# Recommendations for a demonstrator of Molten Salt Fast Reactor

**E. MERLE-LUCOTTE , D. HEUER, M. ALLIBERT, M. BROVCHENKO, V. GHETTA, P. RUBIOLO, A. LAUREAU**

***merle@lpsc.in2p3.fr***

*Professor at Grenoble INP/PHELMA and in the Reactor Physics Group (CNRS-IN2P3-LPSC / Grenoble INP - PHELMA / UJF)*

With the support of the PACEN (Programme sur l'Aval du Cycle et l'Energie Nucléaire) and NEEDS Programs and of the EVOL Euratom FP7 Project

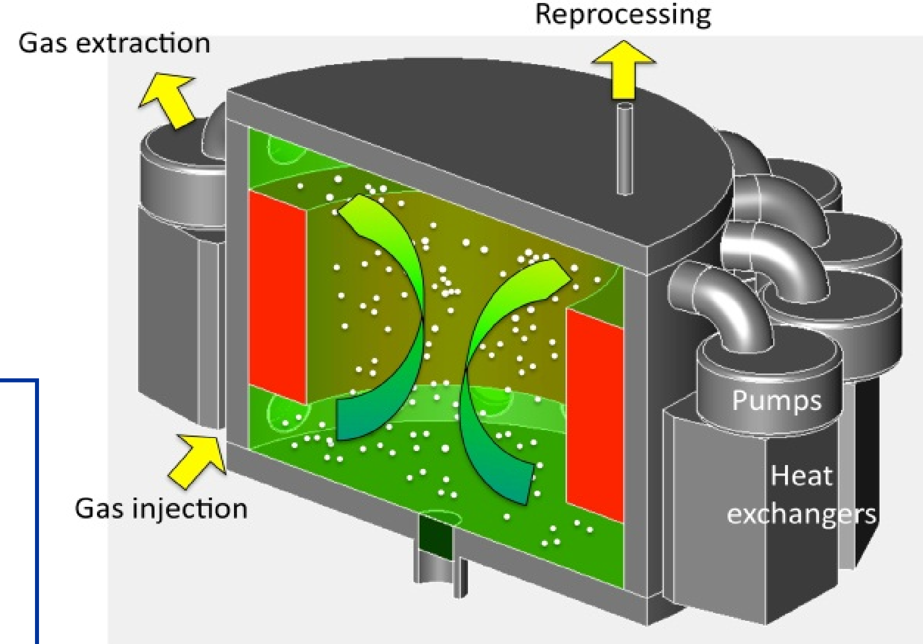
# The concept of Molten Salt Fast Reactor

What is a MSFR ?

Molten Salt Reactor (molten salt = liquid fuel also used as coolant)

Based on the Thorium fuel cycle

With no solid (i.e. moderator) matter in the core ⇒ Fast neutron spectrum




Parameters of study:

Initial fissile matter ($^{233}U$, Pu, enriched U), salt composition, fissile inventory, reprocessing, waste management, deployment capacities, heat exchanges, structural materials, design..

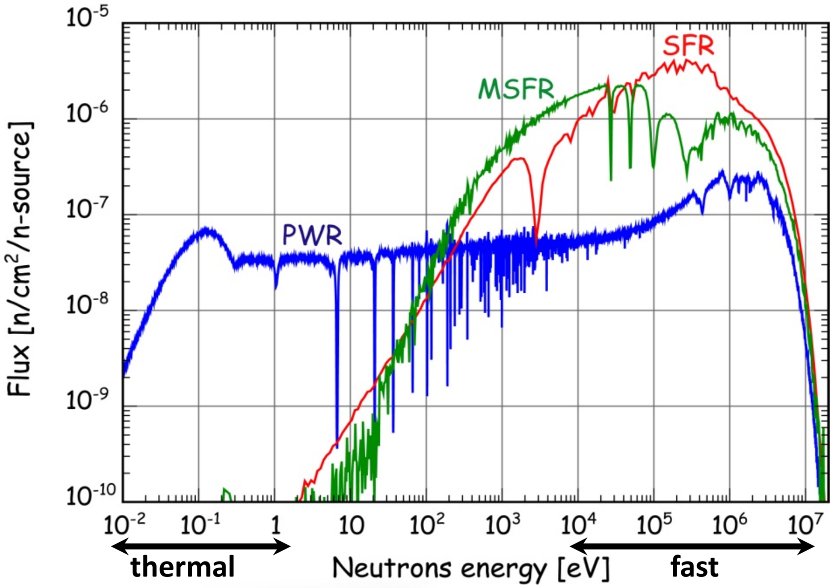
Generation IV reactors: fuel reprocessing mandatory

Neutronic core of the MSFR associated to an on-site reprocessing unit (on-line in-core bubbling and batch chemical reprocessing during reactor operation)

# The concept of Molten Salt Fast Reactor

| | |
|---|---|
| Thermal power | **3000 MWth** |
| Mean fuel salt temperature | **750 °C** |
| Fuel salt temperature rise in the core | **100 °C** |
| Fuel molten salt - Initial composition | **77.5% LiF and 22.5% [$ThF_4$+ (Fissile Matter)$F_4$] with Fissile Matter = $^{233}U$ / $^{enriched}U$ / Pu+MA** |
| Fuel salt melting point | **565 °C** |
| Fuel salt density | **4.1 g/cm³** |
| Fuel salt dilation coefficient | **8.82 $10^{-4}$ / °C** |
| Fertile blanket salt - Initial composition | **LiF-$ThF_4$ (77.5%-22.5%)** |
| Breeding ratio (steady-state) | **1.1** |
| Total feedback coefficient | **-5 pcm/K** |
| Core dimensions | **Diameter: 2.26 m<br>Height: 2.26 m** |
| Fuel salt volume | **18 m³ (½ in the core + ½ in the external circuits)** |
| Blanket salt volume | **7.3 m³** |
| Total fuel salt cycle | **3.9 s** |

## Design of the 'reference' MSFR




***R&D objectives***

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

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

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

# The concept of Molten Salt Fast Reactor

## Which initial load fissile for a MSFR?

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

- Start directly with enriched U: enrichment required > 20%

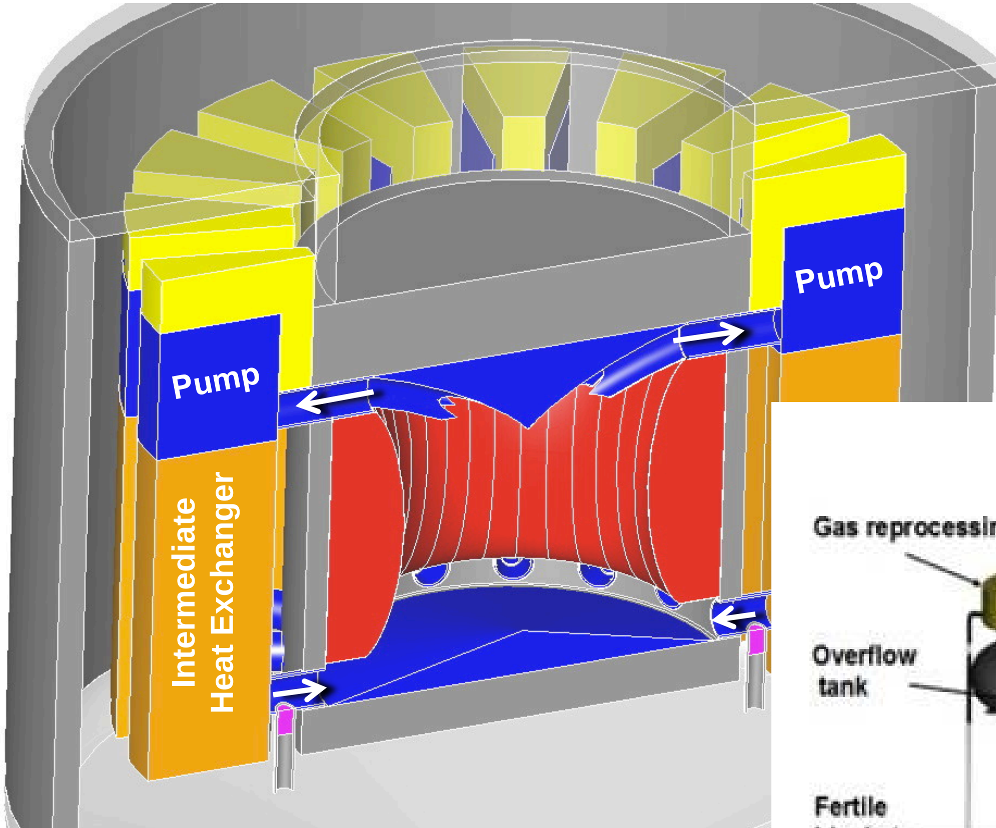
- Start with the Pu of current LWRs mixed with other TRU elements: solubility limit of valence-III elements in LiF

- Mix of these solutions: Thorium as fertile matter +

  - $^{233}U$ + TRU produced in LWRs
  - MOx-Th in Gen3+ / other Gen4
  - **Uranium enriched at 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 | |

# The concept of Molten Salt Fast Reactor



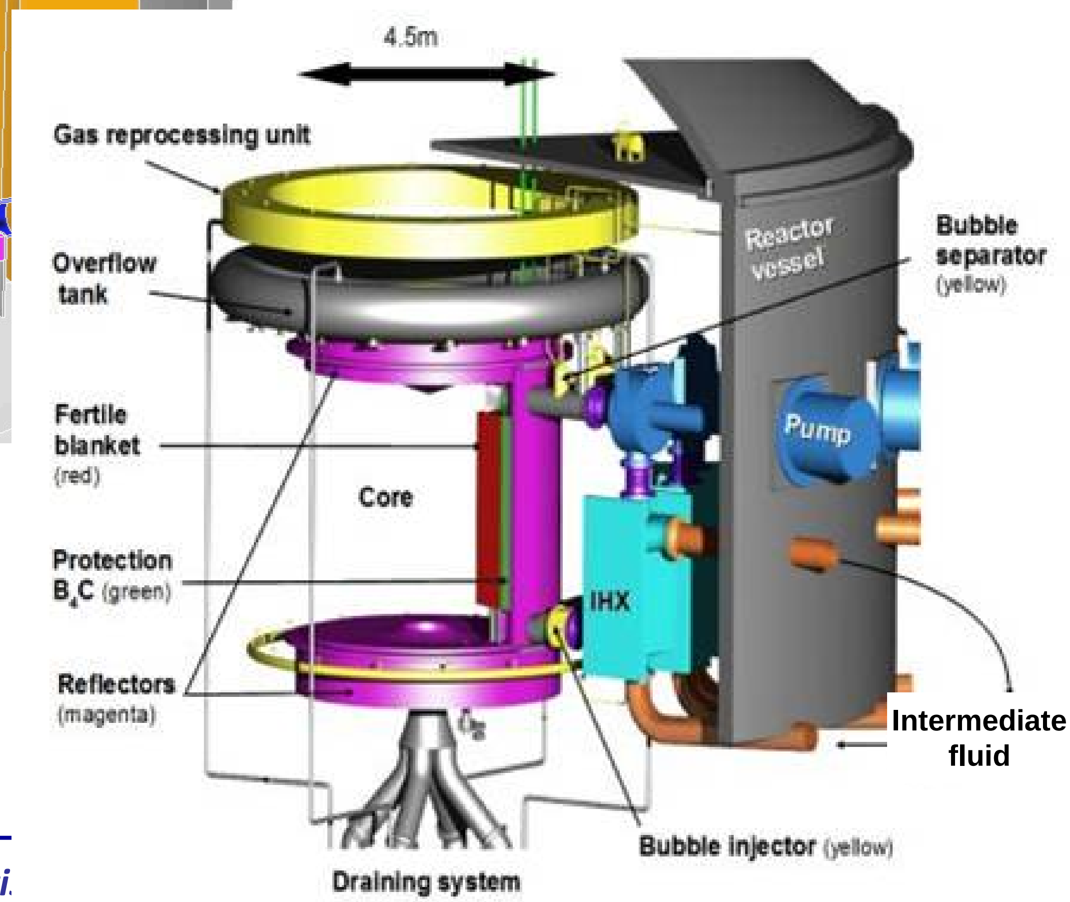

## Core:

*No inside structure*

*Outside structure*: Upper and lower Reflectors, Fertile Blanket Wall

## + 16 external modules:

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



# Demonstration and Demonstrator of MSFR

**Sizing of the facilities:**

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

Pyrochemistry: basic chemical data, processing, monitoring

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

Process analysis, modeling, technology tests

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

Validation of technology integration and hydrodynamics models

**3 levels of radio protection:**

- ✓ Inactive simulant salt ⇨ Standard laboratory

  Hydrodynamics, material, measurements, model validation
- ✓ Low activity level (Th, depleted U) ⇨ Standard lab + radio protect

  Pyrochemistry, corrosion, chemical monitoring
- ✓ High activity level ($^{enriched}U$, $^{233}U$, Pu, MA) ⇨ Nuclear facility

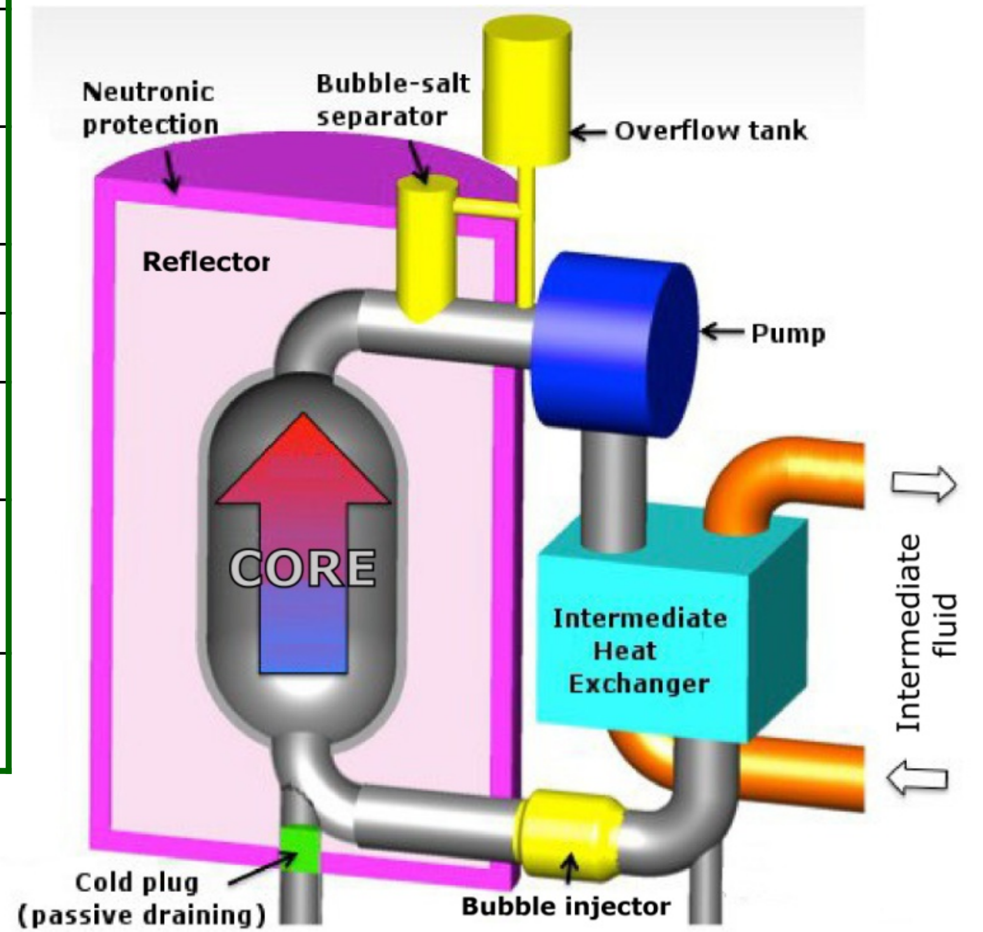
  Fuel salt processing: Pyrochemistry, , Actinides recycling

# Power Demonstrator of the MSFR

| | |
|---|---|
| Thermal power | 100 MWth |
| Mean fuel salt temperature | 725 °C |
| Fuel salt temperature rise in the core | 30 °C |
| Fuel Molten salt initial composition | 75% LiF-$ThF_4$-$^{233}UF_4$ or LiF-$ThF_4$-($^{enriched}$U+MOx-Th)$F_3$ |
| Fuel salt melting point | 565 °C |
| Fuel salt density | 4.1 g/cm³ |
| Core dimensions | Diameter: 1.112 m<br>Height: 1.112 m |
| Fuel Salt Volume | 1.8 m³<br>1.08 in core<br>0.72 in external circuits |
| Total fuel salt cycle in the fuel circuit | 3.5 s |

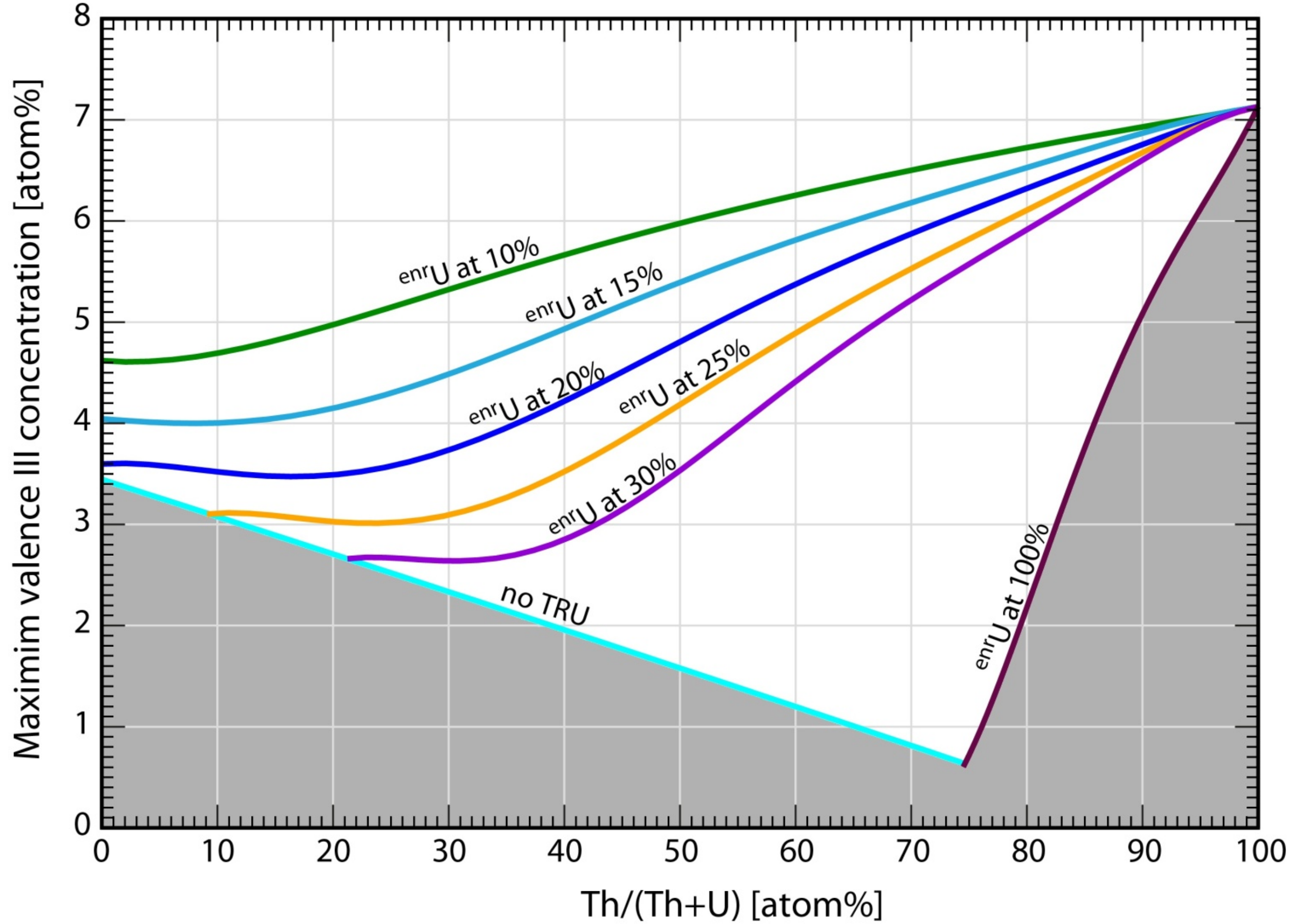
**Demonstrator characteristics representative of the MSFR**

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

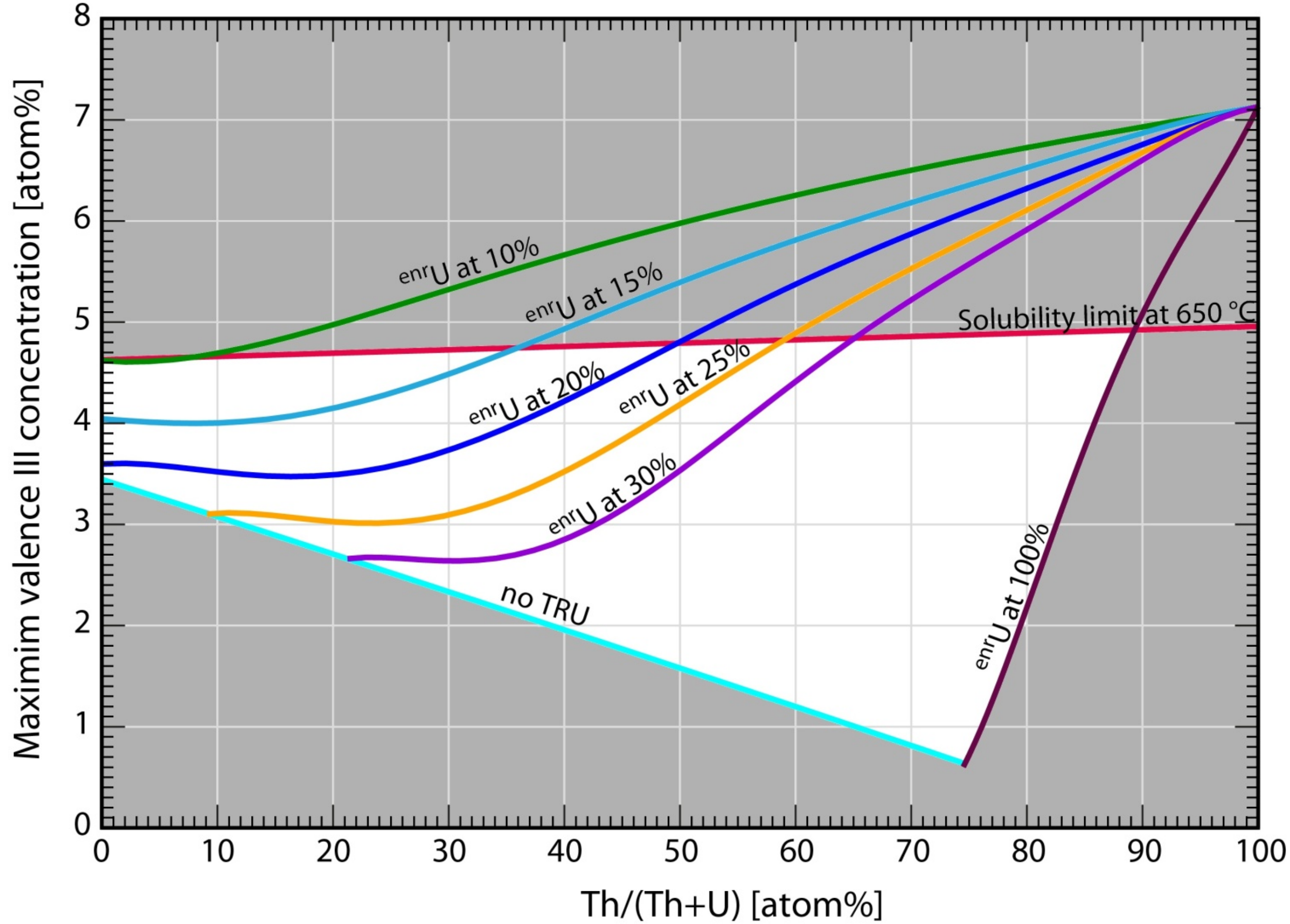



6 external loops

# Power Demonstrator of the MSFR: initial fissile load

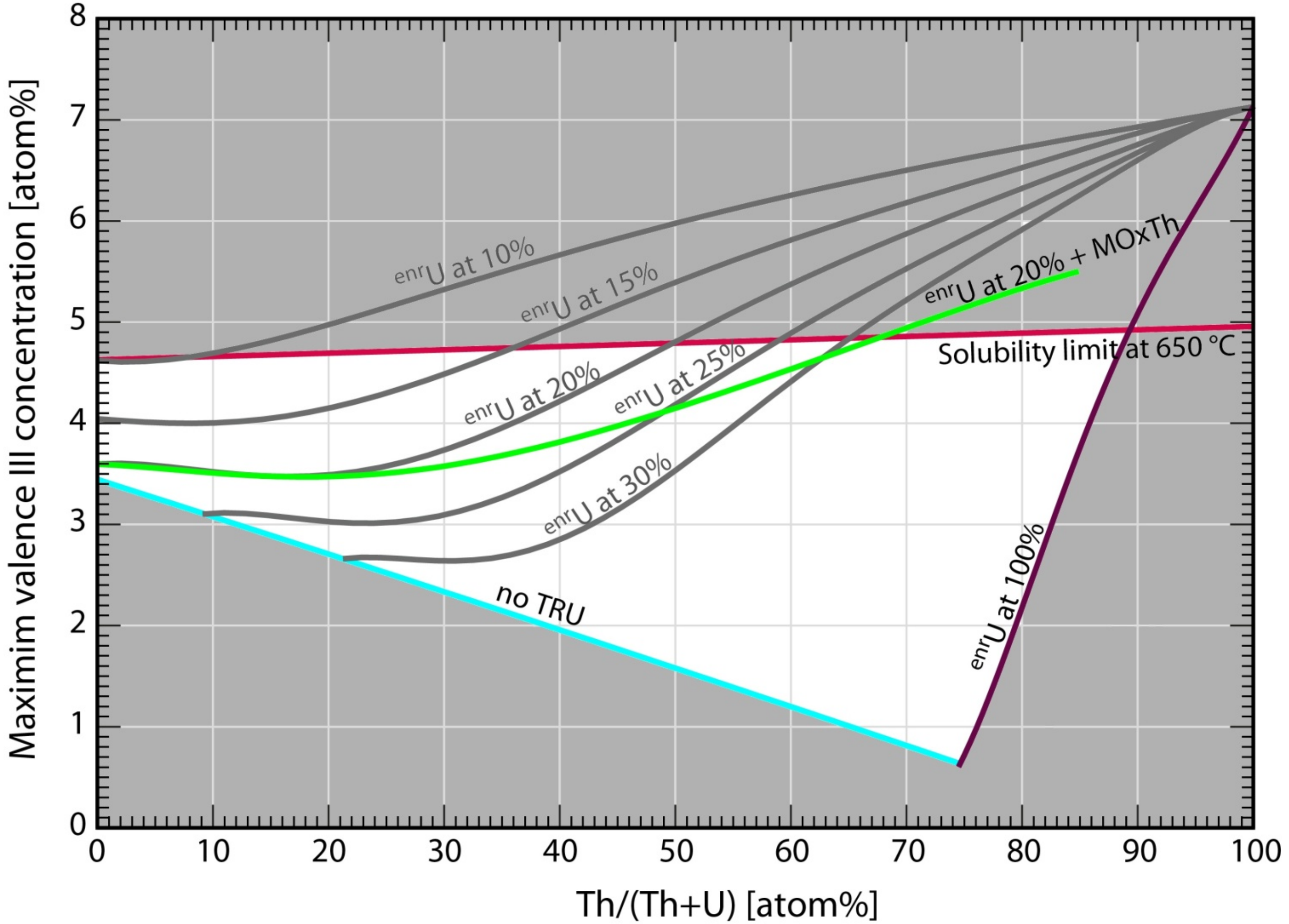


# Power Demonstrator of the MSFR: initial fissile load




✓ $^{enriched}$U mixed with transuranic elements possible with U enrichment of 15% - 20%

# Power Demonstrator of the MSFR: initial fissile load




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

# From Power Demonstrator of the MSFR to SMR

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

*Around 650kg of $^{233}U$ to start*

*Under-breeder reactor*

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

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

# From Power Demonstrator of the MSFR to SMR

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

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

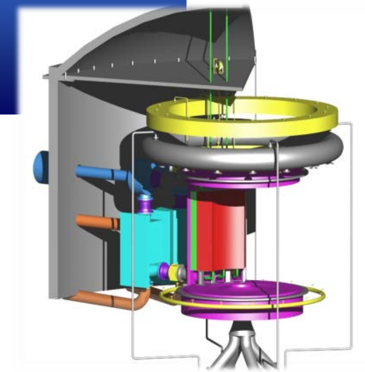
# From Power Demonstrator of the MSFR to SMR

| | 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 | Radial blanket and H/D=1.5 | Radial blanket and H/D=1.5 |
|---|---|---|---|---|---|---|
| **Power [$MW_{th}$]** | **100** | **200** | **100** | **200** | **100** | **200** |
| **Initial $^{233}U$ load [kg]** | 654 | 654 | 667 | 667 | 677 | 677 |
| **Fuel reprocessing of 1l/day** | | | | | | |
| Feeding in $^{233}U$ [kg/an] | 11.38 | 23.38 | 1.72 | 4.70 | -0.07 | 0.98 |
| Breeding ratio | **-29.83%** | **-30.64%** | **-4.52%** | **-6.16%** | ***0.18%*** | **-1.29%** |
| Total $^{233}U$ needed [kg] | 1013.87 | 1388.37 | 738.83 | 835.16 | 715.05 | 754.25 |
| **Breeding ratio (radial + axial fertile blankets)** | | | ***1.81%*** | ***-0.04%*** | | |
| **Fuel reprocessing of 4l/day** | | | | | | |
| Feeding in $^{233}U$ [kg/an] | 11.20 | 22.58 | 1. 48 | 3.58 | -0.38 | -0.26 |
| Breeding ratio | **-29.37%** | **-29.59%** | **-3.88%** | **-4.69%** | ***1.00%*** | ***0.34%*** |
| Total $^{233}U$ needed [kg] | 1001.86 | 1353.13 | 722.50 | 794.21 | 709.74 | 723.03 |
| **Breeding ratio (radial + axial fertile blankets)** | | | ***2.49%*** | ***1.54%*** | | |

**Addition of a radial fertile blanket + Elongated core ⇨ small modular breeder MSFR**

# European 'EVOL' (Evaluation and Viability Of Liquid fuel fast reactor systems) Project (7th PCRD) - *EURATOM/ROSATOM cooperation*

SEVENTH FRAMEWORK PROGRAMME



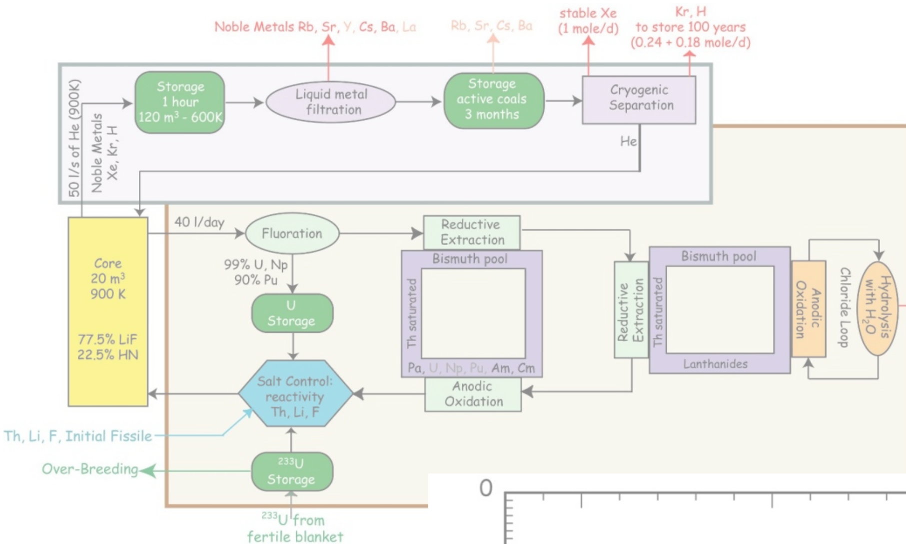
EVOL objective: to propose a design of MSFR by 2014 given the best system configuration issued from physical, chemical and material studies

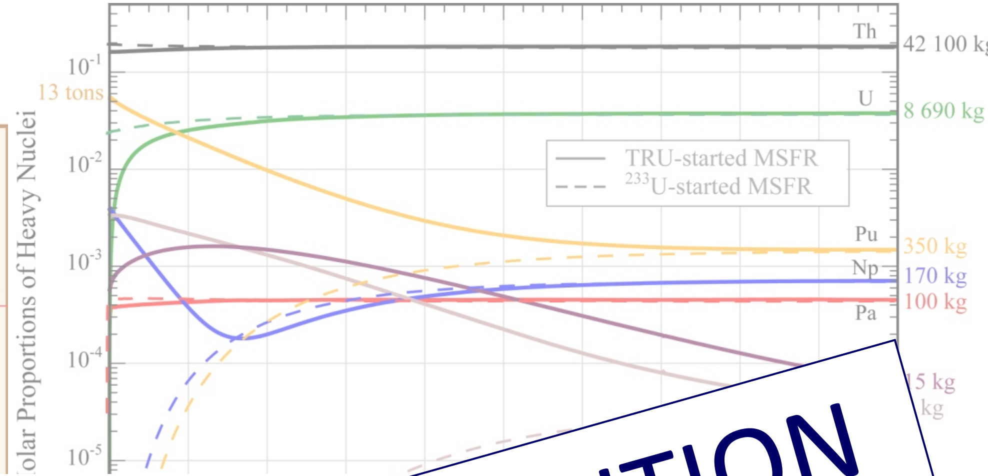
- **Recommendations for the design of the core and fuel heat exchangers**
- **Definition of a safety approach dedicated to liquid-fuel reactors - Transposition of the defence in depth principle - Development of dedicated tools for transient simulations of molten salt reactors**
- **Determination of the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

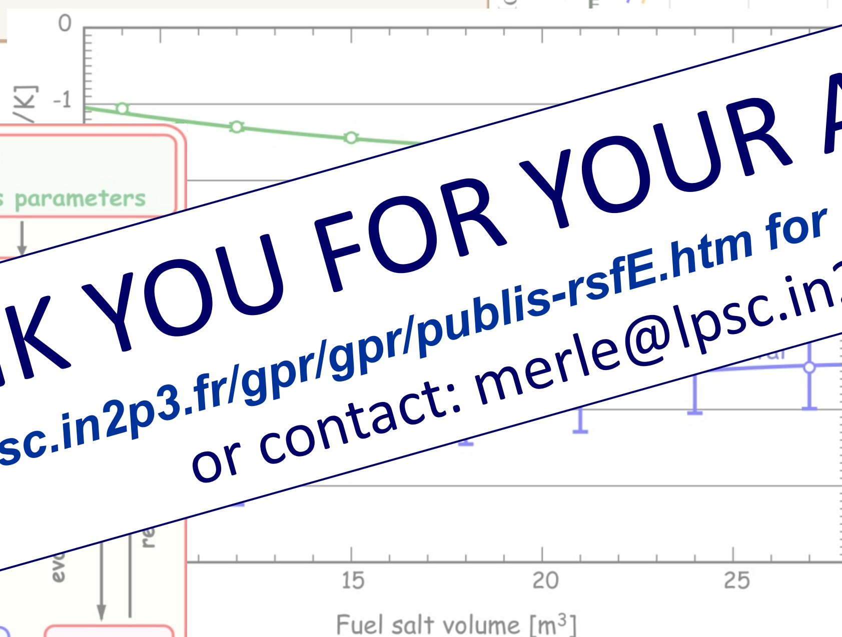
**WP2: Design and Safety**
**WP3: Fuel Salt Chemistry and Reprocessing**
**WP4: Structural Materials**

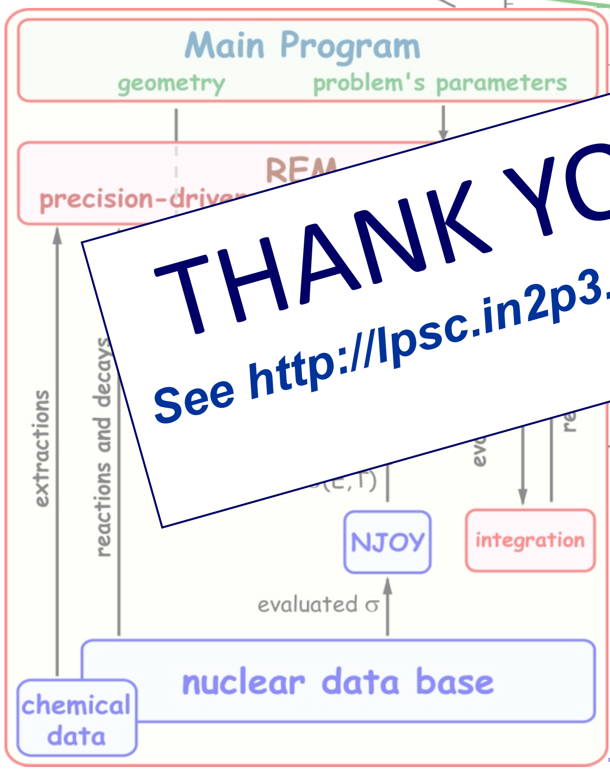
European participants to EVOL: France (CNRS: Coordinator, Aubert&Duval, INOPRO, Grenoble INP), EU (JRC – Institute for TransU Elements), Netherlands (Delft University of Technology), Germany (KIT-G, FZD), Italy (Politecnico di Torino), United Kingdom (Oxford University), Czech Republic (Energovyzkum Ltd), Hungary (Budapest University of Technology) + 2 observers (Politecnico di Milano, Italy and Paul Scherrer Institute, Switzerland)

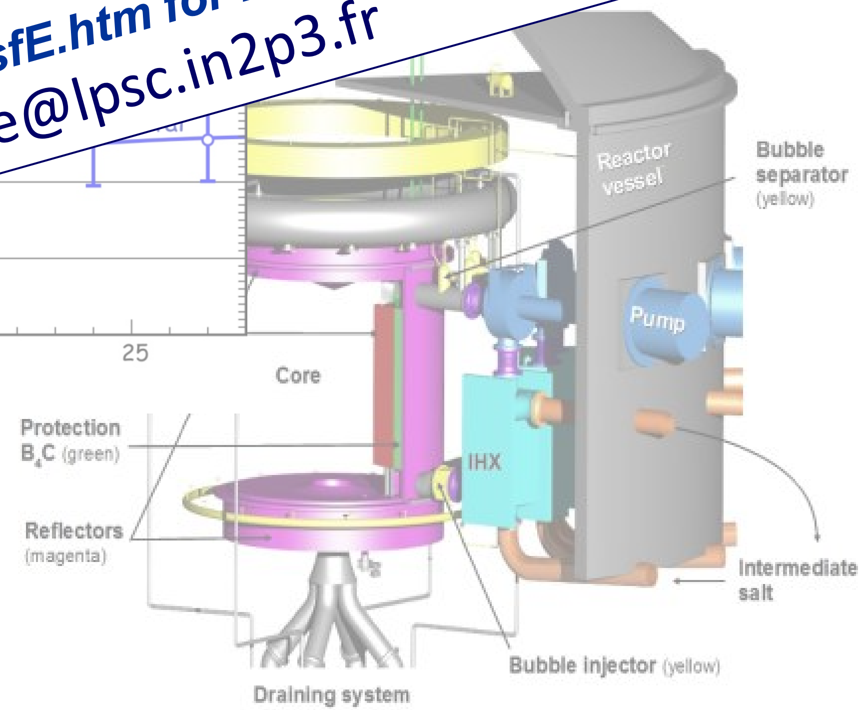
+ Coupled to the ROSATOM project MARS (Minor Actinides Recycling in Molten Salt)



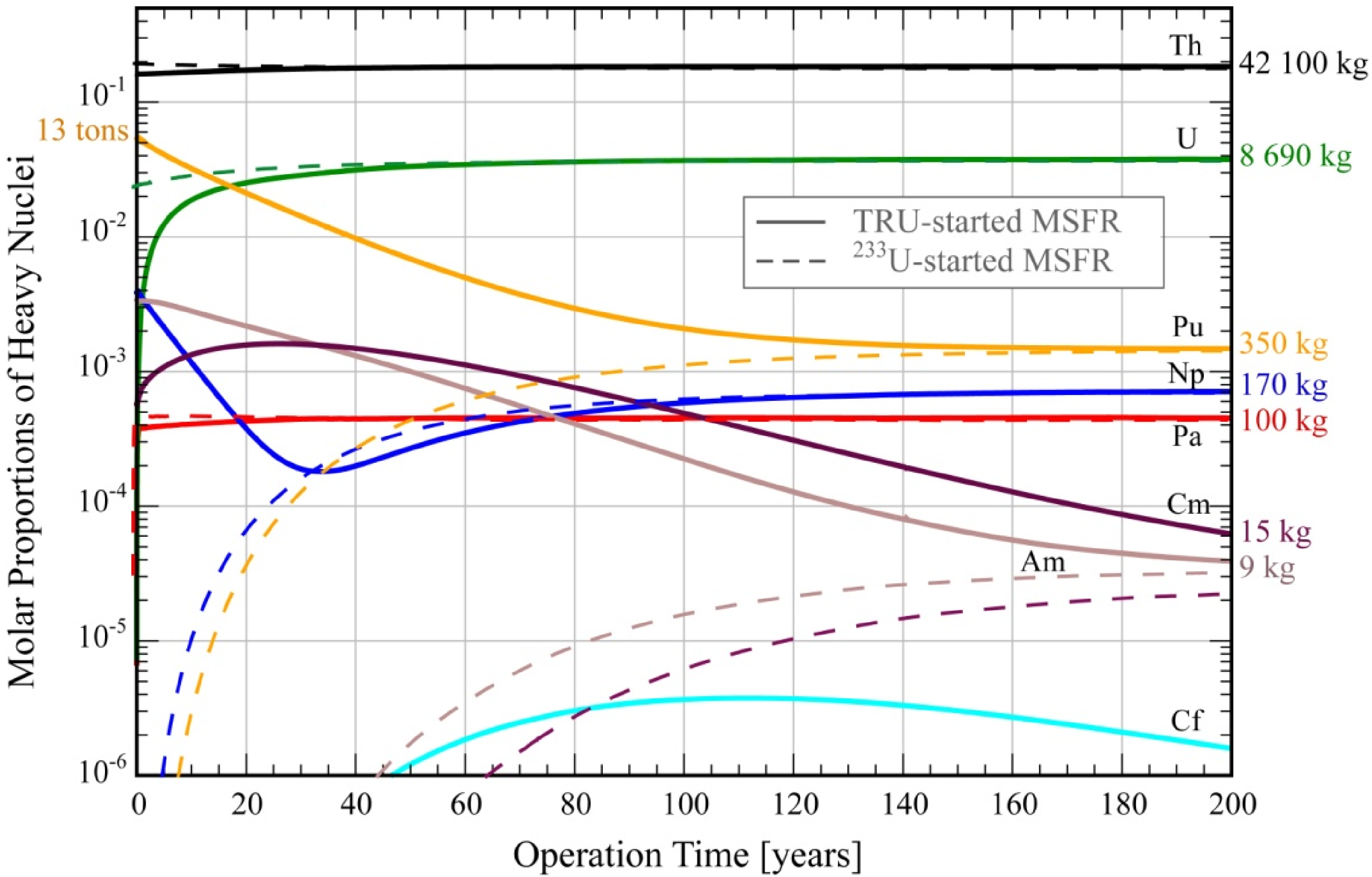




# THANK YOU FOR YOUR ATTENTION

**See http://lpsc.in2p3.fr/gpr/gpr/publis-rsfE.htm for more details on the MSFR**

or contact: merle@lpsc.in2p3.fr

# MSFR: Starting Modes / Initial Heavy Nuclei Inventory



# MSFR: Starting Modes / Initial Heavy Nuclei Inventory