The concept of Fast Spectrum Molten Salt Reactor (MSFR)

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For the ‘MSFR Team’ of LPSC - M. ALLIBERT, M. BROVCHENKO, V. GHETTA, D. HEUER, A. LAUREAU, E. MERLE-LUCOTTE, P. RUBIOLO

With the support of the IN2P3 institute and the PACEN and NEEDS Programs of CNRS, and of the EVOL Euratom FP7 Project
Liquid fuelled-reactors

Which constraints for a liquid fuel?
- Melting temperature not too high
- High boiling temperature
- Low vapor pressure
- 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 salt**
(LiF – 99.995% of $^7$Li)

**Molten Salt Reactors**

Neutronic properties of F not favorable to the U/Pu fuel cycle

**Advantages of a Liquid Fuel**
- Homogeneity of the fuel (no loading plan)
- Heat produced directly in the heat transfer fluid
- Possibility to reconfigure quickly and passively the geometry of the fuel (gravitational draining)
  - One configuration optimized for the electricity production managing the criticality
  - An other configuration allowing 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 physicochem. properties
  - No reactivity reserve (fertile/fissile matter adjusted during reactor operation)

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Thorium /$^{233}$U Fuel Cycle

Neutronic properties of F not favorable to the U/Pu fuel cycle
Liquid fuelled-reactors: MSR

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**Molten Salt Reactors**

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**Thorium /$^{233}$U Fuel Cycle**

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**
From MSR to Molten Salt Fast Reactor (MSFR)

Neutronic Optimization of MSR (Gen4 criteria):
- Safety: negative feedback coefficients
- Sustainability: reduce irradiation damages in the core
- Deployment: good breeding of the fuel + reduced initial fissile inventory

2008: Definition of an innovative MSR concept based on a fast neutron spectrum, and called MSFR (Molten Salt Fast Reactor) by the GIF Policy Group

- All feedback thermal coefficients negative
- No solid material in the high flux area: reduction of the waste production of irradiated structural elements and less in core maintenance operations
- Good breeding of the fissile matter thanks to the fast neutron spectrum
- Actinides burning improved thanks to the fast neutron spectrum

PhD Thesis of L. Mathieu
The concept of Molten Salt Fast Reactor (MSFR)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>3000 MWth</td>
</tr>
<tr>
<td>Mean fuel salt temperature</td>
<td>750 °C</td>
</tr>
<tr>
<td>Fuel salt temperature rise in the core</td>
<td>100 °C</td>
</tr>
<tr>
<td>Fuel molten salt - Initial composition</td>
<td>77.5% LiF and 22.5% [ThF₄⁺ (Fissile Matter)F₄] with Fissile Matter = ²³³U / enrichedU / Pu+MA</td>
</tr>
<tr>
<td>Fuel salt melting point</td>
<td>565 °C</td>
</tr>
<tr>
<td>Fuel salt density</td>
<td>4.1 g/cm³</td>
</tr>
<tr>
<td>Fuel salt dilation coefficient</td>
<td>8.82 10⁻⁴ / °C</td>
</tr>
<tr>
<td>Fertile blanket salt - Initial composition</td>
<td>LiF-ThF₄ (77.5%-22.5%)</td>
</tr>
<tr>
<td>Breeding ratio (steady-state)</td>
<td>1.1</td>
</tr>
<tr>
<td>Total feedback coefficient</td>
<td>-5 pcm/K</td>
</tr>
<tr>
<td>Core dimensions</td>
<td>Diameter: 2.26 m</td>
</tr>
<tr>
<td></td>
<td>Height: 2.26 m</td>
</tr>
<tr>
<td>Fuel salt volume</td>
<td>18 m³ (½ in the core + ½ in the external circuits)</td>
</tr>
<tr>
<td>Blanket salt volume</td>
<td>7.3 m³</td>
</tr>
<tr>
<td>Total fuel salt cycle</td>
<td>3.9 s</td>
</tr>
</tbody>
</table>

Design of the ‘reference’ MSFR

Optimization Criteria:
Initial fissile matter (²³³U, Pu, enriched U), salt composition, fissile inventory, reprocessing, waste management, deployment capacities, heat exchanges, structural materials, design...
MSFR: R&D collaborations

4th Generation reactors ⇒ Breeder reactors

Fuel reprocessing mandatory to recover the produced fissile matter – Liquid fuel = reprocessing during reactor operation
MSFR: R&D collaborations

4th Generation reactors => Breeder reactors
Fuel reprocessing mandatory to recover the produced fissile matter – Liquid fuel = reprocessing during reactor operation

Conclusions of the studies: very low impact of the reprocessings (chemical and bubbling) on the neutronic behavior of the MSFR thanks to the fast neutron spectrum = neutronic and chemical (physico-chemical properties of the salt) studies driven in parallel

PhD Thesis of X. Doligez

Studies requiring multidisciplinary expertise (reactor physics, chemistry, safety, materials, design...)

Collaboration at different levels:
- World: Generation 4 International Forum
- Europe: Collaborative Project EVOL Euratom/Rosatom + SNETP SRIA Annex
- National: IN2P3/CNRS and interdisciplinary programs PACEN and NEEDS (CNRS, CEA, IRSN, AREVA, EdF), structuring project ‘CLEF’ of Grenoble INP
MSFR and the European project EVOL

European Project “EVOL” Evaluation and Viability Of Liquid fuel fast reactor

*FP7 (2011-2013): Euratom/Rosatom cooperation*

**Objective:** to propose a design of MSFR by end of 2013 given the best system configuration issued from physical, chemical and material studies

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

**WP2: Design and Safety**

**WP3: Fuel Salt Chemistry and Reprocessing**

**WP4: Structural Materials**

**12 European Partners:** France (CNRS: Coordinateur, Grenoble INP, INOPRO, Aubert & Duval), Pays-Bas (Université Techno. de Delft), Allemagne (ITU, KIT-G, HZDR), Italie (Ecole polytechnique de Turin), Angleterre (Oxford), Hongrie (Univ Techno de Budapest)

+ 2 observers since 2012: Politecnico di Milano et Paul Scherrer Institute

+ Coupled to the MARS (Minor Actinides Recycling in Molten Salt) project of ROSATOM (2011-2013)

Partners: RIAR (Dimitrovgrad), KI (Moscow), VNIITF (Snezinsk), IHTE (Ekateriburg), VNIKHT (Moscow) et MUCATEX (Moscow)
Largely negative feedback coefficients, ∀ the simulation tool or the database used

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

PhD Thesis of M. Brovchenko
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: $^{233}$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

<table>
<thead>
<tr>
<th>[kg per GWe]</th>
<th>$^{233}$U started MSFR</th>
<th>TRU (Pu UOx) started MSFR</th>
<th>Enriched U (13%) + TRU started MSFR</th>
<th>Th Pu-MOx started MSFR</th>
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<tbody>
<tr>
<td>Th 232</td>
<td>25 553</td>
<td>20 396</td>
<td>10 135</td>
<td>18 301</td>
</tr>
<tr>
<td>Pa 231</td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>U 232</td>
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<tr>
<td>U 233</td>
<td>3 260</td>
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<tr>
<td>U 238</td>
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<td></td>
<td></td>
<td>11 758</td>
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<tr>
<td>Np 237</td>
<td>531</td>
<td>335</td>
<td>54</td>
<td></td>
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<tr>
<td>Pu 238</td>
<td>229</td>
<td>144</td>
<td>315</td>
<td></td>
</tr>
<tr>
<td>Pu 239</td>
<td>3 902</td>
<td>2 464</td>
<td>1 390</td>
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<tr>
<td>Pu 240</td>
<td>1 835</td>
<td>1 159</td>
<td>2 643</td>
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<td>Pu 241</td>
<td>917</td>
<td>579</td>
<td>297</td>
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<tr>
<td>Pu 242</td>
<td>577</td>
<td>364</td>
<td>1 389</td>
<td></td>
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<tr>
<td>Am 241</td>
<td>291</td>
<td>184</td>
<td>1 423</td>
<td></td>
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<tr>
<td>Am 243</td>
<td>164</td>
<td>104</td>
<td>354</td>
<td></td>
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<tr>
<td>Cm 244</td>
<td>69</td>
<td>44</td>
<td>54</td>
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<tr>
<td>Cm 245</td>
<td>6</td>
<td>4</td>
<td></td>
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</tbody>
</table>
MSFR optimization: thermal-hydraulic studies

PhD Thesis of A. Laureau

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

CFD mesh - 1/16 core 300 k cells

Velocity - m/s

Temperature - °C

Thorium Energy Conference 2013 (ThEC13) – CERN, Geneva
Molten Salt Fast Reactor (MSFR): fuel circuit

Core (active area):
No inside structure
Outside structure: Upper and lower Reflectors, Fertile Blanket Wall

+ 16 external recirculation loops:
- Pipes (cold and hot region)
- Bubble Separator
- Pump
- Heat Exchanger
- Bubble Injection
Molten Salt Fast Reactor (MSFR)

Three circuits:
- Fuel salt circuit
- Intermediate circuit
- Thermal conversion circuit
MSFR and Safety Evaluation

Design aspects impacting the MSFR safety analysis

• Liquid fuel
  ✓ Molten fuel salt acts as reactor fuel and coolant
  ✓ Relative uniform fuel irradiation
  ✓ A significant part of the fissile inventory is outside the core
  ✓ Fuel reprocessing and loading during reactor operation

• No control rods in the core
  ✓ Reactivity is controlled by the heat transfer rate in the HX + fuel salt feedback coefficients, continuous fissile loading, and by the geometry of the fuel salt mass
  ✓ No requirement for controlling the neutron flux shape (no DNB, uniform fuel irradiation, etc.)

• Fuel salt draining
  ✓ 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
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

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 analysis: objectives

• Develop a safety approach dedicated to MSFR
  • Based on current safety principles e.g. defense-in-depth, multiple barriers, the 3 safety functions (reactivity control, fuel cooling, confinement) etc. but adapted to the MSFR.
  • Integrate both deterministic and probabilistic approaches
  • Specific approach dedicated to severe accidents:
    – Fuel liquid during normal operation
    – Fuel solubility in water (draining tanks)
    – Source term evaluation

• Build a reactor risk analysis model
  • Identify the initiators and high risk scenarios that require detailed transient analysis
  • Evaluate the risk due to the residual heat and the radioactive inventory in the whole system, including the reprocessing units (chemical and )
  • Evaluate some potential design solutions (barriers)
  • Allow reactor designer to estimate impact of design changes (design by safety)
MSFR and Safety Evaluation: example of accidental scenario

- **Initiators (failure mode)**
  - Identification + occurrence probability

- **Dangerous Phenomena**
  - Accident classification

- **Transient**
  - Physical study of the reactor

- **Consequences**
  - Identified risks?
  - Loss of barriers?

  - Prevention barrier?
  - Protection?
  - Damages limitation?

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MSFR and Safety Evaluation: example of accidental scenario

Identification + occurrence probability

Accident classification

Physical study of the reactor

Identified risks? Loss of barriers?

Prevention barrier? Protection? Damages limitation?

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Loss Of Heat sink (LOH)

Different transients depending on initial failure

Intermediate salt fault mode

Draining failure

Pipes melting down

Confinement failure mode

Loss of fuel salt circulation

Cooling failure

Overheating
MSFR and Safety Evaluation: example of accidental scenario

**PhD Thesis of M. Brovchenko**

- **Initiators** (failure mode)
- Dangerous Phenomena
- **Transient**
- Consequences
- Concept adaptation

Identification + occurrence probability

- Accident classification
- Physical study of the reactor
- Identified risks?
- Loss of barriers?
- Prevention barrier?
- Protection?
- Damages limitation?

**Scenario** = passive decrease of the chain reaction (thermal feedback coefficients) + increase of the fuel salt temperature due to residual heat

\[ \tau = \text{inertia of the cooling system} \]
MSFR and Safety Evaluation: example of accidental scenario

**Initiators (failure mode)**
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**Transient**
- Physical study of the reactor

**Consequences**
- Identified risks? Loss of barriers?

**Concept adaptation**
- Prevention barrier? Protection? Damages limitation?

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**Risks identified:**
- Continuous heating due to the residual power (physics)
- Increase of temperature: impact of the pump inertia (technology)

**Protection:**
- Draining of the fuel salt
- Thermal protection on the walls?

*‘Design by Safety’ approach*

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**Quantitatively: Risk = Probability x Severity**

Accident probabilities and severity difficult to quantify at the current preliminary design stage
Demonstration and Demonstrator of MSFR

**Sizing of the facilities:**

**Small size:** ~1 liter - 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 m³ 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, ²³³U, Pu, MA) ⇒ Nuclear facility
  Fuel salt processing: Pyrochemistry, Actinides recycling
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Demonstration and Demonstrator of MSFR: the FFFER facility

The Forced Fluoride Flow Experiment
Reproduces the gases and particles extractions at 1/10th flow scale in simulant salt
Demonstration and Demonstrator of MSFR

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### Power Demonstrator of the MSFR

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<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>100 MWth</td>
</tr>
<tr>
<td>Mean fuel salt temperature</td>
<td>725 °C</td>
</tr>
<tr>
<td>Fuel salt temperature rise in the core</td>
<td>30 °C</td>
</tr>
<tr>
<td>Fuel Molten salt initial composition</td>
<td>75% LiF-ThF$_4$-$^{233}$UF$_4$ or LiF-ThF$_4$-(enrichedU+MOx-Th)F$_3$</td>
</tr>
<tr>
<td>Fuel salt melting point</td>
<td>565 °C</td>
</tr>
<tr>
<td>Fuel salt density</td>
<td>4.1 g/cm$^3$</td>
</tr>
<tr>
<td>Core dimensions</td>
<td>Diameter: 1.112 m, Height: 1.112 m</td>
</tr>
<tr>
<td>Fuel Salt Volume</td>
<td>1.8 m$^3$</td>
</tr>
<tr>
<td>Total fuel salt cycle in the fuel circuit</td>
<td>3.5 s</td>
</tr>
<tr>
<td>Fuel Salt Volume</td>
<td>1.08 in core, 0.72 in external circuits</td>
</tr>
</tbody>
</table>

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

**Demonstrator characteristics representative of the MSFR**
- 6 external loops

![Diagram of the MSFR demonstrator](Image)
**Summary:** Definition of an innovative Molten Salt configuration with a Fast Neutron Spectrum, based firstly on reactor physics studies and including now more largely system developments (chemistry, thermal-hydraulics, materials, safety, design...)

**Perspectives**

⇒ Where?

- National programs: CNRS (IN2P3...) and multidisciplinary program NEEDS – Collaborations with IRSN (and EdF/AREVA?) + Structuring project CLEF of Grenoble INP
- European project EVOL (FP7) with Rosatom: finished end 2013 – Next project in Horizon 2020?
- International: MSR MoU (GIF) to be signed by ROSATOM - Other collaborations (China, Japan, USA...)?

⇒ Optimization of the system and symbiotic safety/design studies

- Multi-physics and multi-scale coupling tool for a global simulation of the system
- Design of the reactor, draining and processing systems (including materials, components...)
- Risk analysis and safety approach dedicated to MSFR
- Define the demonstration steps and experimental facilities
Thank you for your attention!

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