Interregional Workshop on Aspects of Modelling and Simulation in Gen-IV Type SMR Development
IAEA-ROSATOM

Molten Salt Reactors: Prospects and problems

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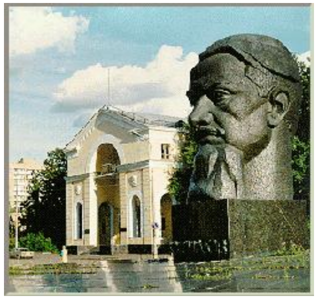


3-7 November 2025

INTERNATIONAL INNOVATIVE PROJECTS (INPRO) OF THE IAEA ON THE DEVELOPMENT OF NUCLEAR POWER PLANTS AND NUCLEAR FUEL CYCLE FOR FUTURE NUCLEAR ENERGY

The INPRO methodology is a tool that can be used:

To analyze the INES for its ability to meet the requirements of sustainable development;

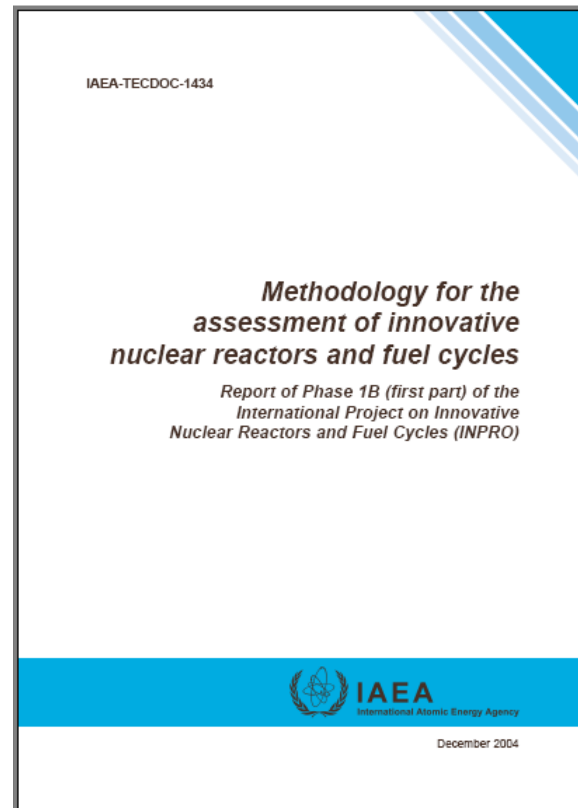
To compare different INES to find preferred or optimal INES meeting the requirements of a given state;

To determine the research, development and demonstration facilities required to improve existing installations and new construction of missing components INES.

The assessment should include all components of the INES system in order to gain a holistic vision and ensure that the system meets the requirements of sustainability.

INPRO methodology

IAEA-TECDOC-1434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Methodology for the assessment of innovative nuclear reactors and fuel cycles

Report of Phase 1B (first part) of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

IAEA
International Atomic Energy Agency

December 2004

2

User requirements
Basic principals
Guides, rules

Energy source
U-238
Th-232

Neutron
source
U-235
D
Li

INS:

- NFC enterprises
- Thermal reactors
- Fast reactors
- Burner reactors
- Fusion neutron source

Fission
products,
Useful radio
nuclides,
Energy

Non nuclear recourses

ROLE OF DIFFERENT REACTOR TYPES

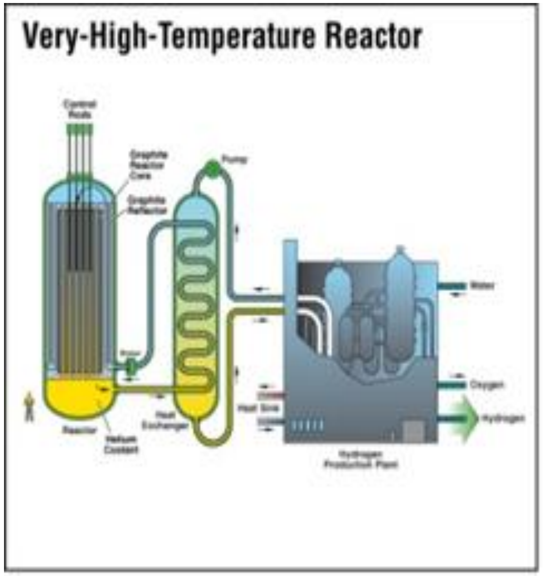
Thermal neutron reactors: energy generation for various consumers (electricity, district heating, technologies, hydrogen); wide capacity range (SMR – regional/autonomous applications, large reactors – grid applications); operation in load maneuvering mode; flexible fuel cycle (Pu, U, Th).

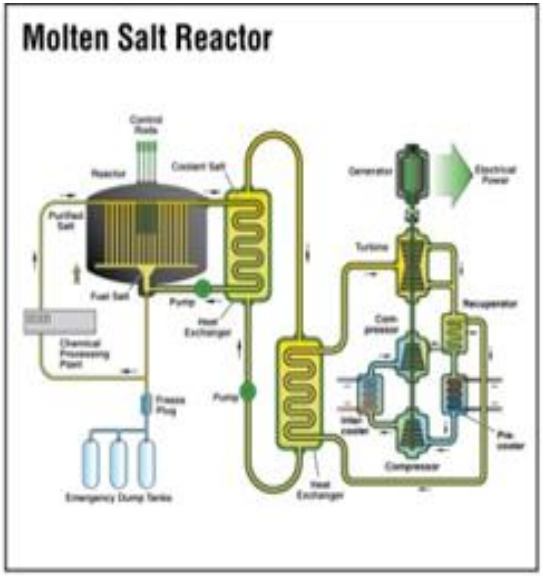
Fast neutron reactors (FR): basic energy generation; fuel breeding (Pu, U-233); nuclear fuel cycle closing by U, Pu and minor actinides.

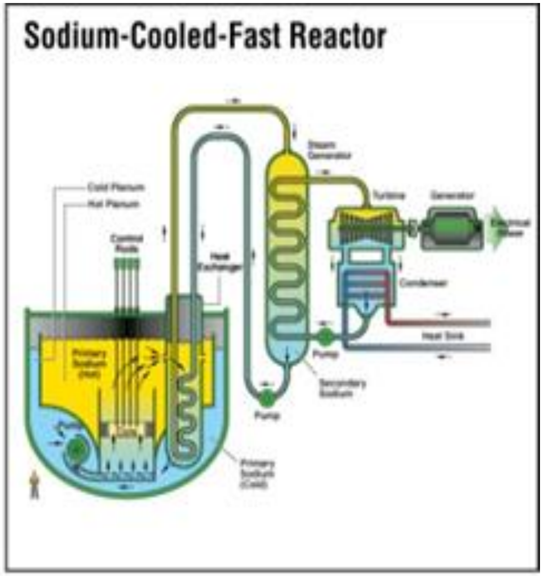
Liquid-fuel reactors intended for minimizing the amounts of minor actinides within the system could be required by 2050 at the earliest, in case no acceptable ways would be found by then to dispose of minor actinides or utilize them in solid-fuel reactors.

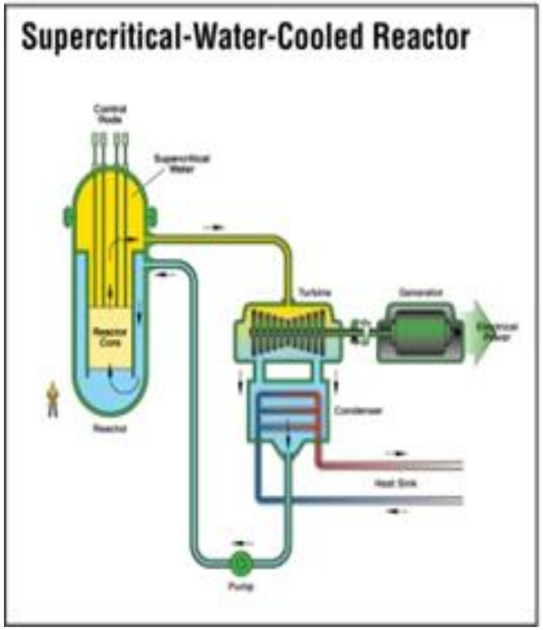
Fusion neutron sources (FNS): increasing the rates of Th-232 and U-238 involvement in the nuclear fuel cycle; increasing the neutron potential of the NES; most likely, FNS would be required in the maximum nuclear energy development scenario;

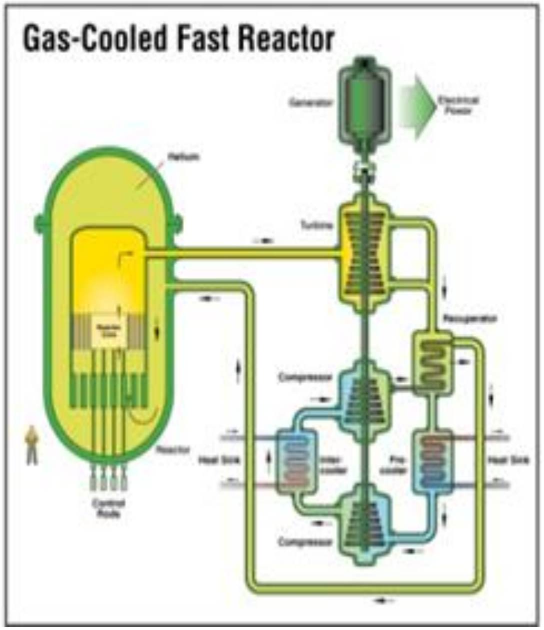
GENERATION 4 REACTORS

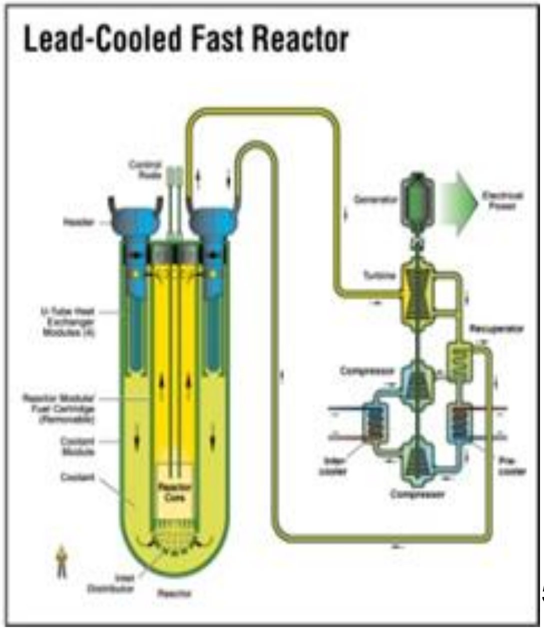












THE HISTORY OF MSR

ARE reactor (1954, Oak Ridge, USA) of kW-MW power, as a fuel composition (FC), the $NaF-ZrF_4-UF_4$ system (53-41-5 mol.%) was used at max operating temperature of 860 ° C.

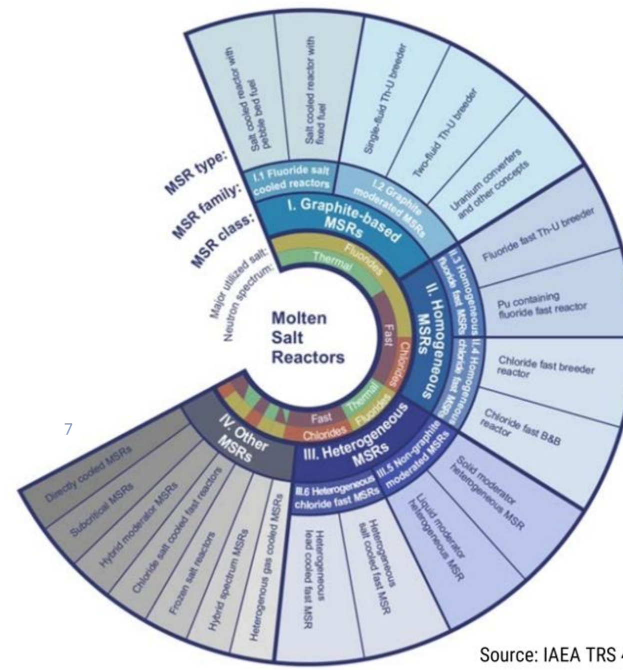
The MSRE reactor (Molten Salt Reactor Experiment) with a capacity of 7.4 MW used FC composition $^7LiF-BeF_2-ZrF_4-UF_4$ (65-30-5-0,1 mol.%) at a temperature of 650 °C and worked for 5 years (January 1965 - December 1969) on both ^{235}U and ^{233}U.

At this reactor, it was confirmed the operability of all the main components of the MSR: pumps, heat exchangers, a system for cleaning from gaseous radioactive waste, the corrosion activity of FC, etc.

In MSR devices solid fuel elements are replaced by liquids

Chemical engineering device has not only possibilities of general benefits such as unlimited burn-up, easy and relatively low cost of purifying and reconstituting the fuel (fluid), but also there are other specific potential gains:

- Minimum number of parasitic absorbers and as a consequence less loading of fissile materials in the core;
- On-site fuel processing - no temporary storage is required to hold UNF, transportation of UNF and fuel loading for the next transmutation cycle;
- Multiple actinides recycling with minimal losses to waste;
- Flexibility in operation, deployment and product, including the ability to work: with fuels of various nuclide composition without reactor shutdown and core modifications; in load follow mode; with high thermal efficiency, due to the fuel salt temperature >700°C, for electricity and hydrogen production



Source: IAEA TRS 489

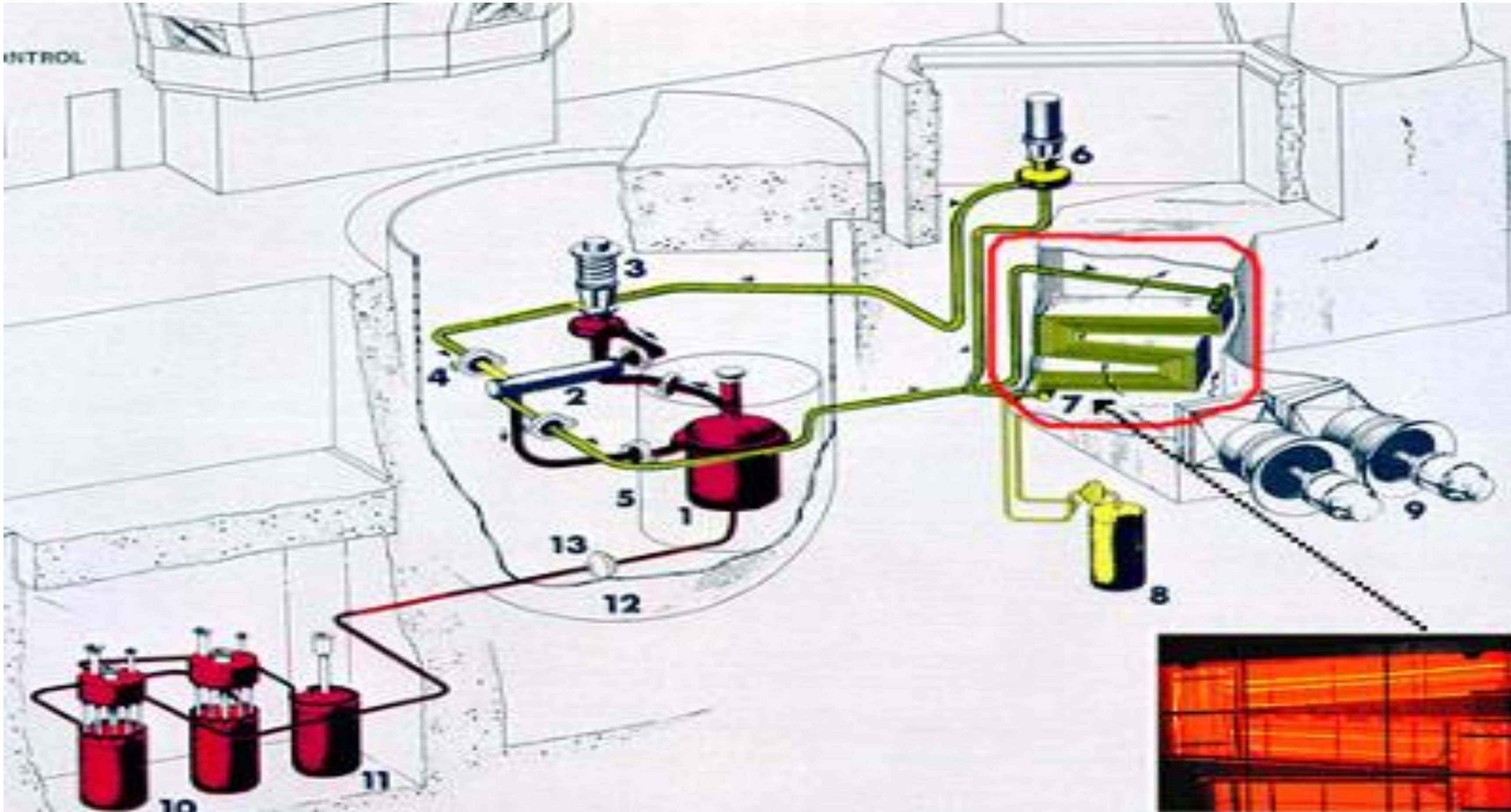
Liquid fuel MSR makes the following possible:

- minimize the initial reactivity excess, which in solid-fuel reactors is compensated by control rods;
- maintain low pressure in the fuel by removing gaseous FP’s from it;
- reduce the amount of fission products and decay heat in the fuel salt.

The radiation safety of MSR is determined by reliable sealing of the actinides and fission products within the reactor circuit and by an effective system for fuel processing.

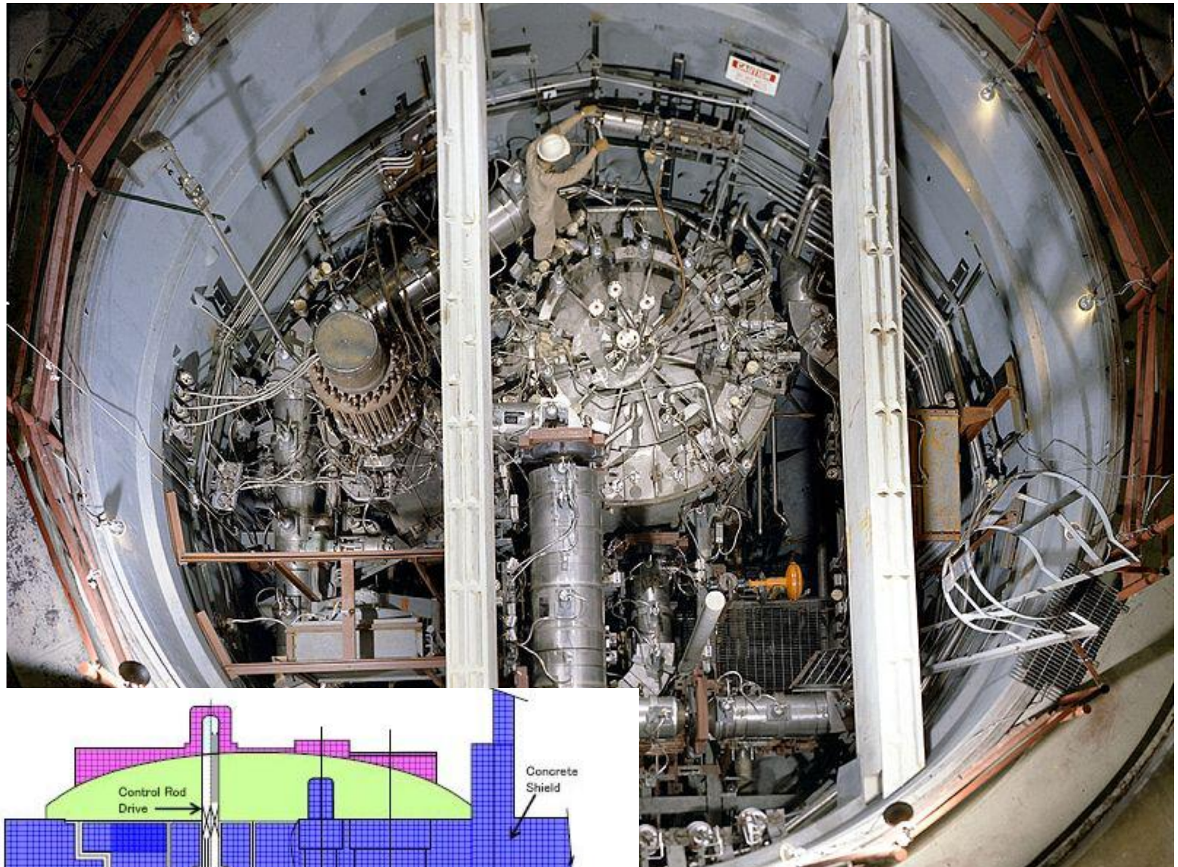
The capacity of the fuel salt mixture to retain many dangerous radionuclides in a wide range of the physical parameters, which are characteristic for emergency modes and disruption of normal operation, also is playing an important role.

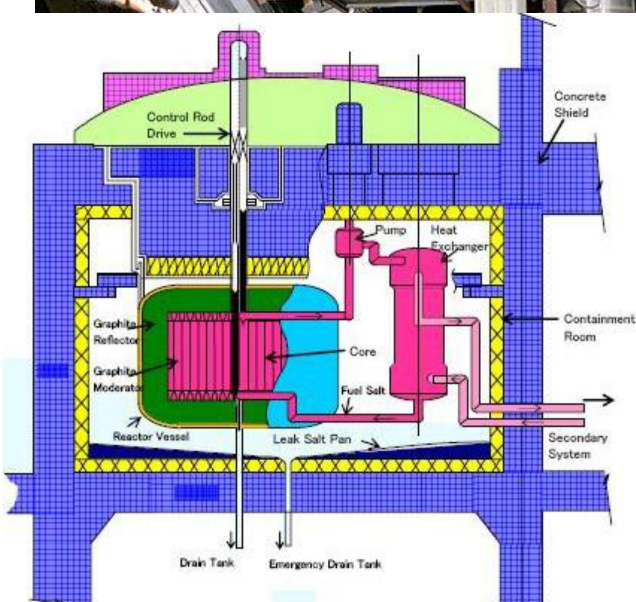
MSRE SCHEME



1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

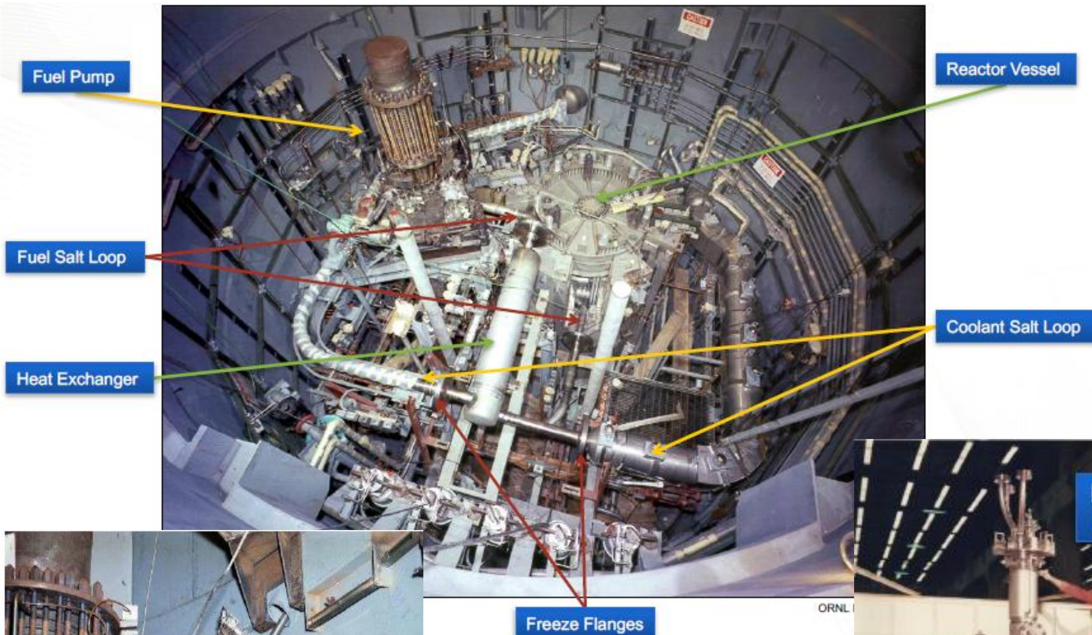
GENERAL VIEW OF MSRE

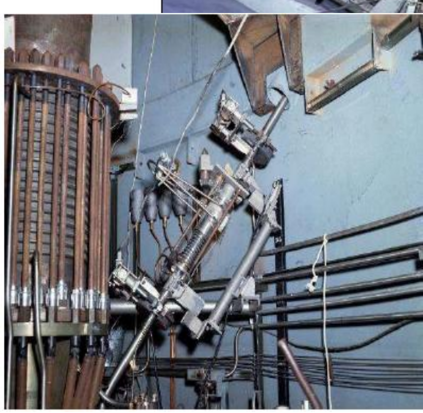


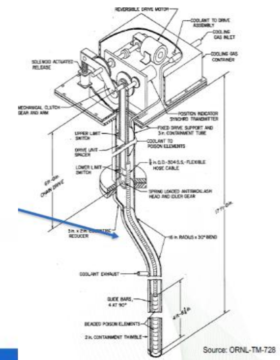


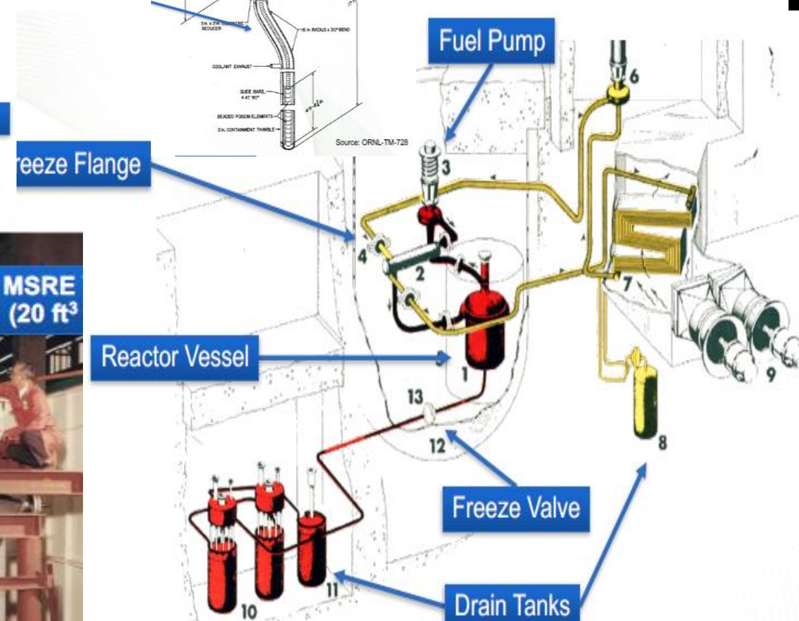
Core of MSRE

8MWt Li,Be,Zr,U/F MSRE, US ORNL









1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield,
6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks,
11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

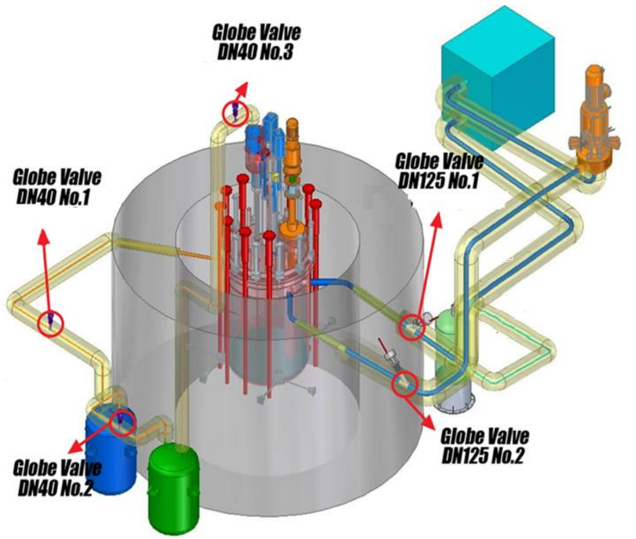
MSBR

The design of the MSBR reactor (Molten Salt Breeder Reactor)with a capacity of 1 GW (electric) was developed in 1971. It was planned to use FC 7LiF-BeF2-ThF4-UF4(72-16-11,7-0.3 mol.%), and graphite is the moderator.

The neutron spectrum of all these reactors is thermal, and all MSR projects in the 70s were closed in favor of sodium cooled reactors, since by that time advantages of fast neutron spectrum for solving the breading problem had become clear.

ORNL Director and MSRE and MSBR Project Manager A. Weinberg was forced to resign as a result.

2MWt Li,Be,Th,U/F TMSR-LF1, CAS, China



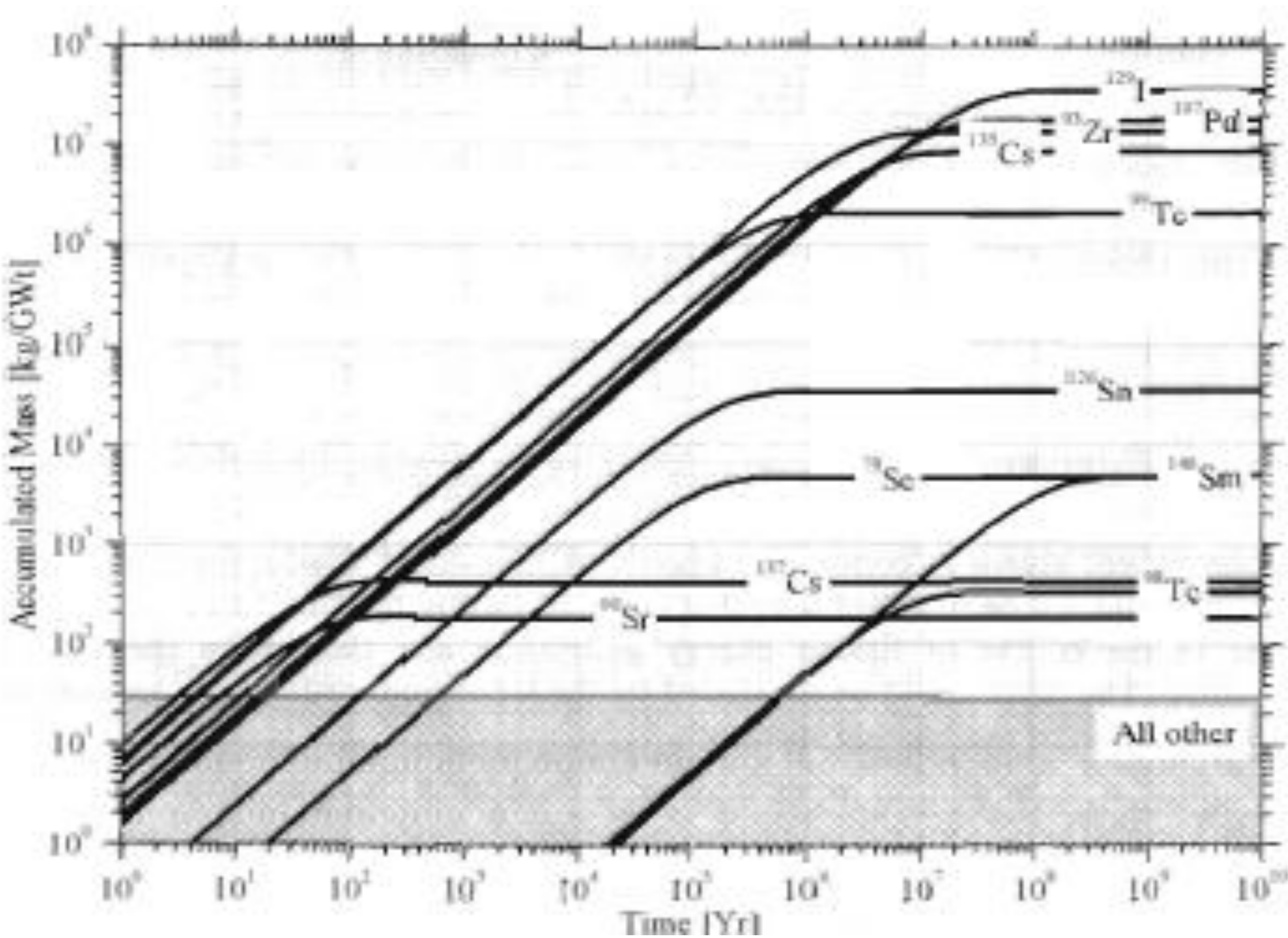
- At 11:08 on October 11, 2023, TMSR-LF1 achieved first criticality.
- At 12:10 on June 17, 2024, 2MWt full power operation was achieved.
- On October 8, 2024, TMSR-LF1 operated at full power for 10 days with thorium fuel, and Pa-233 was detected

FUNDAMENTAL ADVANTAGES OF MOLTEN SALT REACTORS:

- Autonomy in terms of the inherent possibility of organizing a technological process with only thorium-232 supply and unloading only fission products.
- Production of a wide range of stable and radioactive nuclides.
- No reactivity accidents.
- The use of gamma radiation for the organization of various technological processes.

But all this requires a higher level of culture, both technology and radiation safety.

ACCUMULATION OF FISSION PRODUCTS (M.SAITO...) IN THE NE SYSTEM



Possible options for accumulation of nuclides in nuclear energy system
Closure of the NFC by the required nuclide

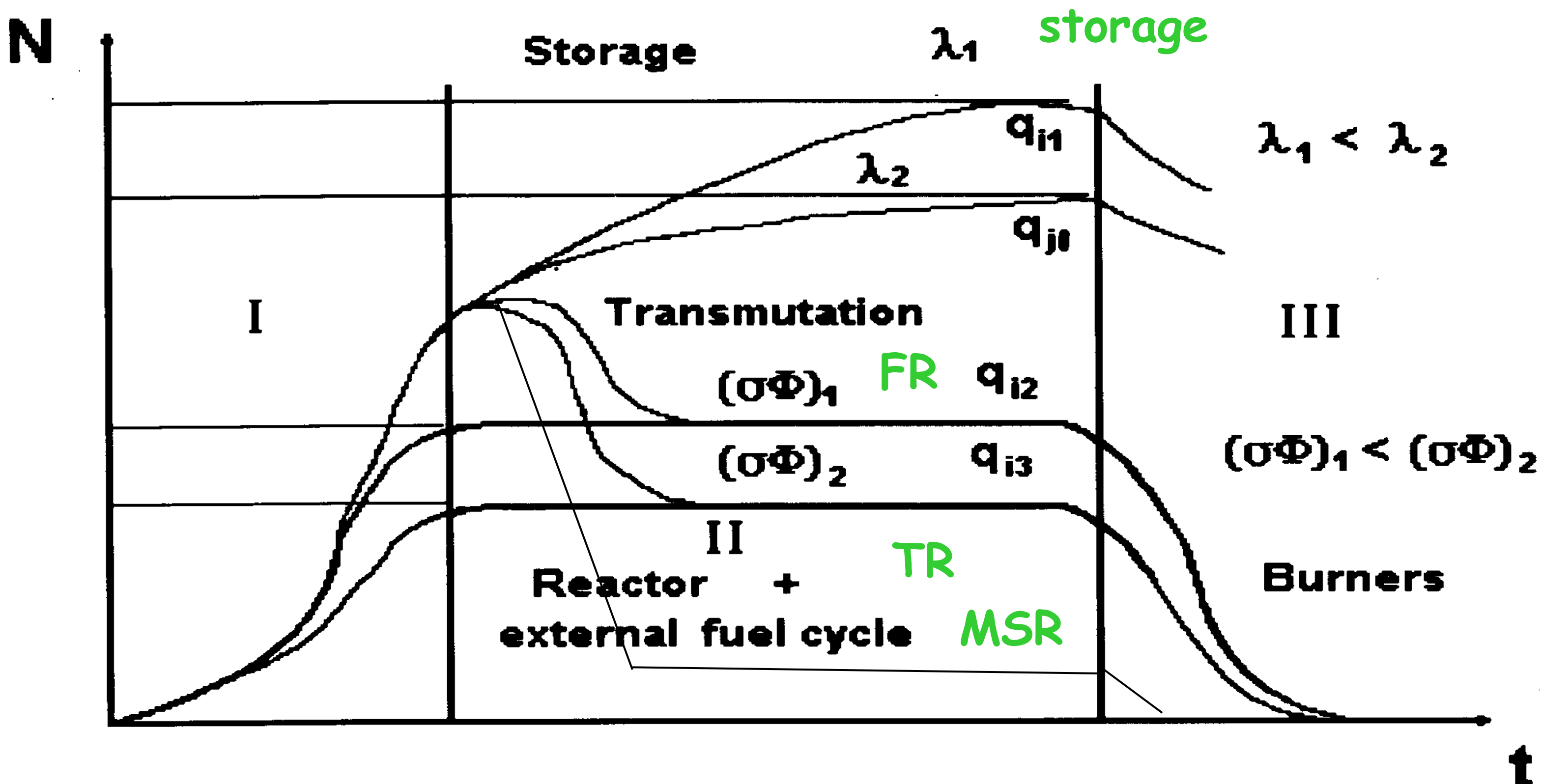


Fig.3. The typical fates of radionuclide

The "fate" of artificial radionuclides
in nuclear energy system

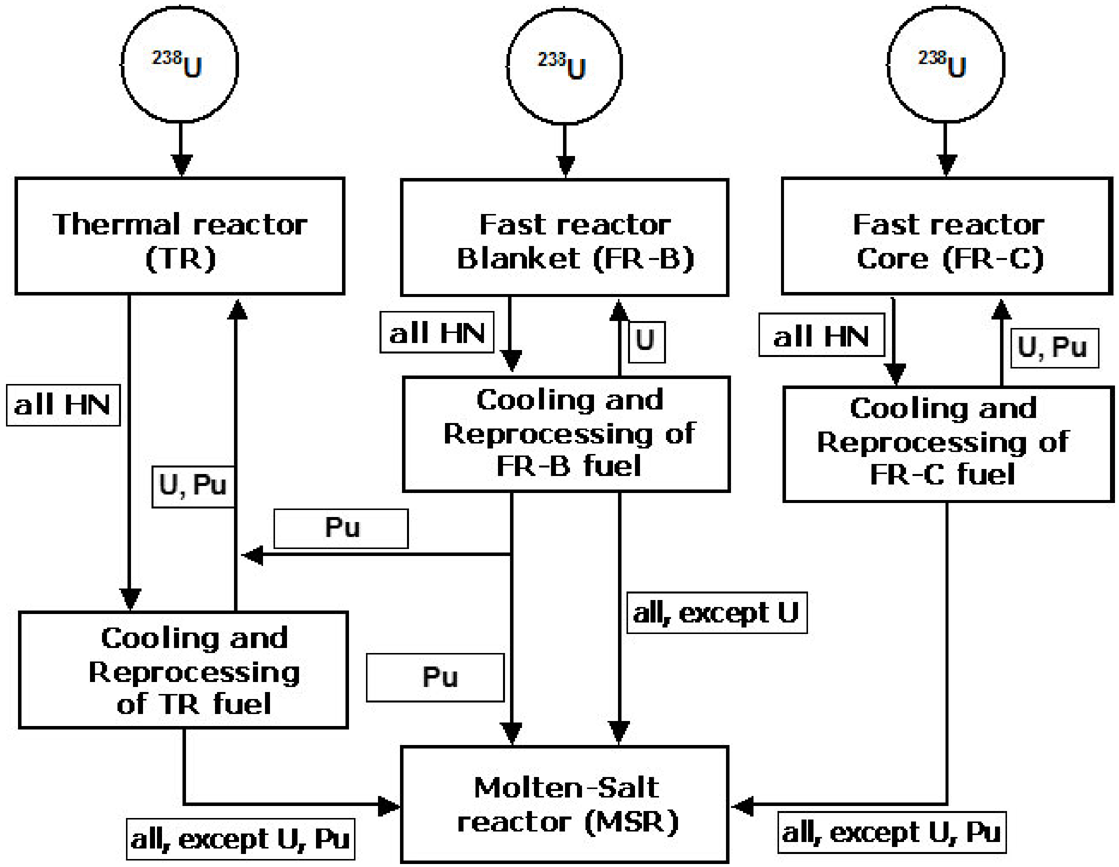
MSR – MA BURNERS

In the 90s, interest in MSR revived due to problem of utilization of minor actinides (MA) – Np, Am, Cm.

Since the proportion of delayed neutrons during fission is small (β=0.17%), subcritical variants of MSR were mainly considered.

In particular, it was shown that on this way, it is possible to create a MSR-burner MA with capacity of ~300 kg Am/GW (heat) year, i.e. one such reactor is capable of destroying MA from SNF ~ 10 VVER-1000 reactors.

Structure of INES for uranium-plutonium nuclear fuel cycle



Share of reactor power in the system

59% TR

33% BR

8% MSR

The amount of fuel for 1 GW(e)

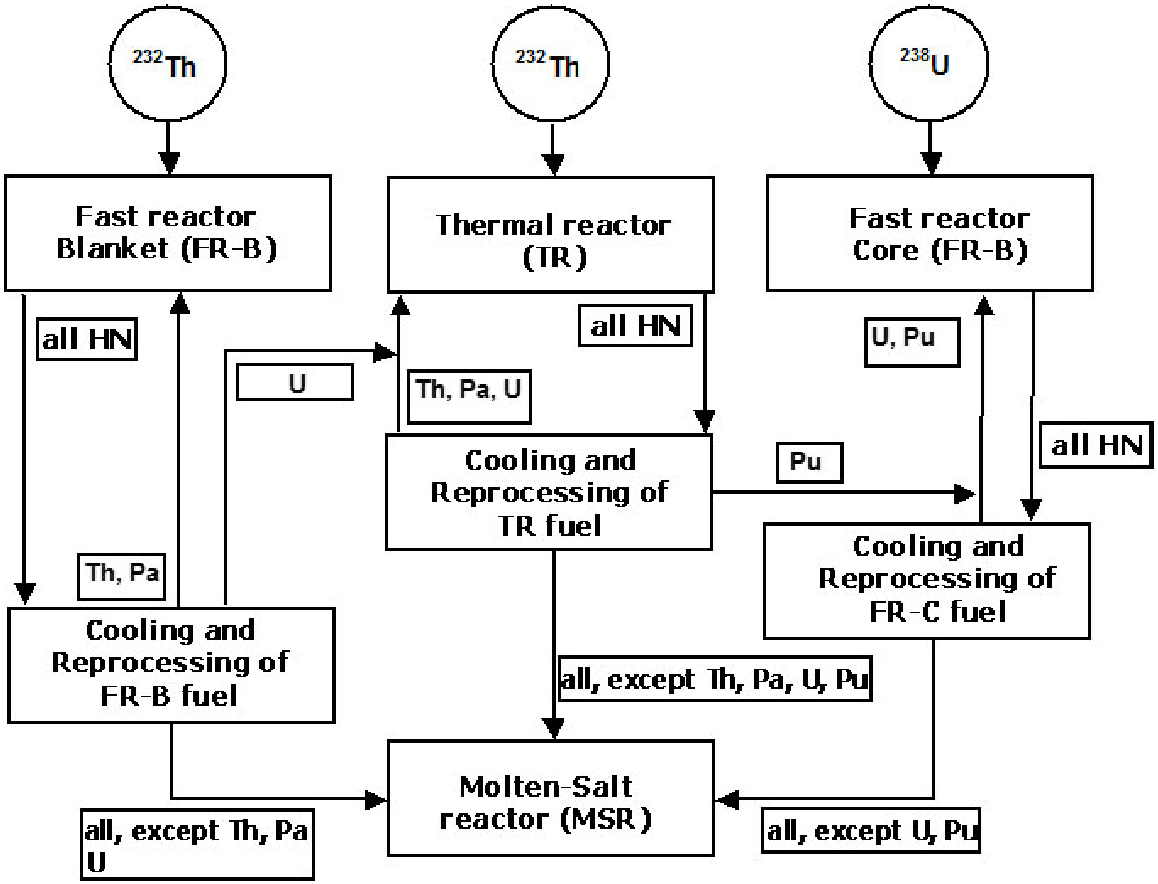
Total in INES

285.0 t

In the external NFC

175.3 t

Structure of INES for uranium-plutonium-thorium nuclear fuel cycle



Share of reactor power in the system

88% TR

9% BR

3% MSR

The amount of fuel for a INES for 1 GW(e)

Total in INES

136.2 t

In the external NFC

87.8 t

MSR Designs Discussed at GIF Meetings

- R&D studies are on-going in order to verify that fast spectrum MSR systems satisfy the goals of Gen-IV reactors in terms of sustainability, non-proliferation, safety and waste management.
- Two fast spectrum MSR concepts are being studied, large power units based on cavity type core with liquid fluoride-salt circulating fuel: Th-U MSFR design in France, Euratom and Switzerland as well as TRU MOSART concept in the RF.
- China is working on TMSR (Thorium Molten fluoride Salt thermal Reactor) graphite moderated design.
- Japan, and South Korea are focused on the development of the small and medium power liquid fuel units with thermal spectrum graphite moderated cores.

List of the selected liquid fuel systems

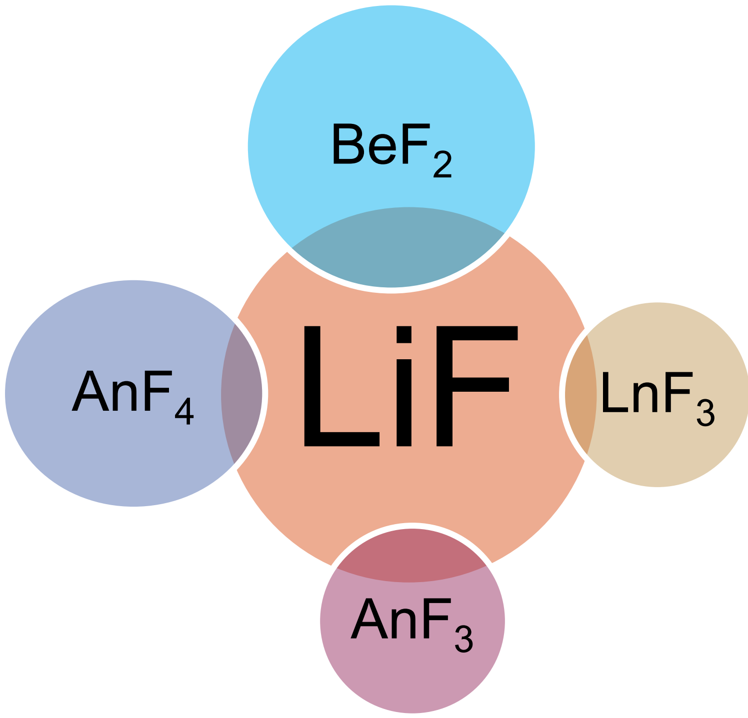
Name	Developer	Power, MWt	Fuel / Carrier / Moderator
Thermal Spectrum MSRs			
Thorium Molten Salt Reactor - Liquid Fuel (TMSR-LF)	SINAP, China	395	ThF_4-$^{233}UF_4$ / ^7LiF-BeF_2 /Graphite
Integral Molten Salt Reactor (IMSR)	Terrestrial Energy, Canada and USA	400	UF_4 / Fluorides / Graphite
ThorCon Reactor	ThorCon International, Singapore	557×2	ThF_4-$^{233\text{-}235}UF_4$ / NaF-BeF_2 / Graphite
Liquid-Fluoride Thorium Reactor (LFTR)	Flibe Energy, USA	600	ThF_4-$^{233}UF_4$ / ^7LiF-BeF_2 / Graphite
FUJI-U3	Japan	450	ThF_4-$^{233}UF_4$ / ^7LiF-BeF_2 / Graphite
Compact Used fuel BurnEr (CUBE)	Seaborg Technologies, Denmark	250	SNF /Fluorides / Graphite
Process Heat Reactor	Thorenco, USA	50	UF_4 / NaF-BeF_2, / Be rods
Stable Salt Thermal Reactor (SSR-U)	Moltex Energy, UK	300-2500	UF_4 /Fluorides / Graphite

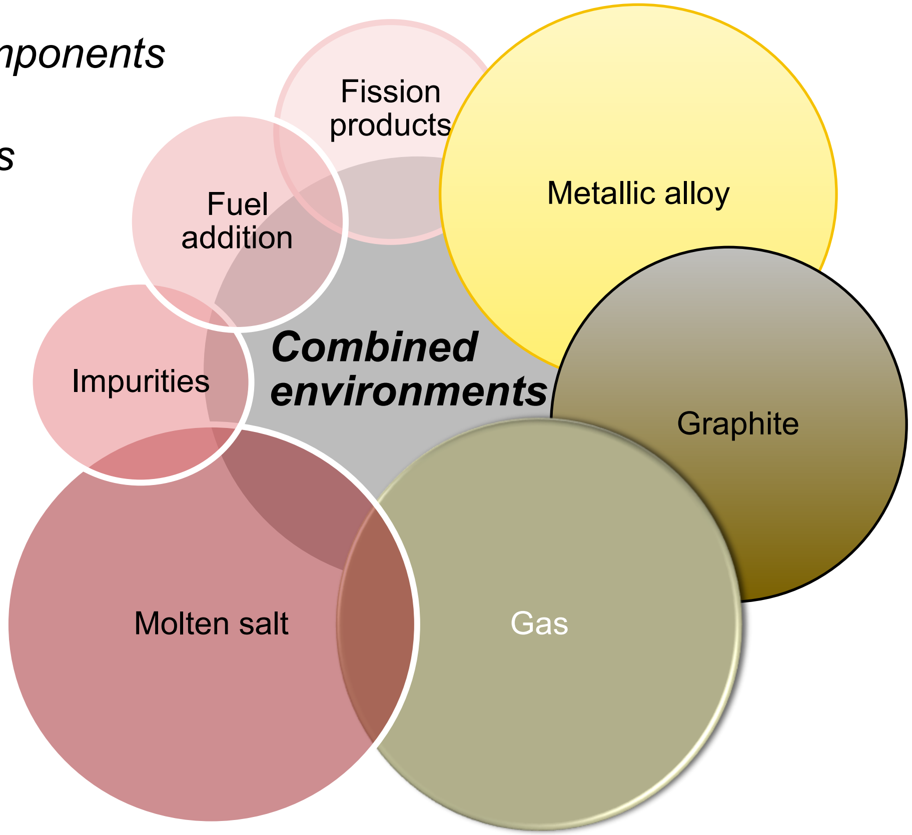
List of the selected liquid fuel systems

Name	Developer	Power, MWt	Fuel / Carrier / Moderator
Fast/Epithermal Spectrum MSRs			
Molten Salt Fast Reactor (MSFR)	France – Euratom	3000	ThF_4-UF_4 / ^7LiF
Molten Salt Actinide Recycler and Transformer (MOSART)	Kurchatov Institute, Russia	2400	$TRUF_3$ or ThF_4-UF_4 / ^7LiF-BeF_2 or NaF-^7LiF-BeF_2
Fast Molten Salt Reactor (FMSR)	VNIINM, Russia	1500	$TRUF_3$ / ^7LiF-NaF-KF
Indian Molten Salt Breeder Reactor (IMSBR)	BARC, India	1900	ThF_4-UF_4 / LiF-
Stable Salt Fast Reactor (SSR-W)	Moltex Energy, UK	750-2500	PuF_3 / Fluorides
Molten Chloride Fast Reactor (MCFR)	TerraPower (USA)	30	U- Pu / Chlorides
Molten Chloride Salt Fast Reactor (MCSFR)	Elysium Industries (USA and Canada)	100-5000	U-Pu / Chlorides
Dual Fluid Reactor (DFR)	Dual Fluid Reactor, Germany	3000	U-Pu / Chlorides

In most cases the base-line fuel / coolant salt is lithium-based fluoride salt as it has best properties

- *Low neutron cross section for the solvent*
- *Thermal stability of the salt components*
- *Low vapor pressure*
- *Radiation stability*
- *Adequate solubility of fuel and FP's components*
- *Adequate transport properties*
- *Compatibility with construction materials*
- *Low fuel and processing costs*





Rationale for using MSRs for actinide burning from LWR used fuel is based on engineering, cost, and operational issues

Recycle and fabrication of minor-actinide solid fuels are very expensive and difficult.

Waste burning has large impacts on conventional reactors:

- **Complicates operations.**
- **High actinide inventory to reach acceptable destruction rate with added safety system requirements.**

Molten Salt Systems

- Add actinides to salt
- Actinides remain in salt until full burnout with lower actinide inventory than in other reactors
- Fission products removed from salt

R&D is required to define the best waste burning strategy

SOME PHENOMENA RELATED TO SAFETY:

• Stable / chemically inert fuel salt. **M**ixture of uranium or plutonium fluorides with other salts is used as fuel and coolant in MSR:

a. High boiling point temperatures;
b. Low vapor pressures;
c. High heat capacities;
d. Low chemical reactivity;
e. High radiation resistance

- Negative Reactivity Coefficient of Temperature for Rapid Response
- Low Pressure Operation
- Inherent fission product retention capability (Ce, I)
- Loss of primary coolant event is eliminated because fuel salt is also a coolant.
- Gaseous fission produced are continuously removed from the fuel salt.

Key R&D challenges for the MSR System in the coming 10-15 years

- Development of salt and material combinations (characterization and qualification).
- Development of integrated (physics and fuel chemistry) reactor performance modelling and safety assessment capabilities.
- Demonstration of the MSR safety characteristics at laboratory level and beyond.
- Establishment of a MSR infrastructure and economy that includes affordable and practical systems for the production, processing, transportation, and storage of radioactive salt constituents.
- Development of the MSR licensing and safeguards framework development.
- Progress towards MSR demonstration.

Soluble Fission Products

- Rb, Ce, Sr, Ba, Y, the lanthanides, and Zr all form quite stable fluorides that are relatively soluble in fuel salts.

- Bromine and iodine would be expected to appear in the fuel as soluble Br and I, particularly in the case where the fuel contains an appreciable concentration of UF_3.

- Analyses for ^{131}I showed that a large fraction of the iodine was present in the fuel and that ^{131}I deposited on metal or graphite surfaces in the core region. However, material balances for ^{131}I were generally low. It is possible that some of the precursor, ^{131}Te (25 min), was volatilized and sparged with the krypton and xenon. Further, ^{131}I produced by decay of ^{131}Te in complex metallic deposits (as in the heat exchanger) may not have been able to return to the salt.

Noble and Semi Noble Fission Products

- Some FP metals (Ge, As, Nb, Mo, Ru, Rh, Pd, Ag, Cd, Sn, and Sb) have fluorides that are unstable toward reduction by fuel mixtures with appreciable concentrations of UF_3; thus, they must be expected to exist entirely in the elemental state in the MSR. Selenium and tellurium were also expected to be present as elements within the reactor circuit, and this behavior was generally confirmed during operation of the MSRE
- Precipitation on the metal surface (most of which is in the heat exchanger) will be quite insufficient to impede fuel flow, but radioactive decay of the deposited material contributes to heat generation during reactor shutdown
- Operation of the MSRE did produce one untoward effect of FPs. These studies implicated tellurium FP as responsible for the embrittlement of the metal surface exposed, and subsequent work has confirmed this. Later work strongly suggest that (1) if the molten fuels were made to contain as much as 2-5% of the uranium as UF_3, the tellurium would be present as Te^{2-} and (2) in that form, tellurium is much less aggressive

Noble-gas Fission Products

- Kr and Xe form no compounds under conditions existing in a MSR. Moreover, these gases are only very sparingly soluble in molten fluoride mixtures. This low solubility is a distinct advantage because it enables the ready removal of Xe and Kr from the reactor by sparging with helium.

- The transmutation of Li is essential for production of tritium. This tritium will originate in principle as ^3HF; however, with appreciable concentrations of UF_3 present, this ^3HF will be reduced largely to $^3H_2$. Some of this $^3H_2$ would be removed, along with krypton and xenon, by sparging with helium. However, the extraordinary ability of hydrogen isotopes to diffuse through hot metals will permit a large fraction of the $^3H_2$ to penetrate the primary heat exchanger to enter the secondary coolant.

- Such a stripping circuit would remove an appreciable (but not a major) fraction of the tritium and a small (perhaps very small) fraction of the noble and semi noble fission products as gas-borne particulates.

CONCLUSION

Globalisation of Nuclear Power Development are:

- More international cooperations
- Progress in multilateral framework
- Competition on short term issues
- Cooperation on long-term ones (sustainability, non-proliferation, safety, security)

Thank you for attention!

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