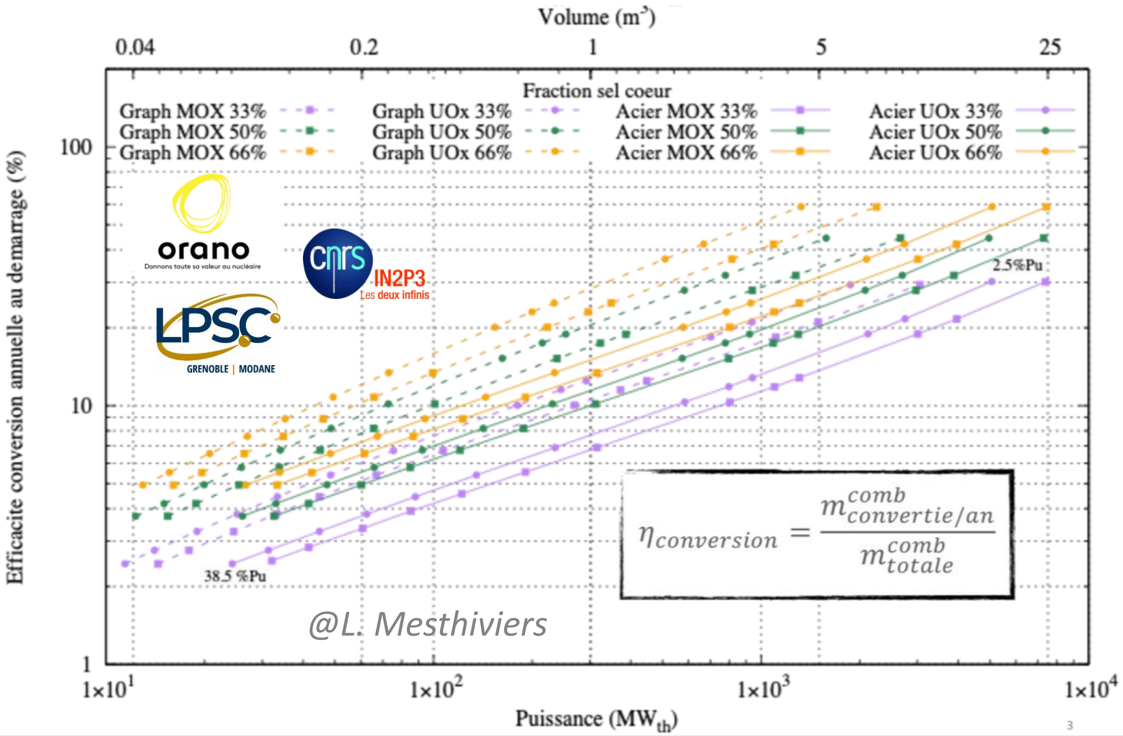
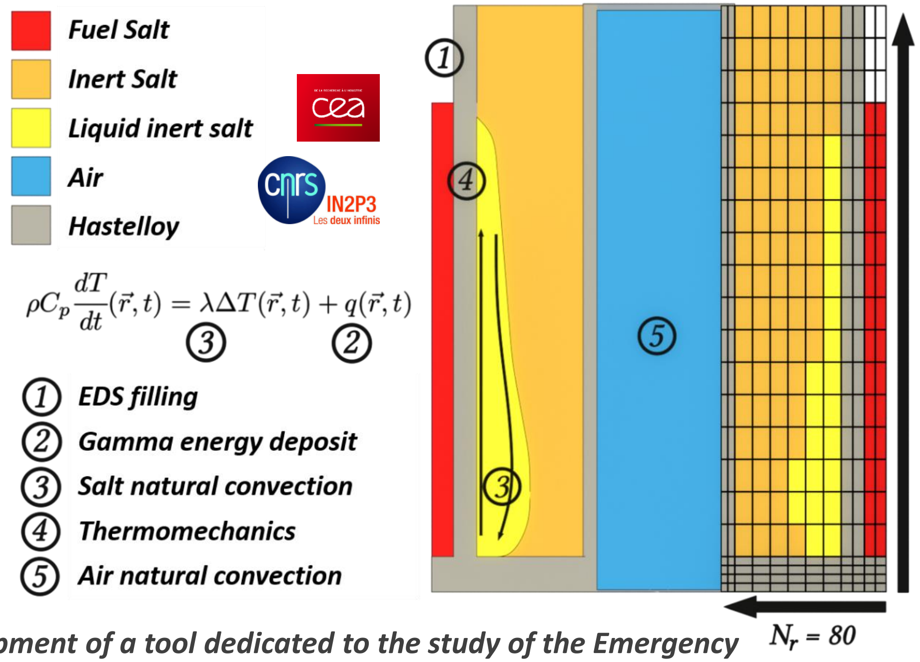
- **With ORANO:** continuation of the collaboration on **actinide burning capacities of chloride SMR MSR** (PhD of L. Mesthiviers, 2019-2022) **+ deployment and burning scenarios** in ISAC and MIMOSA projects (new common PhD thesis beg. 11/2022) + evaluation of the **Thorizon concept** (see MIMOSA European project)
- **With CEA:** **severe accident studies** (PhD thesis T. Le Meute 2019-2022) + **MSR operation** (PhD thesis M. Mascaron)





Development of a tool dedicated to the study of the Emergency Draining System and based on an analytical approach @ T. Le Meute

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- **With Framatome Lyon**: **Design and safety studies of a Small-MSFR (S-MSFR) in U/Pu cycle and chloride salt** (PhD thesis Framatome/CNRS-LPSC of T. Sornay, 2021-2024)
- **Nuclear data for decay heat evaluation and cross section uncertainties:** **residual power calculations and the associated uncertainties propagation for the safety evaluation of MSR concepts and to define the safety margins** (PhD thesis of Y. Molla, Subatech, 2021-2024, 50% MSR)

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- **ISAC (Innovative System for Actinides Conversion) national PIA4 project:** collaboration CEA (leader), CNRS, Orano, Framatome, EDF (2022-2025) with **1 PhD thesis between Subatech and LPSC (neutronics, decay heat, safety)**
- **MIMOSA (MultI-recycling with MOlten SAlt technology) European project:** submitted in 10/2021 (leader Orano)
- **Participation to the XSMR-MSR project of the NAAREA start-up: micro-reactors from 1 MW to 40 MW**, prototype in the coming years, in charge of the core part of the **scenarios and digital twin** – 2 postdocs foreseen in 2022

MSR project @ IN2P3: state of the art and IN2P3 implications

	CA	CH	CN	FR	IN	EU	RU	TR	UK	US
Programs	-	-	X	?	-	X	?	?	-	X
Teams	X	X	-	X	X	-	X	-	-	-
Start-ups	X	-	-	X	-	-	-	-	X	X

In the world:

- **Generation 4 Forum International (GIF): concept of 'MSFR' (lead. CNRS) selected in 2008, members of the MSR steering committee**
- **IAEA: Meetings on the technology of MSRs** (French representative) + **Technical Report Series (TRS no.489)** ("IAEA Technical Reports Series on the Status of Molten Salt Reactor Technology", 2021 – French chapter https://preprint.iaea.org/search.aspx?orig_q=RN:52090830
- **Canada: panel of nuclear safety experts Canadian Nuclear Laboratories**
- **NEA: expert in the Technical Review Group** for the International Assay Data of Spent Nuclear Fuel Database

In France

- **NEEDS** (co-leader of MSR safety PIRT exploratory project 2021)
- **Industrial expertise** (IRSN 2014, ORANO 2019/21, NAAREA 2020)
- **Co-organisation with CEA of the first national MSR bootcamp** (4-8 october 2021, Avignon, 80 participants) https://www.youtube.com/watch?v=8DNzzGAeWLU

MSR projects in the world

- China builds in Gobi Desert a thermal MSR demonstrator (ancient MSRE)

- Predesign stage of the Molten Chloride Salt Reactor funded by the DOE under the supervision of TerraPower

- SMR concepts including MSRs evaluated in Canada to produce heat and electricity in isolated places

- French NAAREA start-up: molten salt micro-reactor (XSMR) prototype in the coming years, aiming at producing energy and burning wastes

In Europe: 2 European Projects of Horizon2020

- **SAMOFAR** - H2020 - 2015-2019 – 3 M€ - 11 partners – IN2P3 in charge of WP "safety approach and system integration"
- **SAMOSAFER** - H2020 - 2019-2023 – 3.5 M€ - 14 partners – IN2P3 in charge of WP "Reactor Operation and safety demonstration" and of 5 tasks among which the neutronic benchmark
- **SNETP/ESNII** board decided to integrate MSR (01/2022)

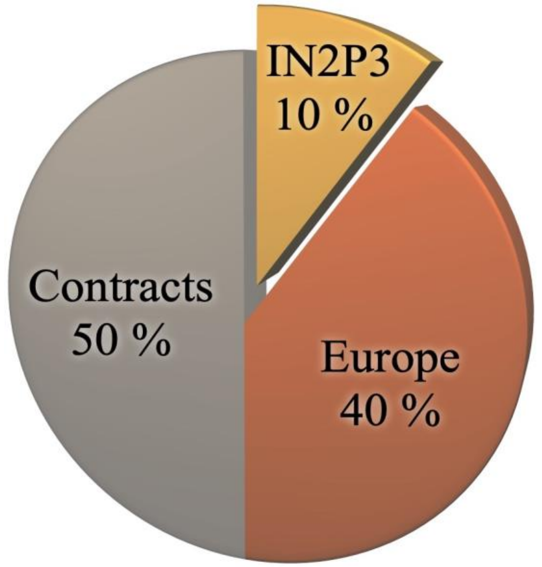
- **Set-up of industrial collaborations with Framatome** (MoU in 2020 + co-funded PhD thesis), with **ORANO** (1 co-funded PhD thesis + 1 to come in 2022), with **CORYS** (regular co-supervision of internships)
- Nominated member of the **Scientific Council of IRSN** (since 2021)

MSR project @ IN2P3: conclusions

➢ Strengths and Opportunities

- The teams develop and use **unique simulation methods and codes, generic and adapted** to this type of reactor
- **Strong support of the two concerned laboratories** LPSC and Subatech
- **Recognized skills and expertise** (reactor physics, safety, data, MSR...) and, more broadly, the driving role of France and CNRS/IN2P3 at the national and international levels
- Many **collaborations and research projects in progress**
- **Very favorable context to valorize our assets** (competences, codes) = rise in power of MSR concepts in the world, evolution of Astrid project in France

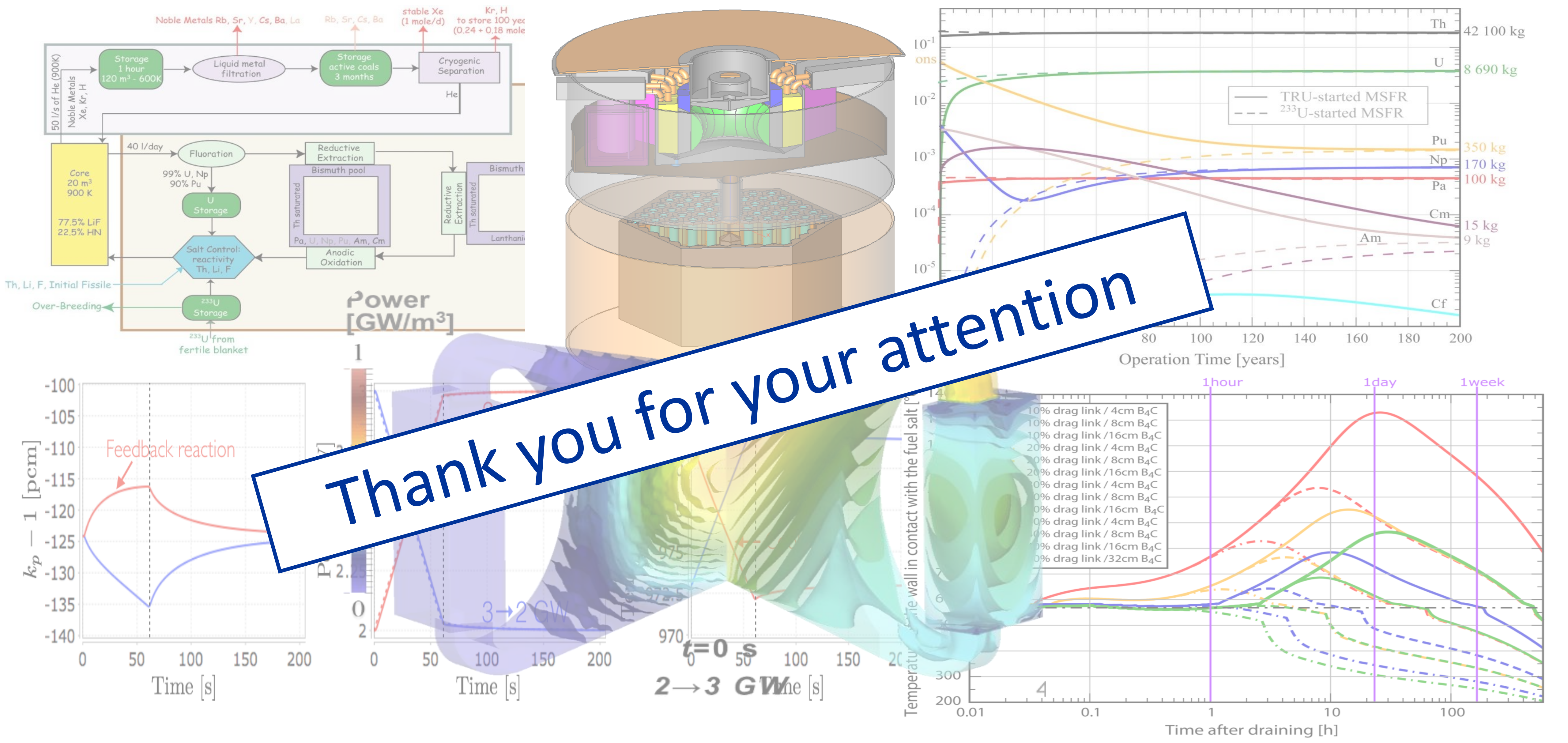
Budget without salaries



➢ Weaknesses and Threats

- **Very low number of permanent researchers** working on the project (only 2 teachers-researchers today)
- **Practical support of IN2P3 quite small in terms of budget and PhD funding** (none since 2010)
- **Suppression of the MSFR Master Project** some years ago (as for quasi all interdisciplinary MPs): reduces the visibility of our research activities and the IN2P3 support

The context is of course difficult at CNRS financially and for human resources. But the main threat is that the MSR thematic seems today not clearly a priority of IN2P3, while other countries and institutions increase there fundings and human resources on the topic at the same time. This is a pity because **IN2P3 has really a defined and capital role on the subject, with the associated skills.**



Thank you for your attention

BACKUP SLIDES

PhD Theses defended at CNRS/IN2P3 on Gen4-MSR

Delphine GERARDIN, "***Développement d'outils numériques et réalisation d'études pour le pilotage et la sûreté du réacteur à sels fondus MSFR***", PhD Thesis, Grenoble Alpes University, France (2018)

Gabriela DURAN-KLIE, "***Étude du comportement de l'uranium et de l'iode dans le mélange de fluorures fondus LiF-ThF$_4$ à 650 °C***", Paris Saclay University (2017)

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

Davide RODRIGUES, ***"Solvatation du thorium par les fluorures en milieu sel fondu à haute tempéra… é d'extraction réductrice pour le concept MSFR"***, PhD Thesis, Paris Sud University (2015)

Mariya BROVCHENKO, ***"Etudes préliminaires de sûreté du réacteur à sels fondus …*** …nology, France (2013)

Xavier DOLIGEZ, ***"Influence du retraitement physico-chimique du sel … sur le dimensionnement de son unité de retraitement",*** PhD Thesis, Grenoble Institute of Technolo…

Elsa MERLE-LUCOTTE, ***"Le cycle Thorium en réact… problème énergétique du XXIème siècle ? Le concept de TMSR-NM",*** Habilitation à Diriger les Rech… …nce (2008)

Ludovic MATHIEU, ***"Cycle Thori… champ des Paramètres et des Contraintes définissant le Thorium Molten Salt Reactor",*** PhD Thesis, G… …, France (2005)

Jorgen FINNE, ***"Chimie des me… pplication à l'extraction réductrice d'actinides et de lanthanides par un métal liquide"***, PhD Thesis, EDF-CEA-ENSCP, Paris, F…

Fabien PERDU, ***"Contributions au… 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/MSFR-biblio or 'MSFR LPSC' in google search

MSR project @ IN2P3: Scientific production

- 76 publications (29 peer-review articles and 47 proceedings), 6 book chapters, 21 deliverables and milestones of European projects and 3 other publications
- 42 communications in international conferences and workshops
- Invited to give presentations, lectures and webinars in national and international frames, both for experts or general public

• **Audition CEA/CNRS lors du « SNETP/ESNII Workshop on MSR »** sur “Molten Salt Reactor Research for Europe” (octobre 2021)

• **Audition invitée devant le comité de prospective en énergie de l’Académie des Sciences** sur les réacteurs à sels fondus (mars 2021)

• **Présentation invitée grand public scientifique** lors de la journée « Le nucléaire et ses innovations au service d’une reprise durable en Europe ? » des Entretiens Européens (11/2020)

• **Présentation invitée à l’AIEA** dans le cadre des “Webinar Series on Nuclear Technology Breakthroughs for the 21st Century” sur “Molten Salt Reactors: A Game Changer in the Nuclear Industry” - plus de 230 auditeurs (août 2020)

• **Audition publique invitée** “Les réacteurs de 4ème génération à combustible liquide ” devant **l’Office Parlementaire d’Evaluation des Choix Scientifiques et Technologiques (OPECST**) dans le cadre de « NOUVELLES TENDANCES DE LA RECHERCHE SUR L’ÉNERGIE : I - L’AVENIR DU NUCLÉAIRE », Assemblée Nationale, Paris, mai 2018

• **Talk expert invité**, “Molten Salt Fast Reactor as SMR: activities and perspectives” dans l’International Workshop on Design and Technology Status of Innovative (non-water cooled) SMRs for Near Term Deployment, Agence Internationale de l’Energie Atomique (**IAEA**), Vienne, Autriche (novembre 2018)

• **Webinaire invité** sur “Molten Salt Reactors (MSR)” du forum Generation 4 dans le cadre des Webinar series, GIF Education and Training Task Force, **Forum International Generation4** (https://www.gen-4.org/gif/jcms/c_82831/webinars (may 2017)

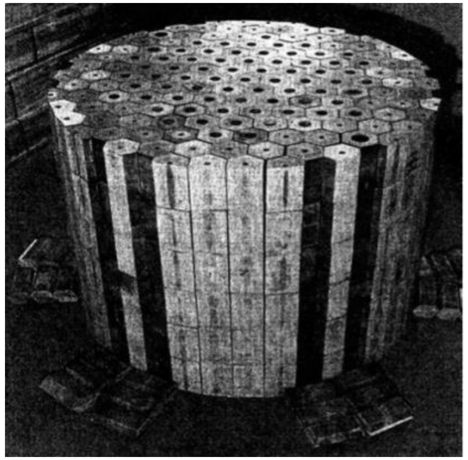
• Audition invitée à la Direction de l'Environnement, du Climat, de la Santé et de l'Energie (DCESE) de la Région Rhône-Alpes Auvergne, décembre 2016

• 3 présentations invitées au Molten Salt Reactor Technology Determination Workshop, TUBITAK, Marmara Research Center, Turquie, décembre 2017

• **Audition** “Contribution du CNRS : Les MSFR, Réacteurs rapides à sels fondus” **devant le Comité d'Orientation et de Suivi des recherches pour les SYstèmes Nucléaires (COSSYN)** dans le cadre du bilan des recherches conduites sur le développement de réacteurs nucléaires de nouvelle génération et perspectives, 2013

• **Audition** “Thorium en combustible liquide : le concept MSFR (Molten Salt Fast Reactor)” devant la **Commission Nationale d’Evaluation (CNE)** des recherches et études relatives à la gestion des matières et déchets radioactifs, février 2013

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



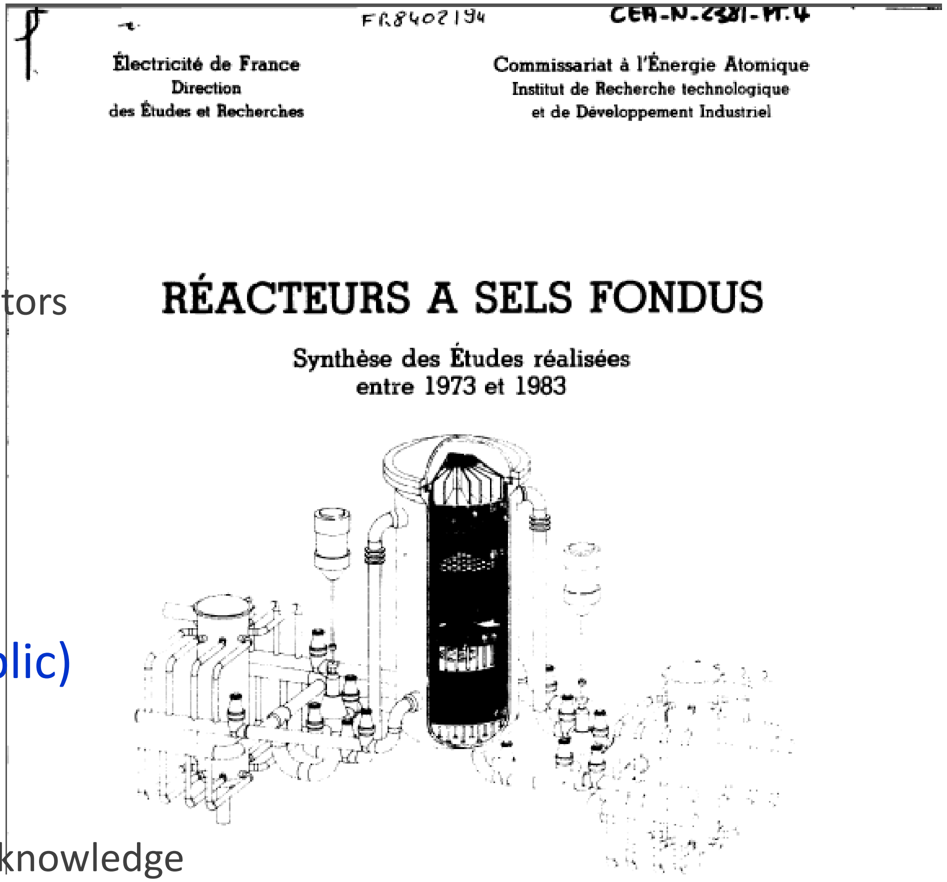
- 1954 : **Aircraft Reactor Experiment (ARE)**
  Operated during 1000 hours
  Power = 2.5 MWth

- 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/fertile matter 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 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.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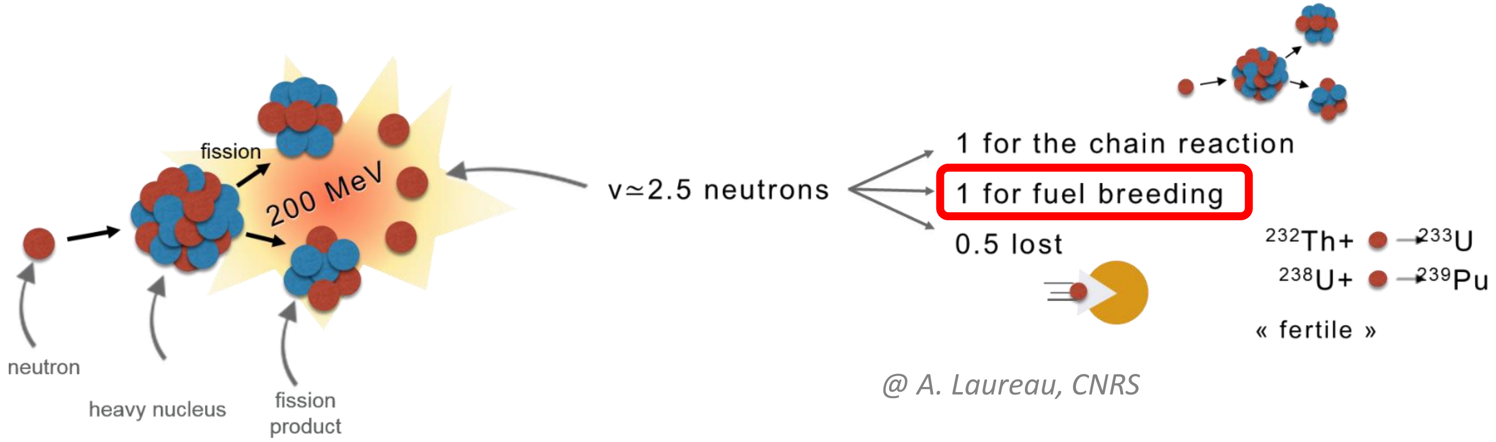
Électricité de France
Direction
des Études et Recherches

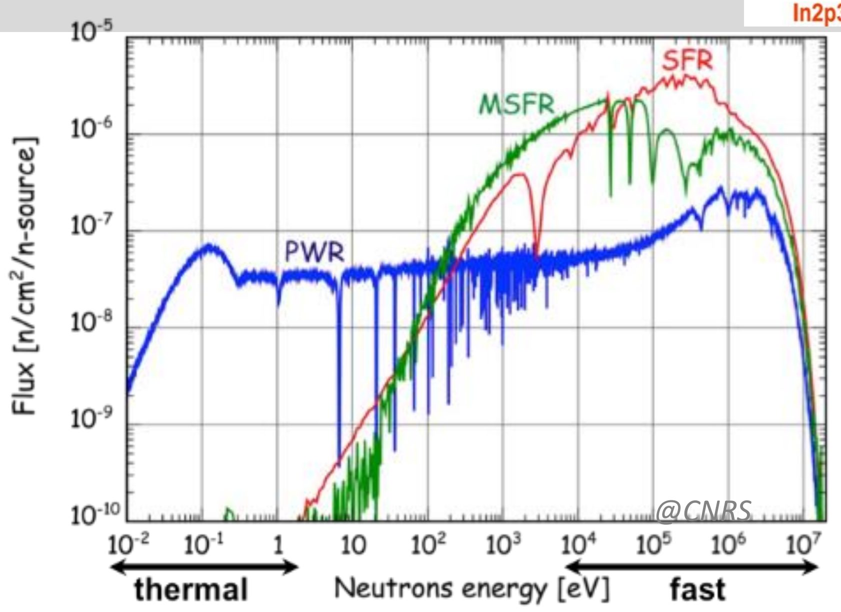
Commissariat à l'Énergie Atomique
Institut de Recherche technologique
et de Développement Industriel

RÉACTEURS A SELS FONDUS

Synthèse des Études réalisées
entre 1973 et 1983

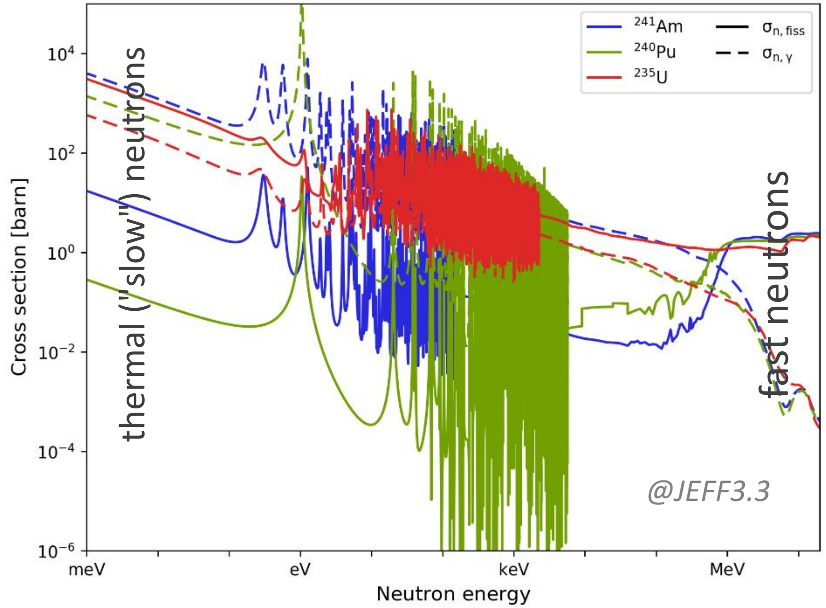
Generation 4 reactors: mainly fast neutrons reactors





Goal = **sustainable use of the nuclear resources**, i.e. don't use only ^{235}U as fissile matter (also Pu and minor actinides produced in present LWRs) + self-production of fissile matter by the reactor itself (breeder reactor in the ^{238}U/Pu of Th/^{233}U fuel cycle)

→ Use fast neutrons (as produced by fission): all heavy nuclei able to fission (waste used as fuel!) + limit the neutrons losses



Some consequences of using fast neutrons:

- More neutron leakage out of the core → add **fertile blankets** around the core to use these neutrons for breeding
- More **irradiation damages** to materials → see lecture on nuclear materials
- **Impact on safety**: lower fraction of delayed neutrons, feedback coefficients…

Familles de RSF : grande flexibilité permettant de nombreux concepts acceptables

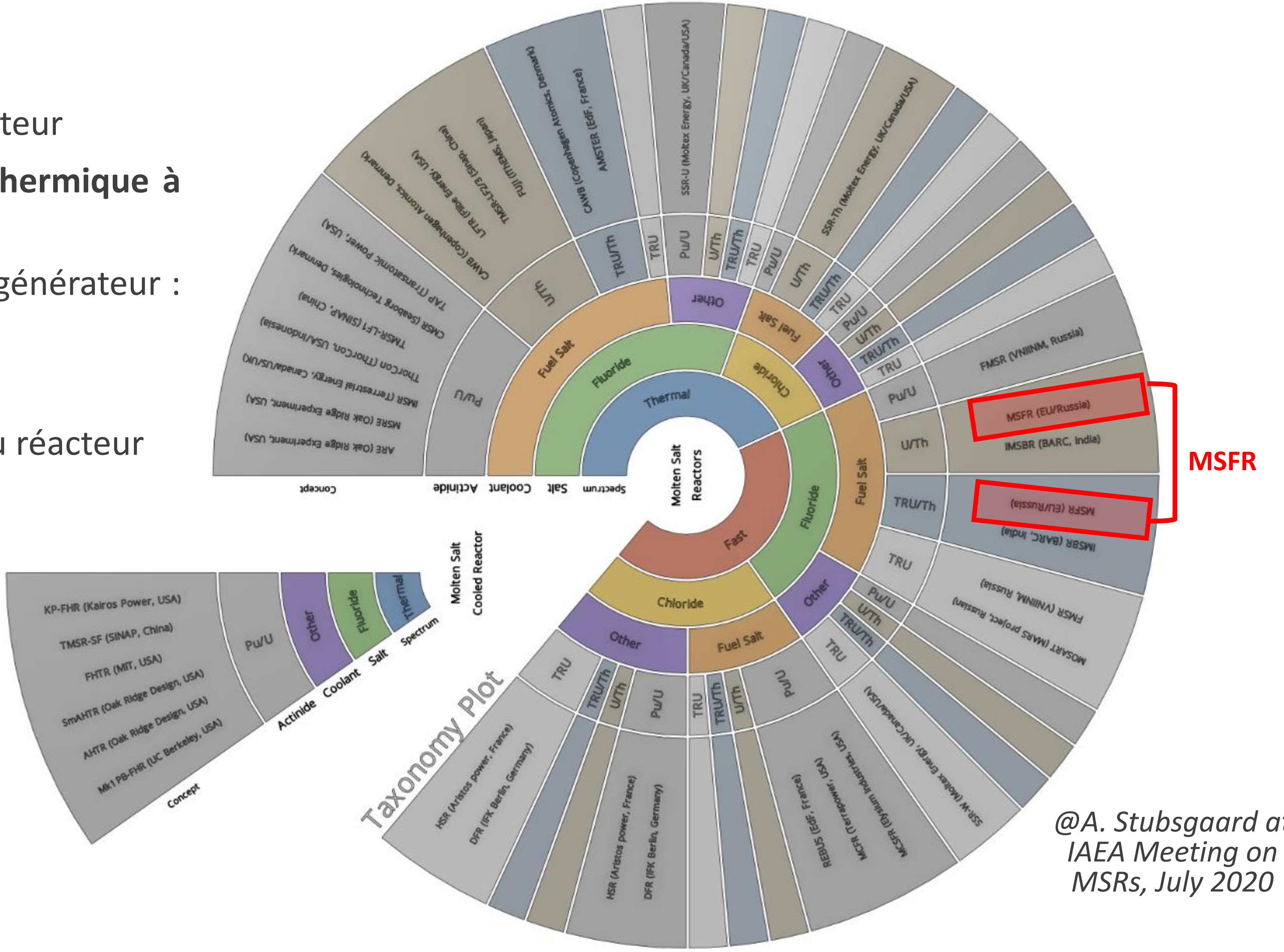
1. Choix de l'objectif / utilisation du réacteur
2. **Choix du spectre neutronique : de thermique à rapide**
3. **Si réacteur producteur d'énergie** / régénérateur : choix du cycle du combustible
4. **Choix d'un sel chlorure ou fluorure**
5. Choix de la puissance et du volume du réacteur

⇩

Versions de MSFR régénérateurs :

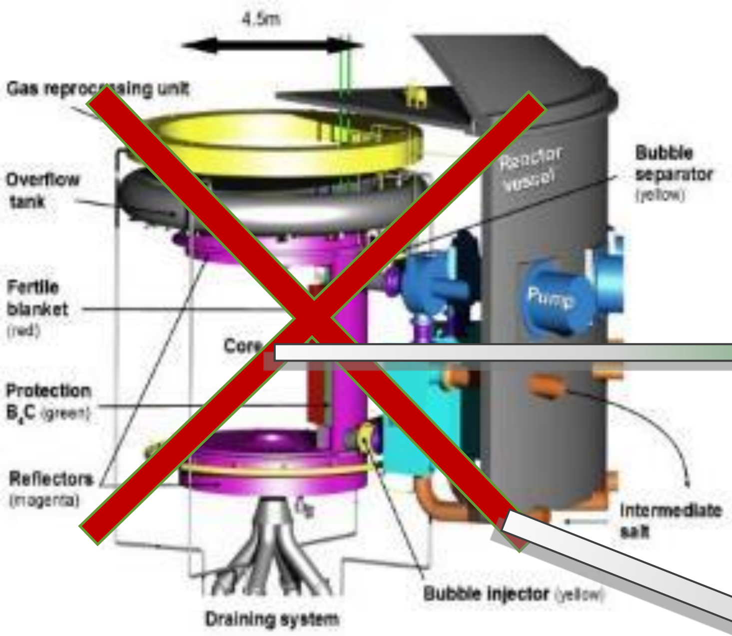
Sel / Cycle	$^{232}Th/^{233}U$	$^{238}U/^{239}Pu$
Fluoride	TMFR	PMFR
Chloride	TMCR	PMCR

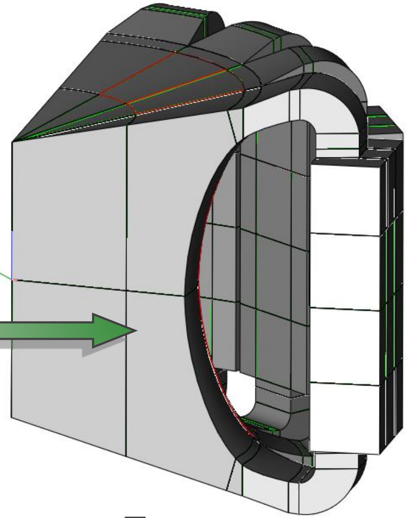
@L. Clot



@A. Stubsgaard at IAEA Meeting on MSRs, July 2020

Design evolutions of the MSFR fuel circuit

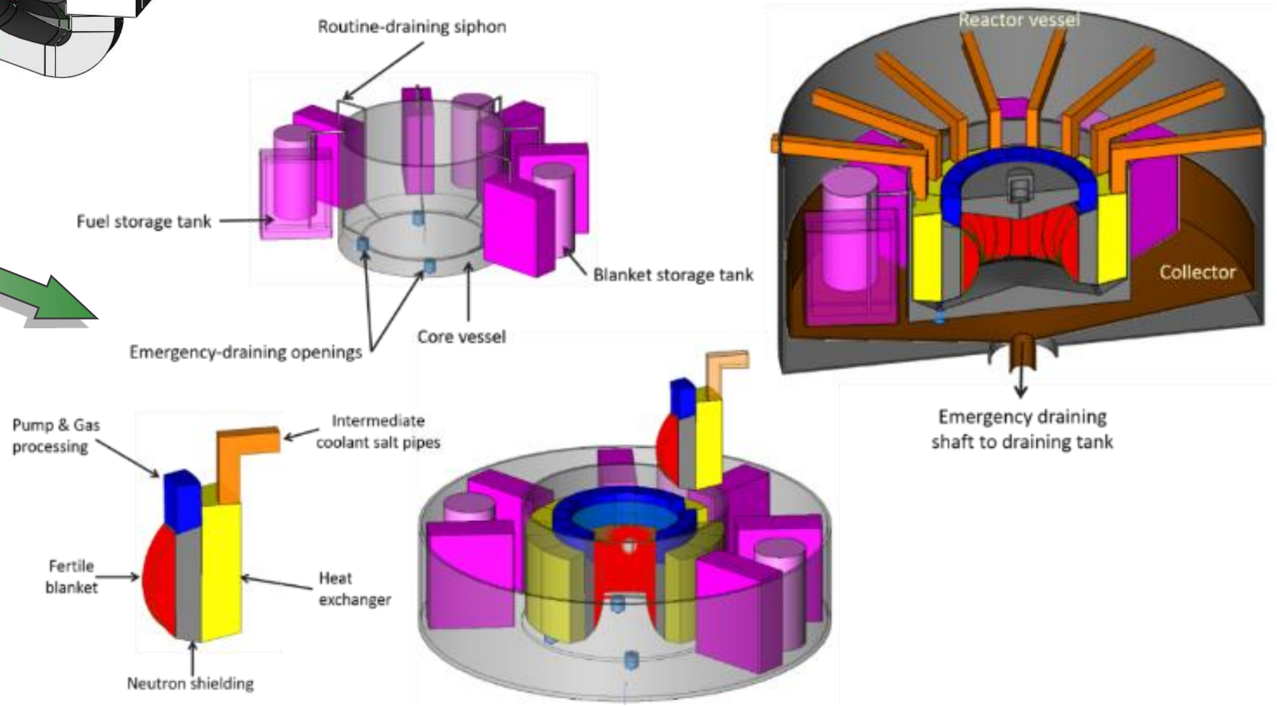




1/ Core design for a uniform salt heating

→ RANS CFD calculations

→ **core toroidal shape**



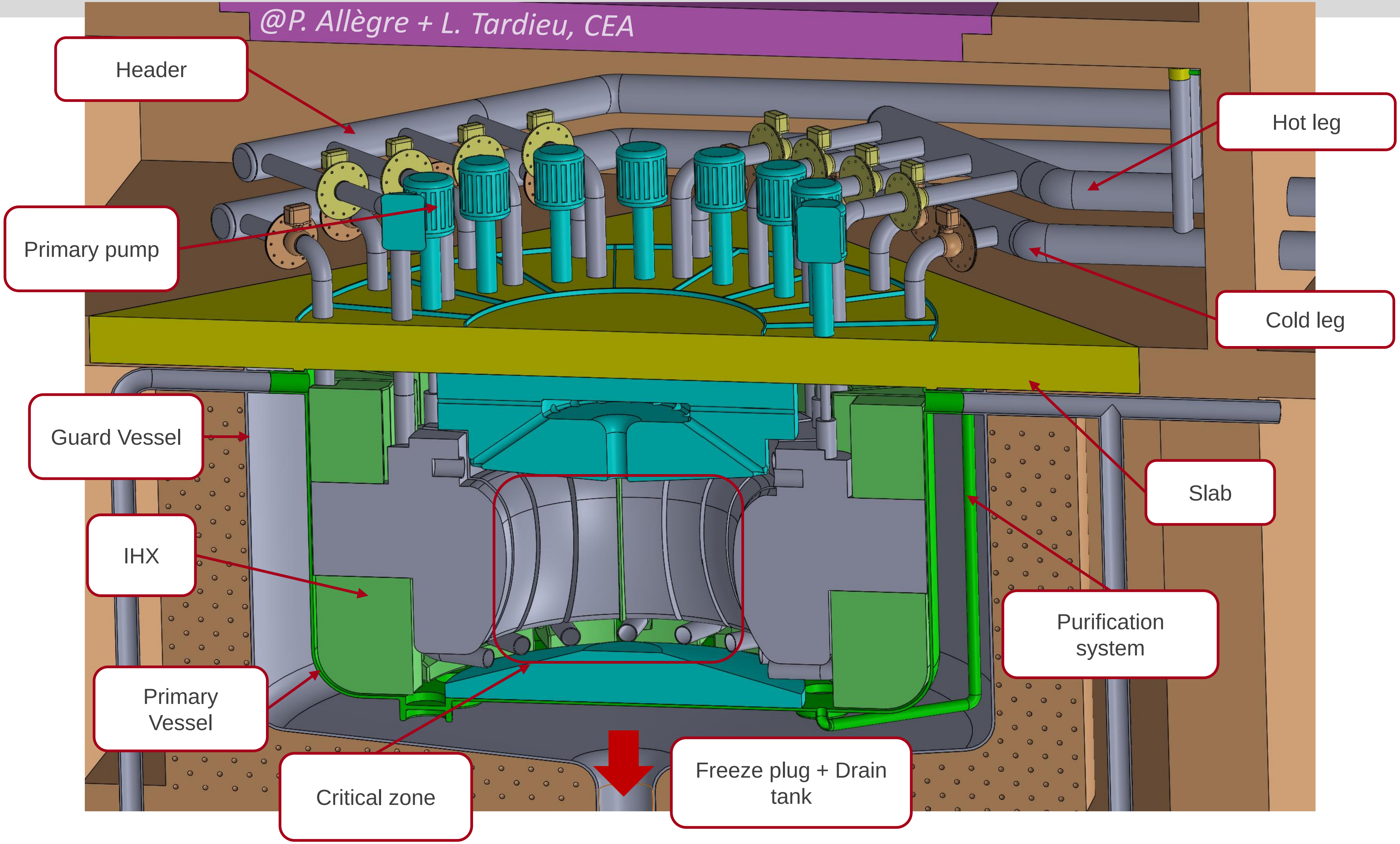
2/ LOLF accident (Loss of Liquid Fuel) → no tools available for quantitative analysis but qualitatively:

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

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

SAMOFAR

Design evolutions of the MSFR fuel circuit



Reference MSFR design studies: 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 core?)

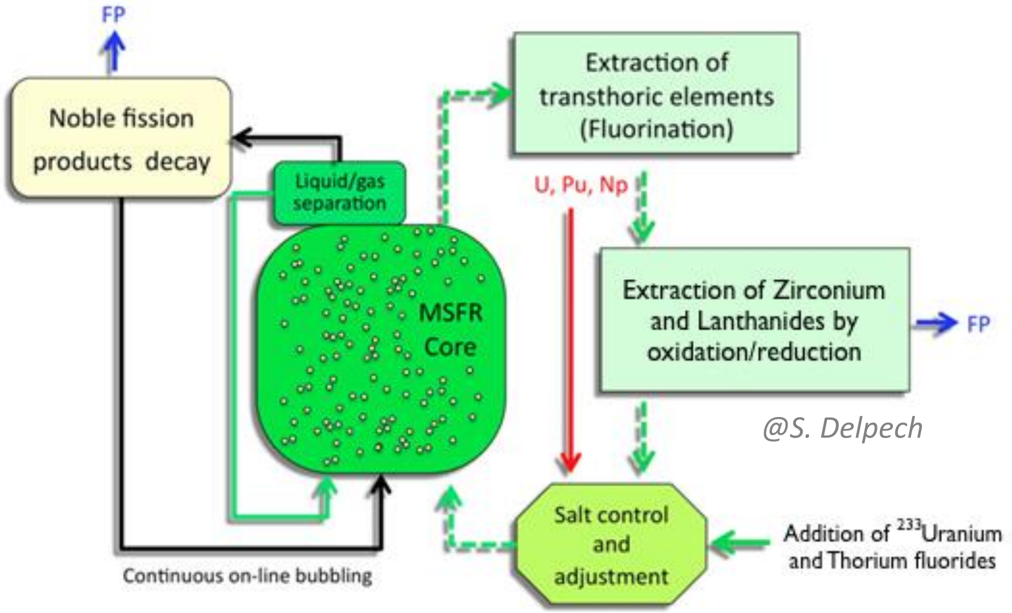
➢ Gas Processing Unit through bubbling extraction

➢ Extract Kr, Xe, He and particles in suspension

Chemical Separation (by batch)

➢ Pyrochemical processing Unit

➢ Located elsewhere (as La Hague today) or on-site, but outside the reactor vessel

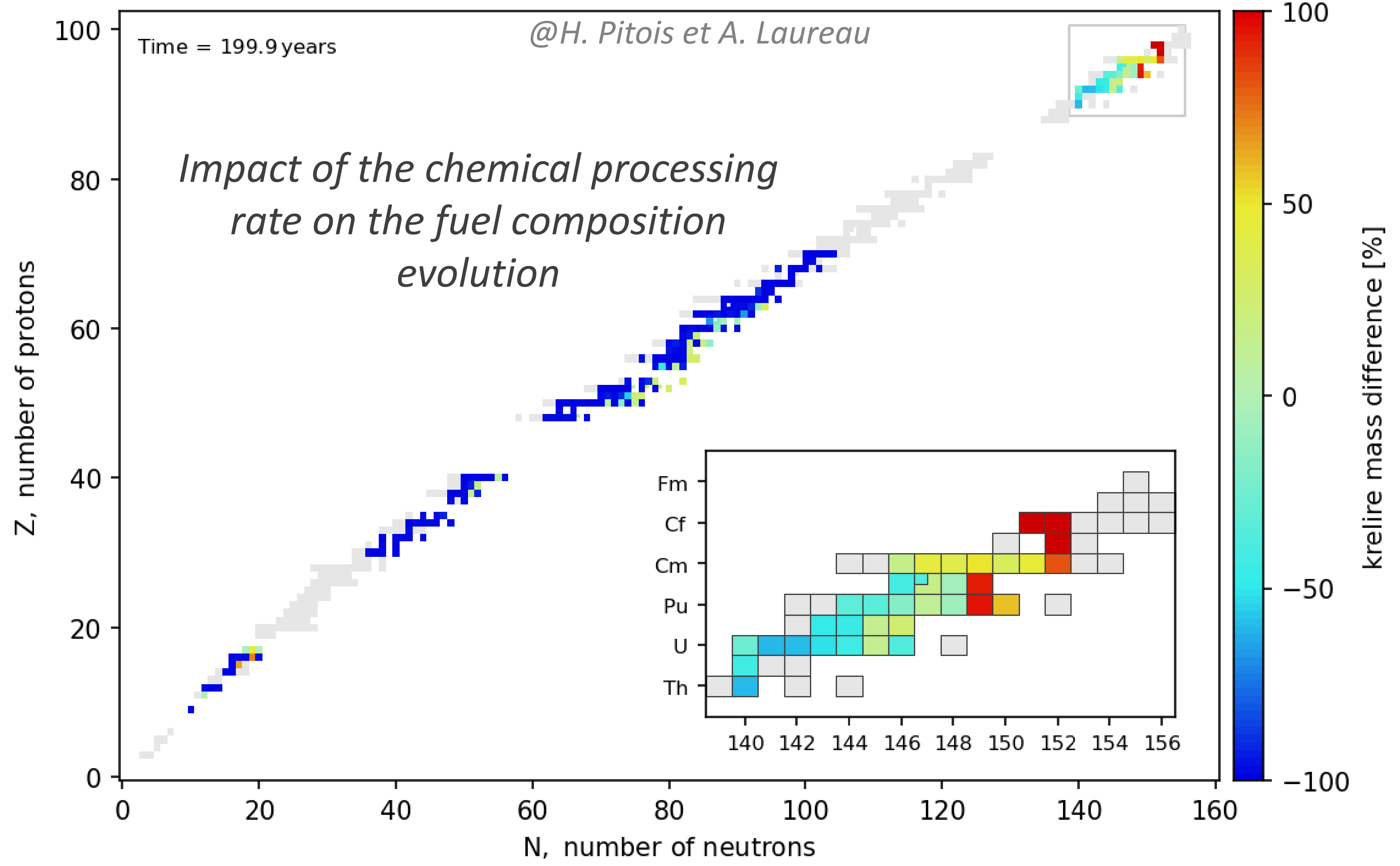


@S. Delpech

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)

Tools for the Simulation of Reactor Evolution: Evolving neutronic Monte-Carlo calc.

Large PMFR version (U/Pu fuel cycle, chloride salt, P=3 GW_{th} and 80m^3) – *PhD thesis of H. Pitois (CNRS-LPSC, SAMOSAFER)*



Concept of MSFR: irradiation damages

Example of material proposed in the EVOL project (Hastelloy-N with Tungsten):

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

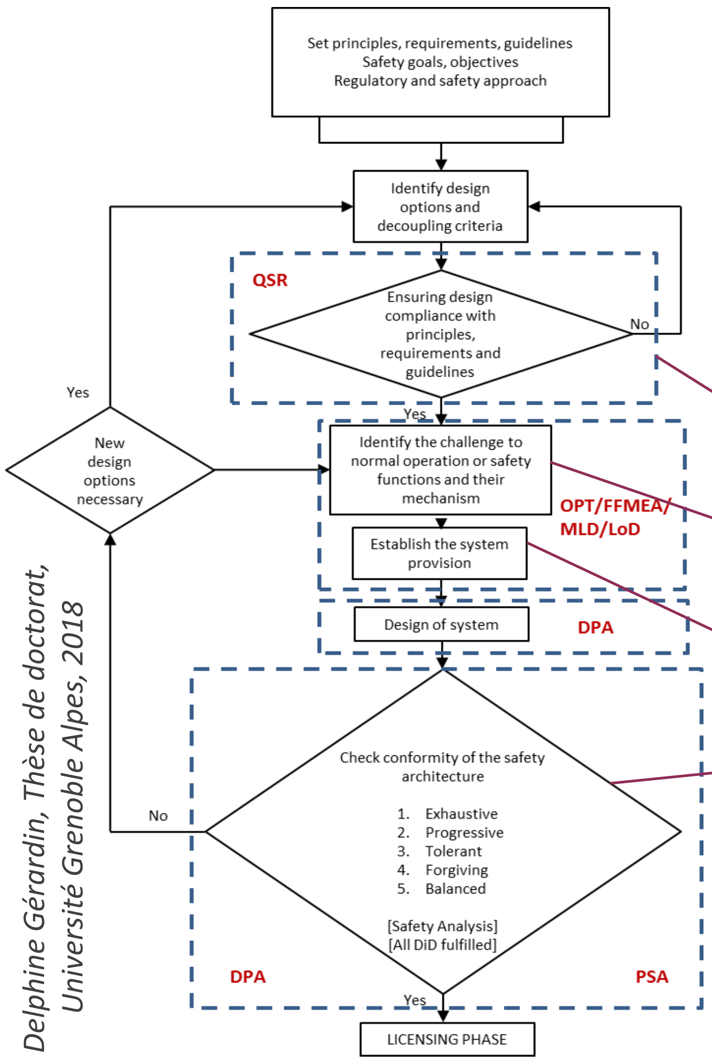
Neutronic irradiation damages to the structural materials (modify their physicochemical properties) = displacements per atom, production of Helium gas, transmutation of Tungsten in Osmium, activation

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

MSFR : Projet SAMOFAR – Analyse de sûreté



Delphine Gérardin, Thèse de doctorat, Université Grenoble Alpes, 2018

LPSC Grenoble — framatome — Politecnico di Torino 1859 1906 — SAMOFAR

- Objectif : méthode suffisamment générale pour être applicable malgré les spécificités des RSFs et utilisable dès les premières phases de design
- Basée sur la méthodologie **ISAM** (Integrated Safety Assessment Methodology) préconisée par le GIF
- Principales étapes :
  1. Vérifier la conformité du design avec les principes et exigences de sûreté (Tableau du QSR)
  2. Identifier les risques et élaborer une liste d'évènements initiateurs (FFMEA / Master Logic Diagram)
  3. Définir l'architecture de sûreté (LDD / OPT)
     - Proportionnée aux enjeux (étude en mode non protégé)
     - En privilégiant des solutions « robustes »
  4. Vérifier la conformité de l'architecture de sûreté (DPA / PSA niveau 1)
- Itérer au fur et à mesure de l'avancement des analyses de sûreté et de la conception

→ Plus généralement, pour la France, réglementation adaptée au concept qui serait à élaborer à terme

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 advantages identified for the MSFR concept:

(conclusions du projet européen SAMOFAR, 2019)

▶ Liquid fuel and fast neutron spectrum → negative temperature feedback coefficient: **ensures an intrinsic safety with respect to reactivity accidents**

▶ The fuel unloading from the core zone is easier and faster compared to the unloading of a solid fuel **→ allows to maintain sub-critical the salt and to cool the fuel in a dedicated fuel tank**

▶ **Fuel circuit not pressurized + fluoride salt not likely to cause violent exothermic chemical reactions** when it is in contact with the materials of the plant + no violent chemical reaction with air or water

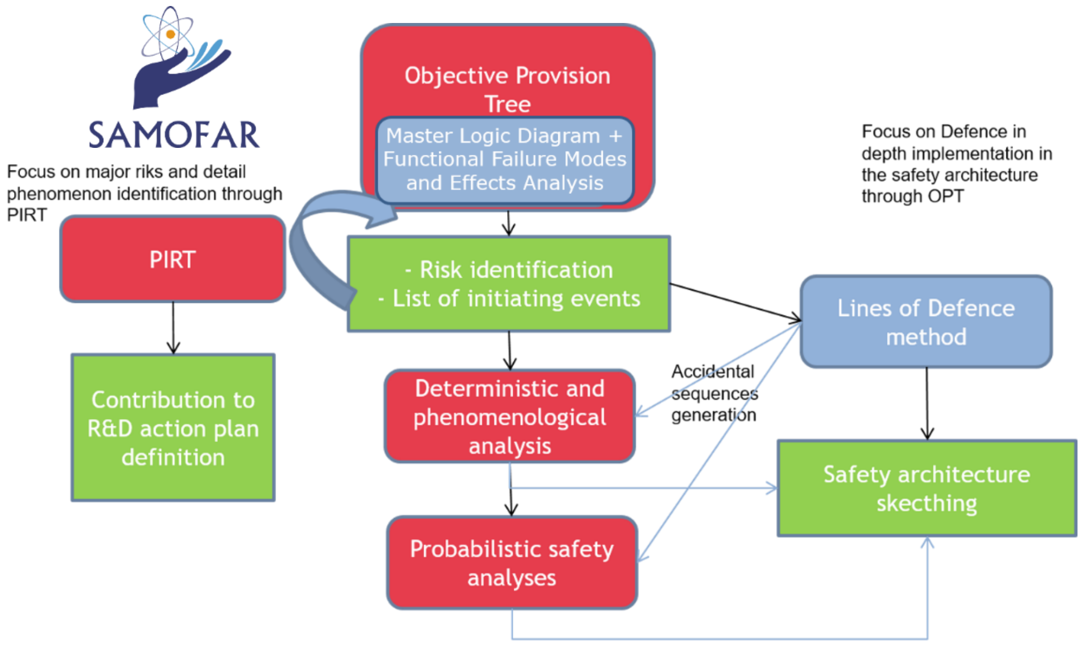
▶ Fission gases (and possibly some non-volatile and non-soluble fission products) can be removed during operation **→ reduces the radiological salt inventory**

▶ Absence of fuel structures in the core such as cladding and subassemblies **→ removes any risk of fuel compaction, which may lead to an increase of reactivity**

▶ Intrinsic temperature feedback effect → may eliminate the need of a control rod system for adjusting the operating conditions + fissile material dissolved in the critical zone of the fuel circuit is just the necessary amount to maintain a critical state **→ intrinsically reduce the risk of accidental reactivity insertion**

Concept MSFR – Analyse de sûreté

▶ **Développement d'une approche de sûreté dédiée aux réacteurs à combustible liquide circulant et analyse de risques du MSFR : cf thèses de Delphine Gérardin (2015-2018) et Mariya Brovchenko (2010-2013) et projet européen SAMOFAR (2015-2019)**



▶ **Collaboration CNRS/IRSN/Framatome/POLITO/EDF : développement d'une méthodologie d'analyse de risques, identification des initiateurs d'accidents, confirmation des avantages en terme de sûreté du MSFR, retours sur design, évaluation des challenges et besoins de recherches liés à la sûreté nucléaire**

	Selected Postulated Initiating Events	Types
LoD method already applied	Loss of main heat sink	Incident
	Overcooling at start up or low power	Accident
	Leak of an heat exchanger between the fuel circuit and the intermediate circuit	Accident
	Leak of a fuel salt storage tank	Accident
LoD method under application/to be applied	Loss of electric power supply	Accident
	Fuel salt leak - rupture of the core vessel	Accident
	Reactivity insertion: Addition of fuel salt with a too high concentration of fissile matter	Incident
	Reactivity insertion: Fertile blanket loading with fuel salt	Limiting event

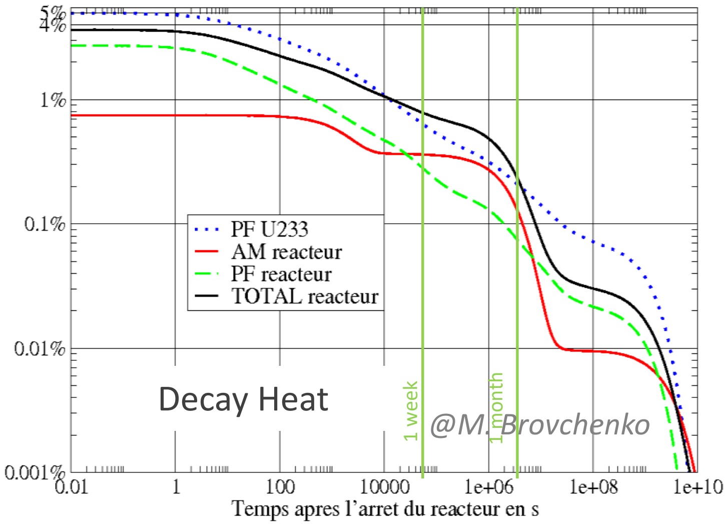
▶ **Etape en cours : projet européen SAMOSAFER (2019-2023) :** **Collaboration CNRS (IJC Lab – LPSC – SUBATECH) / Framatome / CEA / EDF / IRSN - Thèses de T. Le Meute (CEA Cadarache / CNRS/LPSC – début 10/2019) et de H. Pitois (CNRS financée par le projet – début 10/2020)**

MSFR design studies: decay heat removal & Emergency Draining System (EDS)

Normal situation

normal fuel T° (< 600-700°C)

Removing decay heat = passive or active HX



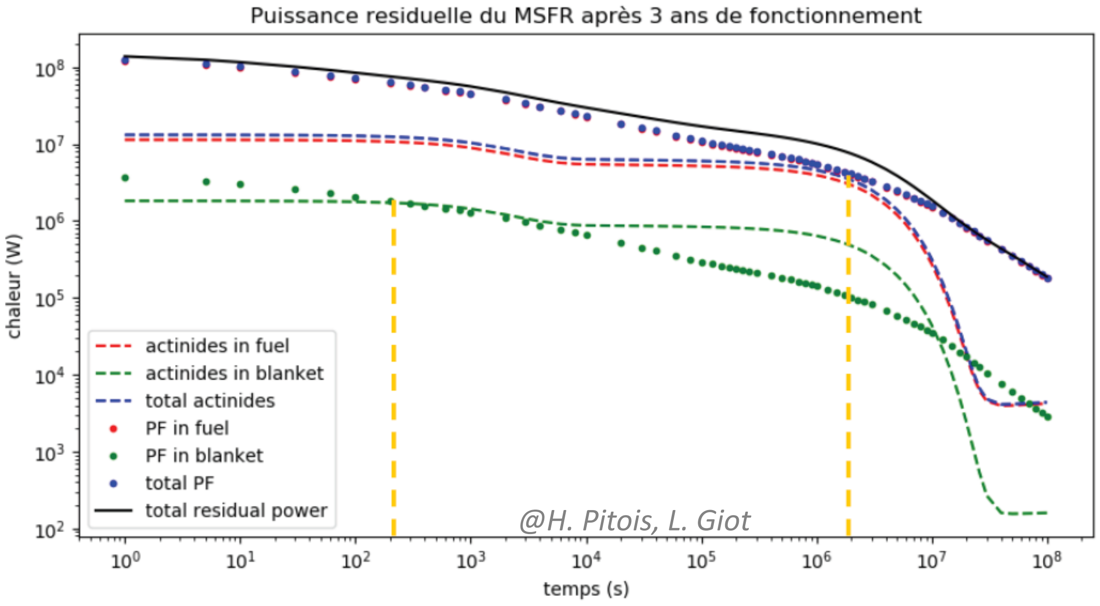
Emergency situation

Lost of control = high fuel T° (up to 1200°C)

Removing extra heat + decay heat = inertial storage + passive HX

H. Pitois, "Développement de calculs de puissance résiduelle pour un concept de réacteur à neutrons rapides et à sels fondus", Master report, Subatech, 2018

+ PhD thesis of Y. MOLLA starting at SUBATECH in 10/2021



MSFR design studies: decay heat removal & Emergency Draining System (EDS)

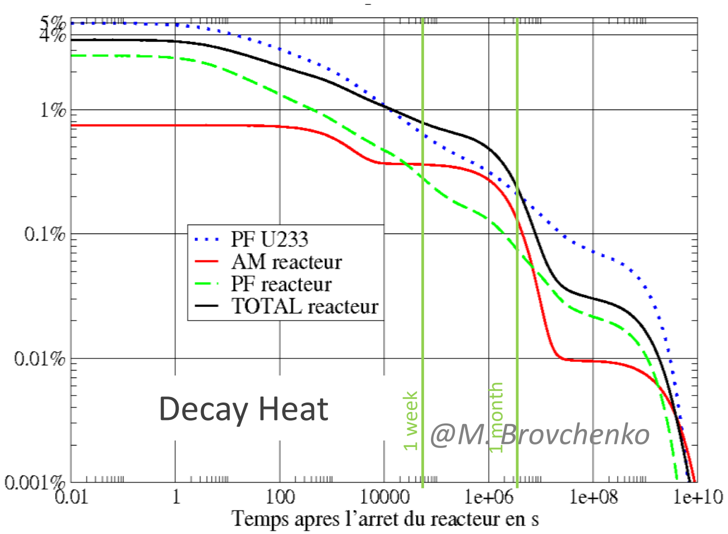
Normal situation

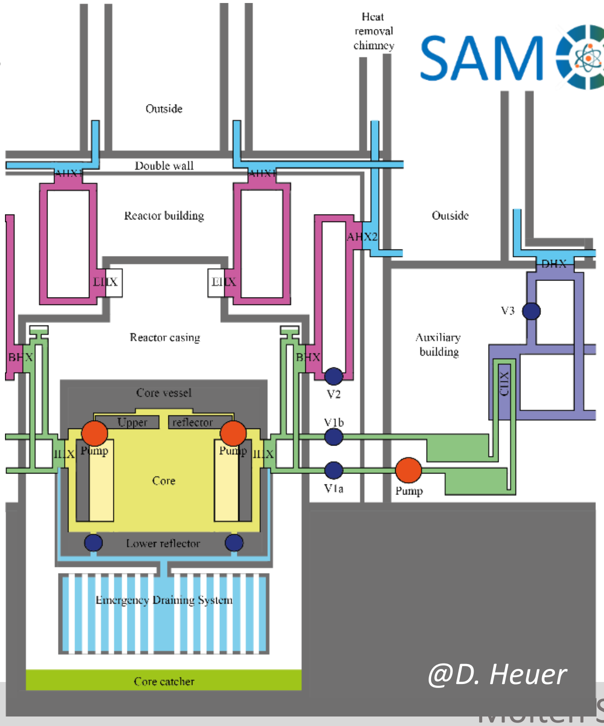
normal fuel T° (< 600-700°C)
Removing decay heat = passive or active HX

Case1 = shut-down of the reactor with the fuel in the fuel circuit – Cf. decay heat removal (DHR) systems

OR

Case2 = maintenance: transfer/draining to local or remote tanks
(non critical geometry)



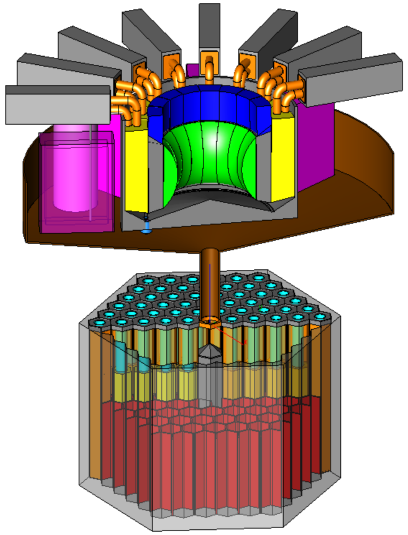


Emergency situation

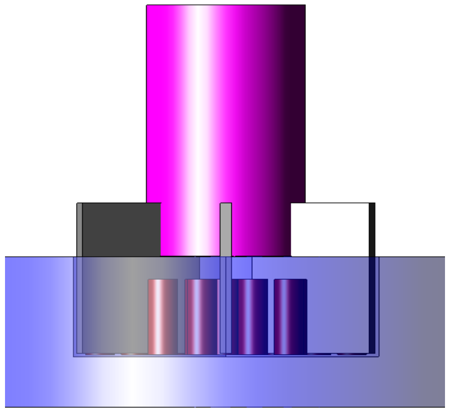
Lost of control = high fuel T° (up to 1200°C)
Removing extra heat + decay heat = inertial storage + passive HX

OR /AND ?

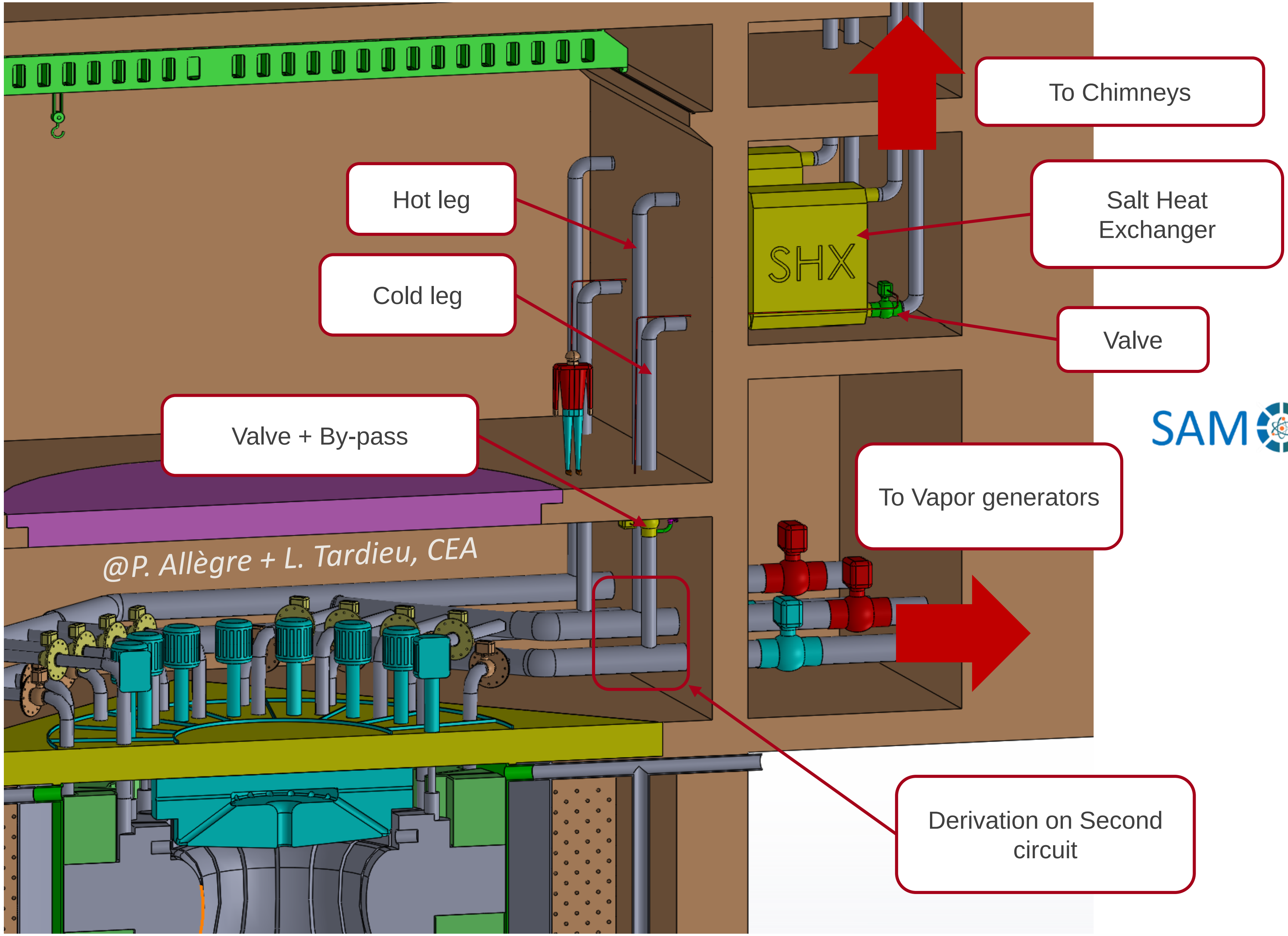
Reversible Emergency Draining Tank **(EDT)**
(non critical <u>integrated</u> geometry)



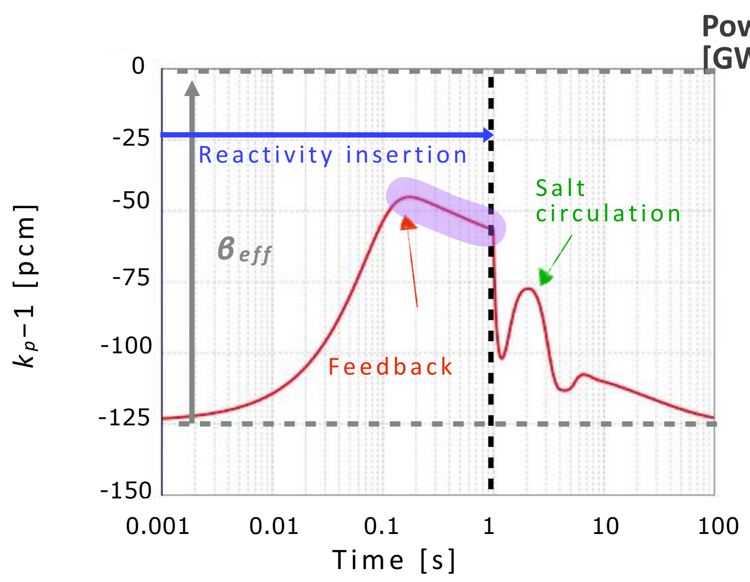
Core Catcher
(non critical geometry)

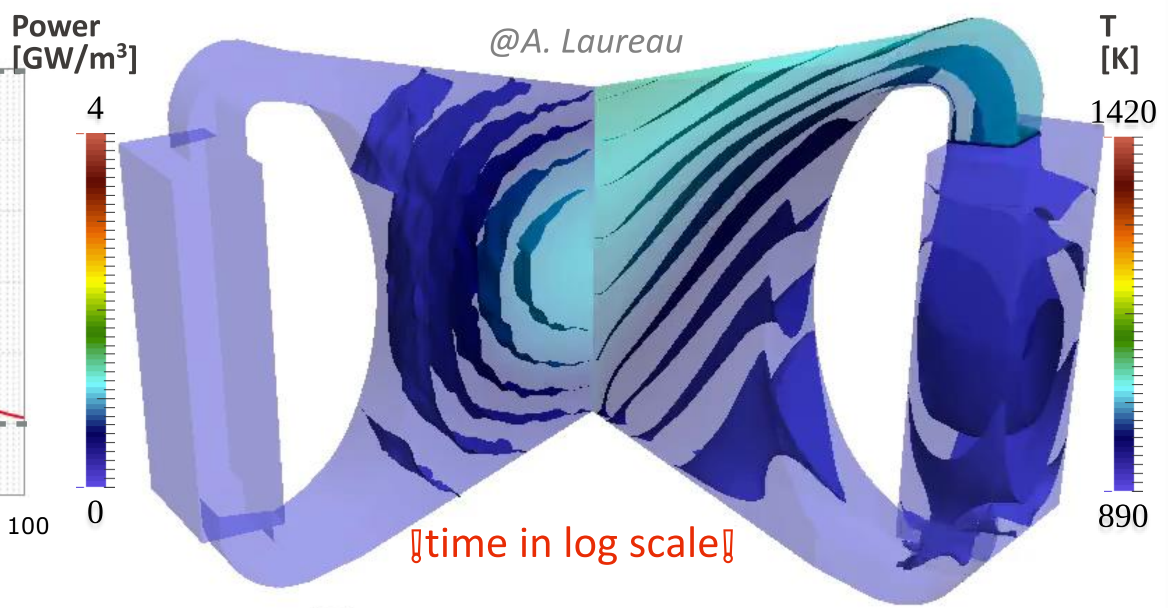


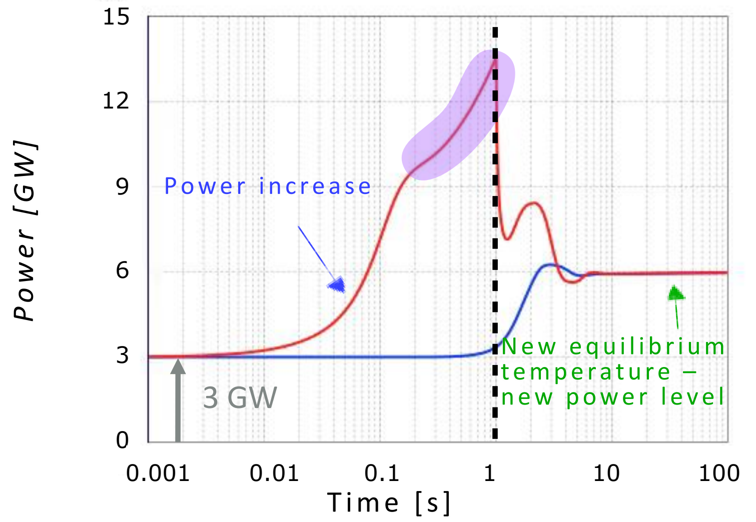
MSFR design studies: decay heat removal & Emergency Draining System (EDS)

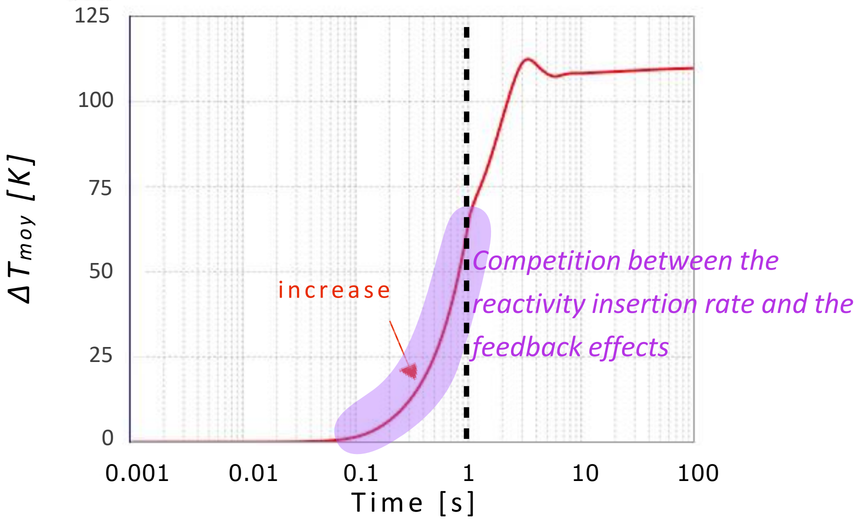


Concept of MSFR: the TFM approach – Application to accident transient calculations (reactivity insertion – 1000 pcm in 1s)









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

Reference MSFR design studies: Starting modes and deployment capacities

MSR deployment capacities ?

Thorium fuel cycle?

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

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)

French Scenario: stockpile of heavy nuclei

- Stockpiles of uranium from reprocessing largely reduced

- Stockpiles of Pu-Uox, Pu-Mox and AM-Mox totally burned in MSFR ⇨ remains only MA extracted from Uox fuel when using Pu-Mox in PWRs and EPRs

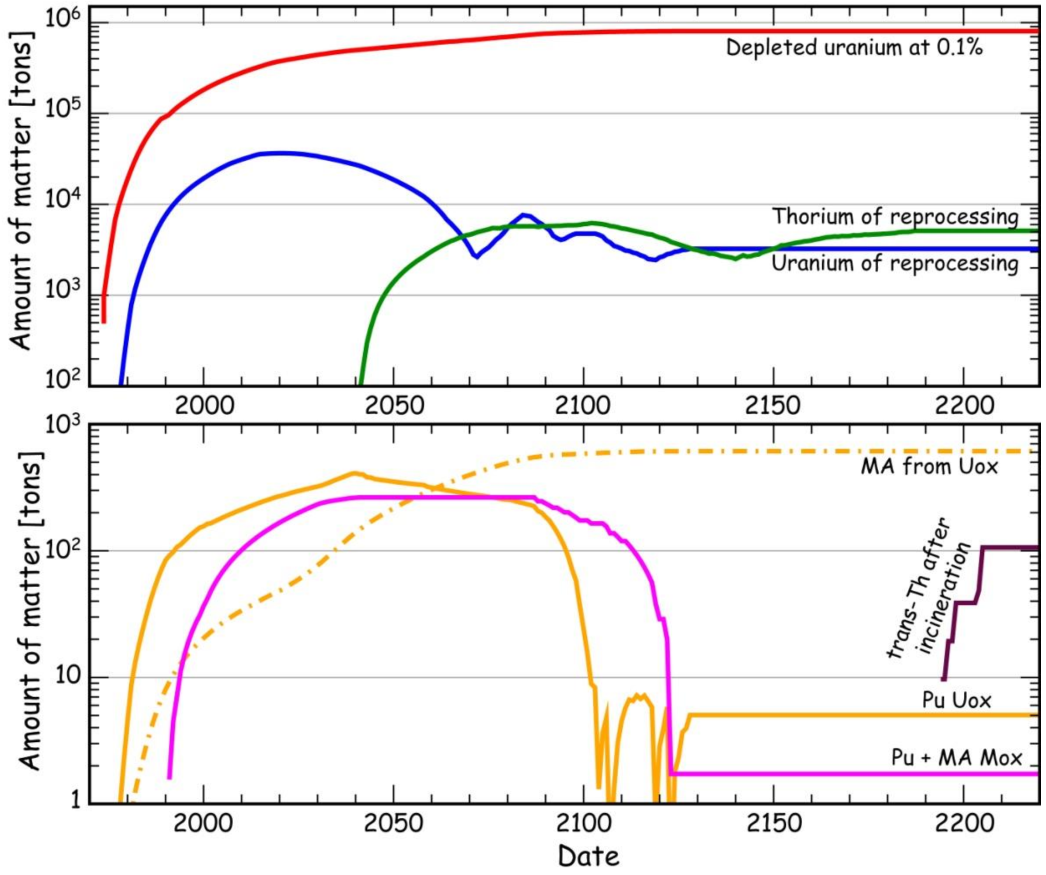
- After incinerator MSFRs: only 100 tons of transthorian elements remaining

-Around 18 000 t of actinides used for fission (138 000 TWh

- 11 700 t from natural U
- 6 300 t from Th

- Natural resources needed for this nuclear deployment:

  - 821 400 t of natural U
  - 11 600 t of Th



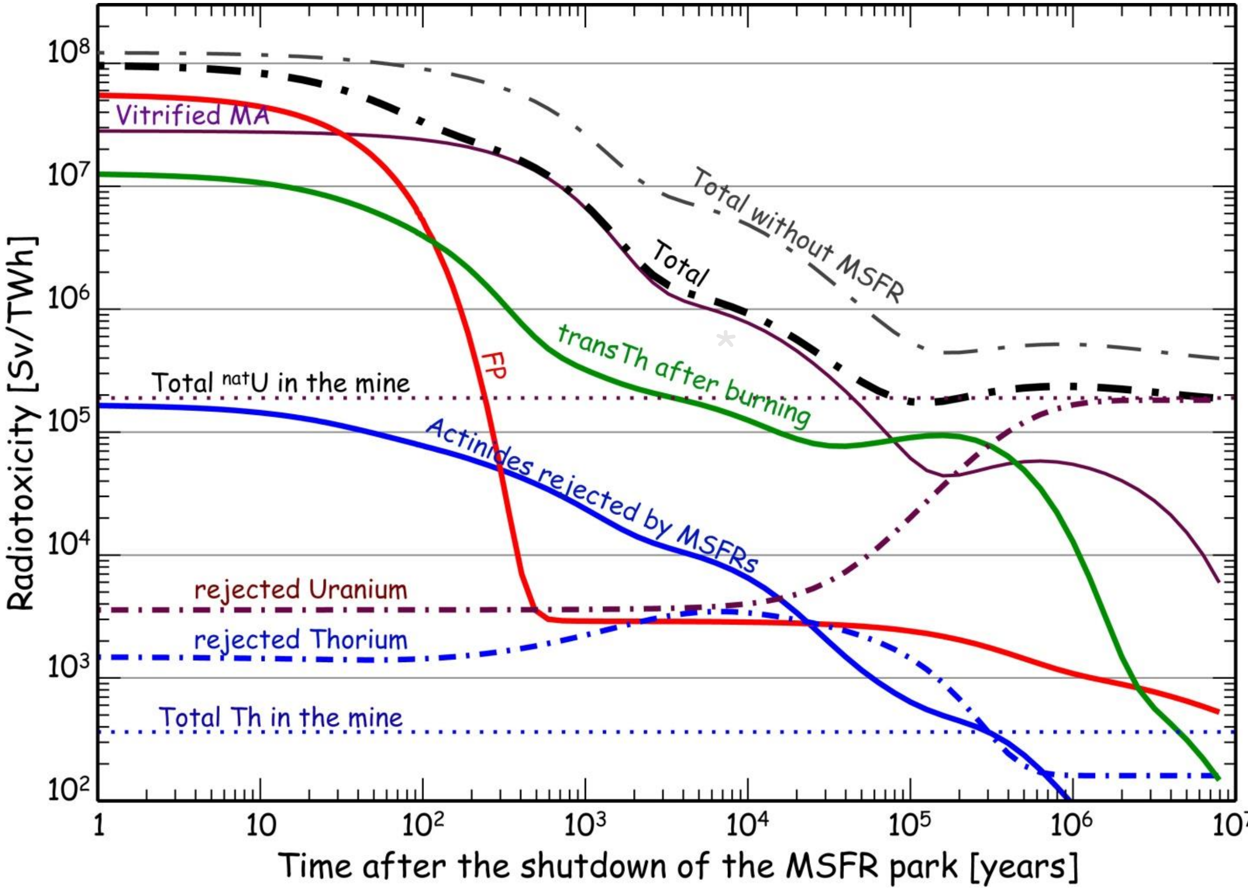
Reference MSFR design studies: Starting modes and deployment capacities

French Scenario: stockpile of radiotoxicit

- Long term radiotoxicity dominated by the vitrified MA from Uox fuel mixed with the FPs (Gen2 and Gen3 reactors)

- Very long term radio-toxicity (after 300 000 years) dominated by the rejected uranium (depleted + reproc.) – see long life decay products of ^{238}U (as ^{230}Th and ^{234}U)

- Radiotoxicity of the transthorian elements from the MSFR fleet (final inventories) lower than the extracted natural U after 3 000 years



* Based on a production with PWRs and EPRs of 65 700 TWh minimizing the actinides stockpiles

→ Compared to a scenario optimized but without MSFR and the Th fuel cycle: radiotoxicity 3 to 5 times higher between 1000 and 100 000 years

Features and characteristics of MSRs: waste management

- **Objective**: reduce the amount and lifetime of radioactive materials sent to waste disposal by present and future reactors
- **Needs**: fuel management flexibility, safety margins, technical feasibility

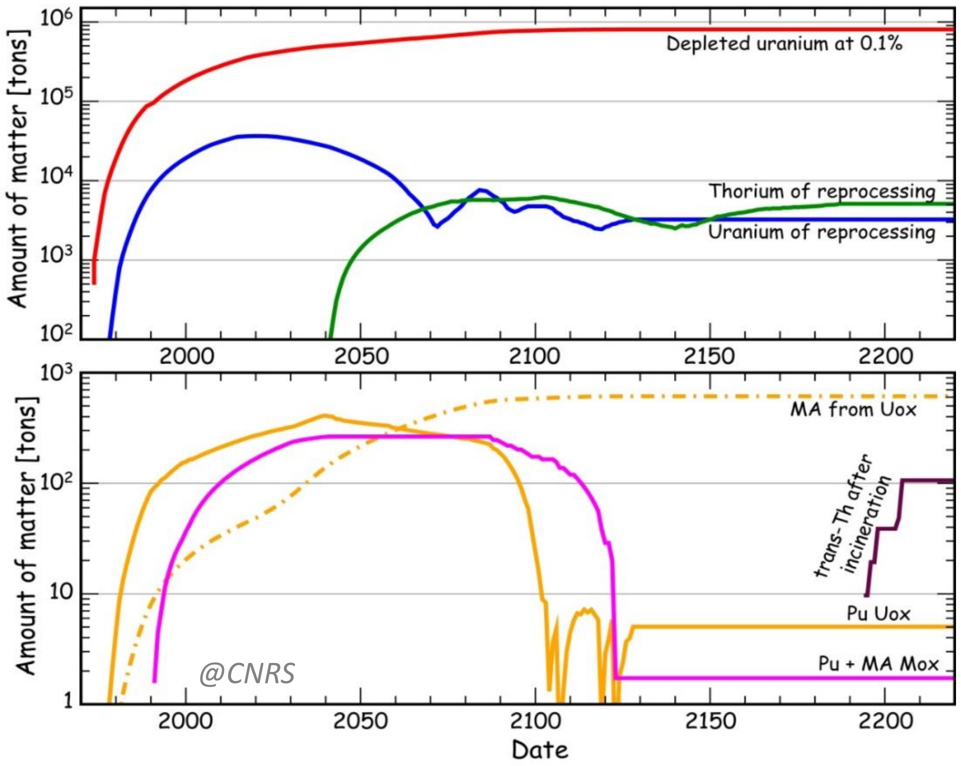
PhD thesis of L. Mesthiviers (CNRS-IN2P3/Orano

MSR characteristics:

- No complex fuel fabrication with cladding and assemblies
- Actinide solubility in the fuel salt
- Fast neutron spectrum available depending of the design choice
- Possibility to adjust the actinide composition during the reactor lifetime
- Safety coefficients excellent and quasi-independent of the fuel composition

Waste toxicity of a nuclear fleet reduced by a factor 3 to 10 and dominated by the waste already vitrified = efficient burning

French scenario with PWRs, EPRs and MSRs (breeder and burner): only 100 tons of transthorian elements remaining

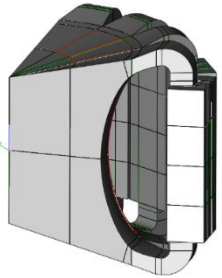


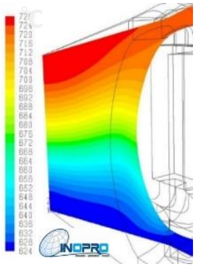
European Projects on MSR (FP7 and H2020)

"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

- **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)
- Recommendations for the choice of core structural materials

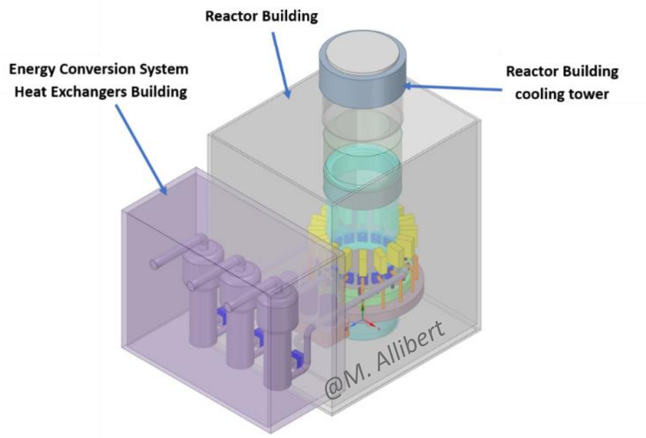
"SAMOFAR" Safety Assessment of a MOlten salt FAst Reactor – *H2020 (2015-2019) – 12 partners*

Objective : to prove the innovative safety concepts of the MSFR by advanced experimental and numerical techniques, to deliver a breakthrough in nuclear safety and optimal waste management, and to create a consortium of stakeholders to demonstrate the MSFR beyond SAMOFAR

- **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**

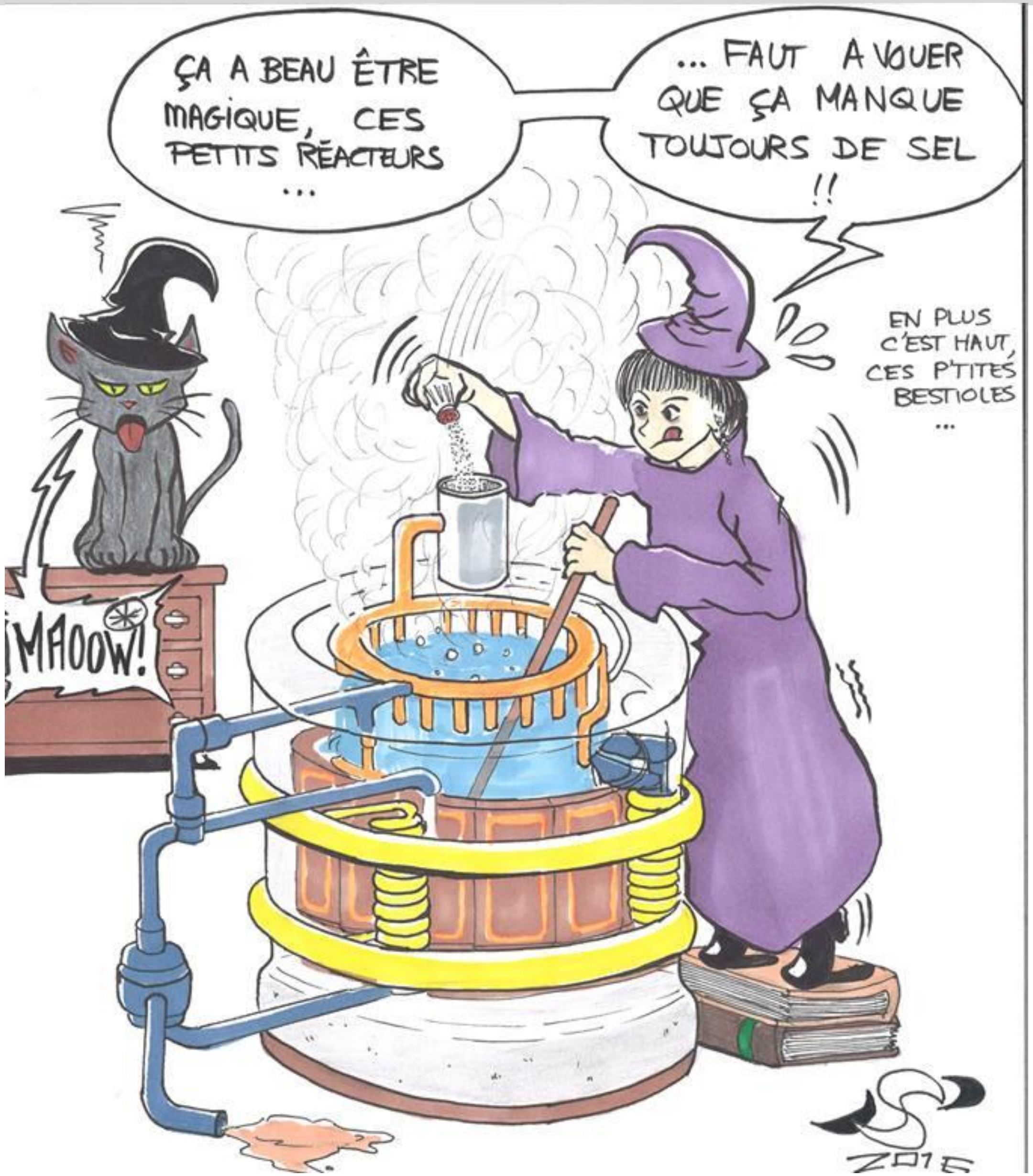
Examples of outputs of the project:

- Significant results in safety assessment, reactor design, salt data, experimental evaluation, and synthesis of salts and coatings
- Progress on risk assessment methods with a dedicated approach defined
- Safety analysis of reactor and chemical processing plant
- Update of the conceptual design of the MSFR incorporating all safety recommendations




Swath facility @CNRS

MSR


ÇA A BEAU ÊTRE MAGIQUE, CES PETITS RÉACTEURS ...
... FAUT AVOUER QUE ÇA MANQUE TOUJOURS DE SEL !!
EN PLUS C'EST HAUT, CES P'TITES BESTIOLES ...
MAOOW!