Overview of separation methods applicable for the Molten Salt Reactor fuel cycle

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Joint IAEA-NEA-EC/JRC Workshop on the Taxonomy and Related Terminology of Fuel Cycles for Molten Salt Reactors

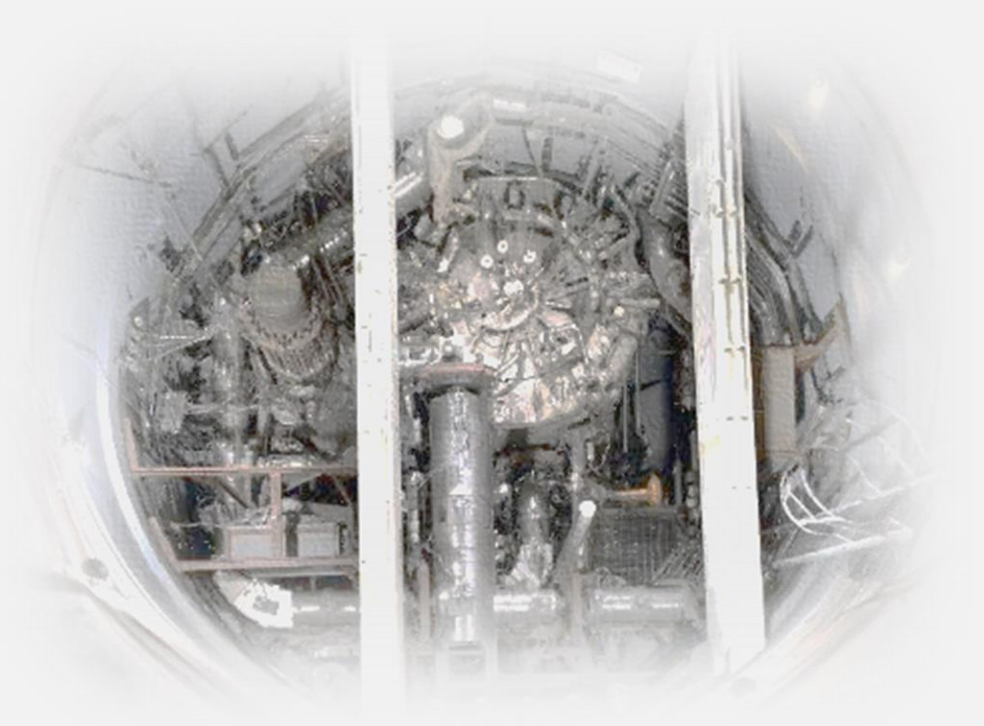
IAEA Headquarters, Vienna, Austria

3 - 7 November 2025

European Commission

SCOPE

1. Background and MSR fuel cycles
2. Pyrochemical separation methods
3. Aqueous separation method
4. Summary



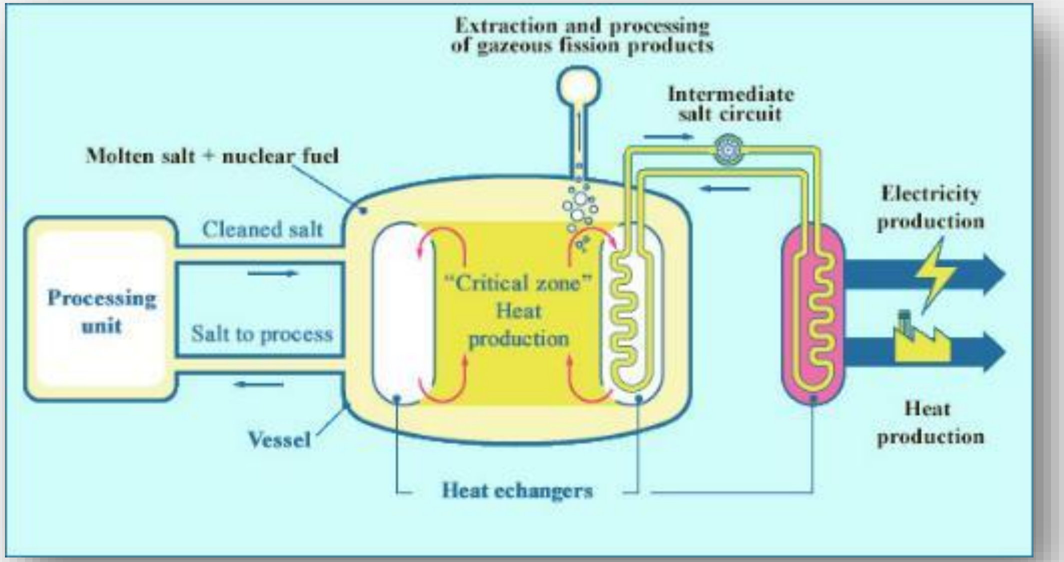
1. Background and MSR fuel cycles

- Why reprocess Molten Salt Reactor fuel?
- Examples of Molten Salt Reactor fuel cycles

Why reprocess Molten Salt Reactor fuel?

Key Reasons:

- **Remove noble gases (Xe, Kr)**
  prevent neutron absorption and reactivity loss
- **Remove rare-earth fission products**
  strong neutron poisons that reduce fuel efficiency
- **Maintain salt chemistry & material compatibility:**
  prevent corrosion and degradation
- **Enable higher fuel burn-up:**
  longer operation and better resource use
- **Recover actinides:**
  supports a closed fuel cycle and reduces long-lived waste
- **Improve reactor safety and predictability:**
  stable reactivity and reduced decay heat inventory



Gaseous fission products are continuously extracted. Other fission products are extracted from the molten salts in a reprocessing unit on the left. This extraction would probably not be carried in a continuous flow, but rather in the form of daily or weekly punctures.
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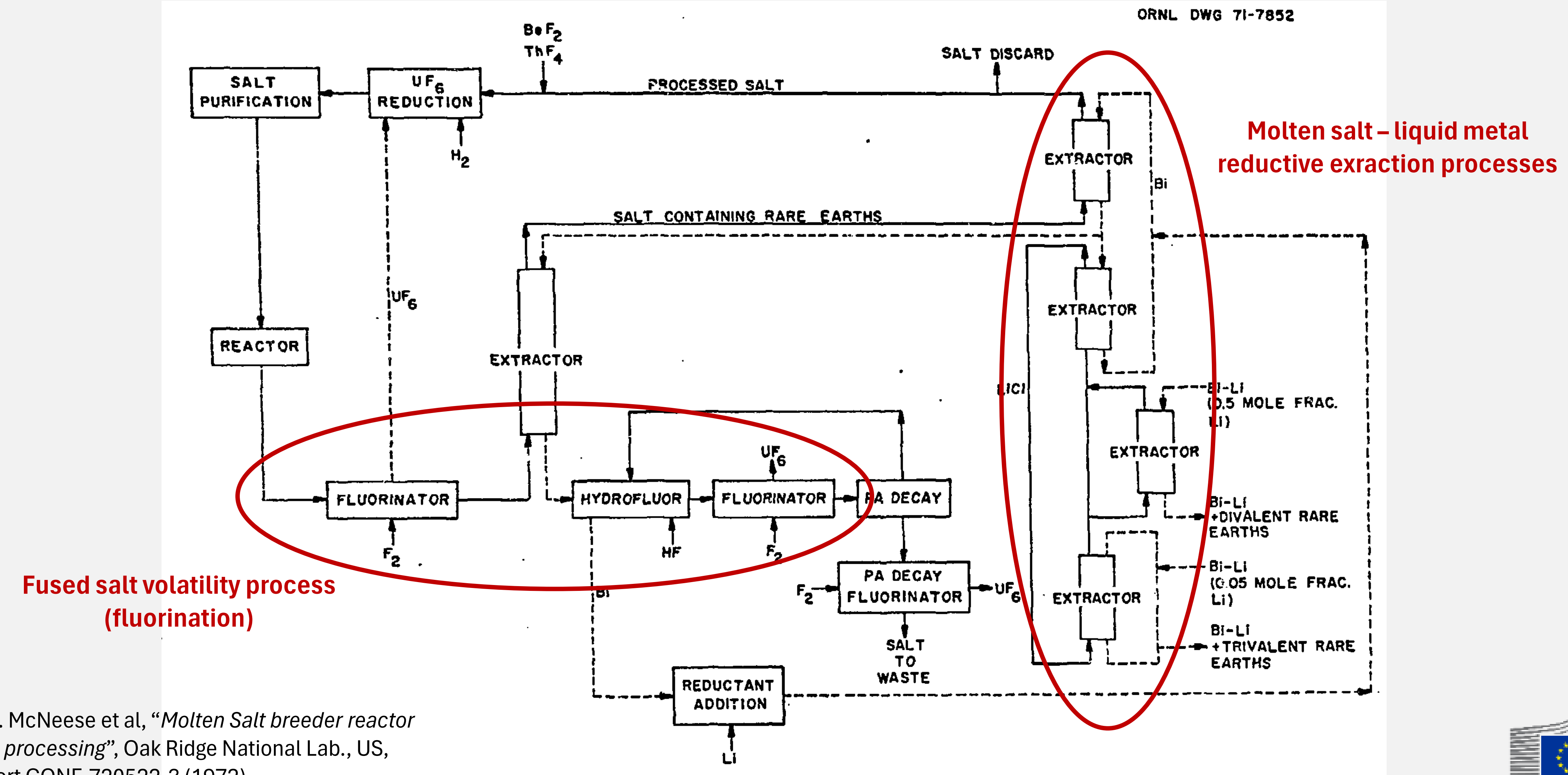
Examples of Molten Salt Reactor fuel cycles

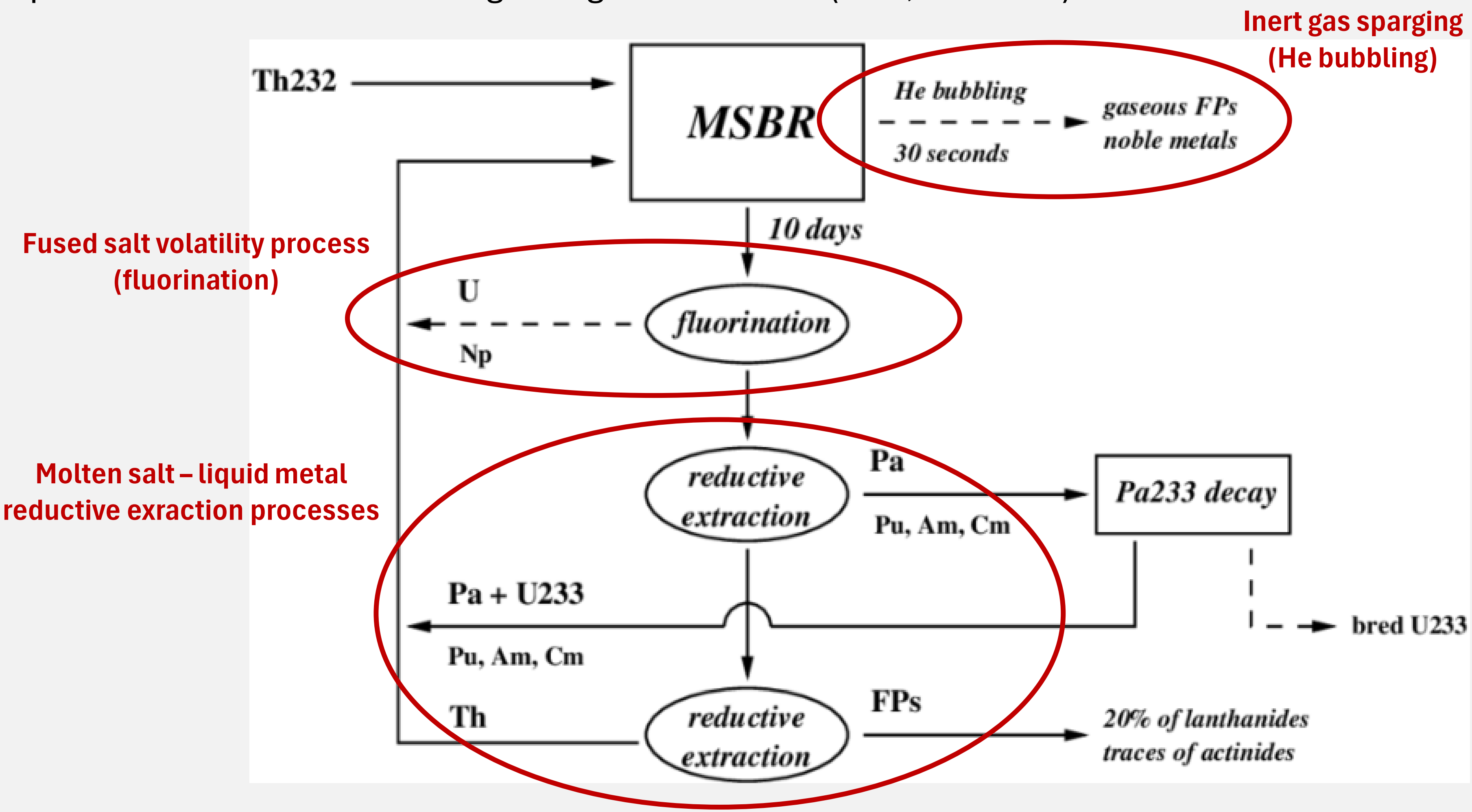
Conceptual Flowsheet for Processing a Single-Fluid MSBR (USA, fluorides)



L. E. McNeese et al, "*Molten Salt breeder reactor fuel processing*", Oak Ridge National Lab., US, report CONF-720522-3 (1972)

Examples of Molten Salt Reactor fuel cycles

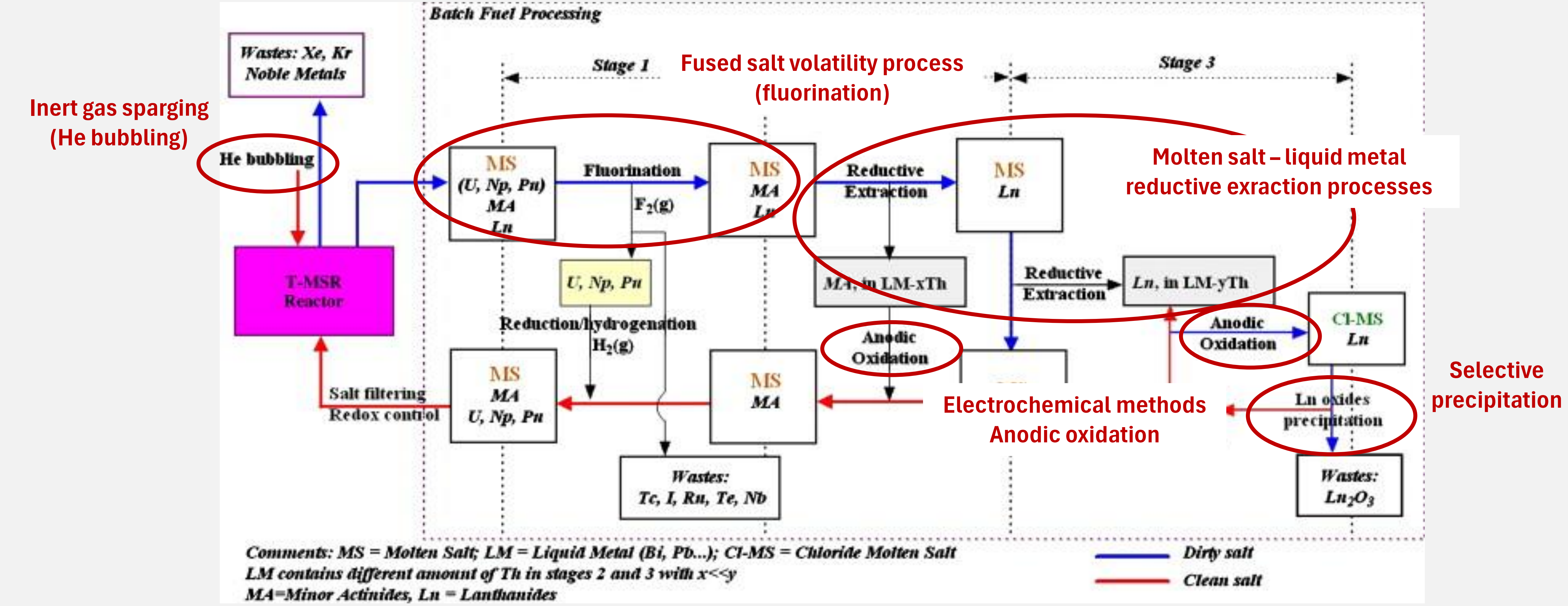
Conceptual Flowsheet for Processing a Single-Fluid MSBR (USA, fluorides)



A. Nuttin et al, Progress in Nuclear Energy **46**(1), 2005, pp. 77-99

Examples of Molten Salt Reactor fuel cycles

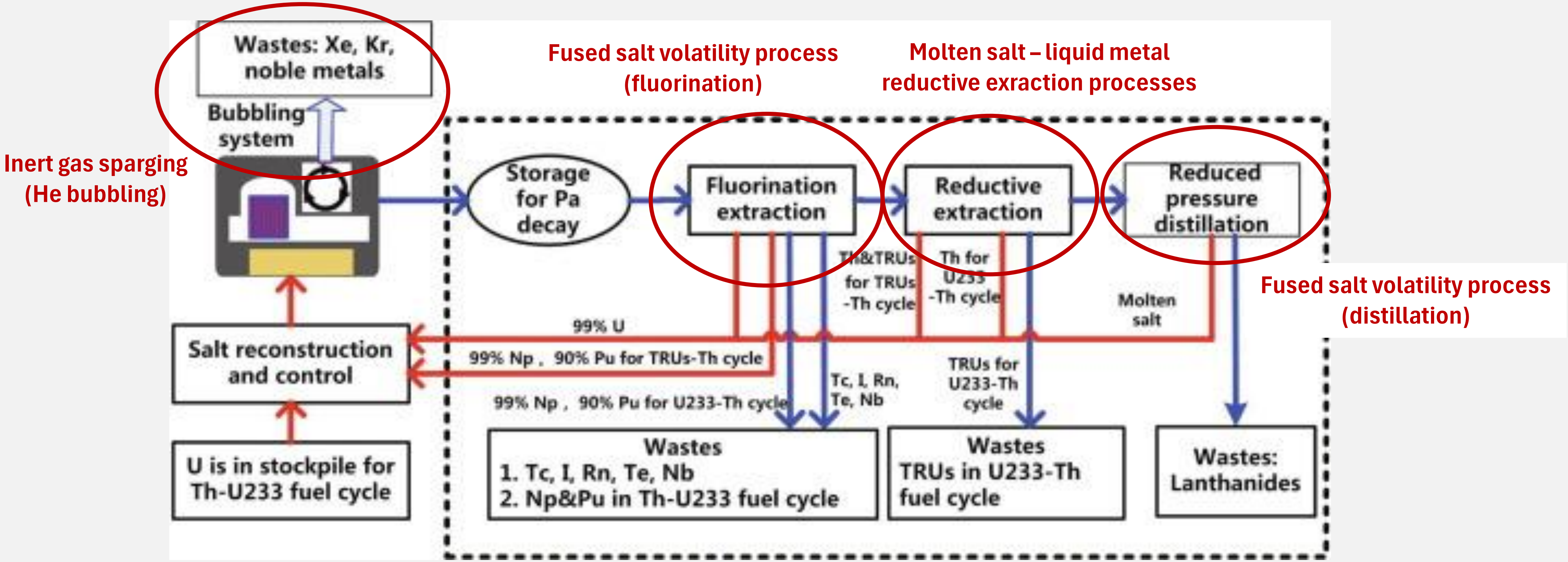
TMSR-NM (non-moderated thorium molten salt reactor) (France, fluorides)



Delpech, S., Merle-Lucotte, E., et al., Journal of Fluorine Chemistry **130**(1):11 (2009)

Examples of Molten Salt Reactor fuel cycles

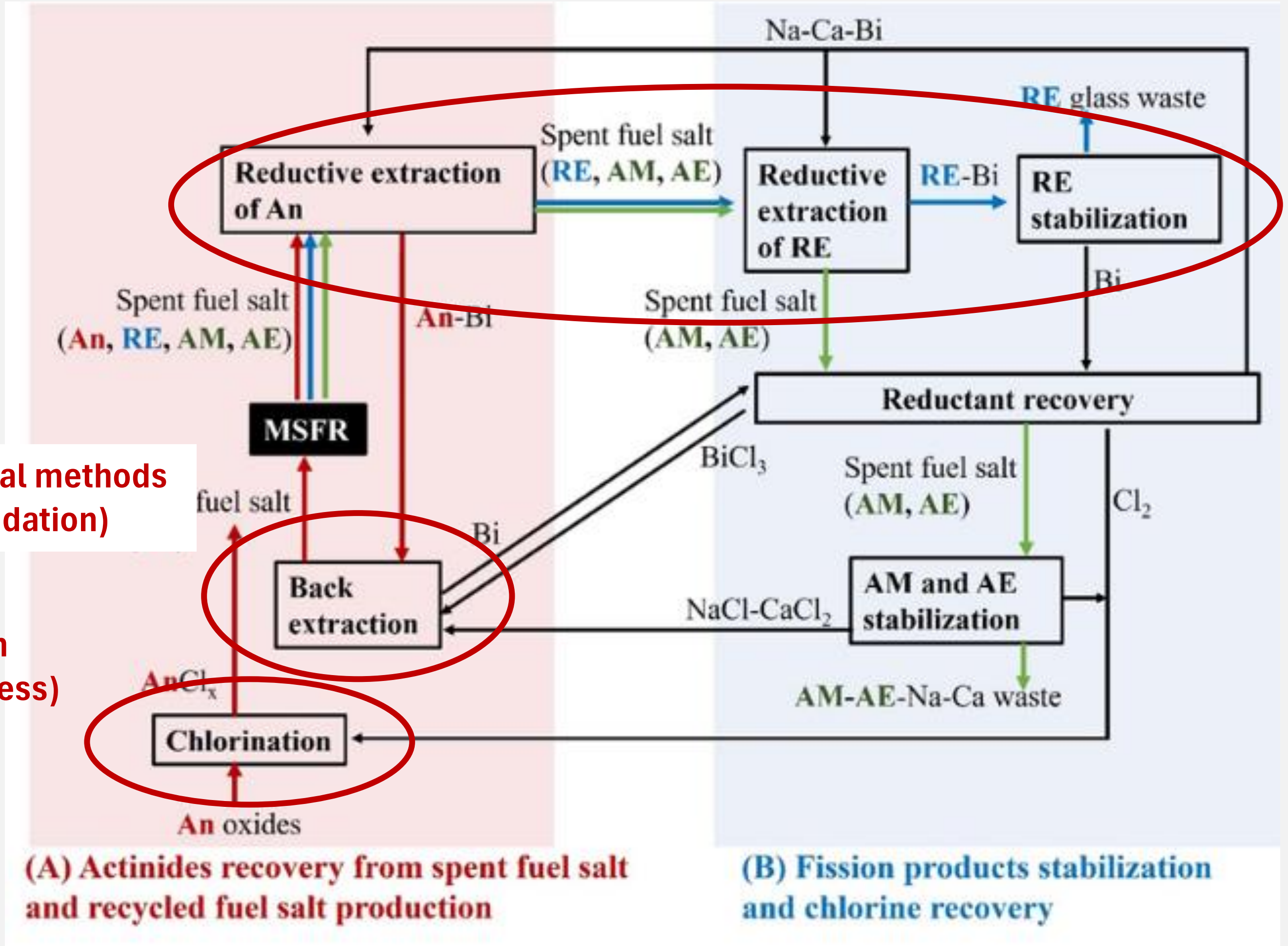
Small modular molten salt reactor (sm-MSR) (China, fluorides)



Chunyan Zou, et al., Annals of Nuclear Energy **138** April 2020, pp. 107163

Examples of Molten Salt Reactor fuel cycles

Chloride molten salt fast reactor (Japan, chlorides)

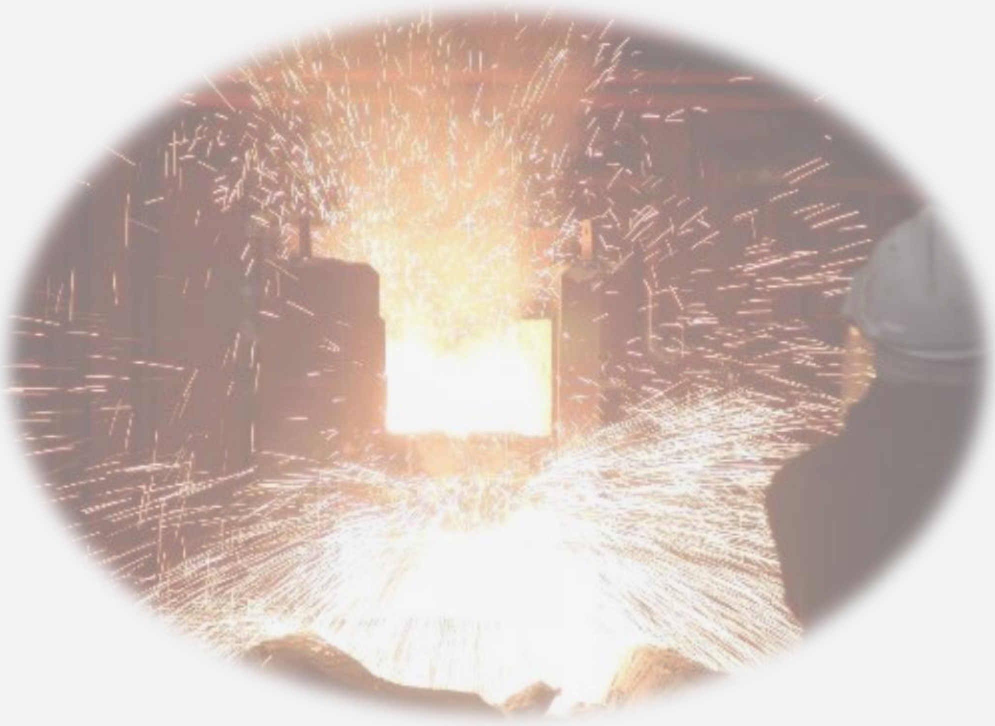


Molten salt – liquid metal reductive exraction processes

Electrochemical methods (anodic oxidation)

Chlorination (front-end process)

T. Murakami, et al., "*Pyrochemical Reprocessing of Spent Fuel Salt of Molten Salt Fast Reactor*" in proceedings of 16th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (16IEMPT), 4 - 27 October 2023 NEA Headquarters, Boulogne-Billancourt, France



2. Pyrochemical separation methods

- Specification of the pyrochemical processes
- Gas extraction process
- Fused salt volatilization
- Electrochemical methods
- Reductive extraction
- Oxidative precipitation
- Salt crystallization

Specification of the pyrochemical processes

Pyrochemical methods for recovery of actinides from spent fuel

- **Applicable for advanced fuels –** molten salt, metallic, inert matrices…
- **Compact process** - reduced number of transports, lower costs
- **More "proliferation-resistant" process** - "Impure" product fractions (homogeneous recycling of the actinides)
- **Safer reprocessing** - no water present $\Rightarrow$ reduced criticality risk
- **Faster P&T cycle** - used chemicals radiation resistant
  $\Rightarrow$ short fuel cooling-times

Chemicals – simple inorganic molecules

- Chemical properties – An metals are stable in molten salts (*not in water!*)
- Thermal and radiation stability
- Fast kinetics due to high temperature

- Corrosive, hygroscopic
- Demanding working conditions
  - inert gas atmosphere needed
  - high temperature apparatuses

Gas extraction process (helium bubbling)

Principle of the method

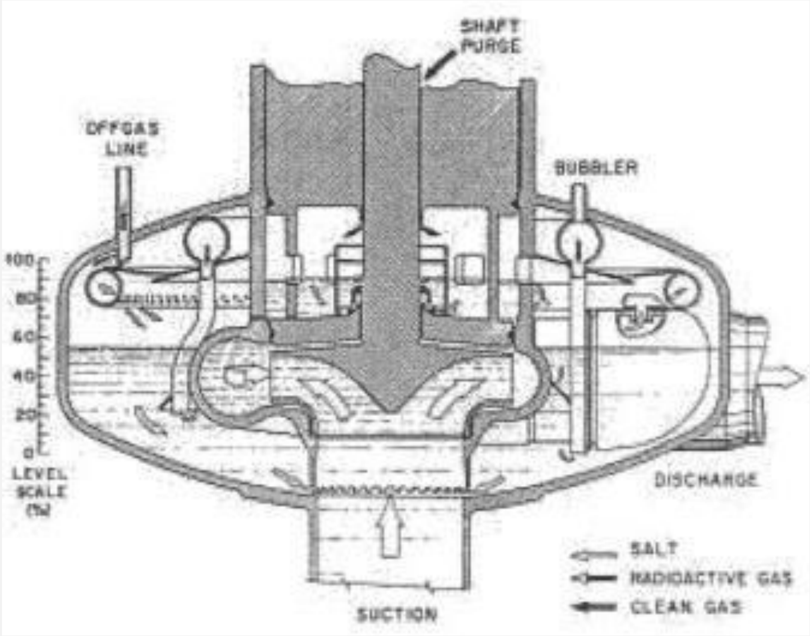
Bubbles of an inert gas (e.g., helium) are passed through the molten fuel salt, carrying out dissolved noble gases (Xe, Kr) and entrained noble metal particles (Ru, Rh, Pd, Pt,...) from the melt.

The feature enabling selective separation

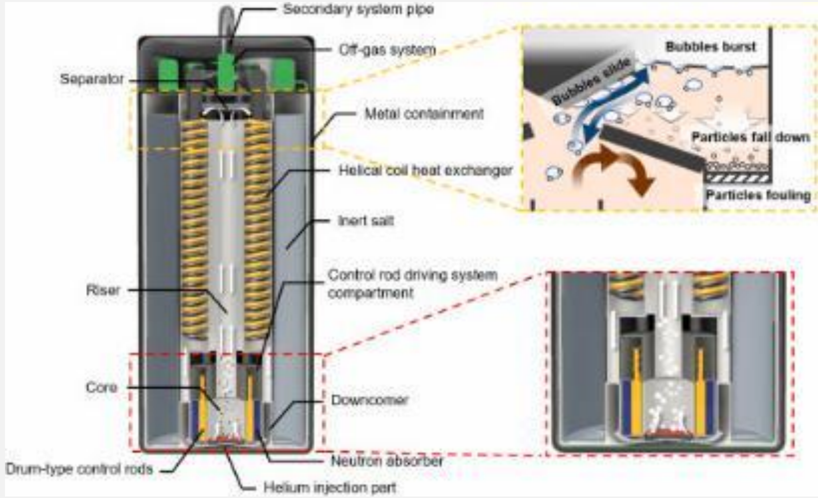
Selectivity is based on the low solubility of noble gases in the salt and the ability of gas bubbles to entrain suspended metal particles, allowing their extraction without affecting the bulk fuel.

MSR fuel cycle: USABLE (designed for)

- The off-gas treatment must safely handle radioactive noble gases, aerosols, salt mists and particles. Systems include traps, filters, cold-traps, molecular sieves.



Vertical section of fuel pump with helium sparging system. *Source*: Courtesy of ORNL, US-DOE.



Schematic of Passive Molten salt Fast Reactor including helium bubbling system: W.J. Choi et al., Nuclear Engineering and Technology 56 (2024) 1002–1012

Fused salt volatilisation

Principle of the method

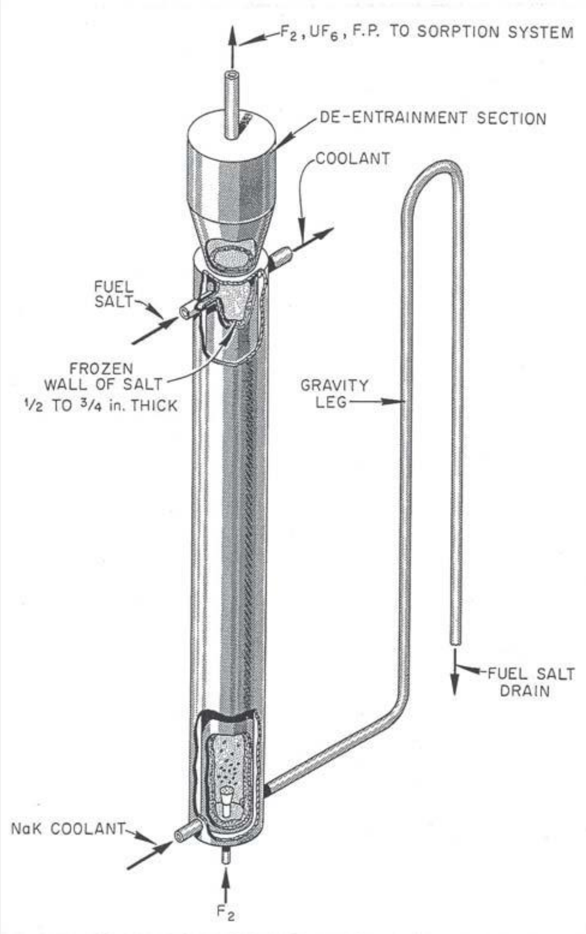
Molten fuel salt is contacted with a reactive gas (e.g., F_2), converting some species into volatile compounds that are released and separated from the melt (e.g. UF_4(s) to UF_6(g), while non-volatile species remain in the salt.

The features enabling selective separation

Differences in volatility and halide stability of the elements in the molten salt.

MSR fuel cycle: **USABLE** and recommendable

- Some actinides (e.g., Pu) form mixed volatile /non-volatile fluorides (PuF_6 /PuF_4) which complicates the process
- Very corrosive chemicals and high T brings materials and safety challenges



Continuous fluorinator with frozen wall developed at ORNL, US: ORNL report 3936 (1966)

Special case: **Fluoride Volatility Method** - reaction of fluorine gas with powdered **solid fuel** components is **NOT USABLE** for MSR fuel

Electrorefining

Principle of the method

The fuel is anodically dissolved in a molten salt and part of the ions are electrochemically reduced and recovered on a cathode

Cathodes:

<u>Inert</u> (*e.g. stainless steel*): recovery of U as metal

<u>Reactive</u> (*e.g. liquid Cd, Bi, solid Al*): recovery of Pu and MA as alloys

The feature enabling selective separation

Different electrochemical "red-ox" potentials

Applications: Advanced nuclear fuel reprocessing – metallic fuels or ceramic fuels electro-reduced to metals in the preceding step

MSR fuel cycle: **NOT USABLE**

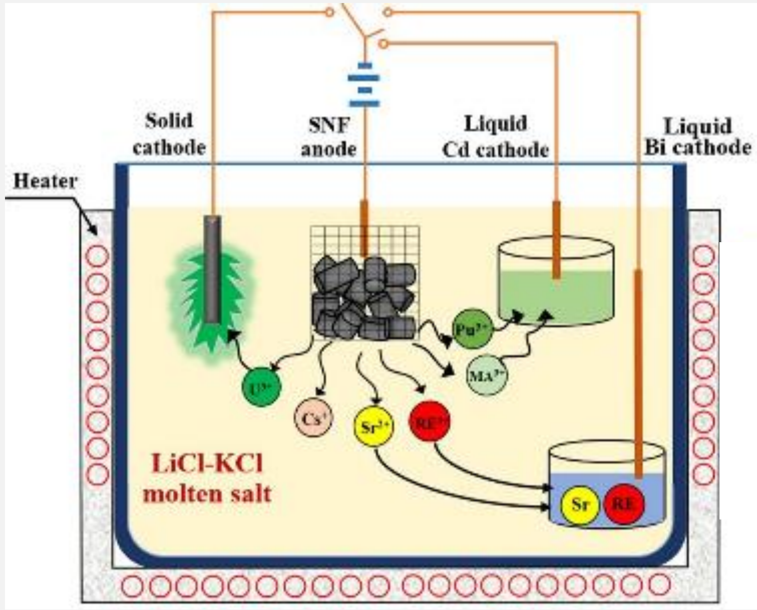


Illustration from: Hong Zhang et al., Separation and Purification Technology **313** (2023), pp. 123441

Developed to an industrial scale

Hundreds kilograms of sodium-bonded and highly enriched spent EBR-II driver fuel has been processed in the Idaho National Laboratory (INL), US

Illustration from: https://mfc.inl.gov/SitePages/Instruments/Fuel%20Conditioning%20Facility/Mark%20IV%20electrorefiner.aspx

Electrowinning

Principle of the method

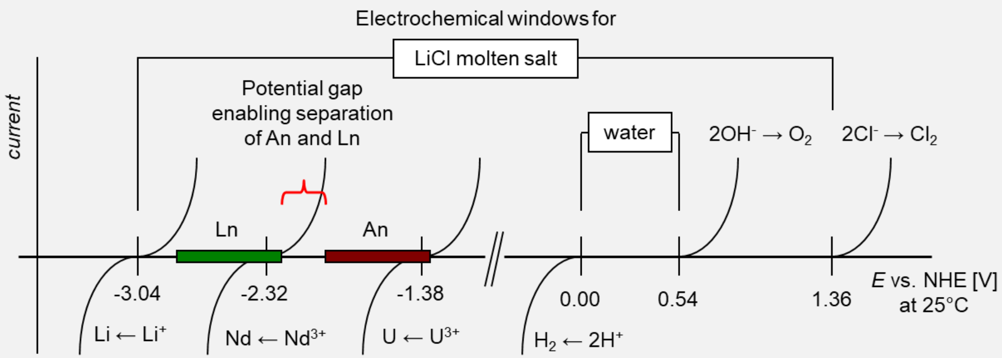
The less stable species dissolved in molten salt are electrochemically reduced on a cathode, while the melt is oxidized at an anode

Cathodes:

<u>Inert</u> (*e.g. stainless steel*): recovery of U as metal

<u>Reactive</u> (*e.g. liquid Cd, Bi, solid Al*): recovery of Pu and MA as alloys

The feature enabling selective separation



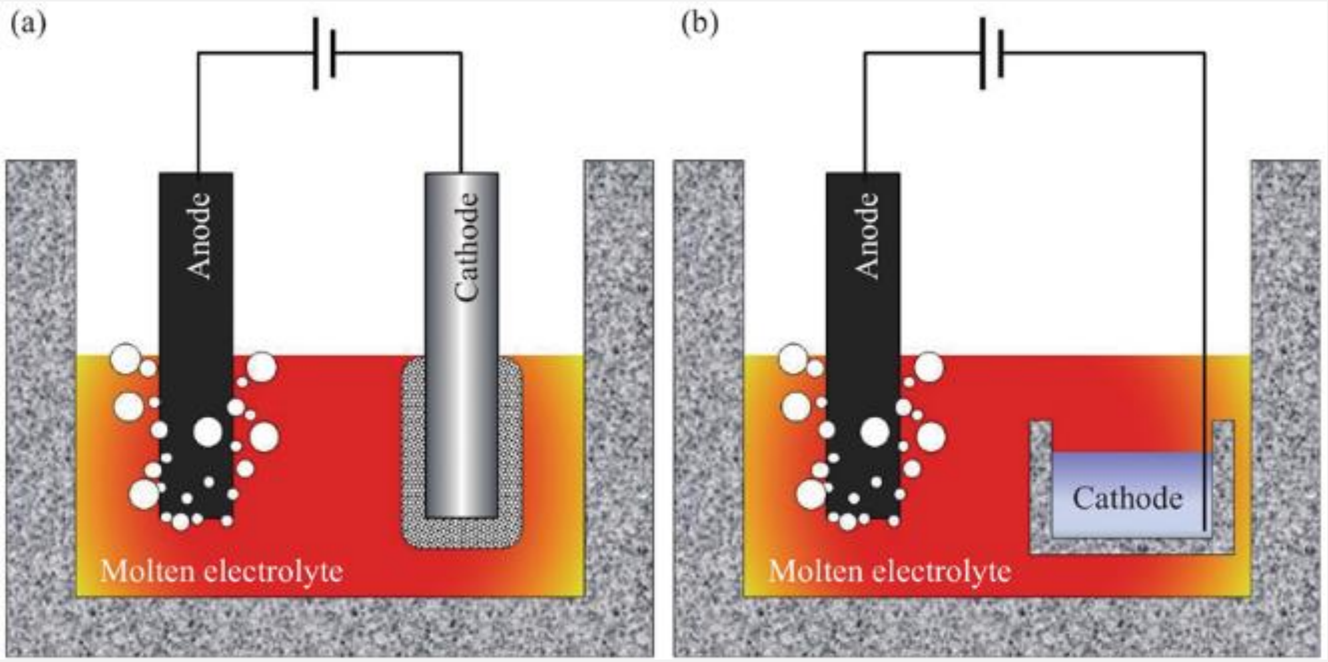


Illustration from: Hong Zhang et al., Separation and Purification Technology **313** (2023), pp. 123441

MSR fuel cycle: **USABLE** with limitations: Actinides are recovered prior lanthanides and Cs, Sr
Handling gas evolving anode is difficult

Molten Salt / Liquid Metal Reductive Extraction

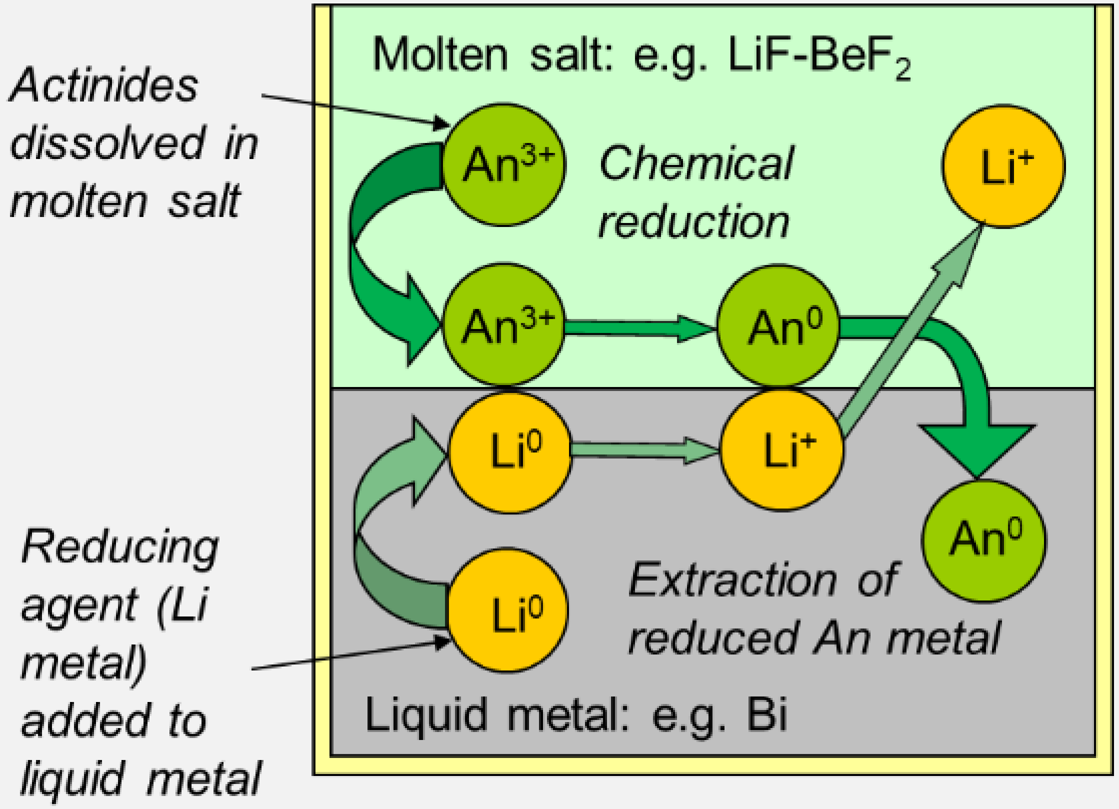
Principle of the method

The less thermodynamically stable species dissolved in molten salt are chemically reduced to metallic form by reducing agent (e.g. Li) added to a liquid metal (e.g. Bi, Cd, Al), into which they are extracted, forming alloys with the metal

The features enabling selective separation

Different thermodynamic stabilities (chemical potentials) of the dissolved species and the reduction power of the extraction agent.

Typically, Li metal dissolved in a Bi alloy acts as the reductant: the higher the Li concentration, the stronger the reduction potential, enabling selective extraction of less stable species.



MSR fuel cycle: **USABLE** and highly recommendable, however, actinides are recovered prior lanthanides and Cs, Sr

Oxidative Precipitation

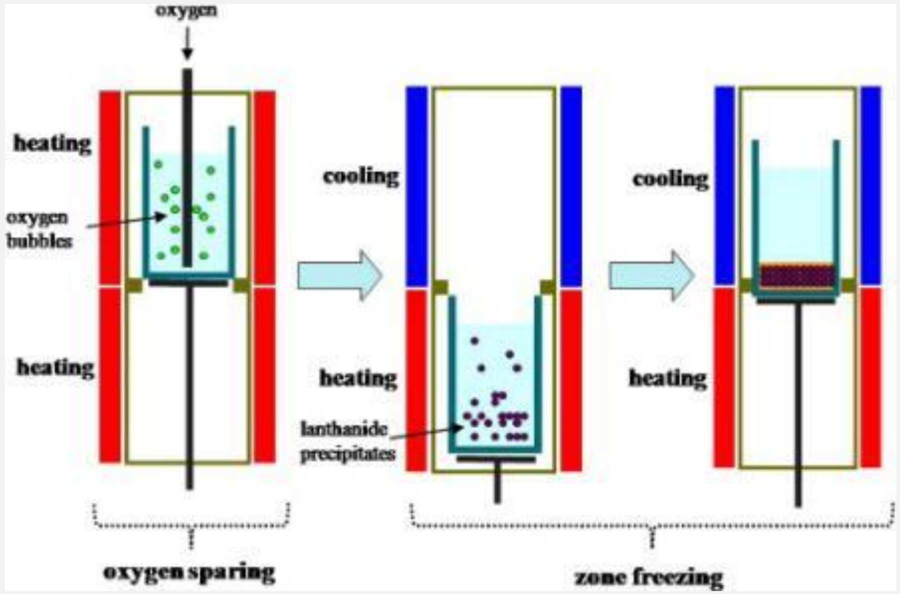
Principle of the method

Sparging oxygen or wet argon through a molten eutectic salt (typically LiCl-KCl) at high temperature, prompting rare-earth chlorides ($RECl_3$) dissolved in the salt to convert into insoluble oxides and oxychlorides.

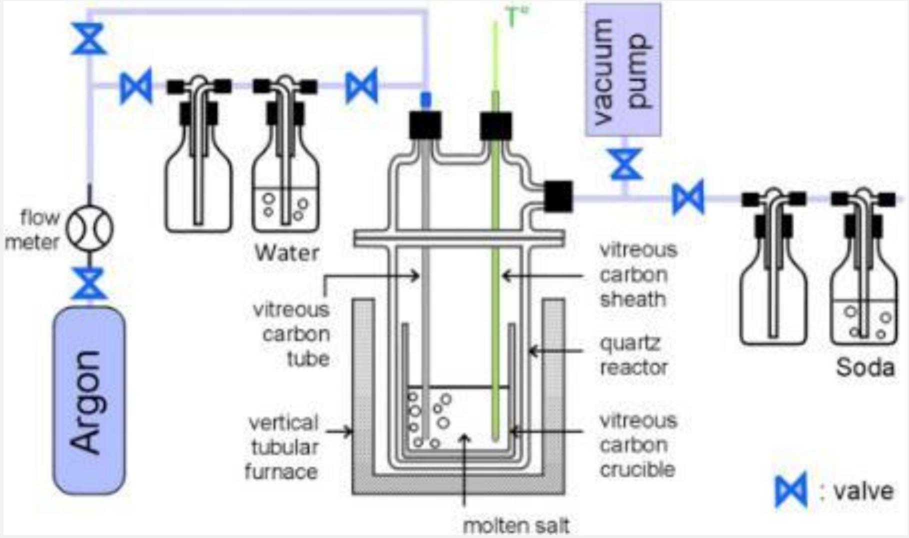
The features enabling selective separation

Rare-earth dissolved in the fuel form oxides and oxychlorides, which are far less soluble in the molten salt and have higher density than the surrounding melt, causing them to settle out and allowing the purified salt to be removed

MSR fuel cycle: USABLE
used in fuel processing to remove rare earth fission products from the salt after recovery of uranium and plutonium.



CHO et al., *Eutectic(LiCl-KCl) Waste Salt Treatment by Sequential Separation Process*, NUCLEAR ENGINEERING AND TECHNOLOGY, VOL.45 NO.5 OCTOBER 2013

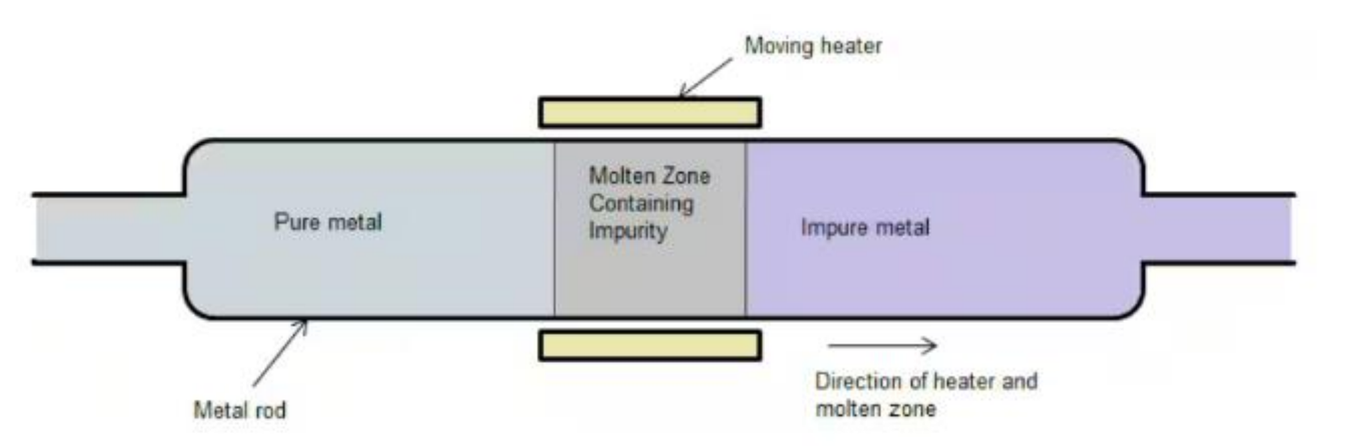


J.-F. Vigier et al., *Uranium (III) precipitation in molten chloride by wet argon sparging,* Journal of Nuclear Materials 474 (2016) 19-27

Zone-melting / Melt crystallisation process

Principle of the method

A molten salt is gradually solidified under controlled temperature conditions. As the solidification front moves, components with lower solubility in the solid phase (e.g., Cs and Sr) are concentrated into the liquid melt.



Visualization of the zone-refining process on an example of metal purification

The features enabling selective separation

Differences in solubilities of the impurities between the solid (i.e. crystal) and melt phases during the partial crystallisation of multi-component melts.

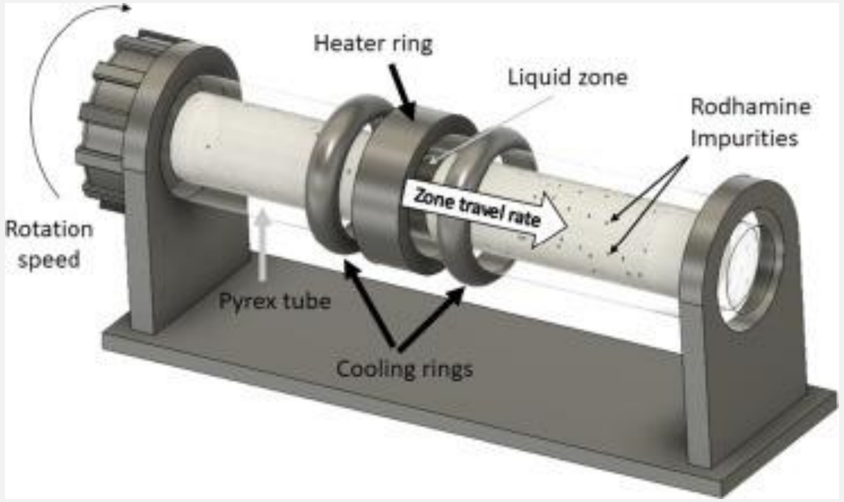
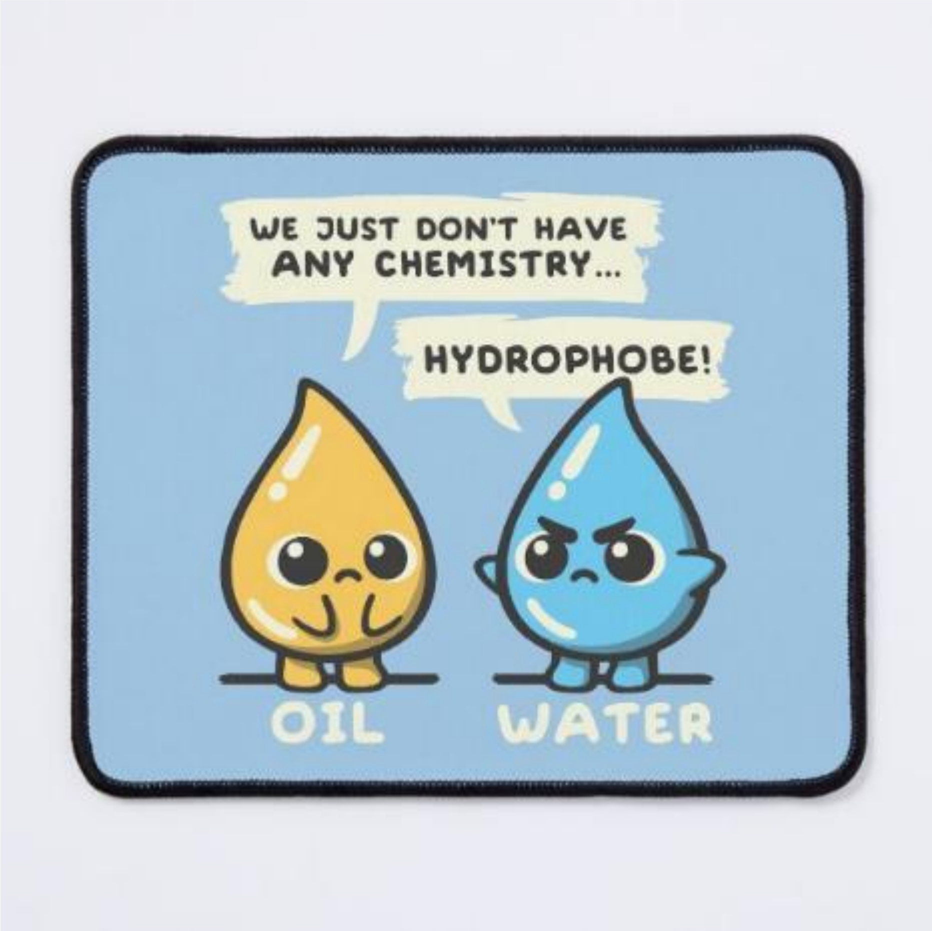


Illustration from: C.H. Silva-Santos, et al. Separation and Purification Technology 234 (2020) 116089

MSR fuel cycle: likely **USABLE** for Cs and Sr removal from the salt (shown by Y.-Z. Cho et al. for purification of LiCl melt from Cs and Sr)

J. Ulrich, M. Neumann, Journal of thermal analysis, 48 (1997) 527-533
Y.-Z. Cho, et al., Nuclear Technology, 171 (2010) 325-334
Y.-Z. Cho, et al., Energy Procedia, 7 (2011) 525-528

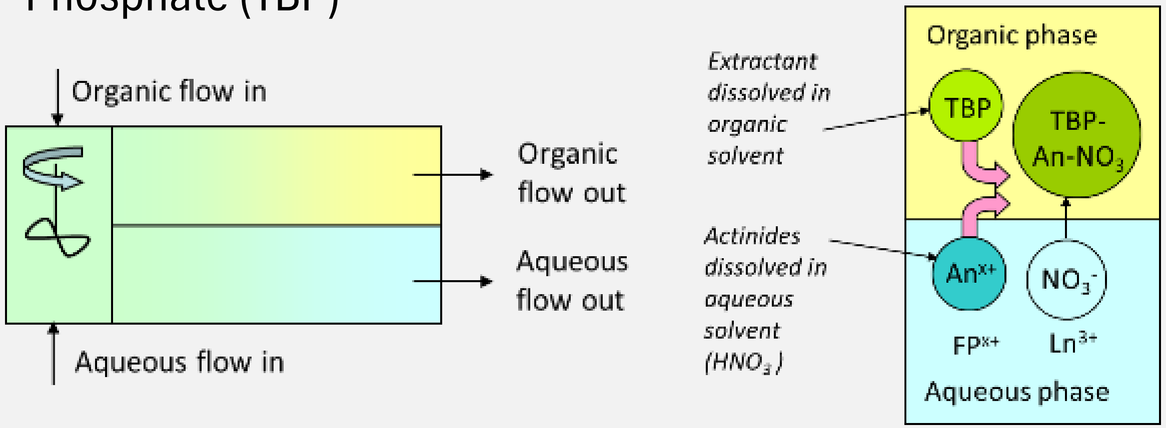


3. Aqueous separation method

- Why reprocess Molten Salt Reactor fuel?
- Examples of Molten Salt Reactor fuel cycles

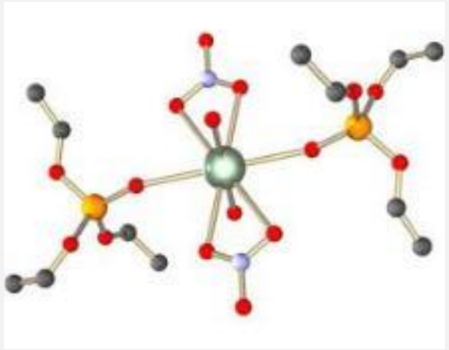
Hydrometallurgical method : Aqueous solvent extraction

Industrial process for recovery of U and Pu from the spent fuel:
PUREX – Plutonium and URanium EXtraction by Tri-Butyl-Phosphate (TBP)



The La Hague site in northern France (Image: Orano)

Country	Site	Status	Capacity
France	La Hague (UP2-800, UP3)	Operating (civil commercial)	1,700 tHM/yr
Russia	Mayak (Ozersk) / RT-1	Operating (smaller scale)	400 tHM/yr nominal
Japan	Rokkasho-mura	Under construction	Design ~800 tHM/yr
India	Tarapur & Kalpakkam	Operating (PHWR fuel)	100 + 100-150 tHM/yr
China	Lanzhou	Planned / pilot	Planned 400-800 tHM/yr



Hydrometallurgical method : Aqueous solvent extraction

MSR fuel cycle: applicability investigated

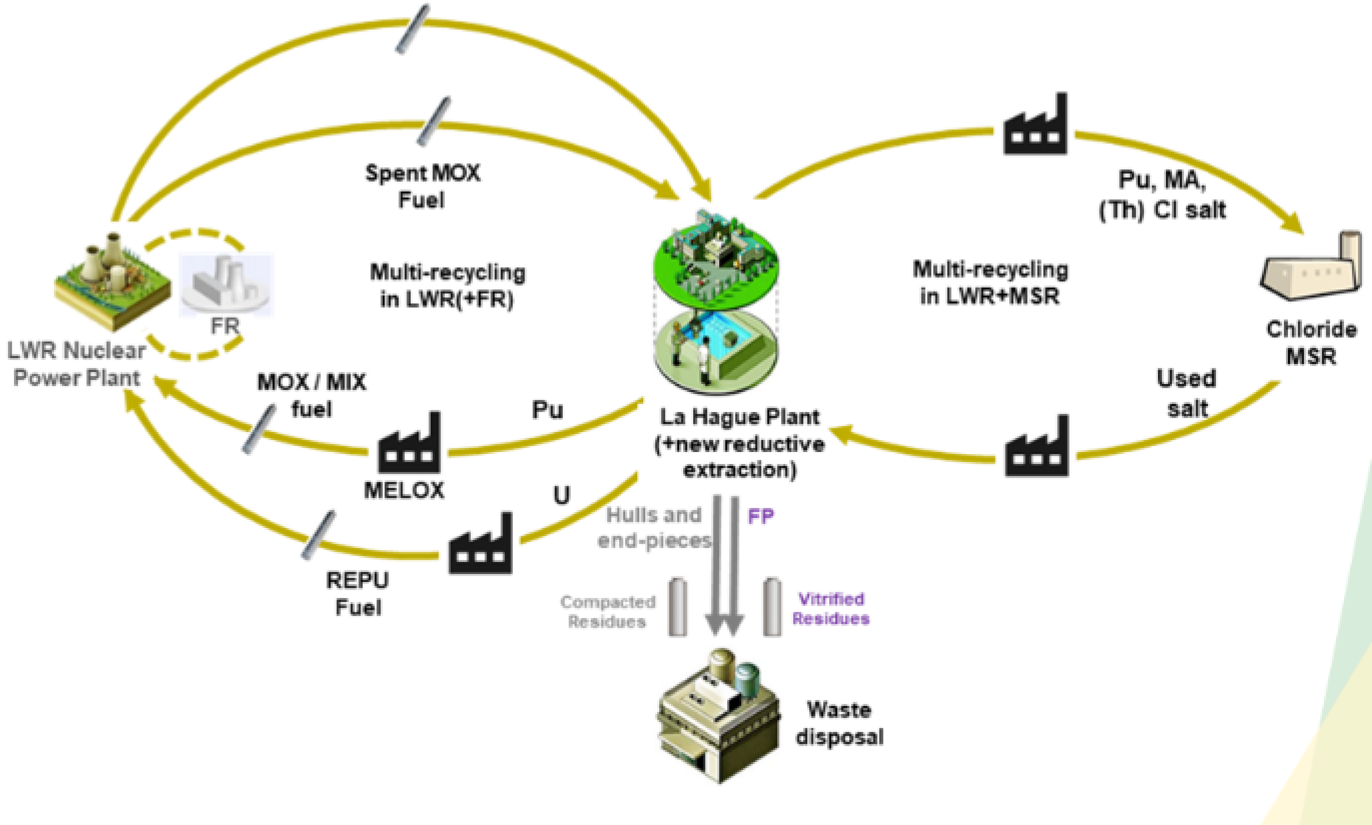
MIMOSA

Multi-recycling strategies of LWR SNF focusing on MOlten SAlt technology

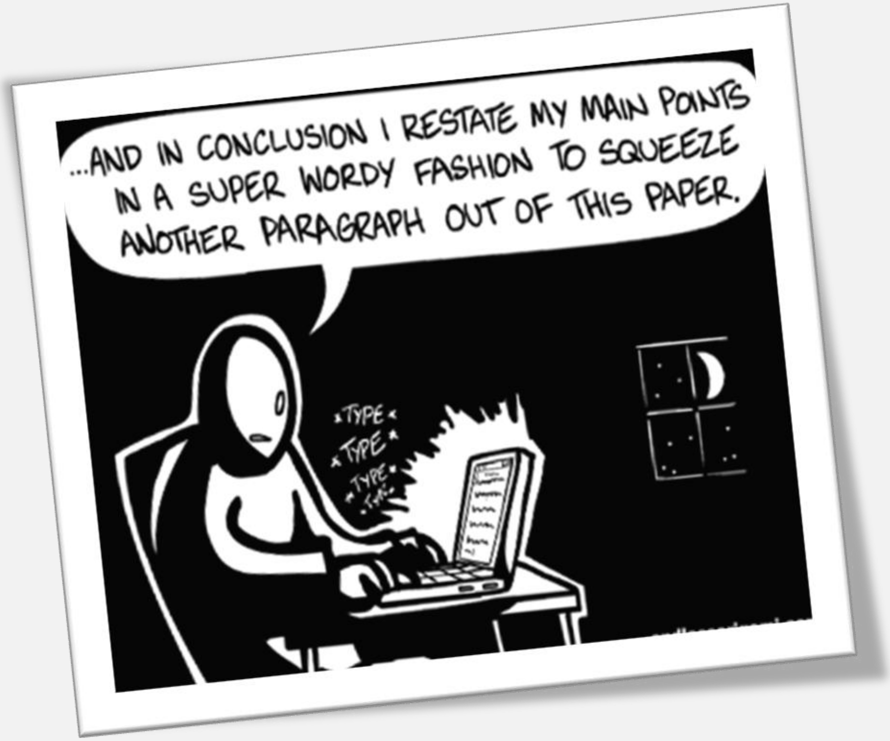
Project 101061142 – HORIZON-EURATOM-2021-NRT-01

MIMOSA aims to develop an **accessible and cost/risk optimized multi-recycling strategy of SNF from LWR in the EU** that:

- ✓ is based primarily on **multi-recycling of Pu and reprocessed U in LWRs**, combined with one of the most promising advanced nuclear energy systems, **Fast Cl MSR**,
- ✓ **optimizes costs and risks** by using already available infrastructure in the EU such as the Orano reprocessing plant in La Hague (France),
- ✓ maintains and develops the EU's knowhow on the safe management of radioactive waste.



MIMOSA overall concept



4. Summary

- Comparison of all mentioned methods
- EUROMOST'26 conference announcement

Summary

Method	Principle	Property governing selectivity	Separated elements	MSR applicability
Gas extraction process (He bubbling)	Bubbling or sparging the salt with inert gas	Solubility of gas in the melt	Noble gases (Xe, Kr) and insoluble noble metals	YES
Fused salt volatilization	Fluorination / chlorination of the melt	Volatility	Uranium, possibly Pu in fluoride melt	YES
Electrorefining	Electrochemical dissolution and deposition in molten salt	Electrochemical stability (red-ox potential, activity coefficient in the melt)	U, Pu, MA	NO
Electrowinning	Electrochemical reduction of species dissolved in molten salt		U, Pu, MA	YES with limits
Reductive Extraction	Chemical reduction of species dissolved in molten salt	Chemical stability (activity coefficient)	U, Pu, MA, RE	YES with limits
Oxidative Precipitation	Oxidation of dissolved species to form insoluble oxides	Solubility of oxides in molten salt	Actinides, RE in chlorides	YES
Melt crystallization	Gradually solidification under controlled temperature	Solubilities in the salt and melting points	Sr, Cs	YES
Aqueous solvent extraction	Transfer of species between aqueous and organic phases	Affinity to aqueous and organic phases	U, Pu MA, RE – under development	Is evaluated

1st European Conference on MOLTEN SALT REACTOR TECHNOLOGY

Announcement

EUROMOST 26’

26.05. - 29.05.2026

Heidelberg, Germany

- 1st European Conference purely dedicated to MSR technology
- For all partners involved in the MSR field (researchers, industries, SMEs, regulators, standard organizations, government representatives, international organizations, etc.)
- Key topics include:

  - Reactor design and innovation
  - Materials science and fuel cycle technology
  - Thermal-hydraulics and safety analysis
  - Regulatory frameworks and deployment strategies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